A REVIEW ON THE ROOIBOS TEA INDUSTRY AND THIN-LAYER DRYING LITERATURE

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ABSTRACT

Rooibos tea is a uniquely South African product whose market growth has been aided recently by the rising worldwide demand for health-conscious and natural or organic products. Rooibos has many health benefits, some of which include high anti-oxidant levels (believed to combat cancer), lower tannin content than black tea and no caffeine contents. Although the majority of rooibos tea is exported, the international opinion of the rooibos industry has been damaged by the variability in availability and quality of the product. This is due mainly to the reliance of post-harvest processing on weather conditions.

Rooibos tea is made by fermenting and drying freshly harvested leaves. The current industry norm is the use of uncontrolled or open sun fermentation and drying. The fermentation process is important in order to develop the characteristic taste and aroma and drying is needed to preserve by preventing microbial growth. These two processes are the main inhibitors that produce the inconsistency in availability and quality that negatively affects the products international reputation.

Because there is much research into fermentation, this study will focus on the drying aspect of rooibos tea production. Due to the many complexities in dehydration, simplifications and assumptions are applied to mathematical data to provide workable analytical solutions. Of particular practical importance is the concept of thin-layer drying. Thin-layer drying assumes that there is no temperature gradient within the product column, an assumption only valid when the product is arranged in a one particle layer during drying. This is then categorised into three types of models including theoretical, semi-empirical and empirical. These models and their derivations are reviewed here to provide awareness of the assumptions made and to gain an understanding of current accepted scientific norms. These will provide a good framework on which to apply these to the drying of rooibos tea.

Although research will be conducted on a hot air tray dryer, an overview of the current drying technology has been summarised to put the study into context. A look at methods used to improve energy efficiency is included. The main objectives of this study therefore are to generate drying data under different drying air conditions, optimise coefficients for selected drying models and determine energy use in the drying process at different drying conditions.

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NOMENCLATURE

If no units are defined, symbol is dimensionless.

Psychrometry

Note: there is no standard nomenclature for psychrometric terms so the symbols represented here may differ in literature.

Subscripts

a – air

w – water

t – total (water+air)

ha – humid air

s - saturated

Symbols

P – pressure $[Pa]$

V – volume $[m^3]$

T – Temperature $[K]$

M – Molar Mass $[g.mol^{-1}]$

R – Gas Constant of Air $[m^2.s^{-2}.K^{-1}]$

C_p – specific heat capacity $[kJ.kg^{-1}.K^{-1}]$

$\emptyset$ - Humidity Ratio/Specific Humidity

m – mass $[kg]$

x – mole fraction

n – mole $[mol]$

φ – relative humidity [%]

h - specific enthalpy $[J.kg^{-1}]$

ΔH_{V_0} – latent heat of vapourisation at T_0 $[J.kg^{-1}]$

Thin-layer drying

MC – Moisture content

wb – wet basis

db – dry basis

J – mass flux $[kg.m^{-2}.s^{-1}]$

D – diffusivity $[m^2.s^{-1}]$

c – concentration $[kg.m^{-3}][mol.m^{-3}]$

x – distance $[m]$

t – time $[s]$

K_{11}, K_{22}, K_{33} – phenomenological coefficients for Luikov equations

$K_{12}, K_{13}, K_{21}, K_{23}, K_{31}, K_{32}$ – coupling coefficients for Luikov equations

D_{eff} – effective diffusivity $[m^2.s^{-1}]$

α – thermal diffusivity $[m^2.s^{-1}]$

α_1 – geometric coefficient

f – relative drying rate

N – drying rate per square area $[kg.m^{-2}.s^{-1}]$

N_i – Initial drying rate at saturation $[kg.m^{-2}.s^{-1}]$

MC_{db}^* - equilibrium moisture content on a dry basis

MC_{cr} – critical moisture content

MR – Moisture ratio

N_C – drying rate during constant rate period $[kg.m^{-2}.s^{-1}]$

MC_i – initial moisture content

t_C – time for constant rate drying $[s]$

A – surface area of product being heated $[m^2]$

ϕ_a – air humidity ratio

H_L – latent heat of vapourisation $[J.kg^{-1}]$

$\dot{m}_a$ – mass flow rate of air $[kg.s^{-1}]$

$\dot{m}_p$ – mass flow rate of product $[kg/s]$

α_1 – geometric coefficient for Luikov equation (=0 for planar, =1 for cylindrical and = 2 for spherical)

A_1, A_2 – geometric constraints

K, k – drying constants $[1/s]$

n – dimensionless model constant for Page Models

l – dimensionless model constant for Modified Page-III Model

a, c – dimensionless empirical constants for Henderson and Pabis Models and derivatives

b – empirical constant for Midilli et al Model $[s^{-1}]$

D_0 – Arrhenius Factor $[m^2.s^{-1}]$

E_a – activation energy for diffusion $[kJ.mol^{-1}]$

P – atmospheric pressure $[Pa]$

R – universal gas constant $[kJ.kmol^{-1}.K^{-1}]$

T_A – ambient temperature $[K]$

ϕ_s – surface humidity ratio

φ – specific humidity

h - specific enthalpy $[J.kg^{-1}.K^{-1}]$

q – specific thermal energy loss $[J.kg^{-1}]$

1. INTRODUCTION

Rooibos tea is grown exclusively in the Cape Regions of South Africa (Joubert *et al.*, 2008). The market for this crop has grown steadily and has recently been bolstered by international demand for organic and healthy foods and beverages (DAFF, 2012). Rooibos tea has numerous health benefits that put it at the fore-front of the herbal tea market internationally and as a competitor for black oriental tea within South Africa. Of primary attraction are the low tannin levels, lack of caffeine, various healing properties and anti-oxidant numbers (popularly believed to help prevent cancer) (Joubert *et al.*, 2008; Joubert and de Beer, 2011; Van Wyk, 2011; DAFF, 2012; Street and Prinsloo, 2013a).

These useful marketing tools have pushed rooibos tea into the international market where the majority of produce is exported (DAFF, 2012). However, the international opinion of the rooibos industry is damaged by the variability in availability and quality of the tea (Joubert and de Beer, 2011; DAFF, 2012). This is mainly due to the strong reliance of the industry on weather conditions during post-harvest production (Joubert, 1994). Post-harvest processing of rooibos tea is composed chiefly of the fermentation and drying stages. Both these critical stages occur in open, weather controlled "tea courtyards." (Joubert and Schulz, 2006).

Due to exposure to the elements, the natural sun fermentation and drying have disadvantages despite being cost effective. It can be unhygienic (especially with regard to export standards), prone to insect infestations, losses may occur or delays may be encountered due to unfavourable weather conditions (Joubert and De Villiers, 1997; Joubert, 1998; Joubert and de Beer, 2011; DAFF, 2012). These disadvantages negatively affect international market opinion. The development of better post-processing techniques would allow for the rooibos market to expand and encourage a suitable international reputation for consistent quality.

There is existing information on the fermentation process and a deep-bed fermenter has been developed specifically for the rooibos industry (Joubert and Muller, 1997). Although some research on drying has been conducted, it has focused mainly on the effect of drying variables on quality. Thus, this study will undertake to provide empirical information to the rooibos industry about the drying kinetics and energy consumption of rooibos drying under different conditions.

Before undertaking a study, it is important to understand the mechanisms behind the drying process. Because of the many complexities in dehydration, simplifications and assumptions are applied to mathematical data to provide workable analytical solutions. Thin-layer drying provides a practical and sufficiently accurate solution which can be determined experimentally. Thin-layer theory and application is well suited to the drying of rooibos due to the small, foliage-based structure of the plant (Erbay and Icier, 2010). Thin-layer drying models and their derivations are reviewed here to provide awareness of the assumptions made and to gain an understanding of current accepted scientific norms.

Because the rooibos industry does not currently employ forced drying, a summary on drying energy considerations has been included as well as an overview of existing thin-layer research. The main objectives of this study therefore are to generate drying data under different drying air conditions, optimise coefficients for selected drying models and determine energy use in the drying process at different drying conditions. These results will provide information regarding the kinetics and energy efficiency for forced convective drying of rooibos. This will in turn encourage the rooibos industry to make a more informed decision concerning the possible use of controlled (as opposed to natural) drying. By converting to controlled drying, the overall quality of the rooibos tea produced will be standardised, hygienic risk minimised and encourage further export growth.

A project proposal is also included to provide further information on the specific objectives and proposed methodology of the study.

2. ROOIBOS TEA

Rooibos tea is a blend made from the fermented and dried leaves of the *Aspalathus Linearis* plant. It grows exclusively in the Western Cape region of South Africa where it was first used by the Khoi San for medicinal purposes. It is normally served by steeping fermented and dried rooibos leaves in hot water with the addition of milk or sugar as desired. In South Africa rooibos competes with black oriental tea, *Camellia sinensis*, but has gained demand during the twenty-first century in international markets as competition to herbal teas. This is evident by the statement from the Swiss Business Hub South Africa which reported: "Rooibos appears to be headed towards becoming the second most common beverage tea ingredient in the world after ordinary tea (*Camellia sinensis*)" (Anon, 2007)

2.1 Market Value

Rooibos history dates back to the Khoi-San people who introduced it to colonial settlers in the Cape. It was often adopted as a substitute for black oriental tea due to high prices. As early as 1904, its market value was recognised for this very reason and a successful commercial enterprise started in the 1930's (Street and Prinsloo, 2013b). The rooibos market grew to the extent that a Rooibos Tea Control Board was established in the 1960's to administer and control quality (Joubert *et al.*, 2008). This was replaced with the South African Rooibos Council (SARC) in the 1990's which currently regulates standards, promotes market growth and conducts research within the rooibos field (Joubert *et al.*, 2008).

Rooibos is enjoyed either as a hot tea or a cold iced-tea, sometimes blended with other teas such as *Buchu*, *Chai* or *Honeybush*. In Germany, who demand the highest export share on average, it is commonly purchased as a vanilla blend (Joubert *et al.*, 2008). Although research was conducted into the invention of an "instant" Rooibos (similar to instant coffee) by Joubert (1984; 1988) the flavor was not of adequate quality to compare with standard brewed tea. It was only in 2000 that instant rooibos found a use in the food, cosmetic and pharmaceutical industries (Joubert *et al.*, 2008).

The health benefits of rooibos have been crucial to its success – anti-oxidants, no caffeine and low tannin content have proved useful marketing tools in the emerging world-wide trends of health conscious consumers and natural or organic market inclinations. Other health benefits of rooibos include:

a) no known stimulants,
b) a lower tannin content in comparison to black tea,
c) anti-spasmodic properties,
d) anti-oxidant content,
e) anti-aging effect,
f) it contains anti-eczema activities,
g) general relaxer,
h) relief for colic suffering infants, and
i) as a supplement for unweaned babies

(Watt and Breyer-Brandwijk, 1962; Morton, 1983; Van Wyk *et al.*, 1997; Joubert *et al.*, 2008; Joubert and de Beer, 2011; Street and Prinsloo, 2013a).

With international movements pushing the health and wellness market, the majority of rooibos production was exported for the first time in 2003 (DAFF, 2012). The market has been sporadic, mainly due to supply and demand cycles (Joubert and de Beer, 2011; DAFF, 2012). Although demand has risen steadily over longer times, in shorter periods supply and demand issues have led to volatility. Production rose steadily from the early 1990's to a high in 2008 of 18 000 tonnes however this dropped to just below 12 000 tonnes in 2012 (DAFF, 2012). This is due to fluctuations in the producer price – peaking in 2004 at R16.kg^{-1} (prompting interest and over-expansion resulting in the 2008 over-supply) which then dropped steadily to about R4.kg^{-1} in 2010. This increased again with producers earning roughly R12.kg^{-1} in 2012 (DAFF, 2012).

2.2 Production

The instabilities in the rooibos market are due in part to the variability of production – the crop is affected by low rainfall (due to minimal or lack of irrigation), fires, currency fluctuations and a post-harvest industry that primarily uses uncontrolled processing techniques (Joubert and De Villiers, 1997; Joubert and Schulz, 2006; Joubert *et al.*, 2008; Joubert and de Beer, 2011; DAFF, 2012; Street and Prinsloo, 2013a). These instabilities negatively affect the reputation of rooibos as the international market expects consistent quality.

The most common method of processing rooibos tea leaves is for the fresh material to be hand cut from the plant, cut into smaller pieces, bruised, fermented, dried, treated for microbial activity and sent for packaging as illustrated in Figure 2.1. These processes are detailed in the following sub-sections.

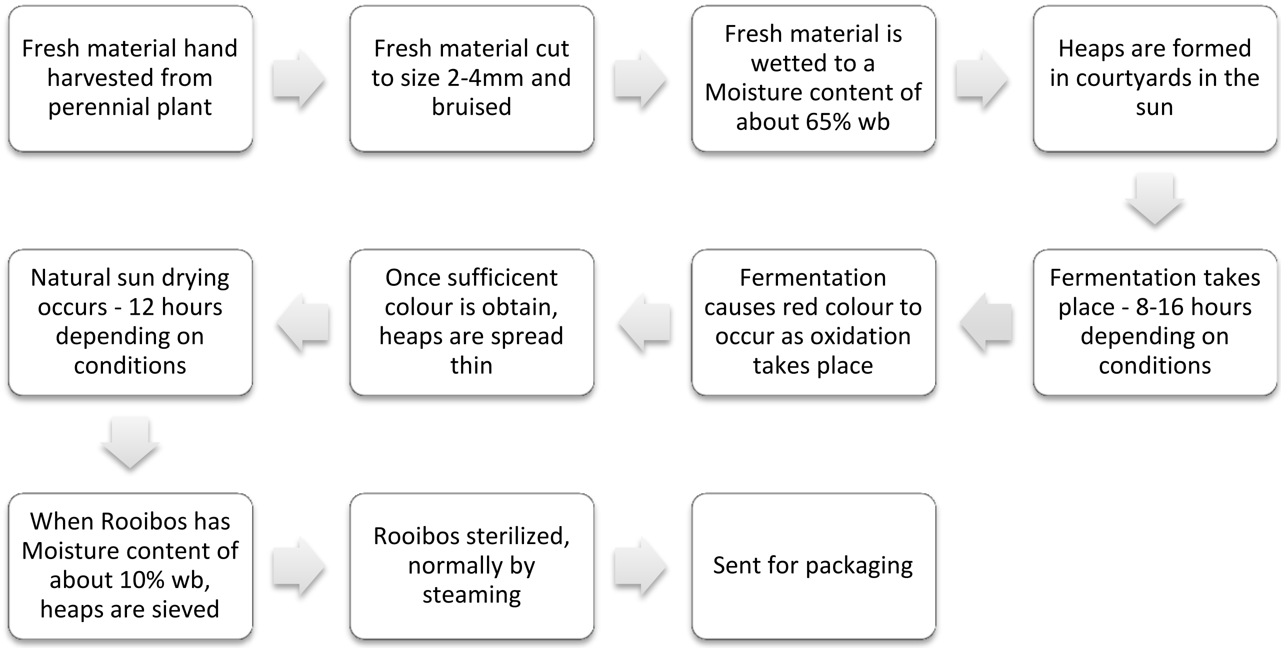


Figure 2.1 Flow Chart of Rooibos Processing from Plant to Packaging (Joubert and De Villiers, 1997; Joubert and Muller, 1997; Joubert, 1998; Joubert *et al.*, 1998; Joubert and Schulz, 2006; Joubert *et al.*, 2008; Joubert and de Beer, 2011).

2.2.1 Harvesting, cutting and bruising

Rooibos plants are perennial with a typical useful lifespan of 7 years (Joubert *et al.*, 2008). Practical experience has shown that the presence of young growth, the age of the bush and the area of cultivation all affect the quality of the final plant (Joubert, 1994). After the material has been harvested, it is cut into small pieces of 2-4 mm lengths in a rough manner and bruised (Joubert and De Villiers, 1997). Bruising can be done by hand (with a wooden mallet), by tractor (Joubert, 1998; Joubert and de Beer, 2011) or by the recent innovation of a neoprene wrapped twin roller system developed by Joubert and De Villiers (1997). Bruising initiates the enzymatic oxidation of the polyphenols which will eventually create the characteristic brown-red colour associated with Rooibos (Joubert *et al.*, 2008).

2.2.2 Fermentation

Fermentation is the expression of phenolic compounds by oxidation and in rooibos this presents itself as the presence of Aspalathin (the defining molecular characteristic of rooibos) (Joubert and de Beer, 2011). In practice fermentation progress is measured by the degree of redness in the heaps, judged by eye as seen in Figures 2.2 (pre-fermentation) and 2.3 (post fermentation). There has been intensive research into the causes of aspalathin variations, especially during fermentation, due to the important role it plays in the health benefits and quality of the rooibos (Heinrich *et al.*, 2012; Joubert *et al.*, 2012; Stanimirova *et al.*, 2013).

Figure 2.2 Rooibos being deposited in fermentation heaps (SARC, 2013)

Figure 2.3 Rooibos after fermentation and drying (drying does not produce a significant colour change) (SARC, 2013).

Fermentation commonly takes place in heaps in outside “tea courtyards”. The shredded material is first wetted to a moisture content of approximately 65% (wet basis) which helps accelerate the fermentation process (Joubert *et al.*, 2008). Fermentation takes roughly 12-14 hours with regular turning but is reliant on ambient conditions (Joubert *et al.*, 2008). The temperature inside the heap averages 40˚C in the middle, again, weather dependent (Joubert and De Villiers, 1997).

Although the above described methods of fermentation are cost effective, require little specialist equipment and skills there are many drawbacks to natural sun fermentation. Weather dependence often hinders processing of rooibos due to clouds, temperatures deficits or the presence of the previous batch of slow drying rooibos (Joubert and de Beer, 2011). Rooibos must be processed as soon as possible after harvesting to prevent drying or microbial growth. The fermentation heaps can often be unhygienic, promote mould growth due to low temperatures and there can be losses in the outer layer of leaves to drying and under- or over-fermentation (Joubert, 1994; Joubert and De Villiers, 1997; Joubert and Muller, 1997; Joubert, 1998; Joubert and Schulz, 2006; Joubert and de Beer, 2011). All these lead to an inconsistent product and product quality which harm international opinion of rooibos.

Research has been conducted into the fermentation process, with emphasis on quality. These studies have proven that controlled conditions create consistent and better quality products (Joubert, 1994; Joubert and De Villiers, 1997; Joubert, 1998). A small-scale rotary batch fermenter was developed by Joubert and Muller (1997) to provide controlled conditions for rooibos fermentation as well as a laboratory deep bed fermenter (Joubert *et al.*, 1998) to monitor and control the fermentation conditions during experiments. Using this new equipment and pre-frozen material, Joubert proved that fermentation temperature and time affect the aroma and taste of rooibos and that higher fermentation temperatures produce a better taste and aroma (Joubert and De Villiers, 1997; Joubert, 1998). The use of a deep bed fermenter provided better aeration which resulted in a more consistent product (Joubert, 1998). Optimal fermenting for aroma was determined as 8 hours at 40˚C or 14 hours at 34˚C whilst for taste, was 10 hours at 38˚C or 12 hours at 36˚C was best (Joubert, 1998).

Much of the focus of the research into the fermentation process has been into the quality and level of molecular products affected by different parameters (Joubert and De Villiers, 1997; Joubert, 1998; Joubert and Schulz, 2006; Heinrich *et al.*, 2012) but not on energy efficiency.

2.2.3 Drying

In industry practice, after fermentation, the heaps are spread thin and allowed to dry in the sun until they reach a moisture content of about 10% wet basis (wb) (Joubert *et al.*, 2008). Although solar energy is free, the process can be unhygienic, lead to a non-uniform dried product, requires longer drying time and is highly weather dependant. The drying process is imperative to halt the fermenting, to inhibit microbial growth (Joubert and Schulz, 2006) and prevent browning during transport (Joubert and de Beer, 2011). South African regulations stipulate moisture content, pesticide residues, microbial contamination and the percentage of white stems allowed (Joubert and de Beer, 2011).

Some research has been done in the drying process with emphasis on dried rooibos quality (Joubert and De Villiers, 1997; Joubert, 1998; Joubert and Schulz, 2006). Joubert and De Villiers (1997) showed that increasing drying temperatures negatively affected aroma but not taste by drying rooibos in a rotary batch drier at 40˚C, 50˚C, 60˚C and 70˚C. It has also been validated that there is no difference in taste or aroma between natural sun and controlled drying, although the rooibos dried by a controlled dryer had a redder colour as indicated by a difference in L* values (used to measure colour) which is desirable (Joubert and De Villiers, 1997). This was validated by Joubert (1998) who experimented with deep bed and thin-layer drying (as a controlled substitute for sun drying).

Research was focused on assessment of the effect of temperature on the quality of dried rooibos without considering the drying kinetics or energy requirements. These could be areas of research that would provide valuable information into understanding the drying characteristics and energy optimization for the drying process. This will provide the rooibos industry with information and incentives that may lead to an increased use of forced drying and hence better quality rooibos needed for the export market.

2.2.4 Processing and packaging

After drying, the rooibos leaves are sieved to ensure evenness of product. The rooibos is then steam pasteurised or sterilized to ensure low microbial levels, especially if intended for export (Joubert and Schulz, 2006). Packaging varies between retail, loose leaf (bulk) and specialised blends (DAFF, 2012).

2.2.5 Green rooibos

Green rooibos is made by excluding the fermentation process – tea leaves are dried directly from cutting. Quality green rooibos contains additional anti-oxidants which are lost in the fermentation process (Joubert and Schulz, 2006; Joubert *et al.*, 2008; Joubert and de Beer, 2011; Van Wyk, 2011). Immediate drying of green rooibos is imperative to prevent the oxidative reactions that take place during fermentation from occurring. This is achieved by rapid sun drying, rapid steaming or the exclusion of oxygen during forced drying (Joubert and de Beer, 2011). A patented vacuum procedure provides excellent results but due to the cost is utilized only for high end products (Joubert *et al.*, 2008).

3. PSYCHROMETRIC PROPERTIES

Psychrometry is the study of moist air (Singh and Heldman, 2009). It is relevant to the drying or dehydration process as water is removed from the food product and carried away by the air. To induce this water transfer, a concentration gradient is needed and this is provided by hot dry air in the case of hot air convective drying. Before this mass and energy transfer can be studied further, a background into Psychrometric moist air properties and their mathematical relationships needs to be reviewed.

3.1 Properties and Definitions

To determine the properties of moist air, the Gibbs-Dalton Law or Partial Pressures Law is commonly utilised. This law states that the total pressure of the mixture is the sum of the individual pressures – temperature and volume are considered to be the same (the total amount) for both the air and water (Singh and Heldman, 2009). Thus, for a humid air mixture at atmospheric pressure the air will have a specific pressure (air vapour pressure) and the water vapour will have a specific pressure which in summation will equal atmospheric pressure. This is expressed mathematically as:

$$P_t = P_w + P_a \tag{3.1}$$

Where the vapour pressure (P_w) and air pressure (P_a) can be calculated from the ideal gas law:

$$P_w = \frac{R_w T}{V} \tag{3.2}$$

Both the temperature and specific volume used are the total temperature and total volume.

Of consideration is the air to water ratio. By definition the humidity ratio or **specific humidity** is (Singh and Heldman, 2009):

$$\emptyset = \frac{m_w}{m_a} = \frac{0.622x_w}{x_a} = 0.622 \times \frac{p_w}{p_a} = 0.622 \times \frac{p_w}{p_t - p_w} \tag{3.3}$$

Where x_a is the mole fraction defined for Gibbs-Dalton Law as (Singh and Heldman, 2009):

$$x_a = \frac{n_a}{n_a + n_w} = \frac{p_a}{p_a + p_w} \tag{3.4}$$

The number 0.622 is the ratio of water to air molar masses and is a common number in psychrometric equations. Another method to determine the amount of moisture present in air is the relative humidity. This is the ratio between how much water is in the air to how much water that air could potentially carry (in other words before saturation occurs) (Singh and Heldman, 2009). This is a percentage that ranges from 0-100% in comparison with specific humidity which is a ratio that is often a number less than 0.01. The **relative humidity** is defined with moles as(Singh and Heldman, 2009):

$$\varphi = \frac{x_w}{x_{ws}} \times 100 = \frac{p_w}{p_{ws}} \times 100 \qquad (3.5)$$

Relative humidity is dependent on temperature and must thus always be specified with a given temperature (Singh and Heldman, 2009).

To determine the specific heat capacity of humid air, Equation 3.6 is used (Menon and Mujumdar, 1987).

$$C_{p_{ha}} = C_{p_a} + C_{p_w}\emptyset. \qquad (3.6)$$

This leads to the definition of the enthalpy of humid air as (Menon and Mujumdar, 1987):

$$h_{ha} = C_{p_{ha}}\Delta T + \Delta H_{V_0}\emptyset \qquad (3.7)$$

Where ΔH_{V_0} is the latent heat of vapourisation. Enthalpy is the energy associated with the pressure required to flow and is a combination of the internal energy (energy due to kinetic and potential energies of the elements) and this flow energy. Enthalpy is measured relative to a certain set “zero” point which is commonly defined as the fluid at triple point temperature of 0.01˚C and its own vapour pressure of 611.2 Pa (Menon and Mujumdar, 1987). Enthalpy is oft referred to in a specific form (per unit mass) as in Equation 3.7.

To calculate enthalpy the temperature needs to be known. There are two types of temperature in Psychrometry – dry bulb and wet bulb temperatures. The dry bulb temperature is defined as the temperature as indicated by a temperature sensor (such as a mercury thermometer) where the bulb is exposed to the fluid without interference (Singh and Heldman, 2009). This is the standard form of measuring temperature and gives an indication of sensible heat (Singh and Heldman, 2009).

Wet-bulb temperature is defined as the temperature read when the thermometer’s bulb is covered by a wet wick and exposed to flowing unsaturated air (normally achieved by swinging the thermometer around like a sling) (Singh and Heldman, 2009). This causes the moisture in the wet wick to evaporate which requires latent heat causing a “drop” in temperature as seen on the thermometer. The wet-bulb temperature is thus an indication of the latent heat. Wet-bulb temperature is dependent on humidity (the wick will only evaporate until it is at the same relative humidity as the air). Thus, the difference between the wet and dry bulb temperatures can be used to read relative humidity (Singh and Heldman, 2009).

Another important property is the **dew point temperature**. This is the point at which vapour will condense because it has reached saturation for its specific partial pressure (Singh and Heldman, 2009).

3.2 Psychrometric Chart

The psychrometric chart is a graphical representation of the above properties. It is usually defined for a specific pressure, the most common being 101,3 kPa (sea level atmosphere). The y-axes display specific humidity and the x-axis the dry bulb temperature. Other curves and lines on the graph depict constant relative humidity, constant specific volume, constant enthalpy and constant wet bulb temperatures as seen in Appendix A (Singh and Heldman, 2009). The lines of constant wet bulb temperature and enthalpy coincide whilst the dew point is indicated along the 100% relative humidity line. The psychrometric chart can be used for calculating processes as well which makes it a useful and quick reference point provided two or more parameters are known.

4. THIN-LAYER DRYING

Drying or dehydration is the process of removing moisture from an object and is one of the least understood energy processes due to the complexity of the process. It is one of the oldest forms of preservation as the dehydration procedure reduces or eliminates microbial deteriation (Singh and Heldman, 2009). Within the food industry it is used to protect foods from chemical, microbial or physical changes that could take place during packaging, transport and storage (Jangam, 2011). Due to wide variations in properties of food products, each product reacts differently to different drying conditions, increasing the complexity of drying within the food industry.

Despite onerous research into understanding and mathematically describing the drying process, most solutions are empirically based. There is no theoretical model that unifies every drying situation (Erbay and Icier, 2010). The concept of thin-layer drying assumes negligible internal temperature difference which enables simplification of the founding principles (Menon and Mujumdar, 1987). Thin-layer drying, when practically applied and verified, can provide accurate results under certain conditions and is further elaborated below.

4.1 Dehydration – a Theoretical Explanation

The following theories are the current commonly accepted descriptions of the drying process. A detailed description of their origins and alternatives are beyond the scope of this text.

Drying can be explained on a microscopic level as having four different processes happening simultaneously. Typically one procedure will limit the whole process although this may change during the drying process. For the simple example of hot, dry air blowing over a wet food the four processes are:

a) the heat transfer from the air to the surface of the product (convection),
b) The mass transfer from the surface of the product to the immediate air,
c) The heat transfer from the surface of the product to the internals of the product (conduction), and
d) mass transfer from the internals of the product to the surface.

4.2 Heat transfer

The heat from the air is transferred to the solid using convective means. The rate of this is determined by material properties and the temperature gradient. The heat from the hotter air is transferred to the cooler product which is then used as latent heat to vapourise the moisture at the surface, essentially lowering the temperature of the exiting air (Menon and Mujumdar, 1987). Due to the heating of the surface by air convection, a temperature gradient arises within the product. This causes heat to flow from the surface to the centre area and is controlled by the thermal resistance of the product to conductive heat transfer. This is dependent on the material properties (Menon and Mujumdar, 1987).

4.3 Mass transfer

The vapourised moisture is carried away by the air, increasing the humidity of the air and decreasing the moisture content of the product (Menon and Mujumdar, 1987). This is again controlled by convective means. All solids exert a pressure on the internal moisture which is dependent on ambient surroundings and material properties. With the surface evaporation, a concentration gradient occurs within the product increasing the vapour pressure within the product. The moisture transfer will continue until the vapour pressure within the product equates the partial pressure of the water in the air. This condition is known as equilibrium moisture content and is specific for the particular ambient conditions (Menon and Mujumdar, 1987).

The vapour pressure is caused by the manner in which water is held by a product. This could be as a solution within the solid, held in capillaries, within the cellular structures or by chemical or physical forces. This has led to a definition of materials by the way they hold water as non-hygroscopic capillary-porous, hygroscopic-porous or colloidal media (Menon and Mujumdar, 1987)

4.4 Drying Behaviour

Drying is typically measured and expressed by moisture content or drying rate over time. **Moisture content** has two definitions: on a wet basis and on a dry basis. Wet basis is based on the ratio of mass of water to mass of wet product whilst dry basis is the ratio of water mass to mass of dry product. This is expressed mathematically as (Menon and Mujumdar, 1987):

$$MC_{wb} = \frac{mass\ of\ water}{mass\ wet\ sample} \tag{4.1}$$

$$MC_{db} = \frac{mass\ of\ water}{mass\ dry\ sample} \tag{4.2}$$

Moisture content is typically expressed as a percentage and whilst done on a wet basis this cannot exceed 100%, however on a dry basis, it could. To convert between the two Equation 4.3 (Menon and Mujumdar, 1987) is used:

$$MC_{wb} = \frac{MC_{db}}{MC_{wb} + 1} \tag{4.3}$$

In practice determining moisture content is done by measuring humidity difference and weight. Typically a graph is produced of normalised drying rate versus moisture content, called the characteristic drying curve, which is specific to a particular material. **Relative drying rate** is defined as (Menon and Mujumdar, 1987):

$$f = \frac{N}{N_i} \tag{4.4}$$

where N is the instantaneous drying rate and N_i is the initial drying rate at saturation per area. The relative moisture content is called the **moisture ratio** (Menon and Mujumdar, 1987):

$$MR = \frac{MC - MC_{db}^{*}}{MC_{cr} - MC_{db}^{*}} \tag{4.5}$$

The critical moisture content is assumed to be independent of the initial moisture content. The curves must also be geometrically similar over a range of conditions (Menon and Mujumdar, 1987). The definition for critical moisture content is described in section 4.5.2.

Although the moisture ratio is commonly normalised with the difference of the equilibrium moisture content, if the relative humidity fluctuates then the moisture ratio is defined as (Diamente and Munro, 1993):

$$MR = \frac{MC}{MC_i} \tag{4.6}$$

These curves display certain characteristics that are common although not every media displays every characteristic.

4.5 Drying Rate Characteristics

Drying curves characteristically display four defined regions or periods. Not every product will display all four, sometimes only one will appear and although the definition of each period is clear it may be difficult to ascertain in practice. Many agricultural products do not display typical drying curves, notably a lack of constant drying time (Erbay and Icier, 2010).

4.5.1 Initial drying period

There is often an initial drying rate where the drying rate increases as the surface of the product is heated to the temperature of the immediate ambient air. A sufficient temperature gradient is required between the air and the product's initial temperature to vapourise the moisture (Singh and Heldman, 2009).

4.5.2 Constant rate period

After the initial period, curves display a constant drying rate through a limited time. During this time the surface of the product still contains free moisture, which is vapourised, diffused into the air and taken away by the air (Singh and Heldman, 2009). The rate is controlled by the diffusion process for water removed from the surface and into the air (Menon and Mujumdar, 1987). Critical moisture content (MC_{cr}) is defined as the moisture content at the end in the very last instant of the constant rate period (Menon and Mujumdar, 1987).

4.5.3 First falling drying rate period

Although a general "falling rate" period is normally described, it is due to two different phenomena, which sometimes can be seen clearly by a change in the rate of change of the drying rate. These are called the first and second falling rates. Some products only display one or the other. The falling rate as a whole is described as the time from the critical moisture content until the equilibrium moisture content (Chen, 2007). Equilibrium moisture content is the point at which the moisture vapour pressure in the solid is equal to the partial pressure of the vapour in the air (Menon and Mujumdar, 1987).

During the first falling rate period moisture must be transferred from within the solid to the surface (modelled as capillary flow) (Menon and Mujumdar, 1987). This is caused by the gradient between the air vapourisation pressure and the vapour vapourisation pressure at the surface (Singh and Heldman, 2009). This continues until the surface film of liquid is entirely evaporated (Menon and Mujumdar, 1987).

4.5.4 Second falling drying rate period

The second falling rate commences when the drying process is controlled by the rate at which moisture can move through the solid. The two possibilities that could be the limiter are the material heat conduction rate and the material mass diffusion rate. Several other factors come into play in this period – shrinkage may cause internal pressures or case hardening can occur, both of which hinder the drying process. This continues until the product reaches the equilibrium moisture content for the prevailing conditions (Menon and Mujumdar, 1987).

Although there are mathematical descriptions available to attempt to describe this period, they often are simplified and dependent on geometry (for which only highly simple cases are solved). Chen (2007) for example describes the time for the falling rate for an infinite plate, sphere and cylinder if the diffusion of the moisture is modelled with Cranks's basic solution of diffusion (Crank, 1975) although each situation requires a unique solution based on geometry. But even this contains errors which are presumed to be due to the isothermal assumption.

4.6 Dehydration – A Mathematical Explanation

Due to the vast complexities of the drying process, the mathematical equations surrounding the process are not exact and can only be solved with certain assumptions. Computer software packages can attempt to solve them numerically but lack the ability to account for the inefficiencies in the original mathematical constraints. There are two general models: the diffusion model which take into account both heat and mass transfer, internally and externally and the thin-layer models which treat the temperature gradient within the product as negligible (Erbay and Icier, 2010).

4.6.1 Diffusion model

The diffusion models are derived from Fick's Laws of Diffusion (Erbay and Icier, 2010). The first law states that the mass flux is proportional to the derivative of concentration with respect to distance, under steady state conditions (Singh and Heldman, 2009):

$$J = D\frac{\partial c}{\partial x} \tag{4.7}$$

Using Fick's First Law combined with mass conservation it is possible to derive Fick's Second Law which describes the change in concentration with time, assuming the diffusivity is constant (Singh and Heldman, 2009):

$$\frac{\partial c}{\partial t} = D(\frac{\partial^2 c}{\partial x^2}) \tag{4.8}$$

It is possible to solve Fick's Diffusion laws by substituting a suitable mathematical description for concentration and integrating with respect to geometry but it is only possible analytically for very simple cases, such as an infinite plate. Common methods for using the above equation include the use of Treybal charts, the use of Biot and Fourier numbers to analyse the flow and deduce simplifications (Singh and Heldman, 2009) and computer aided numerical solutions that use Finite Element Analysis (FEA) (Erbay and Icier, 2010).

Luikov (1975) considered a capillary-porous media and combined Fick’s Second Law with irreversible thermodynamics principles (Nicolai *et al.*, 2001) that resulted in Luikov’s equations:

$$\frac{\partial M}{\partial t} = \nabla^2 K_{11} M + \nabla^2 K_{12} T + \nabla^2 K_{13} P \tag{4.9}$$

$$\frac{\partial T}{\partial t} = \nabla^2 K_{21} M + \nabla^2 K_{22} T + \nabla^2 K_{23} P \tag{4.10}$$

$$\frac{\partial P}{\partial t} = \nabla^2 K_{31} T + \nabla^2 K_{32} T + \nabla^2 K_{33} P \tag{4.11}$$

Where K_{11}, K_{22}, K_{33} are phenomenological coefficients and the others are coupling coefficients. However for most situations pressure is negligible in comparison to temperature and moisture and the last term in the above equations is often dropped (commonly called modified Luikov equations). Even with this simplification the equations cannot be solved analytically (Erbay and Icier, 2010) but can be solved with the finite element method (Ozilgen and Ozdemir, 2001).

4.6.2 Thin-layer models

Thin-layer models, also known as lumped parameter models make the assumption that there is negligible temperature gradient within the product and that the entire product is in thermal equilibrium with its immediate surroundings. This simplifies the Luikov equations to (Erbay and Icier, 2010):

$$\frac{\partial M}{\partial t} = \nabla^2 K_{11} M \tag{4.12}$$

$$\frac{\partial T}{\partial t} = \nabla^2 K_{22} T \tag{4.13}$$

K_{11} is more commonly known as effective moisture diffusivity (D_{eff}) and K_{22} is known as thermal diffusivity (α). The effective moisture diffusivity encapsulates both the vapour and liquid diffusivities into one effective diffusivity (Chen, 2007). For constant moisture and thermal diffusivities, in one-dimensional flow, the equations can be expressed as:

$$\frac{\partial M}{\partial t} = D_{eff} [\frac{\partial^2 M}{\partial x^2} + \frac{\frac{\alpha_1}{x} \partial M}{\partial x}] \tag{4.14}$$

$$\frac{\partial T}{\partial t} = \alpha[\frac{\partial^2 T}{\partial x^2} + \frac{\frac{\alpha_1}{x}\partial T}{\partial x}] \tag{4.15}$$

Where α_1 is a geometric coefficient (Erbay and Icier, 2010).

The assumption of uniform temperature distribution is only accurate enough when the thickness of the product is sufficiently thin. As long as this “thinness” condition exists, thin layer models are preferred due to their overall simplicity (Erbay and Icier, 2010).

Thin-layer drying models can be divided into two categories: semi-empirical and empirical models. These models only take into account the internal resistance to moisture diffusivity (Henderson, 1974; Suarez *et al.*, 1980). Although a clear explanation is provided enabling the use at all levels of the drying process, the numerous assumptions required can produce errors in certain circumstances (Erbay and Icier, 2010).

Several assumptions are made for thin-layer drying models (Erbay and Icier, 2010). These include:

- homogenous and isotropic particles
- material characteristics (including size) are constant
- pressure variations are negligible
- evaporation occurs only at the surface
- initial moisture content is independent of other parameters
- moisture equilibrium occurs at the surface
- temperature distribution within the product is uniform and equal to air temperature
- internal heat transfer is due to conduction exclusively
- external heat transfer is due to convection exclusively
- effective moisture diffusivity is constant

It is assumed that Equations 4.14 and 4.15 describes mass transfer only (Whitaker *et al.*, 1969; Young, 1969) and with the appropriate boundary conditions a solution can be reached. Crank (1975) solved these for infinite sphere, slab or cylinder. Because most foods do not dry at a constant drying rate, it is assumed that the critical moisture content equals the initial moisture content. If this is so then the MR is called the characteristic moisture content (ϕ). (Erbay and Icier, 2010).

4.6.3 Semi-theoretical models

These models either use a modified form derived from Fick's second law of diffusion or deduce a solution that is analogous to Newton's laws of cooling. They use experimental data which requires fewer assumptions but they are limited to particular process conditions. There are two models derived from analogies to Newton's cooling laws: the Newton and Page (and its modified forms) models whilst the Fick's law models can further be sub-divided into the number of exponential terms it possess (single term exponential, two term exponential and so on) (Erbay and Icier, 2010).

Lewis (1921) proposed that the change in moisture content in the falling rate period is proportional to the instantaneous difference between the moisture content and the expected moisture content when it comes into equilibrium with drying air. This essentially assumed that the material is thin enough, the velocity high enough and the drying conditions constant enough that:

$$\frac{dM}{dt} = -K(M - M_e) \tag{4.16}$$

Where K is the drying constant – for thin layer concepts this will encompass the moisture diffusivity, thermal conductivity, interface heat and mass coefficients (Marinous-Kouris and Maroulis, 1995). If K is independent of the moisture content then:

$$MR = \frac{M_t - M_e}{M_i - M_e} = \exp[-kt] \tag{4.17}$$

Where k can be obtained from experimental data. This is known as the **Lewis (or Newton) Model**.Page (1949) modified the Lewis model by adding the dimensionless model constant, n, to make the **Page Model**:

$$MR = \exp[-kt^n] \tag{4.18}$$

This was used to model the drying of shelled corn (Page, 1949).

Overhults *et al.* (1973) modified Page's model for their model of drying soybeans:

$$MR = \exp[-kt]^n \tag{4.19}$$

This is also known as the **Modified Page-I Model**. White *et al.* (1978) optimised the arrangement of the coefficients for drying of soybeans to produce what is known as the **Modified Page-II Model**:

$$MR = \exp[-(kt)^n] \tag{4.20}$$

Subsequently, Diamente and Munro (1993) formulated the **Modified Page-III Model** which is slightly different from the original Page equation to describe the drying of sweet potatoes:

$$MR = \exp[-k\left(\frac{t}{l^2}\right)^n] \tag{4.21}$$

Where l is another empirical dimensionless constant.

The **Henderson and Pabis model** (Equation 4.22) is a single-term exponential model. Henderson and Pabis (1961) suggested that for sufficiently long drying times only the first term of the solution is needed. Provided the effective moisture diffusivity is constant this is expressed as:

$$MR = a\exp[(-kt)] \tag{4.22}$$

Where a is an indication of shape –generally called a model constant that is normally obtained from experimental data. It was used successfully to describe drying of corn (Henderson and Pabis, 1961).

The **Logarithmic or Asymptotic model** is a modification of the Henderson and Page Model, developed by Chandra and Singh (1995):

$$MR = a\exp[-kt] + c \tag{4.23}$$

Where c is an empirical dimensionless constant. Yagcioglu *et al.* (1999) successfully used it to describe the drying of laurel leaves. Midilli *et al.* (2002) included a time dimension to the Henderson and Pabis Model, which they applied to the drying of pollen, mushrooms and pistachios in various drying methods. The **Midilli et al. model** is expressed mathematically as:

$$MR = a\exp[-kt] + bt \tag{4.24}$$

Where b is an empirical constant of units s^{-1}. This model is also called the **Midilli-Kucuk Model**. Ghazanfari *et al.* (2006) proposed a **Modified Midilli Model** which excluded the shape model constant, a:

$$MR = \exp[-kt] + bt \tag{4.25}$$

This was not applied to a food material but worked sufficiently well for flax fiber (Ghazanfari *et al.*, 2006). Another modified Midilli Model (Equation 2.41) was put forward by **Demir *et al.*** (2007) for the drying of green table olives by including the Modified-I Page model:

$$MR = a\exp[(-kt)^n] + b \tag{4.26}$$

A new semi-theoretical model was put forward by Hii *et al.* (2009a) for the air drying of cocoa beans that combined the Page and Two-Term models, called the **Hii et al Model**:

$$MR = a\exp(-kt^n) + c\exp(-gt^n) \tag{4.27}$$

This was also used to describe the hot air drying of carrot pomace (Kumar *et al.*, 2012).

Henderson (1974) proposed that the use of an additional term, to make what is known as the **Two Term Exponential Model** would reduce some errors in the single term models:

$$MR = a\exp[-k_1 t] + b\exp[(-k_2 t)] \tag{4.28}$$

Where a and b are shape constraints, called model constants and k_1 and k_2 are drying constants. All of these are obtained from experimental data. This was used by Glenn (1978) to model the drying of grain.

Karathanos (1999) continued to add a third term to the general solution of Fick's Second Law of Diffusion, in an attempt to further reduce errors, named the **Three Term Model**:

$$MR = a\exp(-k_1 t) + b\exp(-k_2 t) + c\exp(-k_3 t) \tag{4.29}$$

Where a, b and c are geometric constants and the k's are drying constants all obtained from experimental data. Karathanos (1999) explaines that the third term describes the beginning part of a drying curve (whilst the first term explains last part and the second describes the middle part of the drying curve).

4.6.4 Empirical models

Empirical models use experimental data and fit them to mathematical equations. They tend to have similar characteristics to semi-theoretical models and provide minimal explanations for particular drying behaviors (Erbay and Icier, 2010).

The **Thompson Model**, mathematically described as:

$$t = a\ln(MR) + b\,[\ln(\mathrm{MR})]^2 \tag{4.30}$$

Was developed by Thompson *et al.* (1968) using data from the drying of shelled corns but was successfully used by Paulsen and Thompson (1973) for the drying of sorghum. Similarly Wang and Singh (1978) created a model for the intermittent drying of rough rice:

$$MR = 1 + bt + at^2 \tag{4.31}$$

Where b has units s^{-1} and a has units s^{-2} both obtained from experimental data. This is referred to as the **Quadratic or Wang and Singh model**.

Kaleemullah (2002) created a model called the **Kaleemullah Model** (Equation 4.32):

$$MR = \exp(-c)\,T + bt^{pT+n} \tag{4.32}$$

Where c is $1/°\mathrm{C}s$, b is $1/s$ and p is $1/°\mathrm{C}$ and n is dimensionless. This was applied to the drying of red chillies successfully by Kaleemullah and Kailappan (2006).

A model, known as the **Diamante et al Model**, that has the form:

$$\ln(-lnMR) = a + b(\ln t) + c(\ln t)^2 \tag{4.33}$$

Was introduced by Diamante *et al.* (2010) and applied successfully towards to drying of apricots and kiwi fruit.

Corzo *et al.* (2008) proposed the use of a statistical model for the description of drying and used the **Weibull distribution** which had only been used for rehydration characteristics and osmotic dehydration. The normalized Weibull distribution:

$$MR = \exp\left[-\left(\frac{t}{a}\right)^b\right] \tag{4.34}$$

Was used to adequately describe the drying of coroba slices by Corzo *et al.* (2008).

4.7 Effective Moisture Diffusivity

The effective moisture diffusivity (D_{eff}) for a lumped parameter approach takes into account all possible resistances to moisture transport. When interpreted for an infinite slab in one dimension, assuming negligible temperature gradient within the product, constant temperature and diffusivity and no significant external resistance, Fick's Second Law reduces to (Crank, 1975):

$$MR = \frac{8}{\pi^2}\sum\nolimits_{n=0}^{\infty}\left(\frac{1}{2n+1}\right)\exp\left(-\frac{(2n+1)^2\pi^2 D_{eff}t}{4L^2}\right) \tag{4.35}$$

This is simplified by taking the first term of the series ($n = 0$):

$$MR = \frac{8}{\pi^2}\exp\left(-\frac{\pi^2 D_{eff}t}{4L^2}\right) \tag{4.36}$$

Although this seems to indicate that the natural log of the moisture ratio has a linear relationship to time, in reality the drying curves have a slightly concave form. This reveals that the assumption regarding the invariability of the effective diffusivity is not accurate (Bruin and Luyben, 1980). Theory suggests that diffusivity is affected by internal temperature, moisture content and structure which agree with thin-layer assumptions. It is the neglect of the effect of external conditions that causes these errors (Erbay and Icier, 2010). Diffusivity has been shown to be dependent on external temperature and air velocity within certain ranges (Islam and Flink, 1982; Ece and Cihan, 1993) and mathematical descriptions proposed (Ece and Cihan, 1993).

4.8 Activation Energy

Temperature affects diffusivity the most and much research has gone into quantifying this effect. Generally an Arrhenius equation is used to relate effective diffusivity to temperature (Henderson, 1974; Mazza and Lemaguer, 1980; Suarez *et al.*, 1980; Steffe and Singh, 1982; Pinaga *et al.*, 1984; Carbonell *et al.*, 1986; Crisp and Woods, 1994; Madamba *et al.*, 1996):

$$D_{eff} = D_0 \exp\left(-10^3 \frac{E_a}{RT}\right) \tag{4.37}$$

Where D_0 is the Arrhenius factor that is conventionally defined as equal to the effective moisture diffusivity at an infinitely high temperature (Özdemir and Onur Devres, 1999).

The greater the activation energy, the more sensible D_{eff} is to temperature (Kaymak-Ertekin, 2002). By taking the natural log of the Equation 4.37 it can be seen that the natural log of diffusivity varies linearly with temperature. If a strong correlation cannot be determined, it is an indication that other external factors strongly influence the effective diffusivity (Erbay and Icier, 2010). To include the effects of these factors, a mathematical relationship needs to be proposed and tested using non-linear regression. Dadali *et al.* (2007) described effective diffusivity as having an Arrhenius relationship to the ratio of microwave power to sample mass.

5. A REVIEW OF THIN-LAYER DRYING DATA

A review of thin-layer drying experimental data has been tabulated (see Appendix B) highlighting the range of products, the most suitable thin-layer drying model deduced, the effective moisture diffusivity range, activation energy, process conditions and the effect of these conditions on the model constants. Although, there has been research into the drying of tea (in both black and green forms) (Temple and van Boxtel, 1999; Panchariya *et al.*, 2002; Karaaslan and Tuncer, 2011), no investigation into the thin-layer drying kinetics, effective moisture diffusivity, activation energy or specific energy consumption of rooibos has been made, to the authors knowledge, at the date of writing.

6. ENERGY CONSIDERATIONS IN DRYING

Drying is an energy intensive process, estimated to use 10-15% of the total energy consumption in all industries in developed countries (Erbay and Icier, 2010). Fossil fuels are the primary source of energy but they are recognised as being harmful to the environment and have a limited life-span. Thus energy usage has become an important topic, with the choice of reducing the amount of energy usage or to use renewable energy sources.

Within the drying field, energy usage is commonly measured on a specific basis: the amount of energy it takes to dry a kilogram of wet product. This varies with different products, drying conditions and with time during the drying process. Typically, more energy is used in the falling rate periods and with harder products (such as nuts) (Marinous-Kouris and Maroulis, 1995; Özdemir and Onur Devres, 1999)

Process variables also effect the specific energy consumption although there is no rule for determining this as it is a combination of factors. Longer drying times, higher temperatures and higher velocities use more energy. But higher temperatures generally produce shorter drying times. Because energy consumption is so variable and unpredictable, specific energy consumption is generally measured experimentally. A review of the different specific energies available in literature can be viewed in Appendix B. Although the optimum energy efficient drying conditions may be found, this must be weighed with the optimum drying conditions for quality production.

7. DISCUSSION AND CONCLUSION

Rooibos constitutes 10% of the global herbal tea market with the majority of rooibos being exported (DAFF, 2012). With this market expected to expand, the emergence of “Red Espresso” (rooibos that is expressed through a coffee machine), green rooibos and interest from the cosmetic and pharmaceutical industries (DAFF, 2012), it is imperative that the quality and consistency is of export standard – a concern raised by the South African Department of Agriculture (DAFF, 2012). By using natural sun fermentation and drying, there is a higher loss of product leading to higher production costs and the microbial quality and consistency of the leaves are not controlled. This is detrimental to the international reputation of rooibos tea.

Despite much research into the fermentation process, little literature is available on the drying process. The little information that has been published focuses on the impact of drying conditions on the quality of tea as opposed to the efficiency of the drying process and the energy usage. The main advantage of open sun drying over controlled drying is the cost aspect but the lack of control is hampering the expansion of the industry.

Thin-layer drying could be successfully applied to the drying of rooibos tea, given the theoretical background. By finding the most suitable thin-layer drying model for rooibos, drying behaivour could be predicted. The calculation of the activation energies would also highlight energy consumption concerns and providing a relationship between the process conditions and model variables would enable the effect of changing the drying conditions to be pre-determined. An analysis into the specific energy consumption at different process conditions will allow for optimization of the drying process. Combined with the research conducted by Joubert (Joubert, 1994; Joubert and De Villiers, 1997; Joubert, 1998) into the quality of rooibos, useful information would be available to industry to optimize the fermentation and drying processes.

8. PROJECT PROPOSAL

8.1 Introduction

Rooibos tea is a valuable food product to the South African market. However, uncontrolled post-harvest processes are hindering the products reputation and reliability, especially overseas. This study aims to investigate drying of rooibos as there is little information available. Investigation into the drying kinetics and energy efficiency of the rooibos tea leaf drying process will be undertaken. An explanation into the materials and methods is provided as well as the approaches used for data analysis. The estimated project plan is also included.

8.2 Rationale

Rooibos tea is a uniquely South African product which grows exclusively in the Western Cape (Joubert and Schulz, 2006). Rooibos's many health benefits have contributed to a situation where demand is rising, especially in the export market, due to the increases in health and wellness awareness (Joubert *et al.*, 2008). However, the industry's normal post-harvesting techniques are hindering not only production but the reputation of rooibos tea quality overseas (Joubert and De Villiers, 1997; Joubert and Muller, 1997; Joubert and Schulz, 2006; Joubert and de Beer, 2011; DAFF, 2012).

Rooibos tea is traditionally harvested, cut, fermented, dried and packaged. The fermentation and drying processes normally occur in a tea courtyard, which is open to the elements. This is highly reliant on weather and is open to unhygienic contamination. Because of uncontrollable weather conditions, suppliers produce product in varying quality, at unpredictable rates and can suffer losses due to inefficiencies (for example drying in the outer layer during the fermentation process) (Joubert and Schulz, 2006).

The critical factor is industry's lack of trust in controlled fermentation and drying as well as the cost aspect as sun-drying does not require major energy input. There is available literature on the impact of controlled fermentation and drying on quality (Joubert, 1994; Joubert and De Villiers, 1997; Joubert, 1998; Joubert *et al.*, 1998; Joubert and Schulz, 2006), however, there is no information on the drying kinetics and subsequent energy consumption. This study may be of use to industry by providing answers to questions surrounding conditions for the optimal energy consumption. This will naturally complement the existing research on rooibos quality.

Because of the distance between the rooibos farm and laboratory, the rooibos leaves will need to be frozen prior to drying. The effect of this on the experimental outputs will need to be investigated to gain a true understanding of the drying kinetics and energy efficiency of drying rooibos.

8.3 Objectives

In order to provide reasonable data for the drying of rooibos tea leaves the study will aim:

- To determine the drying kinetics of rooibos tea leaves under differing temperature, velocity and relative humidity using a convection air tray dryer;
- To find the most appropriate thin-layer drying model for rooibos tea leaves;
- To qualitatively analyse the effect of pre-freezing on the drying kinetics of rooibos tea leaves; and
- To quantify the specific energy consumption of rooibos drying for varying drying conditions using a convection air dryer.

8.4 Materials and Methods

The study will be split into two experiments: one analyzing the effect of pre-freezing on the drying kinetics and the second looking at the effect of temperature, velocity and relative humidity on drying kinetics.

8.4.1 Sample preparation

The green, fresh, tea leaves will be acquired from Carmien Tea. The exact farm will only be known at harvest time and will be reported. Because of the distance between the growing region of rooibos and the intended laboratory, leaves will be transported immediately after harvest and frozen upon arrival in batches of 2.75 kg, except for 5 batches, which will be used within 3 days. Although this has been shown to have negative effects on the quality of rooibos (Joubert and De Villiers, 1997) a single batch of harvest will reduce sample variance. The sample fresh produce will be stored in the CTS Controlled Environment to allow control of relative humidity. This is done to prevent the product drying whilst being frozen. It is expected that due to the harvesting time of rooibos (mid-summer being the earliest), experimentation will begin in December or January.

Before drying takes place, the product needs to be cut, bruised, thawed (excepting the 5 fresh batches) and fermented. The product will be transported to Ukulinga Farm, cut to sizes of roughly 3 mm, bruised and thawed in an airtight container at room temperature for approximately 12 hours (Joubert and De Villiers, 1997). A 125 g sample from each batch will be taken to determine the dry weight, used for moisture content analysis (see Section 3.4.2. below).

Water will slowly be added to the sample until a moisture content of 65% (wb) is achieved, before being fermented for 15 hours at 42°C (Joubert, 1998). Fermentation will be carried out in an oven, in glass jars of 1000 ml capacity that are covered with moisture-resistant covers. Each jar will hold approximately 500 g of rooibos leaves. This is done to facilitate the fermentation of small batches of rooibos. Immediately after fermentation, a 125 g sample will be taken for moisture content determination and the rest will be transferred to the dryer to start the experiments.

8.4.2 Moisture content determination

To determine moisture content both the wet and dry masses of the product are required. The mass of the wet sample is simply the mass measured in the rooibos natural state with as little alteration or contamination as possible. To determine the dry mass of the rooibos leaves, a *c*125 g sample will be dried in an oven at 103°C for at least 24 hours or until the mass of the sample does not change. This procedure is in accordance with the American Society of Agricultural and Biological Engineers (ASABE) standard S358.2 (ASABE, 2011a). This is done at various stages in the procedure as stated.

8.4.3 Description of dryer

A hot air convective tray dryer will be used for this study. The dryer is a CFW 2215 Laboratory Drying System (34 kW). A flow diagram of the air path taken in the drying system is shown in Figure 9.1. The system can control relative humidity, temperature and velocity.

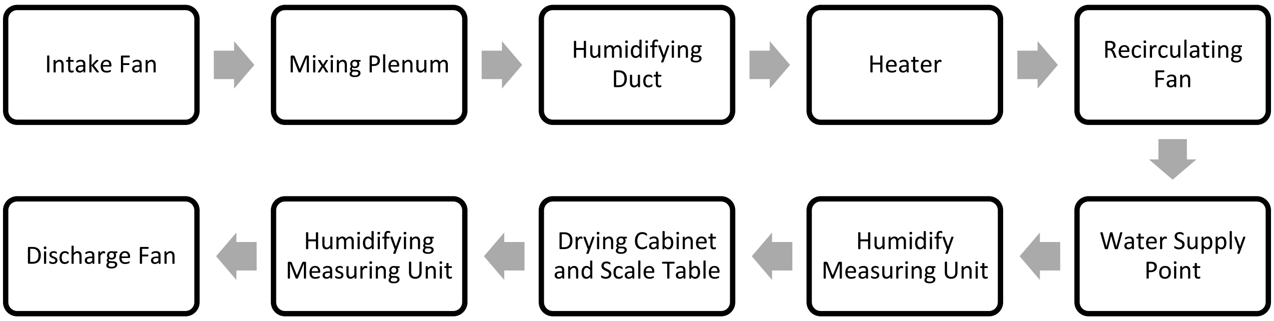


Figure 8.1 Flow Diagram of Air Path for Convection Air Dryer (CFW 2215).

For all trials, the dryer will be run for approximately 1 hour before commencing experimentation to allow for a steady state condition to be attained.

8.4.4 Experiment I: Determination of the effect of pre-freezing on drying kinetics

Experiment I will be to determine the effect of pre-freezing on the drying curves. This is done partially in preparation for Experiment II, where all samples will be pre-frozen. A total of 27.5 kg of rooibos leaves will be required, 13.75 kg of which must be fresh.

After fermentation, samples will be spread on the trays in a 3-4 mm layer, which will occupy approximately 7 trays, totaling 2.5 kg per trial. Each trial will run until the rooibos reaches a moisture content of 10% wb. Mass readings will need to be taken every 5 s for the first 5 minutes, every 1 minute for the next hour and every 15 minutes for the remainder of the time. This is done in keeping with the ASABE S448.1 protocol (ASABE, 2011b). The drying data will be recorded automatically using the built-in data acquisitions system.

Experiment I will be run in a complete randomized block design (2 x 5 factorial). The process input and out variables and constant conditions are outlines in Table 8.1.

Table 8.1. Process Conditions for Experiment I

Input Variables	Pre-treatment	Frozen
		Fresh
Constant Conditions	Temperature ($^{\circ}\ C$)	60
	Velocity ($m.s^{-1}$)	1
	Relative Humidity (%)	10%
	Mass	2.5 kg
	Final Moisture Content	10% wb
Output Variables	Mass for time i	Leads to: Moisture content over time
	Energy Consumption	Leads to the quantification of Specific Energy Consumption

Each experimental condition will be repeated five times for reliability, resulting in a total of ten trials for Experiment I. To determine the equilibrium moisture content (MC^*), a sample of the product will be dried until the mass is constant, indicating equilibrium. This will be done on a dry basis in accordance with ASABE standards (ASABE, 2011b).

8.4.5 Experiment II: Determination of the thin-layer drying kinetics

Experiment II will be to determine the effect of temperature, velocity and relative humidity on the drying curves. All samples will be pre-frozen. A total of 275 kg of rooibos leaves will be required. After fermentation, the samples will undergo the same preparation as described for Experiment I. Equilibrium moisture content will be determined for each trial. Experiment II will be run in a complete randomized block design (5 x 2 x 2 x 5 factorial). The process input and output variables and constant conditions are presented in Table 9.2.

Table 8.2. Process Conditions for Experiment II

Input Variables	Temperature ($^{\circ}\ C$)	40, 50, 60, 70, 80
	Relative Humidity (%)	10, 20
	Velocity ($m.s^{-1}$)	1, 2
Constant Conditions	Pre-treatment	Frozen
	Mass	2.5 kg
	Final Moisture Content	10% wb
Output Variables	Mass for time t	Leads to: the instantaneous moisture content over time
	Energy Consumption	Leads to: Specific Energy Consumption

Each trial in Experiment II will consist of a different specific drying air temperature, drying air velocity and relative humidity combinations, such that every possible combination is explored leading to twenty experiments in total. Each experiment will be repeated five times for reliability bringing the number of trials to one hundred.

8.5 Data Analysis

Once experimental data has been collected from the trials, an uncertainty analysis will be performed. For each condition, the five trials will be combined to give an average value for each treatment. Then this will be fitted to different thin-layer drying models and the most suitable model selected. The effective moisture diffusivity correlating to a particular condition will be calculated and these will be used to find the activation energy. The specific energy consumption will also be determined.

8.5.1 Data validity

Kucuk *et al.* (2014) outlined in a review the need for thin-layer drying studies to include an uncertainty analysis on the raw data. Uncertainty can exist in two forms, specifically, random and systematic. If an experiment is prone to random error, the data will not be precise and is easily measured through standard deviation, or graphically through a box and whisker plot. Systematic error is harder to detect and can be found by comparing experimental data with theoretical values or other experimental data. For the case of drying rooibos, there are no theoretical or experimental values in existence.

For this study, random data will be quantified by calculating the mean and standard deviation for each data set. A box and whisker plot will also be compiled to determine skewness, if any. The precision of the drying apparatus will also be taken into account. Systematic error will be handled by replicating a previously published experiment with the intended apparatus for a different crop that was dried under similar conditions. This will allow for any systematic error to be identified, if it exists within the dryer or drying methodology.

8.5.2 Drying curves

The production of drying curves (moisture ratio versus time) requires the calculation of the moisture ratio:

$$MR = \frac{MC - MC_{db}^{*}}{MC_{cr} - MC_{db}^{*}} \qquad (8.1)$$

This necessitates the need for the dry mass, mass over time and equilibrium mass (used to calculate moisture content and equilibrium moisture content). These are calculated as described in Sections 8.4.2. and 8.4.4. In addition to equilibrium moisture content, critical moisture content is required for the moisture ratio. This can only be determined once a graph of drying rate versus time is drawn up. Most agricultural products, however, do not display a constant rate period (Erbay and Icier, 2010). It is expected that rooibos tea will also not display this trend and thus the equilibrium moisture content will most likely be equal to the initial moisture content, in keeping with literature (Erbay and Icier, 2010). This will be determined for each experiment to account for sample variations.

These will be inputted into a *Microsoft Excel* spreadsheet and then into *Matlab* which will enable an accurate graph production. The drying curves are then ready to be analysed and used for subsequent analysis.

8.5.3 Determination of best fitting thin-layer model

Fitting the thin-layer drying models available in literature consists of three parts: the selection of relevant models from literature, the application of linear regression techniques to the data to determine the model coefficients and the determination of the most suitable model.

8.5.3.1 Model selection

Although sixty-seven thin-layer drying models currently occur in literature (Kucuk *et al.*, 2014), a limited number appear more than once. Eighteen of the most common models have been listed in the literature review in the preceding sections and of these eight have been chosen to be tested in this study as reviewed in Table 8.3. below.

These models have been chosen to represent a wide a range of mathematical expressions and incorporate newer models whilst keeping computation capacity low. The outlined models are all very common solutions for agricultural products, as identified by Kucuk *et al.* (2014). Although the Lewis model is also common, it has been left out of this list due to the similarity to the Henderson and Pabis model. If rooibos displays characteristics most suitable to the Lewis model, it will show up as the Henderson and Pabis model with a coefficient (a) of 1.

Table 8.3. Summary of Thin-Layer Drying Mathematical Models in Literature

Name of Model	**Mathematical Description**	**Reference**
Page	$MR = \exp[-kt^n]$	Page (1949)
Henderson and Pabis	$MR = a\exp[(-kt)]$	Henderson and Pabis (1961)
Logarithmic	$MR = a\exp[-kt] + c$	Chandra and Singh (1995)
Midilli et al./Midilli-Kucuk	$MR = a\exp(-kt^n) + bt$	Midilli *et al.* (2002)
Hii et al.	$MR = a\exp(-kt^n) + c\exp(-gt^n)$	Hii *et al.* (2009a)
Two-Term Exponential	$MR = a\exp[-k_1 t] + b\exp[(-k_2 t)]$	Henderson (1974)
Wang and Singh/Quadratic	$MR = 1 + bt + at^2$	Wang and Singh (1978)
Diamante et al.	$\ln(-lnMR) = a + b(\ln t) + c(\ln t)^2$	Diamante *et al.* (2010)

8.5.3.2 Coefficient determination

Experimental data is fitted to the models through the optimization of statistical assessment criteria (Diamente and Munro, 1993; Yaldiz and Ertekin, 2001; Akpinar *et al.*, 2003; Midilli and Kucuk, 2003; Ertekin and Yaldiz, 2004; Menges and Ertekin, 2006b; Aghbashlo *et al.*, 2009a; Hii *et al.*, 2009b; Kucuk *et al.*, 2014). Although, 28 of these have been encountered in literature (Kucuk *et al.*, 2014), five will be used in this study: Correlation (r), reduced chi-squared (χ^2), root mean square error ($RMSE$), coefficient of determination (r^2) and model efficiency (η) (see Appendix C for mathematical descriptions of these criteria). These were selected as they are the most commonly used assessment criterion in thin-layer drying literature as identified by Kucuk *et al.* (2014).

Optimization includes varying the model coefficients to find the lowest reduced chi-squared, root mean square error and coefficient of determination or the highest correlation and model efficiency. A statistical programme, such as *Matlab (Statistical Package)*, *SAS* or *Stata*, will be used to carry out these operations due to the large amount of data. A trial run of one or two sets of data will be manually programmed in *Microsoft Excel* to check the statistical programme. This is done to eliminate the “black box” effect.

8.5.3.3 Selection of best model

After the coefficients have been determined as outline above, the model with the highest correlation and model efficiency but lowest reduced chi-squared, root mean square error and coefficient of determination will be selected. This model will most precisely describe the drying of rooibos tea leaves out of the tested models.

8.5.4 Effective moisture diffusivity

After finding the thin-layer drying model that best describes the drying of rooibos tea leaves, the effective moisture diffusivity will be calculated. Effective moisture diffusivity (D_{eff}) is a measure of all possible resistances to moisture transport (Erbay and Icier, 2010). As demonstrated in the literature review, Fick's Law can be interpreted for an infinite slab with the stated assumptions and simplified to an analytically solvable form:

$$MR = \frac{8}{\pi^2} \exp\left(-\frac{\pi^2 D_{eff} t}{4L^2}\right) \tag{8.2}$$

The use of this solution can be justified for the drying of rooibos as for the drying process, the leaves will be spread on a drying rack in single-layer to stimulate thin-layer conditions. Inherently the thickness of the sample will be insignificant in comparison to the length and breadth – characteristic of infinite slab conditions.

Experimentally the effective diffusivity can be calculated by plotting the natural log of Equation 8.2 against time:

$$\ln MR = \ln \frac{8}{\pi^2} - Kt \tag{8.3}$$

$$K = \frac{\pi^2 D_{eff}}{4L^2} \tag{8.4}$$

This should theoretically be a straight line. Using statistical linear regression techniques, the effective diffusivity can be found by plotting this line from experimental data (Erbay and Icier, 2010). This needs to be done for all experimental variations as effective diffusivity is dependent on process conditions (Islam and Flink, 1982; Ece and Cihan, 1993).

8.5.5 Activation energy

The strongest factor affecting effective diffusivity is temperature. Generally an Arrhenius equation is used to relate effective diffusivity and temperature (Henderson, 1974; Mazza and

Lemaguer, 1980; Suarez *et al.*, 1980; Steffe and Singh, 1982; Pinaga *et al.*, 1984; Carbonell *et al.*, 1986; Crisp and Woods, 1994; Madamba *et al.*, 1996), which when rearranged is:

$$\ln D_{eff} = \ln(D_0) - \frac{E_a}{RT} \qquad (8.5)$$

By plotting this graph using the experimental values obtained, it is possible to determine the activation energy using linear regression again.

Activation energy is important to determine as it gives an indication as to how sensible the effective diffusivity is to temperature, namely the higher the activation energy, the more sensitive the effective diffusivity is to temperature (Erbay and Icier, 2010). If the correlation is not close to 1, this indicates that other factors (apart from temperature) affect effective diffusivity (Erbay and Icier, 2010). It is expected that rooibos tea drying will fit the Arrhenius-type dependence on temperature as a study conducted on black *Camellia sinensis,* tea adheres to this description well (Panchariya *et al.*, 2002).

8.5.6 Effect of process variables on model constants

To determine how independent the constants are on experimental variables, multiple regression analyses are normally performed with differing equations: linear, logarithmic, exponential, power and Arrhenius equations (Guarte, 1996). These are chosen mainly because they can be linearised (Erbay and Icier, 2010).

For this study, the linear, quadratic, exponential, logarithmic, power and Arrhenius equations will be tested using the same method as outlined in Section 3.5.3. The expected relationship (between temperature, velocity and relative humidity and the coefficient) will be mathematically formulated, substituted for the coefficient into the model formula and regressed (Lewis, 1921; Togrul and Pehlivan, 2003; Akpinar, 2006; Erenturk and Erenturk, 2007; Hossain *et al.*, 2007). This will be repeated with different relationships but only with the best fitting model. This is important to determine how much the process variables affect the drying model.

8.6 Energy Aspects

An important part of drying is that of energy consumption. Drying is an energy intensive process, estimating to use 10-15% of total energy consumption in all industries in developed countries (Erbay and Icier, 2010). A critical aspect of this study will be to analyse the energy consumption of each trial. Energy is directly related to cost, which together with quality, form the two biggest factors of consideration for industry when designing a drying process. For this study, the quantification of the energy used involves two steps: energy measurement and the analysis of this recorded data.

8.6.1 Energy measurement

For the duration of each trial, in both Experiment I and II, the total energy consumption will be measured using a stand-alone three phase clip-on energy measurement device. This will be attached to the incoming power cables of the dryer. The specific energy consumption for rooibos drying will then be calculated using the total mass at the start of the experiment:

$$E_{rooibos} = \frac{E_t}{m_{t=0}} \tag{8.6}$$

The devices also allow for a graphical display of energy consumption over time. Although these graphs are not accurate (the fastest transmission rate from the detector to receiver is approximately 0.13Hz), a general description can be found – qualitative as opposed to quantitative.

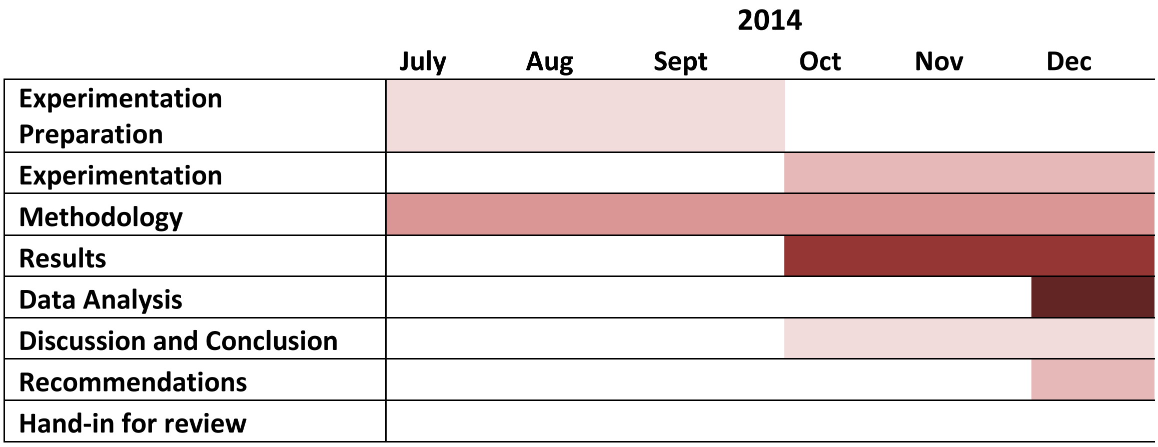
8.6.2 Energy analysis

The specific energy consumption will vary with the differing drying air conditions (Motevali *et al.*, 2012). By comparing the values across the spectrum from both Experiment I and II, the drying conditions that enable the most energy efficient drying can be determined. This will be compared with available literature which has already found the optimum drying conditions for the best quality rooibos tea (Joubert, 1994; Joubert, 1998; Joubert and Schulz, 2006).

The graphical output will also allow for an understanding into which drying period is most energy intensive. It will also give better insight into the effect of temperature, velocity, relative humidity and pre-treatment on the energy consumption during the different time periods. This will allow for potential energy efficient improvements in the process to be identified.

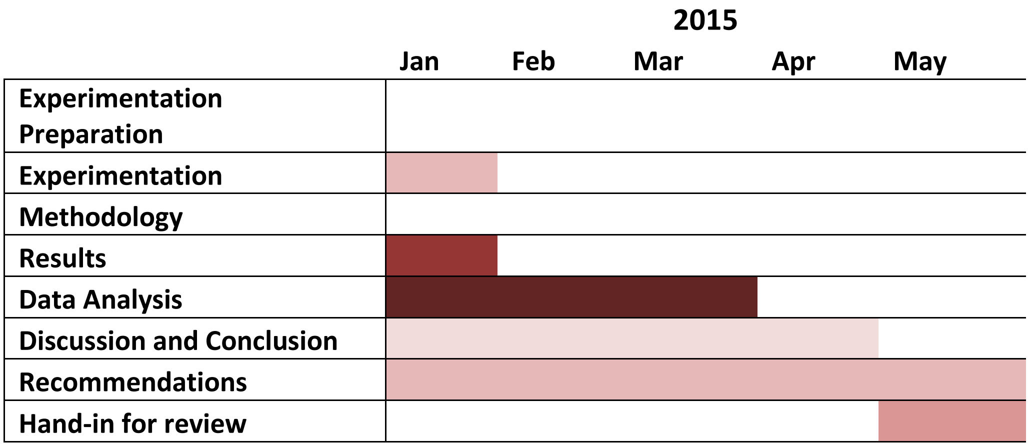
8.7 Project plan

The forecasted Project Plan is outlined in Figures 9.2 and 9.3 below:



2014	July	Aug	Sept	Oct	Nov	Dec
Experimentation Preparation	▨	▨	▨			
Experimentation				▨	▨	▨
Methodology	▨	▨	▨	▨	▨	▨
Results				▨	▨	▨
Data Analysis						▨
Discussion and Conclusion				▨	▨	▨
Recommendations						▨
Hand-in for review						

Figure 8.2. Production Plan for Drying of Rooibos Experimentation 2014



2015	Jan	Feb	Mar	Apr	May
Experimentation Preparation					
Experimentation	▨				
Methodology					
Results	▨				
Data Analysis	▨	▨	▨		
Discussion and Conclusion	▨	▨	▨	▨	
Recommendations	▨	▨	▨	▨	▨
Hand-in for review					▨

The project is hampered mainly the harvesting time of rooibos, which expected to be in October or November 2014.

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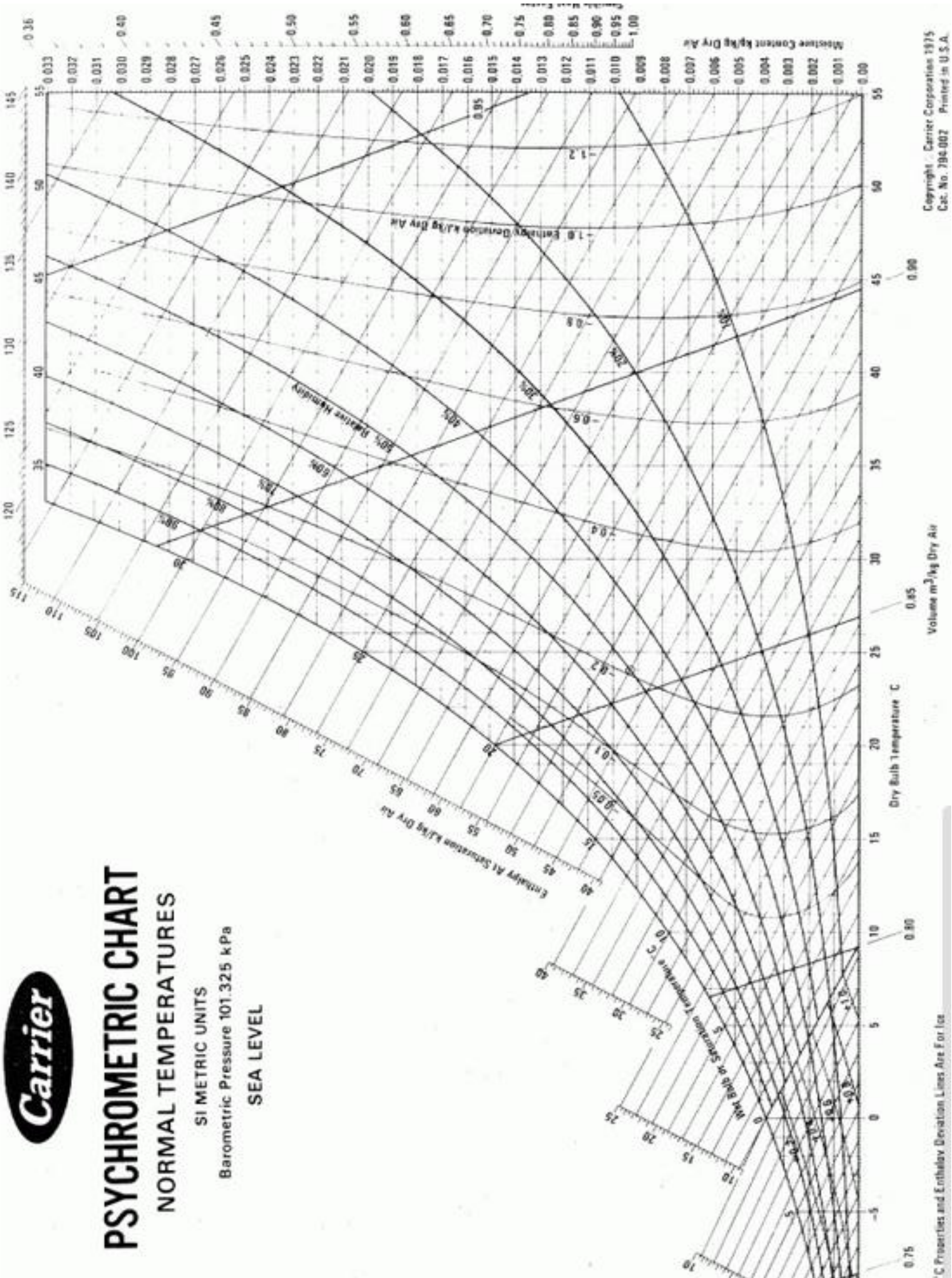
10. APPENDICES

10.1 Appendix A – Psychrometric Chart (Singh and Heldman, 2009)



10.2 Appendix B – Review of Thin-Layer Equations

Two tables are presented: the first looks at the relevant information for the selection of the most appropriate thin-layer drying model, the second at the effect of the process conditions on the model constants. In the Table 10.1, studies from Table 10.2 that did not include a relationship between the process variables and the model coefficients have not been repeated. Due to the large available literature information, only thin-layer drying equations developed using a convective dryer have been presented. The effect of pre-treatment has not been examined unless otherwise stated.

Table 10.1: Thin-Layer Drying of different produces: dryer type, models, effective moisture diffusivity, activation energy.

Reference	**Product**	**Scientific Name**	**Specifications**	**Dryer Type**	**Most Suitable Model**	**Moisture Diffusivity (m^2/s) x10^10**	**Activation Energy (kJ/mol)**
Akpinar (2006)	Apple		sliced and peeled		Midilli		
Menges and Ertekin (2006a)	Apple - Golden	*var. Golden*		Tray	Midilli		
Wang *et al.* (2007)	Apple Pomace				Logarithmic	0.19082-0.39346	24.512
Togrul and Pehlivan (2003)	Apricot				Logarithmic		
Akpinar *et al.* (2004)	Apricot	*Hacihaliloglu var. & Cataloglu var.*		Rotary Drum	Midilli		
Diamante *et al.* (2010)	Apricot	*var. Southern Red & var. Moorpark*		Cabinet	Diamante et al		
Vijayaraj *et al.* (2007)	Bagasse				Page		
Kumar *et al.* (2013)	Bamboo	*Dendrocalamus hamiltonii var. Eni*	slices	Tray	Page		
Kumar *et al.* (2013)	Bamboo	*Dendrocalamus hamiltonii var. Eni*	slices	Tray	Logarithmmic		
Doymaz (2010)	Banana	*var. Cavendish*	slices	tray	Page	0.7374-2.148	32.65
Aghbashlo *et al.* (2009b)	Barberries	*barberries vulgaris*		tunnel	Page		
Gunhan *et al.* (2005)	Bay Leaves	*Laurus nobilis L.*			Page		
Yaldiz and Ertekin (2001)	Bean - Green				Page		
Pin *et al.* (2009)	Betel leaves	*Piper betle L.*		cabinet	Logarithmic		
Rayaguru *et al.* (2011)	Betel leaves	*Piper betel L.*		Tray	Page		
Lidhoo (2008)	Brinjal	*Solanum melongena*	sliced		Page		
Vega-Galvez *et al.* (2014)	CapeGooseberry	*Physalis peruviana L.*		Tray	Midilli-Kucuk	4.67-14.9	38.78
Doymaz (2004a)	Carrot	*Daucus carota L.*	sliced and blanched	Cabinet	Page	0.776-9.335*10^-9	28.36
Erenturk and Erenturk (2007)	Carrot		slices	Tray	Modified Page-II		
Zielinska and Markowski (2010)	Carrot	*Daucus carota cv Macon*	cubed and blanched		Two-term	2.58-20.4	

Reference	**Product**	**Scientific Name**	**Specifications**	**Dryer Type**	**Most Suitable Model**	**Moisture Diffusivity (m^2/s) x10^10**	**Activation Energy (kJ/mol)**
Kumar *et al.* (2012)	Carrot Pomace			Tray	Hii et al	27.4-46.4	23.05
Ojediran and Raji (2011)	Castor Seeds	*Ricinus Communis*		Tray	Modified Page	82.4-181	21.47
Doymaz and Ismail (2011)	Cherry sweet	*var. Napolitane*	pretreated - dipped in ethyl oleate foe 1 min		Page	5.683-15.44	
Hossain *et al.* (2007)	Chilli - Green				Page		
Kaleemullah and Kailappan (2006)	Chilli - Red				Kaleemullah	0.378-0.71	37.76
Hossain *et al.* (2007)	Chilli - Red				Lewis		
Mohamed *et al.* (2005)	Citrus aurantium leaves				Midilli		
Madamba (2003)	Coconut - young	*Cocos nucifera L.*	osmotically pre-treated		Page	1.71-5.51	1173
Hii *et al.* (2009b)	Cocoa beans	*Theobroma cacao*	overnight tempering	Cabinet	Hii et al	74.6-187	44.92
Doymaz and Pala (2003)	Corn			Cabinet	Page	0.9488-1.768	29.56
Corzo *et al.* (2008)	Coroba	*Attalea maripa*		Cabinet	Weibull Distribution	0.0251-0.0427	139.03-214.93
Corzo *et al.* (2010)	Coroba	*Attalea maripa*	slices		Midilli and Kucuk		
Corzo *et al.* (2010)	Coroba	*Attalea maripa*	slices		Logarithmic		
Hassan and Hobani (2000)	Date	*var. Sukkari & var.Sakie*			Page		
Doymaz *et al.* (2006)	Dill Leaves	*Anethum graveolens L.*		Cabinet	Midilli Kucuk	6.693-14.34	35.05
Erenturk *et al.* (2004a)	Echinancea	*Echinacea Angustifolia*			Modified Page-II		
Ertekin and Yaldiz (2004)	Eggplant		pre-treated by hot water dipping	tray	Midilli		
Xanthopoulos *et al.* (2007)	Figs	*Ficus carica L. var Tsapela*	whole		Logarithmic		
Xanthopoulos *et al.* (2009)	Figs	*Ficus carica L. var.*	whole & unpeeled		Logarithmic	1.797-5.162	40.95

Reference	**Product**	**Scientific Name**	**Specifications**	**Dryer Type**	**Most Suitable Model**	**Moisture Diffusivity (m^2/s) x10^10**	**Activation Energy (kJ/mol)**
		tsapela					
Toujani *et al.* (2013)	Fish - silverside		scaled and gutted	Tunnel	Midilli et al	8.763-32.131	35.6471-37.2625
Toujani *et al.* (2013)	Fish - silverside		scaled and gutted	Tunnel	Two-Term	8.763-32.131	35.6471-37.2625
Madamba *et al.* (1996)	Garlic		var. Early Californian		Page	2-4.2	989
Yaldiz *et al.* (2001)	Grape	*var. Sultana*	Pre-treated with potassium carbonate and olive oil dilution	Cabinet	Two-Term		
Sawhney *et al.* (1999)	Grape	*Vitis vinifera*	pretreated with oil dipping	Tray	Page		
Doymaz (2012a)	Grape leaves	*Vitis vinifera*			Wang and Singh and Midilli et al	4.13-18.3	64.56
Özdemir and Onur Devres (1999)	Hazelnut				Thompson	2.301-11.759*10^-7	1891.6
Ozilgen and Ozdemir (2001)	Hazelnut		Mi=6.14%		Two-Term		
Motevali *et al.* (2012)	Jujube	*Zizyphus jujubeMill*				1.1532-5.1895	34.97-74.2
Mwithiga and Olwal (2005)	Kale	*Brassica Oleracea*			Modified Page-I	14.9-55.9	36.115
Doymaz (2009a)	Kiwi	*Actinidia deliciosa*		Cabinet	Modified Henderson and Pabis	1.743-2.241	22.48
Diamante *et al.* (2010)	Kiwi	*var. Hayward & var. Hort16A*		Cabinet	Diamante et al		
Karabulut *et al.* (2007)	Kurut				Two-Term	24.44-35.97	19.88
Doymaz (2008b)	Leeks	*Allium porrum L.*		cabinet	Midilli et al	1.909-4.140	17.54-18.09
Janjai *et al.* (2011)	Litchi	*Litchi chinensis Sonn.*			Page		
Goyal *et al.* (2006)	Mango	*Mangifera indica L. var. Dasehari*	raw	Tunnel	Page	2.62-4.39	
Doymaz (2006)	Mint leaves	*Mentha spicata L.*		Cabinet	Logarithmic	30.67-194.1	62.96

Reference	**Product**	**Scientific Name**	**Specifications**	**Dryer Type**	**Most Suitable Model**	**Moisture Diffusivity (m^2/s) x10^10**	**Activation Energy (kJ/mol)**
Kaya and Aydin (2009)	Mint Leaves	*Mentha spicata L.*				19.75-61.72	66.873-71.987
Doymaz (2004b)	Mulberry, white	*Morus alba L.*			Logarithmic	2.231-6.909	
Kurozawa *et al.* (2012)	Mushroom	*Agaricus blazei*	sliced and osmotically pre-treated	Tray	Logarithmic	4.14-14.28	
Tulek (2011)	Mushroom - oyster	*Pleurotus ostreatus*		Cabinet	Midilli et al	9.619-15.66	22.228
Fan *et al.* (2011)	Nata de coco	*Acetobacter aceti ssp. xylinum*			Logarithmic and Wang and Singh		
Alibas (2010)	Nettle leaves	*Urtica dioica L.*			Page		
Kaya and Aydin (2009)	Nettle leaves	*Urtica dioica*				17.44-49.92	79.873-109.003
Akpinar and Bicer (2008)	Pepper - Long Green			Cabinet	Logarithmic		
Demir *et al.* (2007)	Olive - green table	*Olea europaea L.*	Domat var.		Midilli et al		
Akgun and Doymaz (2005)	Olive cake			Cabinet	Logarithmic	30-110	17.97
Montero *et al.* (2011)	Olive Mill Wastewater			Solar		1.273-4.125	47.64
	Olive Pomace					5.364-14.06	38.64
	Olive Sludge					0.9136-2.02	30.44
Yaldiz and Ertekin (2001)	Onion				Two-Term		
Rao *et al.* (2007)	Paddy		parboiled		Lewis		
Rayaguru and Routray (2010)	Pandus amaryllifolius	*Pandus amaryllifolius*	leaves	Cabinet	Page	21	
Akpinar *et al.* (2006)	Parsely			Tray	Page		
Doymaz *et al.* (2006)	Parsely Leaves	*Petroselinum crispum L.*		Cabinet	Midilli Kucuk	9-23.37	43.92
Pardeshi *et al.* (2009)	Pea -green	*Pisum sativum*	blanched & sulphated		Thomson	3.95-6.23	22.48
Kingsly *et al.* (2007)	Peach	*Prunus persica var. Shan-e-Punjab*	sliced	tunnel	Logarithmic	30.4-36.2	
Doymaz (2013)	Pear	*Pyrus communis L.*	slices		Midilli et al	0.856-2.25	34.95

Reference	**Product**	**Scientific Name**	**Specifications**	**Dryer Type**	**Most Suitable Model**	**Moisture Diffusivity (m^2/s) x10^10**	**Activation Energy (kJ/mol)**
		var. Deveci					
Yaldiz and Ertekin (2001)	Pepper - Green				Diffusion Approach		
Akpinar *et al.* (2003)	Pepper - Red				Diffusion Approach		
Yaldiz and Ertekin (2001)	Pepper - Stuffed		stuffed		Two-Term		
Doymaz (2012b)	Persimmon	*Diospyros kaki L.*	slices	cabinet	Midilli et al, Page and Weibull	0.705-2.34	43.26
Midilli and Kucuk (2003)	Pistachio - shelled		shelled	cabinet	Midilli		
Midilli and Kucuk (2003)	Pistachio - unshelled		unshelled	cabinet	Midilli		
Kashaninejad *et al.* (2007)	Pistachio	*Pistacia spp L.*			Page	0.542-9.29	30.79
Menges and Ertekin (2006b)	Plum	*var. Stanley*		Tray	Midilli	11.79-66.71	
Midilli *et al.* (2002)	Pollen		from Anzer Plaeau		Midilli		
Akpinar (2006)	Potatoe		sliced and peeled		Midilli		
Aghbashlo *et al.* (2009a)	Potatoe	*Solanum tuberosum*		Continous Band	Page	3.17-15.45*10^-7	39.49-42.34
Lahsasni *et al.* (2004)	Prickly Pear Fruit	*Opuntia ficus indica*			Two-Term		
Akpinar (2006)	Pumpkin		sliced and peeled		Midilli		
Basunia and Abe (2001)	Rice		Rough		Page		
Iguaz *et al.* (2003)	Rice	*var. Lido*	Rough		Henderson and Pabis		
Erenturk *et al.* (2004b)	Rosehip	*Rosa canina*			Logarithmic		
Doymaz (2009b)	Spinach	*Spinacia olerace L.*		Cabinet	Logarithmic	6.59-1.927	34.35
Desmorieux and Decaen (2005)	Spirulina	*arthrospiral platensis*					
Chayjan *et al.* (2013)	Squash seeds		seeds		Two-Term	0.551-1.6	31.94-34.49
Akpinar and Bicer (2006)	Strawberry			cyclone	Modified Page-I	4.528-9.631	
Doymaz (2008a)	Strawberry	*Fragaria*			Logarithmic for	4.95-14.2	

Reference	**Product**	**Scientific Name**	**Specifications**	**Dryer Type**	**Most Suitable Model**	**Moisture Diffusivity (m^2/s) x10^10**	**Activation Energy (kJ/mol)**
					T=50-55, Wang and Singh for T=65		
Lee and Hsieh (2008)	Strawberry - fruit leather				Two-term	24-121	30.46-35.57
Phoungchandang and Kongpim (2012)	Sweet Basil	*OCIMUM BASLICUM LINN.*	fresh and blanched	cabinet	Henderson		
Falade and Solademi (2010)	Sweet potato	*Ipomoea batatas L.*	slices		Page	0.636-7.8	11.1
Panchariya *et al.* (2002)	Tea - black	*Camellia sinensis L.*			Lewis	0.114-0.298	406.02
Karaaslan and Tuncer (2011)	Tea - green	*Camellia sinensis L.*			Midilli Kucuk		
Doymaz (2011)	Thyme	*Thymus vulgaris L.*		cabinet	Midilli et al	10.97-59.91	73.84
Tunde-Akintunde and Oke (2012)	Tiger Nuts	*Cyperus Esculentus*			Parabolic	2.39-7.23	28.14
Das Purkayastha *et al.* (2013)	Tomato	*Lycopersicon esculantum L*	sliced and blanched		Logarithmic	5.453-23.871	61.004
Mohapatra and Srinivasa Rao (2005)	Wheat		parboiled		Two-term	1.215-2.861	37.013
Sobukola *et al.* (2008)	Yams	*Dioscorea rotundata*	Blanched and sliced		Two Term	762-906	8.831
Hayaloglu *et al.* (2007)	Yoghurt - strained		strained	tray	Midilli	9.5-13	26.07

Table 10.2: Thin-Layer Drying Experimental Data Part 2 - model, process conditions and effect of process conditions on model

Author	**Product**	**Model**	**Temperature (deg C), velocity (m/s), Relative Humidity**	**model constants**
Akpinar (2006)	Apple	Midilli	T=60-80	a=1.004084-0.000073T-0.001960v+3.944759w
			v=1-1.5	n=1.187734+0.002467T-0.128878v-202.536w
				k=-0.006391+0.000065T+0.009775v+1.576723w
				b*=0.000082-0.0000002T-0.000041v+0.041667w
Wang *et al.* (2007)	Apple Pomace	Logarithmic	T=75-105	a = 271.15 – 8.91T+ 0.097T 2 – 3.52T 3
				k = –0.61 + 0.02T – 0.0002T 2+ 0.0000008T^3
				c = –267.45 + 8.82T – 0.096T 2+ 0.0004T 3
Togrul and Pehlivan (2003)	Apricot	Logarithmic	T=50-80	a = 1.13481exp(0.018352υ)
			v=02-1.5	k = 0.001269 + 0.000018Tx+ 0.00105υ
				c = –1.16416 + exp(1.6982/T) – 0.0138υ
Akpinar *et al.* (2004)	Apricot	Midilli	T=47.3-61.74	a = 1.069931 – 0.001297T – 0.004534υ+0.005478RSC
			v=0.707-2.3	k = –0.086272 + 0.001775T+ 0.035643υ+0.009545RSC
				n = 1.705840 – 0.013076T – 0.167507υ –0.020810RSC
				b∗ = 0.010122 – 0.000162T – 0.001439υ –0.000240RSC
Vijayaraj *et al.* (2007)	Bagasse	Page	T=80-120	k = 0.49123557038 + 0.0031094667H – 0.0031183596869T – 0.03947507753υ+0.113762212L
			v=0.5-2	
			L=20-60	n = –0.86990405 + 0.238750462logt –1.175456904k
			H=9-24	
Kumar *et al.* (2013)	Bamboo	Page	T=55-75	k=0.059-0.133
				n=1.354-1.464
Kumar *et al.* (2013)	Bamboo	Logarithmmic	T=55-75	k=0.08-0.159
				a=1.254-1.476
				c=-0.467--0.235
Aghbashlo *et al.* (2009b)	Barberries	Page	T=50-70	k=2.497*10^20*V^-0.0561*exp(-15997.3/T_abs)
			v=0.5-2	n=13.45V^0.0561exp(-802.5/T_abs)
Gunhan *et al.* (2005)	Bay Leaves	Page	T=40-60	k = exp(-4.4647 + 0.07455T – 0.00714RH)
			RH=5-25%	n = 1.14325
Yaldiz and Ertekin (2001)	Bean - Green	Page	T=50-80	k = 0.3560 – 0.1407υ
			v=0.25-1	n= 0.7832 + 0.0892lnυ
Pin *et al.* (2009)	Betel leaves	Logarithmic	T=40-80	a=1.007-1.0331-

Author	**Product**	**Model**	**Temperature (deg C), velocity (m/s), Relative Humidity**	**model constants**
				k=0.00331-0.0397
				b=-0.0331--0.007
Rayaguru *et al.* (2011)	Betel leaves	Page	T=40-60	k=0.0163-0.0639
				n=0.8071-039829
Erenturk and Erenturk (2007)	Carrot	Modified Page-II	T=60-90	k = 42.66υ0.3123(2L)−0.8437exp(–2386.6/T)
			L=2.5-5	n = 5.48υ−0.0846(2L)−0.1066exp(–452.5/T)
			v=0.5-1.5	
Kumar *et al.* (2012)	Carrot Pomace	Hii et al	T=60-75	a=13905.60529-619.95731*T+9.18210T^2-0.04516T^3
				k=-0.21037+0.01238*T-0.00022T^2
				n=16.45430-0.69205T+0.01039T^2-0.00005T^3
				c=-13908.27+620.14037T-9.18481T^2+0.4517T^3
			v=0.7	g=005894+0.0082T-0.00005T^2
Ojediran and Raji (2011)	Castor Seeds	Modified Page	T=40-70	k=0.011-0.022
				n=0.778-1.049
Hossain *et al.* (2007)	Chilli - Green	Page	T=40-65	k = 0.008759 – 0.00027T+0.000000282T 2+ 0.00166υ – 0.01058RH+ 0.009057RH2
			RH=10-60%	n== 0.563021 + 0.006435T+ 0.088298υ +
			v=0.1-1	
Kaleemullah and Kailappan (2006)	Chilli - Red	Kaleemullah	T=50-65	c*=0.0084766
				b*== -0.34775
				m = 0.00004934
				n = 1.1912
Hossain *et al.* (2007)	Chilli - Red	Lewis	T=40-65	k = 0.003484 – 0.000222T+ 0.00000366T 2– 0.007085RH + 0.00572RH 0.002738υ –0.001235υ2
			RH=10-60	
			v=0.12-1.02	
Mohamed *et al.* (2005)	Citrus aurantium leaves	Midilli	T=50-60	a = –49.079 + 1.838T – 0.0167T 2
				n = 37.447 – 1.346T+ 0.01231T 2
			RH=41-53%	k = –13.604 + 0.498T –0.004518T 2
				b∗ = –0.451 + 0.01576T –0.00014T 2
Madamba (2003)	Coconut - young	Page	T*50-70	k = 21.8exp(–2136.9/Tabs)
			L=2.5-4	n = 0.098 – 0.082L
Hii *et al.* (2009b)	Cocoa beans	Hii et al	T=60-80	a=0.555446-0.729654

Author	**Product**	**Model**	**Temperature (deg C), velocity (m/s), Relative Humidity**	**model constants**
				k=0.0072361-0.220349
				n=1.270623-1.817112
				c=0.267136-0.433171,
				g=0.011612-0.002186
Corzo *et al.* (2008)	Coroba	Weibull Distribution	T=71-93	lna=5.66-0.009T-0.008v
			v=0.82-1.18	
Corzo *et al.* (2010)	Coroba	Midilli and Kucuk	T=71-93	k=-0.0321+0.000252T+0.0276v
			h=0.018	a=1.03-1.14
			v=0.82-1.18	c=3.6-11*10^-2
				k=-0.0162+0.000246T+0.0131v
Corzo *et al.* (2010)	Coroba	Logarithmic	h=0.018	a=0.994-1.004
			v=0.82-1.18	n=1-1.11
			T=71-93	b=-3.95--154*10^-4
Hassan and Hobani (2000)	Date	Page	T=50-70	k = –2.463 + 0.0613T – 0.00035T 2
				n = –1.228 + 0.0524T –0.00032T 2
Doymaz *et al.* (2006)	Dill Leaves	Midilli Kucuk	T=50-70	a=0.96315-0.98274
			v=1.1	k=0.00238-0.01639
				b=-0.00031--0.00023
Erenturk *et al.* (2004a)	Echinancea	Modified Page-II	T=15-45	k = 0.07υ0.1793(2r)−1.2349exp(-20.66/T)
			v=0.3-1.1	n=0.96v^-0.0139(2r)^-0.0433exp(-1.73/T)
Ertekin and Yaldiz (2004)	Eggplant	Midilli	T=30-70	a = 0.98979 − 0.08071 ln υk =0.00160T 1.55945
			v=0.5-2	n=1.09877 + 0.29745 ln υ
				b*== 0.00062
Xanthopoulos *et al.* (2007)	Figs	Logarithmic	T=46.1-60	a = 1.12998 + 0.0006324T - 0.0368791υ -0.00410299H
			H=8.14-13.31	k =−0.0898261 + 0.00244127T+0.00445721υ −0.0000864371H
			v=1-5	c =−0.161594 − 0.000764116T+0.0347936υ+ 0.00720103H
Xanthopoulos *et al.* (2009)	Figs	Logarithmic	T=45-65	a=0.975+1.172*10^-7*(h/v)^6-8.08*10^-13*T^6
			RH=5.6-15.1	k=0.035-0.005*h/v+1.310*10^-10*T_a^5
			v=1-5	c=[8.623-0.011h/v)^6+8.873*10^-8*T_a^6]*10^-5
Toujani *et al.* (2013)	Fish - silverside	Midilli et al	T=45-70	a=1.00051

Author	**Product**	**Model**	**Temperature (deg C), velocity (m/s), Relative Humidity**	**model constants**
			RH=20-40%	k=0.00937-0.02425
				b==-0.00025--0.00003
				n=0.71033-0.92809
Toujani *et al.* (2013)	Fish - silverside	Two-Term	T=45-70	k0=-0.11153--0.00661
			RH=20-40%	k1--3.60707--0.00522
				a=0.10964-0.94988
				b=0.01612-0.90364
Madamba *et al.* (1996)	Garlic	Page	T=50-90	k=0.14+3.72*10^-4*T-0.031d
			RH=8-24%	n=0.38+6.7*10^-3*T
			v=0.5-1	
Yaldiz *et al.* (2001)	Grape	Two-Term	T=32.1-40.3	a = 0.336 - 0.004T
				b = 0.806υ^-0.039
			v=0.5-1.5	k1 = 7.703 – 8.717 lnυ
				k2 = -0.141 + 0.048 lnT
Sawhney *et al.* (1999)	Grape	Page	T=50-80	k = 2.91 × 106υ0.22exp(5749.05/T)
			v=0.25-1	n = 1.14
				k = 3720000υ0.19H−0.13exp(-6032/Tabs)
				n = 1.107
Özdemir and Onur Devres (1999)	Hazelnut	Thompson	T=100-160	a = −116.05 + 0.656T
				b = −19.89 + 0.122T
Ozilgen and Ozdemir (2001)	Hazelnut	Two-Term	T=100-160	a = 0.434 - 0.00304T
				b = 0.00304 + 236248.7T
				k1 = 0.566
				k2 = 5.29
Mwithiga and Olwal (2005)	Kale	Modified Page-I	T=30-60	k = exp(8.0487 – 3836.1/Tabs)
			L=10-50	n = 0.894653
Janjai *et al.* (2011)	Litchi	Page	T=50-70	k=0.184900.41777
			v=0.5	n=1.03366-1.13271
Doymaz (2004b)	Mulberry white	Logarithmic	T=50	k=0.03891
			v=1	a=1.254
Kurozawa *et al.* (2012)	Mushroom	Logarithmic	T=40-80	a=0.939-1.056
			v=1-205	k=2.39-6.26*10^-4

Author	**Product**	**Model**	**Temperature (deg C), velocity (m/s), Relative Humidity**	**model constants**
Tulek (2011)	Mushroom - oyster	Midilli et al	T=50-70	a=0.9996-1.0005
			v=0.2	k=0.4511-0.8403
				n=1.0225-1.2289
				b=0.0003-0.0015
Alibas (2010)	Nettle leaves	Page	T=50-100	k=0.0261-0.0483
			v=1	n=1.04463-1.15199
Akpinar and Bicer (2008)	Pepper - Long Green	Logarithmic	T=43.9-64.8	a=1.164715
				k=0.011395
				c=-0.347193
	Olive Pomace			
	Olive Sludge			
Yaldiz and Ertekin (2001)	Onion	Two-Term	T=50-80	a = 0.4866 + 0.6424 lnυ
			v=0.2-1	b = 0.5143 – 0.6424 lnυ
				k1 = 0.1557 + 0.1995 lnυ
				k2 = 0.1117 – 0.0992 lnυ
Rao *et al.* (2007)	Paddy	Lewis	T=70-150	k = 0.02υ0.473L−0.699d T 0.478
			Ld=50-200	
			v=0.5-2	
Rayaguru and Routray (2010)	Pandus amaryllifolius	Page	T=45	k=0.002
Akpinar *et al.* (2006)	Parsely	Page	T=56-93	k=0.000012*T^0.706263
			v=1	n=0.293914*T^0.299815
Doymaz *et al.* (2006)	Parsely Leaves	Midilli Kucuk	T=50-70	a=0.94186-0.96919
			v=1.1	k=0.00385-0.01656
				b=-0.00052--0.00019
Doymaz (2013)	Pear	Midilli et al	T=50-71	a=1.009054-1.001252
			v=2	b=-0.000483--0.000282
				k=0.002923-0.002903
				n=1.169296-1.019671
Yaldiz and Ertekin (2001)	Pepper - Green	Diffusion Approach	T=50-80	a =−1.6626 + 1.7015υ
			v=0.25-1	b= 0.5868 – 0.0172υ
				k = 0.3549 – 0.1489υ

Author	**Product**	**Model**	**Temperature (deg C), velocity (m/s), Relative Humidity**	**model constants**
Akpinar *et al.* (2003)	Pepper - Red	Diffusion Approach	T=55-70	a = 1844.324 – 493.320 lnT
				b= 1.033970exp(-12.2945/Tabs)
				k = 63319.52exp(-4973.88/Tabs)
Yaldiz and Ertekin (2001)	Pepper - Stuffed	Two-Term	T=50-80	a = 0.6315 – 0.2957υ
			v=0.25-1	b = 0.3679 + 0.2962υ
				k1 = 0.0224exp(4.7396υ)
				k2 = 0.0677 – 0.0117 lnυ
Midilli and Kucuk (2003)	Pistachio - shelled	Midilli	T=40-60	a = 0.9968 + 0.0007 lnT
			RH=5-20%	n = 0.9178 + 0.0008 lnT
			v=0.5-1.5	k= 0.1493 + 0.0006 lnT
				b∗ = 0.0501 + 0.0001 lnT
Midilli and Kucuk (2003)	Pistachio - unshelled	Midilli	T=40-60	a = 0.9968 + 0.0003 lnT
			RH=5-20%	n = 0.9247 + 0.0005 lnT
			v=0.5-1.5	k= 0.1545 + 0.0002 lnT
				b*= 0.0486 + 0.0004 lnT
Kashaninejad *et al.* (2007)	Pistachio	Page	T=25-70	k =−0.00209 + 0.000208T+ 0.00502υ2
			v=0.5-1.5	n = 0.844 + 0.00262T – 0.106υ
Menges and Ertekin (2006b)	Plum	Midilli	T=60-80	a = 3.2180 − 0.5255 lnT
			v=1-3	n = 0.000057T 2.3144
				k= 0.2288υ0.2994
				b*=−0.0028
Midilli *et al.* (2002)	Pollen	Midilli	T=45	a = 0.9987 + 0.0003 lnT
				n = 0.5869 + 0.0005 lnT
				k= 0.2616 + 0.0002 lnT
				b*= 0.0609 + 0.0004 lnT
Akpinar (2006)	Potatoe	Midilli	T=60-80	a = 0.986173 + 0.000069T+ 0.005702υ+0.098206ω
			v=1-1.5	k = -0.015582 + 0.000156T+0.013467υ+ 0.266761ω
				n = 1.218379 + 0.000802T – 0.162776υ –138.528ω
				b*== 0.0000085 + 0.00000029T –0.0000393υ – 0.0203022ω
Aghbashlo *et al.* (2009a)	Potatoe	Page	T=50-70	k=0.3891-1.808
			v=0.5-1.5	m=0.9155-1.058

Author	**Product**	**Model**	**Temperature (deg C), velocity (m/s), Relative Humidity**	**model constants**
Lahsasni *et al.* (2004)	Prickly Pear Fruit	Two-Term	T=50-60	a =−2.9205 + 0.1117T – 0.0011T 2
				b = 2.3099 – 0.0547T+ 0.0005T 2
				k1 = 1.1619 – 0.0439T+0.0004T 2
				k2 = -0.0764 + 0.0027T– 0.000021658T 2
Akpinar (2006)	Pumpkin	Midilli	T=60-80	a = 0.966467 + 0.000184T+ 0.007014υ
			v=1-1.5	n = 0.572175 + 0.009074T– 0.064652υ
				k= 0.005645 - 0.000095T+ 0.003791υ
				b*== 0.000050 - 0.000001T –0.000024υ
Basunia and Abe (2001)	Rice	Page	T=22.3-34.9	k = -0.00209 + 0.000208T+ 0.00502υ2
			RH=34.5-57.9%	n =0.844 + 0.00262T – 0.106υ
Iguaz *et al.* (2003)	Rice	Henderson and Pabis	T=5-35	a = 18.1578 – 1.49019υ -0.027191T –0.263827RH +0.00453363T υ+
			v=0.75-2.5	k = 0.00301414 – 0.000021593T+0.0000000389067T 2+ 0.00000478υ
			RH=30-70%	
Akpinar and Bicer (2006)	Strawberry	Modified Page-I	T=60-85	k=-0.00008781+0.0000035*T+0.000036*v
			v=0.5-1.5	n=0.796264+0.004795*T-0.047211*v
Falade and Solademi (2010)	Sweet potato	Page	T=50-80	k=0.443-0.803
				n=0.641-0.925
Panchariya *et al.* (2002)	Tea - black	Lewis	T=80-120	k = 0.12563υ1.15202exp(−209.12341/Tabs)
			v=0.25-0.65	
Doymaz (2011)	Thyme	Midilli et al	T=40-60	a=0.9903-0.9963
			v=2	k=0.0023-0.0052
				n=1.1678-1.3205
				b=-0.0002-0.0001
Mohapatra and Srinivasa Rao (2005)	Wheat	Two-term	T=40-60	a = 0.03197T – 1.009
				b = -0.032T+ 1.9918
				k1 =−0.034
				k2 =−0.009
Hayaloglu *et al.* (2007)	Yoghurt - strained	Midilli	T=40-50	k =−0.0005569 +0.00001205T+ 0.0002047υ
			v=1-2	b*==−0.00003489 -0.00000038T – 0.00000542υ

10.3 Appendix C - Statistical Assessment Criteria – Mathematical Descriptions

10.3.1 Correlation Coefficient

The correlation coefficient (r) varies between -1 and 0 and 0 and 1 (depending on the sign of the nominator). A good correlation is close to either 1 or -1 but for the case of drying, the correlation should vary between 0 and 1. The mathematical formula for correlation is (Kucuk *et al.*, 2014):

$$r = \frac{N\sum_{i=1}^{N} MR_{pre,i}MR_{exp,i} - \sum_{i=1}^{N} MR_{pre,i}\sum_{i=1}^{N} MR_{exp,i}}{\sqrt{\left(N\sum_{i=1}^{N} MR_{pre,i}^2 - \left(\sum_{i=1}^{N} MR_{pre,i}\right)^2\right)\left(N\sum_{i=1}^{N} MR_{exp,i}^2 - \left(\sum_{i=1}^{N} MR_{exp,i}\right)^2\right)}} \tag{10.1}$$

10.3.2 Reduced Chi-Squared

To optimize the reduced chi-square (χ^2), a number as close to 0 as possible should be obtained. To calculate the reduced chi-squared (Kucuk *et al.*, 2014):

$$\chi^2 = \frac{\sum_{i=1}^{N}\left(MR_{exp,i} - MR_{pre,i}\right)^2}{N-n} \tag{10.2}$$

10.3.3 Root Mean Square Error

Root mean square error ($RMSE$) is found by:

$$RMSE = \sqrt{\frac{\sum_{i=1}^{N}\left(MR_{i,pre} - MR_{i,exp}\right)^2}{N}} \tag{10.3}$$

Ideally a value as close to 0 is optimum.

10.3.4 Model Efficiency

To optimize the model efficiency, a number as close to 1 is desired using the Equation 9.4 (Kucuk *et al.*, 2014).

$$\eta = \frac{\sum_{i=1}^{N}\left(MR_{i,exp} - MR_{i,pre}\right)^2 - \sum_{i=1}^{N}\left(MR_{i,pre} - MR_{i,exp}\right)^2}{\sum_{i=1}^{N}\left(MR_{i,exp} - MR_{i,pre}\right)^2} \tag{10.4}$$

10.3.5 Coefficient of Determination

The coefficient of determination (r^2) is also optimised by finding the higest value. The formula is described in Equation 9.5 (Kucuk *et al.*, 2014).

$$r^2 = 1 - \frac{\sum_{i=1}^{N}\left(MR_{pre,i} - MR_{exp,i}\right)^2}{\sum_{i=1}^{N}\left(\overline{MR_{pre}} - MR_{pre,i}\right)^2} \tag{10.5}$$