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Development of innovative, quick-cook legume products: an investigation of the soaking, cooking and dehydration characteristics of chickpeas (Cicer arietinum L.) and soybeans (Glycine max L. Merr.)

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DEVELOPMENT OF INNOVATIVE, QUICK-COOK LEGUME PRODUCTS

An investigation of the soaking, cooking and dehydration characteristics of chickpeas (*Cicer arietinum* L.) and soybeans (*Glycine max* L. Merr.)

by

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A thesis submitted to the Dublin Institute of Technology, in accordance with the requirements for the degree of Doctor of Philosophy

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Abstract

The primary goal of this research was to create new alternatives to the legume products currently available to consumers, i.e. canned and dry beans. Chickpeas and soybeans are well established in the Irish consumer market and possess excellent nutritional quality, such as high protein, fibre and phytochemical content, low cholesterol and low glycaemic index (G.I.), and therefore have potential for classification as functional foods. The first stage of the research culminated with the development of quick-cook chickpeas and soybeans that could be stored in the chill cabinet or freezer. Water intake and textural attributes during soaking were investigated. Using non-linear regression analysis, asymptotic models were constructed to predict hydration characteristics as functions of soaking time, temperature and blanching pre-treatment. Optimal cooking treatment was estimated by investigating the effect of boiling and microwave processing on texture and sensory characteristics. Shelf life was estimated for pre-cooked samples under chilled, frozen and freeze-chill storage and it was shown that these products could be kept in chilled storage for up to two weeks and in frozen or freeze-chill storage for up to 12 months. In the second stage of research, shelf-stable, dehydrated, quick-cook chickpeas and soybeans were developed. The application of combined microwave-convective drying to pre-cooked chickpeas and soybeans was investigated on a pilot scale. Dehydration kinetics were fitted to an n^{th} order asymptotic model, known as the Page model and rehydration kinetics were fitted to an asymptotic model. Water activity of soybeans and chickpeas was lowered during drying to a value of 0.35, so that the dehydrated products could potentially be stored at room temperature for up to 12 months.

Declaration

I certify that this thesis which I now submit for examination for the award of Doctor of Philosophy, is entirely my own work and has not been taken from the work of others save and to the extent that such work has been cited and acknowledged within the text of my work.

This thesis was prepared according to the regulations for postgraduate study by research of the Dublin Institute of Technology and has not been submitted in whole or in part for an award in any other Institute or University.

The work reported on in this thesis conforms to the principles and requirements of the Institute's guidelines for ethics in research.

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Candidate

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Abbreviations list

a	average radius (m)
a_{Bi}	Bi-exponential model parameter
a_p	linear coefficient for Page model parameter k_p
a_r	linear coefficient for rehydration data (min^{-1})
a_H	Henderson-Pabis model parameter
a_w	water activity
a*	CIELAB redness/greenness value
a_0*	CIELAB redness/greenness value for cooked chickpea
AIC	Akaike Information Criterion
A	coefficient for general form of analytical solution of Ficks 2nd law
b*	CIELAB yellowness/blueness value
b_0*	CIELAB yellowness/blueness value for cooked chickpea
b_{Bi}	Bi-exponential model parameter
b_p	linear coefficient for Page model parameter k_p
b_r	linear coefficient for rehydration data (min^{-1})
BIC	Bayesian Information Criterion
B_n	coefficient for general form of analytical solution of Ficks 2nd law
BPM	Baird Parker Medium
c	constant
cfu	colony forming units
C	Concentration at time t (kg/m^3)
C_n	coefficient for general form of analytical solution of Ficks 2nd law (m^2)

CHD	Coronary Heart Disease
CIE	International Commission on Illumination
Cryo-SEM	Cold stage scanning electron microscopy
D_{eff}	Effective diffusivity (m^2 s^{-1})
d.b.	dry basis
dof	degrees of freedom
DE*	CIELAB total colour difference value ()
E_a	activation energy (kJ mol^{-1})
EU	European Union
G.I.	Glycaemic Index
h	half thickness of slab (m)
H	Hardness (N)
HTST	High Temperature Short Time
H*	CIELAB Hue angle
k	rate constant (min^{-1})
K	reaction rate constant (s^{-1})
k_1,k_2	Bi-exponential model parameters (min^{-1})
k_{p1}	Peleg const 1(min.(% g/g)$^{-1}$)
k_{p2}	Peleg const 2 ((% g/g)$^{-1}$)
k_p	Page model parameter (min^{-np})
L*	CIELAB Lightness/darkness value
L_0*	CIELAB Lightness/darkness value for cooked chickpea
LogLik	Log Likelihood
LTLT	Low Temperature Long Time
m	mass (g)

M	moisture content (% g/g) at time t
MR	moisture ratio
MW	microwave power level (W)
n_p, n_{p1}, n_{p2}	Page model parameters
NA	Nutrient Agar
NEB	Non-Enzymatic Browning
p	probability value ()
PC	Personal Computer
ρ	apparent density (g/cm^3)
r	radial coordinate (m)
r^2	coefficient of determination
R	universal gas constant (8.314 kJ mol^{-1} K^{-1})
RCA	Reinforced Clostridial Agar
RR	Rehydration Ratio ()
RRM	Relative Rehydrated Moisture Content ()
S	synthetic evaluation index ()
S_b	Bulk shrinkage coefficient ()
SE	Pooled Residual Standard Error
SDA	Sabouraud Dextrose Agar
t	time (min)
T	temperature (K or ^oC)
T_g	glass transition temperature (K or ^oC)
TAV	Total Anaerobic Count (cfu/g)
TVC	Total Viable Count (cfu/g)
V	volume (cm^3)

VRBA	Violet Red Bile Agar
w_1, w_2	constants
w.b.	wet basis
WGR	weight gain on rehydration ()
W_d	weight of dried sample (kg)
Y_1	relative product colour change ()
Y_2	relative rehydration rate ()
Y_3	relative rehydration ratio ()
Y_4	relative dehydration rate ()
YMC	Yeast and Mould Count (cfu/g)

Subscripts

0	at time = 0
1	non-blanched
2	blanched
100W	combination drying at 100 W level
200W	combination drying at 200 W level
air	air drying
B	Boil
c	cooked
comb	combination drying
cp	chickpea
d	dehydration
D	diffusion
e	at equilibrium time

F	texture
h	hydration
MW	microwave
o	oil
p	pycnometer
ref	reference
w	water

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CHAPTER 1

GENERAL INTRODUCTION

A brief explanation of the motivation behind the work, and a summary of the principal objectives

1.1 Motivation

1.1.1 Trends towards healthy eating

Clinical studies have shown that excessive consumption of saturated fats and sugars, present in many of today's "convenience" foods, combined with insufficient intake of dietary fibre, facilitates the onset of obesity, type-2 diabetes, certain forms of cancer, and cholesterol-related illnesses such as hypertension, heart disease and thrombosis (Cummings & Bingham, 1998; Willet, 1995; Doll & Peto, 1981). The rising incidence of such diet-related illnesses has been widely publicised: it is estimated that one in every eight Irish persons is obese (Health Promotion Unit, 2003); heart disease is the main cause of premature death in Ireland (Irish Government, 1999) and type-2 diabetes now accounts for 6-10% of Ireland's total healthcare budget (Diabetes Federation of Ireland, 2006).

Consequently, improving the dietary habits of the population has now become a major priority of the Irish government: initiatives such as the National Taskforce on Obesity (2004), the Heart Health Strategy (1999) and the National Healthy Eating Campaign (1992) have helped to raise public awareness of the importance of a healthy diet. People are now willing to pay extra money for healthy, convenient foods (Reuters Business Insight, 2003). Led by this shift in consumer demand, food producers are motivated to develop novel food products that are both healthy and convenient (Zink, 1997).

1.1.2 Legumes – food for life?

Legumes are cheap, easy to store and nutritious (Messina, 1999). They are rich in protein, soluble fibre and phytochemicals (Huang *et al.*, 1994), while low in fat and cholesterol free. They have enjoyed popularity in eastern and developing countries such as China, India and Africa, where their value as an economical source of dietary protein is well recognised. Legumes also represent an important source of protein for vegetarians, and the protein quality of soybeans is equal in quality to animal protein (Dupont Protein Technologies, 2002), with a protein digestibility corrected amino acid score (PDCAAS) equal to 1. Legumes are a low glycaemic index food (Rizkalla *et al.*, 2002) and legume products are therefore suitable for those who suffer from diabetes and obesity (Pathak *et al.*, 2000). A recent study by Bazzano and co-workers (2002) demonstrated a significant inverse relatic nship between legume intake and risk of coronary heart disease in the US and regular dry bean and soy intake can aid in the prevention of many chronic diseases (Anderson *et al.*, 1999).

Considering the general trend towards healthy eating in contemporary culture, it would seem surprising to learn that legumes are underutilised as a food source, both in Europe (Schneider, 2002) and the US (Messina, 1999). Even though experimental evidence, regarding the health benefits of legume consumption, has been mounting over the past decade, the findings have not been publicised by the mass media. Consequently, consumers are not generally aware of these benefits. Legumes are often placed in the protein category of the food pyramid, along with meat and poultry, giving little incentive for non-vegetarians to eat them (Messina, 1999). Moreover, it has been reported that health organisations rarely

mention the health benefits associated with legume consumption (Leterme, 2002).

Convenience is another factor which limits legume consumption in the US and Europe (Schneider, 2002). The cash-rich, time-poor consumer of today wants food that is essentially easy to prepare (Zink, 1997). There have been very few innovations in legume production over the past decade and the consumer is limited to choosing between either canned or dry legumes. Canned foods were first developed in the 19th century. They were invented in 1809, by the Frenchman Nicolas Appert (Food products association, 2005), who received a cash prize of 12,000 francs from Napoleon Bonaparte for his efforts! Nowadays, although canned foods are convenient, people generally regard chilled and frozen foods to be healthier (Mintel, 2005). As a result, canned foods in general, and canned legumes in particular, are limited in terms of their value as health foods. Dry legumes, on the other hand, are cumbersome to prepare, as they require long soaking (up to 16 h) and cooking (up to 1 h) times. An apparent niche exists in the consumer food market for non-canned convenient legume products.

1.2 Objectives

Motivated by the growing consumer demand for health foods and current lack of innovation in legume production, the purpose of this work was the development of quick-cook legumes. Such legumes would be produced in formats already familiar to the consumer, and so could be easily incorporated into existing distribution lines and dietary habits. Important characteristics of the resulting products would include short preparation times, microbial safety and high

quality. Specifically, the research was focussed on chickpeas and soybeans, as they have excellent nutritional properties, mild taste, attractive appearance, and were readily available for the study. Two types of quick-cooking legume products were developed in the course of this research and are described in the following section. Optimal processing conditions were estimated by investigating the effects of different unit processes on product quality. The main tasks and questions addressed in the research are displayed in Tables 1.1 and 1.2.

1.2.1 Pre-cooked, ready-to-heat product

Chilled, ready-to-heat vegetables were introduced into the Irish market just over 15 years ago, in the late eighties (Mintel, 2003). Since then, the chilled vegetables market has consistently grown, both in volume and diversity (Mintel, 2003). Consumers view chilled foods as fresh and healthy, while also convenient (Mintel, 2003). An identifiable gap currently exists in the Irish chilled foods market, in that chilled legumes are not currently available. This gap in the market, along with current trends towards healthy eating, gave inspiration for the development of pre-cooked, ready to heat legumes. Destined for the chilled cabinet, such products would fit in with established chilled-food distribution lines. They could be sold as stand-alone products, potentially substituting other chilled vegetables on the dinner plate. Equally, they could be employed as ingredients in chilled ready meals. It was expected that these products could also be frozen, to fit in with the growing frozen vegetables and peas sector. Furthermore, utilisation of a freeze-chill cycle could produce long shelf life products that would enjoy the healthier image associated with chilled products (Redmond *et al.*, 2004).

In the development of pre-cooked, ready-to-heat legumes, a thorough investigation of the necessary processing steps would be required (Fig. 1.1). Soaking is generally the first step involved in dry bean production. Therefore, the first task would be to analyse the soaking process, with the aim of minimising the soaking time required while maintaining quality. This would be achieved by investigating the effect of processing variables on water intake and texture properties (Table 1.1). The second task would be to study the cooking process, with the aim of minimising the cooking time, while maintaining product quality. This would be achieved by looking at the effect of boiling and microwave cooking on texture and sensory attributes of chickpeas and soybeans (Table 1.1). The third task would comprise of an inspection of the potential applicability of a number of different storage methods to the proposed end products.

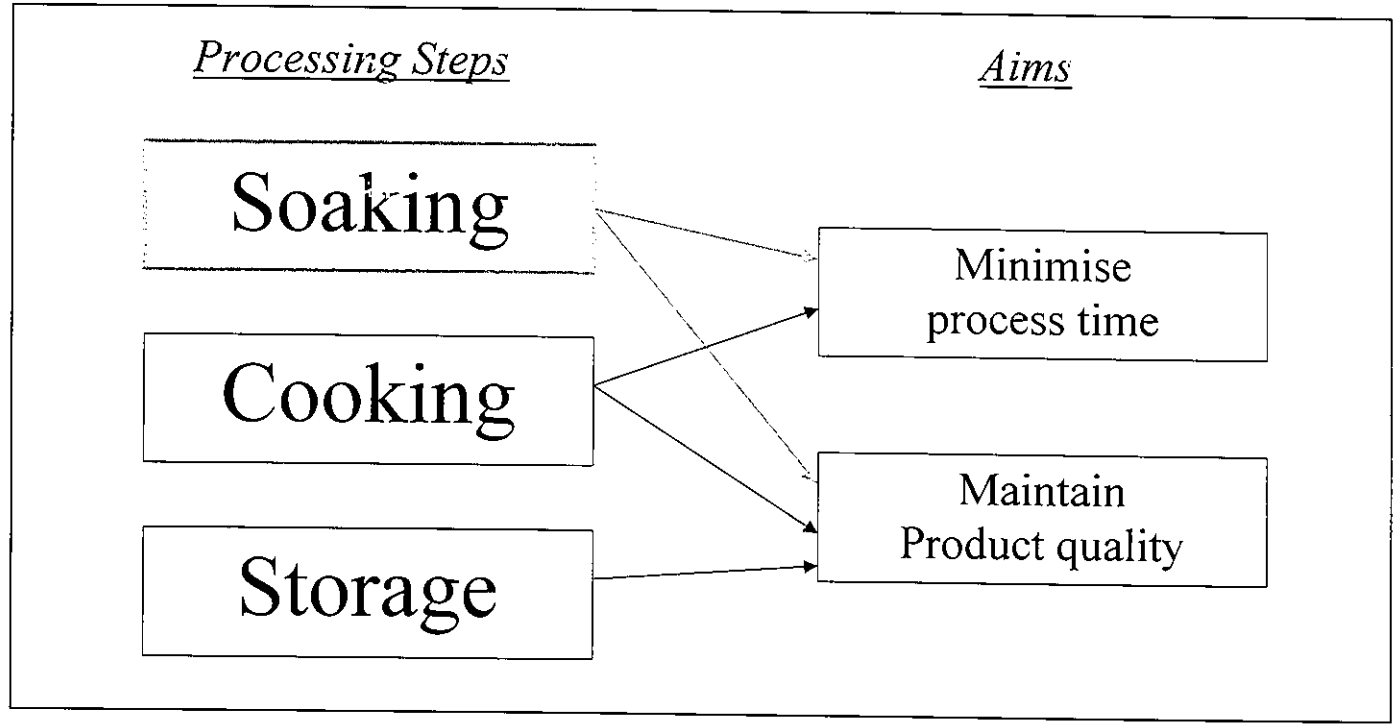


Fig. 1.1. Processing steps for production of pre-cooked, ready-to-heat legumes.

Table 1.1. Tasks, questions and principal investigations involved in development of pre-cooked product.

Chilled Legume Product	
Task 1: Minimise soaking time	
Questions	Investigate
I. How does increasing temperature affect soaking characteristics?	Water intake and texture at different soak temperatures
II. How does blanching pre-treatment affect soaking characteristics?	Water intake and texture for blanched/unblanched samples
III. Is it possible to model the process?	Fit of a number of mathematical models to water intake/texture data
IV. What are the optimal soaking conditions?	Effect of processing parameters on soak time required
Task 2: Minimise cooking time	
Questions	Investigate
I. How does boiling and microwaving affect texture?	Texture for different boil and microwave times
II. How does boiling and microwaving affect sensory attributes?	Sensory attributes for different boil and microwave times
III. What are optimal cooking conditions?	Optimal texture/sensory over range of boil/ microwave times studied
Task 3: Investigate storage methods	
Questions	Investigate
I. Which quality aspects are important?	Literature; previous studies
II. Which storage methods are possible?	Literature; previous studies
III. How long can they be stored?	Quality during storage

1.2.2 Quick-cook dehydrated product

Quick cook rice was introduced to Ireland in the early '80s. Since then, it has become a common household food, and is especially popular among young adults, in the 18-35 year age group (Irish Universities Nutrition Alliance, 2001). The second phase of this study involved the development of quick-cooking, dehydrated legumes. Such products would be dried to moisture levels low enough such that they would have a long shelf life (> 12 months). They could be marketed stand-alone convenience foods, much like quick-cook rice, or as ingredients in dried soups and dried ready meals. The development of such a dehydrated legume product would require an in-depth study of both dehydration and rehydration processes (Fig. 1.2, Table 1.2).

Previous attempts to produce pre-cooked, dehydrated beans, by application of convective drying, have been inhibited by butterflying (skin splitting) and poor rehydratibility of the resultant products (Cai & Chang, 1997; Steinkraus *et al.*, 1964; Dorsey *et al.*, 1961; Feldberg *et al.*, 1956). Slow rehydration and poor water uptake can be related to case hardening and shrinkage, which are common side effects of air-drying (Brennan, 1990). Microwave drying of foods is a relatively new processing technique, which is highly energy efficient (Berteli & Marsaioli, 2005; Ahmad, *et al.*, 2001): however, collapse of product structure during drying limits its utilisation (Maskan, 2000).

Combination of microwave and air drying has been proposed as an economical method to produce highly rehydratable products in short processing times (Nijhuis *et al.*, 1996). This is achieved in the following way: convective hot-air

drying enables the development of an outer crust, which is hard enough to support the sample structure, yet thin enough not to present a barrier to rehydration; simultaneous application of microwave energy encourages internal pore development, due to rapid volumetric heating. Consequently, the resultant dehydrated product should have a high internal porosity and good rehydration characteristics. For the reasons outlined above, application of combined microwave - convective hot-air drying to pre-cooked legumes was investigated in the present work.

The pre-cooked, chilled products developed in the first stage of the research constituted the raw materials for the development of dehydrated legumes. The first task was a preliminary investigation, to see if the development of such products was, in fact, possible. Combined microwave - hot air drying was applied to samples, with the aim of producing a porous dehydrated solid that would rehydrate quickly. Preliminary drying experiments required investigation of the effect of cooking, as opposed to simply soaking, before drying. The second task was to optimise the drying process in terms of process parameters. This required an in-depth investigation of the effects of applying combined microwave – hot air drying at different processing levels to chickpeas and soybeans. The third task was the optimisation of the drying time, by exploring the characteristics of legumes during the actual drying process. The final task was to validate of the process, which was carried out at an external research facility.

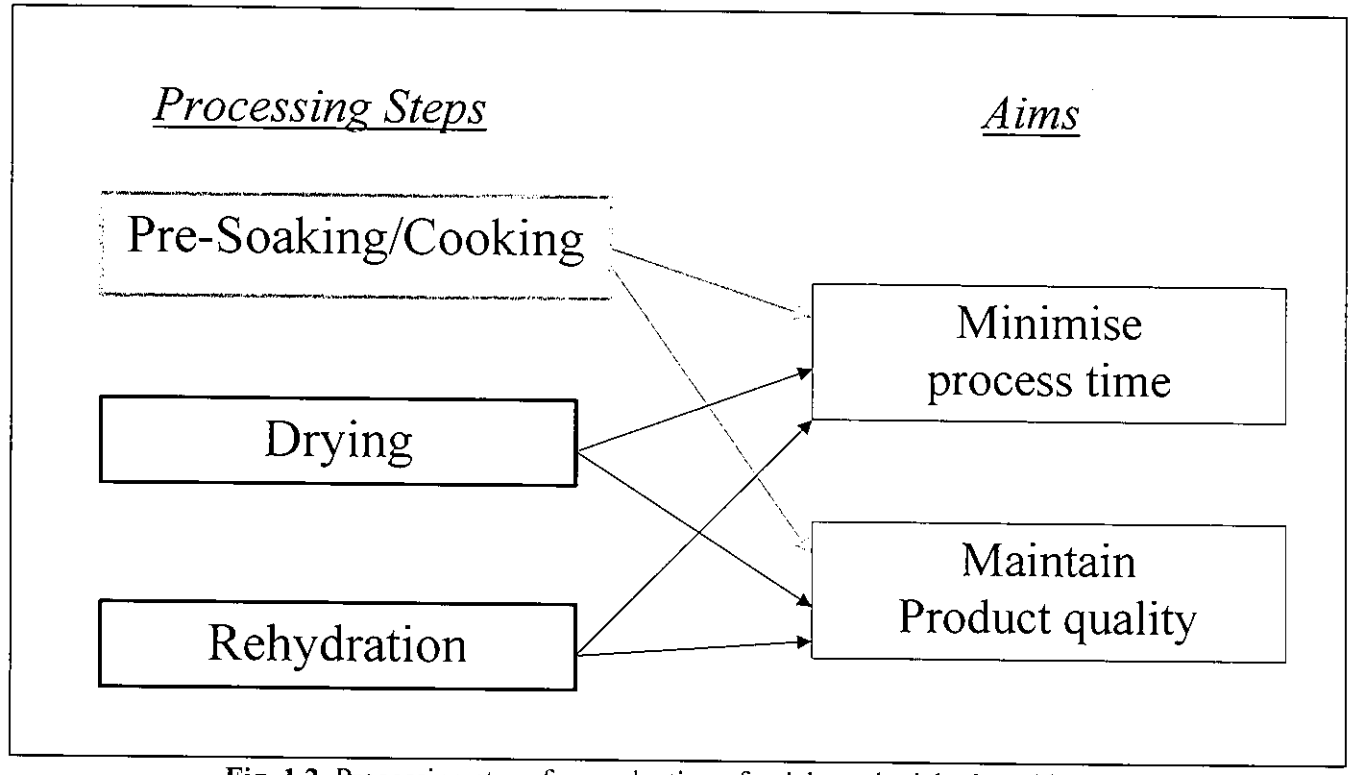


Fig. 1.2. Processing steps for production of quick-cook, dehydrated legumes

Table 1.2. Tasks, questions and principal investigations involved in development of quick-cook dehydrated product.

Dehydrated Legume product	
Task 1: Preliminary investigations	
Questions	Investigate
Is it possible to make dehydrated, quick cook legumes?	Dehydration & rehydration properties of chickpeas and soybeans
Is cooking necessary before drying?	Quality of soaked products vis-à-vis cooked ones
Task 2: Optimise processing conditions	
Questions	Investigate
How does increasing temperature/microwave power affect product?	Dehydration/rehydration properties for different processing conditions
Is it possible to model the dehydration process?	Fit of a number of models to dehydration/rehydration kinetic data
What are optimal processing conditions?	Temperature/microwave power levels yielding best quality product
Task 3: Optimise drying time	
Questions	Investigate
How to mark end of drying?	Moisture content/water activity/colour/texture/shrinkage during drying
What is optimal drying time?	Drying time yielding best quality product
Task 4: Validation of production process	
Questions	Investigate
Are results consistent?	Dehydration and rehydration properties in another drier

CHAPTER 2

LITERATURE REVIEW

An overview of the existing published body of knowledge related to this thesis

2.1 Legumes

Legumes are defined as flowering plants that yield pods containing peas or beans (Parker, 1998). The family *Leguminosae* consists of 650 genera and more than 18,000 species. Members of the family, often referred to as legumes or pulses, are the second most important food source in the world after cereal grains, and more than 80 different legume species are consumed by humans (Sosulski & Sosulski, 2005). Legume plants convert atmospheric nitrogen into nitrogen nodules on their roots, in a process known as nitrogen fixation. Due to their nitrogen fixing ability, legumes are regularly used by farmers in crop rotation, to replenish nitrogen levels in soil. Edible legumes include dry peas, chickpeas, lentils, kidneybeans, aduki beans, white beans, canelli beans, peas, mung beans, soybeans and peanuts. Soybeans and peanuts are also employed as a source of oil.

The general structure of the legume seed is shown in Fig. 2.1. Two cotyledons, separated by an embryonic axis, occupy most (80-90%) of the legume seed. They are enclosed by the seed coat, which makes up 8-18% of the seed. The seed coat acts as a barrier, protecting the seed embryo against water, bacteria and insects. It consists of a thin, hydrophilic cuticle layer, covering a thicker layer of palisade cells. The main opening on the seed, known as the hilum, is a scar, marking the point at which the seed was once attached to the pod. Behind the hilum opening is the tracheid bar, containing ducts which connect the pod with seed vascular systems. Beyond the tracheid bar is a mass of parenchyma cells, residues of the endosperm from the fertilised ovule (Sosulski & Sosulski, 2005).

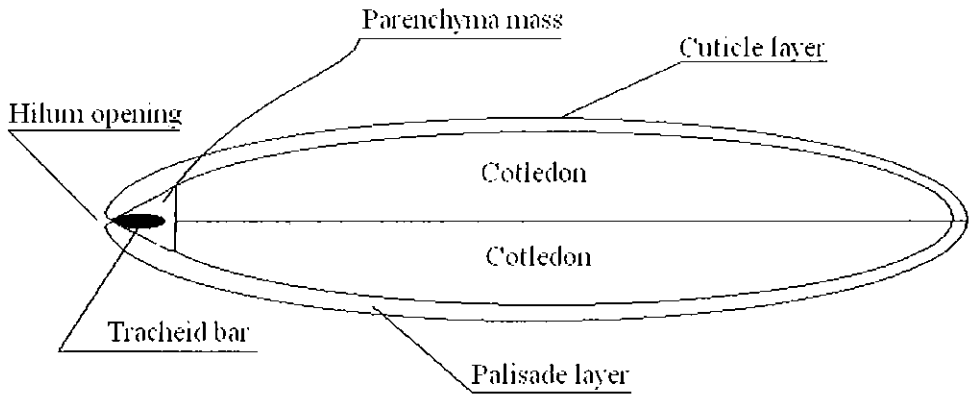


Fig. 2.1. Schematic diagram of structure of cross section through a legume seed (adapted from Sosulski & Sosulski, 2005).

Legumes are nutrient dense and rich in phytochemicals (Anderson *et al.*, 1999; Messsina, 1999). They contain high levels of fibre, protein and minerals, and are generally low in fat (Table 2.1). Compared with cereals, legumes are high in protein and rich in most essential amino acids, but poor in the essential amino acid methionine (Parker, 2001) and are therefore said to be incomplete sources of protein. This is why they are often blended with cereals, which are rich in methionine, in a method known as protein complementation (Parker, 2001). However, the quality of bean protein has been underestimated in the past. Until recently, the standard method of protein evaluation was the protein efficiency ratio. This method measures protein efficiency based on the growth of laboratory animals, usually rats. The protein efficiency ratio is now regarded as flawed, since rats have a methionine requirement about 50% higher than humans (Messina, 1999). Consequently, an alternative measure, known as the protein digestibility corrected amino acid score (PDCAAS), has been adopted by the World Health Organisation (WHO) and the US Food and Drug Administration

(USFDA). This method uses the amino acid score (based on the USFDA estimated amino acid requirement for a 2-5 yr old human) and a correction factor for digestibility to calculate a value for protein quality and is therefore an improvement over the protein efficiency ratio. Using the PDCAAS, most beans are considered to be reasonably good protein sources, although their PDCAAS is reduced by their relatively low protein digestibility (Messina, 1999). Nevertheless, the low levels of sulphur amino acids found in legumes may be responsible for hypercalciuric effects, improving calcium retention levels in humans (Messina, 1999). Additionally, legume proteins seem to have hypocholestremic, or cholesterol-lowering, properties (Anderson *et al.*, 1999).

Legumes are also known to contain a number of anti-nutritional factors, including galactosides, protease inhibitors, phytates, lectins (Abd El-Hady & Habiba, 2003). Such anti-nutritional factors are usually inactivated by soaking followed cooking (Abdel-Gawad, 1993; Vidal-Valverde *et al.*, 1993; Márquez & Alonso, 1999; Egounlety & Aworh, 2003; Abd El-Hady & Habiba, 2003; Lestienne et al., 2004). Ironically, some of these anti-nutritional factors may have associated health benefits. Protease inhibitors block the work of an enzyme involved in protein digestion: however, they may also block the action of many cancer-causing agents (Kennedy, 1994; Harland & Morris, 1995). Galactose-containing oligosaccharides are thought to be responsible for flatulence (Fleming, 1981), but are also important pre-biotics, that could improve colon function (Anderson et al., 1999).

Table 2.1. Energy and chemical constituents in selected food legumes (USDA, 2006).

Common Name	Scientific Name	Physical State	Energy (kJ/100g)	Protein (g/100g)	Fat (g/100g)	Fibre (g/100g)	Ca (mg/100g)	Fe (mg/100g)	Mg (mg/100g)	Zn (mg/100g)
Soybean	Glycine max	Dry	1742	36.49	19.94	9.3	277	15.7	280	4.89
		Cooked	725	16.64	8.97	6	102	5.14	86	1.15
Chickpea	Cicer arietinum	Dry	1525	19.3	6.04	17.4	105	6.24	115	3.43
		Cooked	686	8.86	2.59	7.6	49	2.89	48	1.53
Red kidney bean	Phaseolus vulgaris	Dry	1408	22.53	1.06	15.2	83	6.69	138	2.79
		Cooked	532	8.67	0.5	7.4	28	2.94	45	1.07
Mung bean	Vigna radiata	Dry	1453	23.86	1.15	16.3	132	6.74	189	2.68
		Cooked	441	7.54	0.55	6.4	53	1.75	63	0.83

2.1.1 Soybean (*Glycine max*, L.)

The soybean plant is an annual legume, consisting of bushy, leafy plants, which can grow up to 1 m tall. Over 150 soybean varieties exist, ranging in colour from light yellow to dark.brown. The dry soybean seed (Fig. 2.2) is prolate spheroid in shape, ranging from 3-6 mm in diameter. Soybeans are the most widely produced of all legumes, comprising over 75% of legume world production (Maneepun, 2003). It has been reported that 175 million tonnes of soybeans are produced annually worldwide (Sosulski & Sosulski, 2005). Soybean production was promoted during World War 2, to counteract oil shortages and nowadays soybeans are the most important oilseed crop worldwide (Sosulski & Sosulski, 2005), with more than 80% of world soybean production converted annually into edible oil. Approximately 15% of soybeans produced worldwide are made directly into food products (Sosulski & Sosulski, 2005) such as whole beans, soy milk, tofu and tempeh.

The soybean has been known to possess health-promoting qualities since discovery in China approximately four million years ago. Nowadays, soybeans are particularly well known for their functional properties (Anderson *et al.*, 1995). Soybeans are rich in phyto-chemicals (Lampe, 2003) and their consumption is associated with lower cholesterol levels in humans (Nagata *et al.*, 1998; Anthony, 2000) along with decreased incidence of many hormonal cancers (Wu *et al.*, 1996; Dai *et al.*, 2001). Among pulses, soybeans are the richest in protein, and soy protein quality has an equal PDCAAS to animal protein (Sarwar & McDonough, 1990). In 1999, the USFDA stated that diets low in saturated fat

and cholesterol that included 25g soy protein per day may reduce the risk of CHD (USFDA, 1999).

2.1.2 Chickpea (*Cicer arietinum*, L.)

The cultivated chickpea, *Cicer arietinum* L., was one of the first grain legumes to be domesticated, in the region near modern-day Turkey, over eight thousand years ago (Singh, 1997; Johnson & Jimmerson, 2003). The chickpea plant is a self-pollinating annual crop, 0.2-1 m tall, with branched stems, blue to green in colour, and inflated pods (Muehlbauer & Tullu, 1997). Chickpea seeds are oblong in shape, with a pointed "beak" at one end (Fig. 2.3). Chickpeas are the second most important pulse crop (Singh, 1997), grown in more than 33 countries worldwide and world production of chickpeas estimated to be 8.5 million tonnes per year (Sosulski & Sosulski, 2005). Kabuli and Desi cultivars of chickpea are used for human consumption. Kabuli chickpeas, also known as Garbanzos (Spanish name), are relatively large in size, light yellow in colour, have a thin seed coat and are grown in temperate regions. This type of chickpea is usually sold in either dry or canned format. Desi chickpeas are smaller than the Kabuli variety, light tan to black in colour, have a thick seed coat and are grown in semi-arid tropic regions (Johnson & Jimmerson, 2003). They require de-hulling (removal of skin) prior to processing, and are used to make various food products which are popular in East Asia.

Chickpeas are nutrient-rich, containing one of the richest nutritional compositions among dry edible grain legumes (Table 2.1). They are also rich in calcium, potassium, phosphorous, iron and magnesium. Chickpeas represent a

good source of protein, having one of the highest protein digestibility scores (76-78%) in comparison to other food legumes (Muehlbauer & Tullu, 1997; Clemente *et al.*, 1999). Chickpeas also have the strongest hypocholestremic effect among legumes (Geervani, 1991; Muehlbauer & Tullu, 1997), and may therefore aid in the prevention of cholesterol-related diseases, such as arteriosclerosis and coronary heart disease. In addition to this, chickpeas are a low glycaemic index (G.I.) food, with a G.I. of 28 ± 6 (Foster-Powell *et al.*, 2002), making them important food sources for both vegetarians and diabetics.

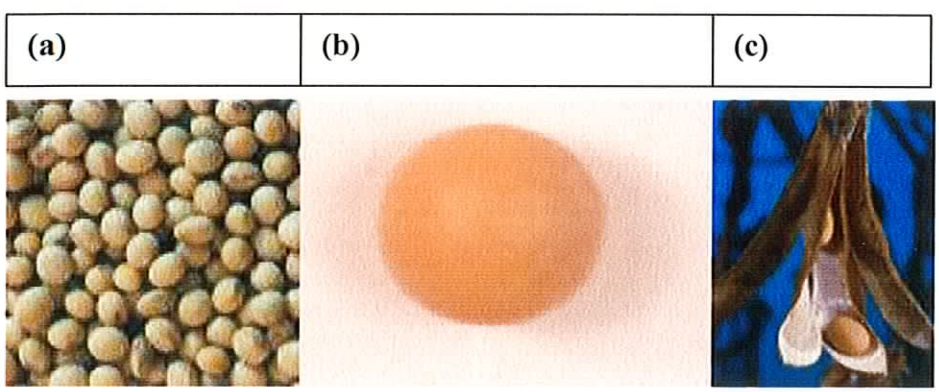


Fig. 2.2. Dry soybeans ((a) & (b)) and soybean pod (c).

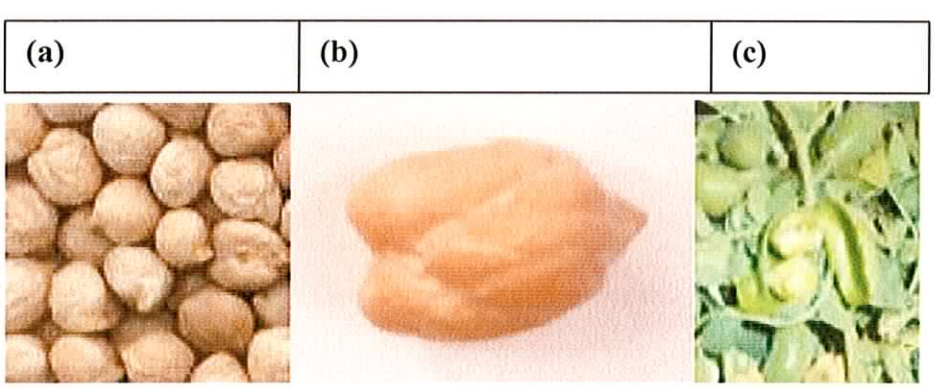


Fig. 2.3. Dry chickpeas ((a) & (b)) and chickpeas in pod (c).

2.2 Legume processing

Legumes can be eaten fresh, as green vegetables, or dried post-harvest, to lengthen their shelf life. After a drying period that can last up to five weeks, legume moisture content is decreased to a level below 15 % (d.b.) (Hnatowich, 2000). Dry legumes are not edible, as they contain harmful anti-nutritional factors, such as phytates, polyphenols, enzyme inhibitors and hemmaglutinins (Abd El-Hady & Habiba, 2002). In order to inactivate anti-nutritional factors, dry legumes require hydration and thermal processing (Abd El-Hady & Habiba, 2002; Estevez & Luh, 1985). This is usually achieved by the application of a soaking step, followed by cooking. As well as deactivation of anti-nutritional factors, this hydrothermal treatment facilitates chemical reactions, such as starch gelatinisation and protein denaturation.

2.2.1 Soaking

During soaking water becomes distributed among starch and protein fractions within the legume. The water thus imbibed is essential for starch gelatinisation and protein denaturation during cooking. Soaking also facilitates the leaching of various oligosaccharides in legumes, such as stachyose and raffinose (Silva & Braga, 1982). Soaking is mainly controlled by the process of diffusion and it can be time consuming, taking up to 18 h at room temperature (Ibarz *et al.*, 2004). Therefore, for convenience, economy and microbial safety, it is often desirable to reduce the soaking time. A number of methods have been employed to decrease the amount of soak time required by legumes and are described in the following paragraphs.

2.2.1.1 Thermal treatment

Warm-water soaking is a traditional method of decreasing legume soaking time. Increasing soak temperature above 20 °C has been shown to increase hydration rates for a wide variety of legumes, such as fababeans (Haladjian *et al.*, 2003), soybeans (Pan & Tangratanavalee, 2002), chickpeas (Turhan *et al.*, 2002) and kidneybeans (Abu-Ghannam & McKenna, 1997a). However, high temperature soaking can be disadvantageous. Kon (1979) reported that soaking at temperatures greater than 50 °C had an undesirable effect on the cooking rate of beans, whereas soaking at 40°C minimized soluble solid losses. Luh & Mikus (1980) recommended soaking below starch gelatinisation temperatures (i.e. below 60 °C for legumes), because expansion of starch granules during gelatinisation may cause seed splitting, and subsequent leaching of nutrients from the legume.

2.2.1.2 Addition of salts

Another traditional method of shortening legume soaking time involves the addition of salts to the soak water. Soaking in alkaline solutions has been shown to enhance hydration rates in faba beans (Haladjian *et al.*, 2003). Moreover, it has been reported that addition of salts, such as carbonate or bicarbonate, can decrease the energy required to make beans edible, by reducing the subsequent cooking time (Silva *et al.*, 1981; de Leon *et al.*, 1992). However, soaking in alkaline solutions can promote nutrient loss: it has been reported that soaking in alkaline water enhanced vitamin losses for faba beans, chickpeas and lentils, when compared with soaking in distilled water and vitamin losses during cooking were greater for those legumes soaked in alkaline solution (Prodanov *et*

al., 2004). From a nutritional perspective, it has been recommended that legumes be soaked in water with a pH ≤ 7 (Prodanov *et al.*, 2004).

2.2.1.3 Pressure treatment

A relatively modern means of decreasing soaking time involves the application of high-pressure. The application of high hydrostatic pressures to black beans during soaking (Sangronis *et al.*, 2002) was found to increase the rate of water absorption, consequently decreasing the soak time required to achieve equilibrium moisture content. However, the nutritional disadvantages associated with the application of high pressure during soaking and cooking may outweigh time-savings: application of high pressure during cooking showed a pronounced effect on the reduction of valuable insoluble dietary fibre content in beans (Rehinan *et al.*, 2004). In another study, it was found that high pressure pre-treatment had no effect on the cooking time required by chickpeas (Ibarz, 2003).

2.2.1.4 Blanching

The term "blanching" usually refers to the immersion of foods in boiling water or steam for a short amount of time. Blanching treatments are frequently applied to foods, in order to deactivate enzymes and reduce microbial populations, prior to chilling, freezing or canning. For example, blanching can be used to improve the firmness and colour of green vegetables, such as broccoli and green beans, prior to freezing (Tijskens *et al.*, 2001). The effect of a variety of blanching treatments on losses of nutritive components of soybeans has been studied (Song *et al.*, 2003) and was found to be minimal for blanching at high temperatures for short times (HTST). As well as influencing the sensory aspects of foods, blanching

applied to legumes prior to soaking ("pre-blanching") can affect water intake characteristics. Abu-Ghannam & McKenna (1997a) found that pre-blanching increased hydration rates for red kidneybeans.

2.2.2 Cooking

Upon completion of soaking, when sufficient water has been imbibed, legumes become ready for cooking. Cooking tenderises the legume by facilitating the deformation of starch and coagulation of protein. During cooking, the water absorbed during soaking is used in starch gelatinisation and protein denaturation reactions (Fig. 2.4), to make the bean ready for human consumption (Sayar *et al.*, 2001). Cooking improves in-vitro starch digestibility (Barampama & Simard, 1995) and protein digestibility (Clemente *et al.*, 1998). The cooking process also promotes deactivation of anti-nutritional factors (Rehman & Shah, 2005). However, expansion of starch during gelatinisation can cause cracks on the legume surface, through which valuable vitamins can be lost to the cooking water (Luh & Mikus, 1980). Moreover, prolonged cooking may reduce nutritive protein quality in dry beans (Van der Poel *et al.*, 1990). Therefore, it is desirable to minimise the cooking time.

Legumes are conventionally cooked in boiling water for periods ranging from 1 to 3 hours (Kabbara *et al.*, 1987; Williams *et al.*, 1983). However, it has been reported that pre-soaked chickpeas can be cooked in boiling water within 50 min (Sabapathy, 2005). Modern methods, such as microwave and high pressure-cooking have recently been applied to decrease the time required to cook legumes. Compared with conventional boiling, microwave cooking has been

shown to minimise nutrient losses in legumes (El-Adawy, 2002), while significantly reducing the amount of cooking time required (Marconi *et al.*, 2000). Reduction in cooking time was reported for black beans subjected to high pressure pre-treatment (Sangronis *et al.*, 2000). It was reported that pressure-cooking required less water and time than microwave cooking (Khatoon & Prakash, 2005). Moreover, Khatoon & Prakash (2004) reported that pressure-cooking resulted in improved protein digestibility in legumes when compared with microwave cooking.

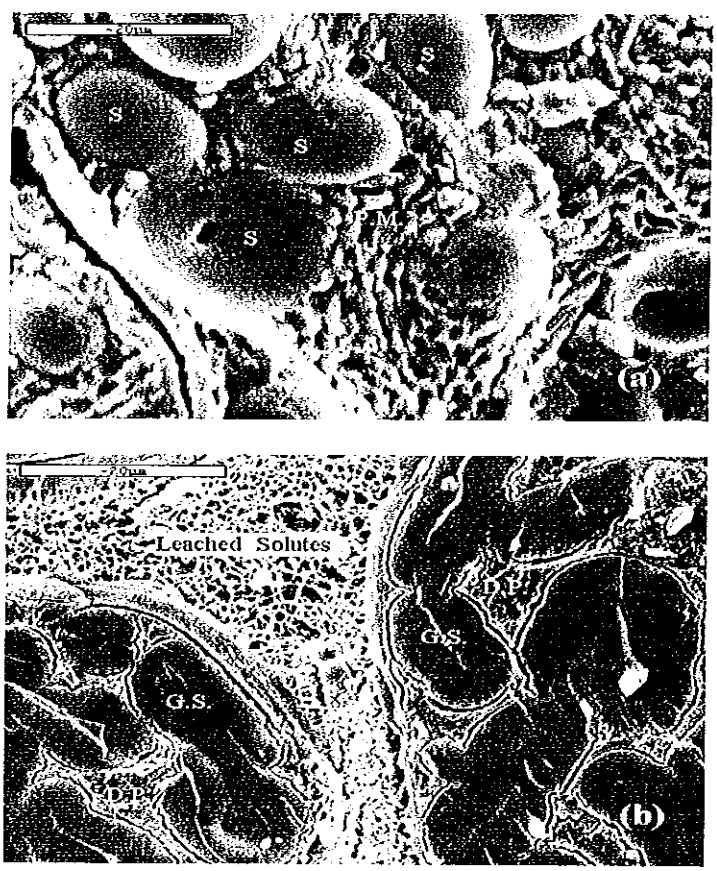


Fig. 2.4. Cryo-SEM micrograph of: **(a)** dry chickpea showing un-gelatinised starch granules (S) embedded in protein matrix (P.M.); **(b)** cooked chickpea showing gelatinised starch (G.S.), denatured protein (D.P.) and leached solutes.

2.2.3 Industrial processing of dry beans

Canned baked-beans, consisting of navy beans in tomato sauce, are the most popular bean product in Ireland (Mintel, 2005). Bean varieties such as kidneybeans, chickpeas and pinto beans, are also available in ready-to-use canned form. Production of canned beans usually requires some combination of the following processing steps: soaking, blanching, canning and pasteurisation. The main features of these processing steps are described below.

2.2.3.1 Industrial Soaking

Industrial soaking of beans is generally carried out as either a low-temperature/ long-time (LTLT) or high-temperature/short-time (HTST) process. The LTLT process, in which dry beans are soaked in large vats at ambient temperature for 12-18 h, is the most common industrial practice (Ogwal & Davis, 1994). The HTST process is usually carried out when production time is limited: this method involves soaking in slowly running continuous blanchers at 85 – 90 °C for 30 min. Although the HTST process is fast and convenient, its application can result in a lower degree of tenderization than the LTLT method, which is undesirable, from a producers point of view (Priestly, 1978).

2.2.3.2 Industrial blanching

Blanching is applied after LTLT processing, to sterilize the bean and improve its tenderness. Typically, soaked beans are blanched in continuous, rotary water or steam blanchers at 90 – 95 °C for 5 min (Priestly, 1978).

2.2.3.3 Canning and pasteurisation

Soaked (HTST) or blanched (LTLT) beans are deposited into cans, into which tomato-sauce (for baked beans) or salted-water (for other bean varieties, e.g. chickpea) is added. Cans are then heat-sealed and the pasteurisation step commences, during which the canned beans are cooked under pressure. Pasteurisation is typically applied at 115 °C for 60 min (Heinen & Van Twisk, 1976).

2.3 Food dehydration

Dehydration is one of the oldest methods of food preservation known to mankind (Brennan, 1990). Drying prolongs shelf life by reducing water available for undesirable chemical reactions and microbial proliferation (Vega-Mercado *et al.*, 2001). Therefore, drying allows foods to be stored at room temperature for extended periods of time without refrigeration. Drying has the added benefit of reducing the weight and bulk of foodstuffs, resulting in lower transport and storage costs. For these and other reasons, dried foods production is a growing sector of the food industry (Strumillo & Adamiec, 1996).

Development of a dehydrated food product requires the consideration of a number of factors. The producer, wishing to remain competitive, must minimise costs of production while maintaining high organoleptic quality. Therefore, from a producer's point of view, the main factors of interest are processing costs, processing time, product shelf life and product quality. Sensory quality is essential, as the consumer can readily determine colour and texture. Moreover, the cash-rich, time-starved consumer demands convenience (Zink, 1997), in

terms of ease and speed of rehydration. Consequently, the choice of one particular drying method above another is dependent upon its ability to produce a convenient shelf stable product, while optimising quality and cost.

In order to maximise consumer acceptability, it is generally accepted that the dry product should resemble the fresh produce as much as possible (Giraldo-Zuniga *et al.*, 2004; Nijhuis *et al.*, 1998). However, the removal of water during drying inevitably alters food structure and composition, and can result in quality deterioration, the extent of which depends on both drying method and processing conditions. Therefore, in order to optimise any particular drying method, it is necessary to quantify the extent of quality change that occurs during the processing (Bonazzi *et al.*, 1996).

The basic drying methods available to food producers can be classified (Vega-Mercado *et al.*, 2001; Brennan, 1990) as follows:

1. Hot air drying: heat is carried to the food sample mainly through convection. Cabinet driers, tunnel driers and fluidised bed driers are some examples of hot-air driers.
2. Drying by direct contact with a heated surface: heat is transported to the food sample by conduction. Drum driers and vacuum shelf driers are some examples.
3. Drying by application of energy from a radiating, microwave or dielectric source: heat is supplied by the interaction of electromagnetic energy with the food sample. Examples include microwave driers and continuous infra-red driers.

4. Freeze-drying: the food sample is frozen, and the moisture within it turns to ice. This is followed by sublimation of ice into water vapour by the application of heat at low pressure. Freeze drying is an expensive method of dehydration, although it usually produces the best quality dehydrated product. Batch, multicabinet and tunnel freeze driers are some examples.
5. Drying by solid/liquid contact: the solid food sample is put in contact with a liquid phase. Osmotic-drying and hot oil immersion drying are two examples.

The drying methods employed in the present study, i.e. hot air drying and microwave drying, will be further explored in the following sections.

2.3.1 Hot air drying

Air-drying is the most common drying method utilised in food processing operations today, as it is relatively cheap and convenient to apply (Krokida *et al.*, 2003). In conventional air-drying, heat is transferred from the surrounding air towards the centre of the food sample, while water is transported from its interior to the surface. Initially, surface moisture is removed by evaporation into the surrounding air. This creates a diffusional gradient within the body, driving more water to the surface. Moisture transport mechanisms include capillary motion, molecular diffusion, liquid diffusion, vapour diffusion and Knudsen flow (Senadeera *et al.*, 2003; Zogzas & Maroulis, 1996). When water reaches the surface of the body, it evaporates, thus continuing the cycle.

The drying of an ideal solid by hot air is presented in Fig. 2.5. The drying process can be divided into three major stages, described below (Brennan, 1990).

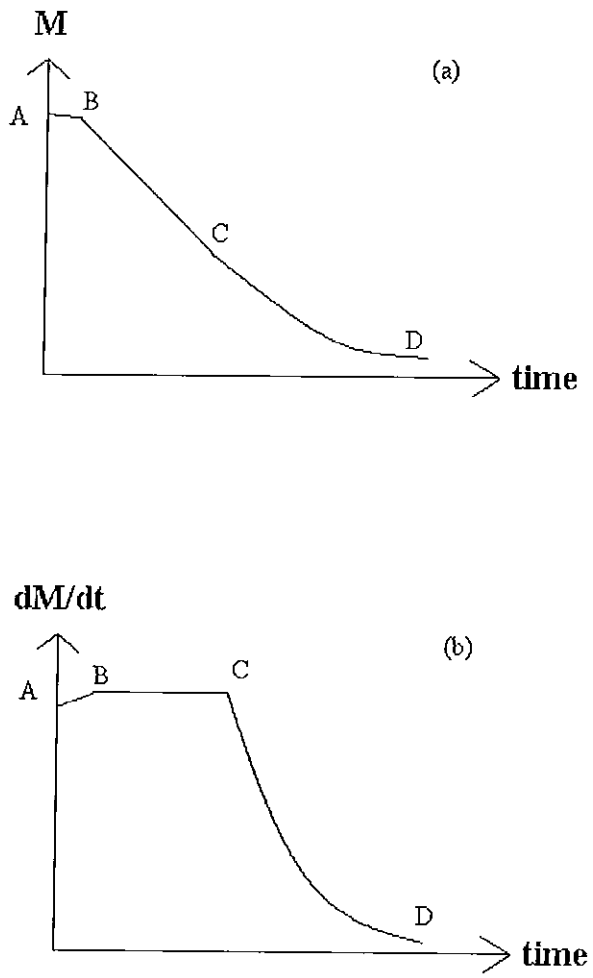


Fig. 2.5. Drying of an ideal solid by hot air, adapted from Brennan (1990). Moisture content (M) is shown as a function of drying time **(a)**, and drying rate (dM/dt) is shown as a function of drying time **(b)**.

1. Settling down stage (A-B in Fig. 2.5): food system equilibrates with drying air. This stage is sometimes negligible, depending on the drying conditions.
2. Constant rate stage (B-C in Fig. 2.5): surface remains saturated with water: rate of water movement within food to surface equals rate of evaporation from surface. Drying rate is controlled by air

temperature, air velocity and food surface area. Surface temperature remains constant during this stage.

3. Falling rate stage (C-D in Fig. 2.5): rate of movement of water within food to surface is reduced to extent that surface begins to dry out. Moisture content at C is known as the "critical moisture content". From C onwards, surface temperature begins to rise.

Drying behaviour of real foods tends to deviate from the ideal situation described above. For instance, in air-drying of fruits and vegetables, the drying rate during the "constant rate stage" is not truly constant, tending to decrease with decreasing moisture content (May *et al.*, 1999).

Increasing air temperature can substantially decrease the dehydration time required during hot air drying (Doymaz, 2005; Simal *et al.*, 2005; Guiné & Fernandes, 2005). As a consequence, food producers have, in recent years, moved from time consuming, low-temperature air-drying to faster, higher temperature drying (Pollini, 1996). Although shorter processing times are economically beneficial to producers, high processing temperatures can accelerate deteriorative reactions in foods. Therefore, it is necessary to control the drying process with great care when applying high temperatures (Migliori *et al.*, 2005).

A number of undesirable attributes are associated with hot-air drying, which can result in the deterioration of dried product quality. These include case hardening, shrinkage and product discolouration (Brennan, 1990). Case hardening refers to

the formation of a hard, impermeable surface during drying, usually due to migration of soluble solids to the product surface during drying (Brennan, 1990), resulting in a reduction of the drying rate. Shrinkage occurs during drying as water is removed. During the early stages of drying, shrinkage is directly proportional to the amount of water lost. However, towards the end of the drying, shrinkage slows down, and the products volume becomes fixed before the drying process has ended (Khraisheh *et al.*, 2004). Product discolouration can occur due to surface browning or pigment destruction during high temperature drying. Other disadvantages of air-drying are long drying times and low energy efficiency (Sharma & Prasad, 2001; Maskan, 2001). Such limitations have lead to the utilisation of alternative technologies, such as microwaves, in the drying of foodstuffs.

2.3.2 Microwave drying

Microwaves are high frequency electromagnetic waves (within the frequency range 300 MHz – 300GHz) that can be reflected, transmitted or absorbed, depending on the target material's properties. The food industry is now a major consumer of microwave energy, especially in the drying of pasta and post-baking of biscuits (Nijhuis *et al.*, 1996; Berteli & Marsaioli, 2005; Ahmad, *et al.*, 2001). Cooking, thawing, drying, sterilization, heating and re-heating are just a selection of operations that can be performed using microwave energy. The two most commonly used microwave frequencies in industry are 915 MHz and 2450 MHz whilst 2450 MHz is the most common frequency found in microwave applications for home use.

The dipole nature of water means it is the main target for microwave energy. During microwave processing, heat is generated throughout the material, leading to faster heating rates and shorter processing times compared to conventional heating, where heat is usually transferred from the surface to the interior. Microwave processing is energy efficient, as most of the electromagnetic energy is converted into heat. However, the application of microwaves can result in uneven heating of certain products, depending on their dielectric and thermal and physical properties (Nijhuis *et al.*, 1998).

Microwave utilisation in legume processing has been associated with nutritional benefits. It has been reported that the application of microwave heating removed lipoxygenase in soybeans (Wang & Toledo, 1987) and winged beans (Esaka *et al.*, 1987): lipoxygenase action is responsible for "beany" flavour development, reducing the consumer acceptability of many bean products. Microwave processing can reduce trypsin inhibitor activity, which is thought to reduce protein digestibility in humans. Trypsin inhibitor activity was completely destroyed in winged beans after 5 min microwave heating (Esaka *et al.*, 1987), and microwave heating reduced the levels of trypsin in soybeans (Yoshida & Kajimoto, 1988). Microwave heating has also been shown to increase the true digestibility of soy protein (Hafez *et al.*, 1985) and minimise nutrient losses in chickpeas (El – Adawy, 2002).

Microwave processing also affects the sensory properties of foods, such as colour and texture. Microwave drying has been shown to cause minimal colour change in foods compared with air-drying (Maskan, 2000, Lin *et al.*, 1998). This has

been attributed to the considerable reduction in drying time resulting from microwave utilisation. Microwave drying resulted in improved texture for cranberries (Yongsawatdigul & Gunasekaran, 1996), carrots (Lin *et al.*, 1998) and garlic (Cui *et al.*, 2003) when compared to air-drying alone, probably due to less case hardening.

2.3.3 Combined microwave – hot-air drying

Combining microwave and air drying has been proposed as a means of overcoming the disadvantages associated with applying each method alone (Andres *et al.*, 2004; Sharma & Prasad, 2000; Funebo & Ohlsson, 1998). The combination of microwave energy with convective drying has delivered dramatic reductions in drying times (up to 90 %) for apples (Bilbao-Sainz *et al.*, 2005), pasta (Berteli & Marsaioli, 2005), kiwis (Maskan, 2001), bananas (Maskan, 2000), garlic cloves (Sharma & Prasad 2001), and mushrooms (Funebo & Ohlsson, 1998), compared to convective drying alone.

One way of combining hot air and microwave drying is known as *microwave-finish* drying. As the name suggests, *microwave-finish* drying involves air-drying followed by microwave drying. This method has been shown to decrease the drying time for both kiwi (Maskan, 2001) and banana (Maskan, 2000). *Microwave finish* drying is useful for removing the water trapped in the interior of foods at the end of the air-drying process. Another method in which there is interest involves applying microwaves simultaneously during the air-drying process. In this case, microwave energy causes water in the interior of the

product to boil and move towards the product exterior where it is then removed by convective air currents.

Simultaneously combining microwave and hot air drying has been shown to reduce the drying time of garlic cloves by 80-90%, in comparison to hot air drying alone, while maintaining a high quality product (Sharma & Prasad, 2000). Berteli & Marsaioli, (2005) found that applying microwaves during the air-drying of pasta reduced the drying time required by more than 90%, without damaging its appearance. The effect of increasing microwave power and air temperature was significant in decreasing drying time for apple cylinders (Andres *et al.*, 2004). The effect of drying parameters on subsequent rehydration properties of a variety of foods has also been investigated. Increasing microwave power level during the drying of apple resulted in higher weight gain and volume recovery, but a lowered water holding capacity (Bilbao-Sainz *et al.*, 2005).

2.4 Food quality

Food quality, although vital for consumer satisfaction, is notoriously difficult to define (Bordeleau *et al.*, 2002). Considering quality from a food technologist's point of view, Martins and co-workers (2001) offered the following description: "quality is the result of the ability to control chemical, physical and microbiological changes during processing and storage". The concept of food quality involves a great number of properties and characteristics, some more quantifiable than others. For example, nutrient content, toxin concentration and microbial contamination can be evaluated experimentally, while many aspects of

sensorial quality, such as taste, odour and texture are more difficult to define and measure.

Quality assessment can be consumer oriented and/or product oriented. Consumer oriented quality assessments attempt to gauge the potential market success of a product, by considering product acceptance from the consumer's point of view. In contrast, product oriented quality is usually assessed under laboratory conditions, using scientific methods and analytical instruments. Therefore, product oriented quality assessments tend to be more precise, repeatable and easy to analyse than consumer oriented studies (Shewfelt, 1999).

Quality assessment formed an integral part of the present study, in the development of novel legume products. Deciding on which quality tests to include required consideration of the following issues: product type; storage method; technological resources and time available to the researcher. For the chilled/frozen products, it was concluded that microbial quality, texture, colour and sensorial quality were of primary importance for investigation. For the dehydrated products, water activity, texture and colour during drying were deemed to be the principal quality indicators of interest. A review of the quality parameters investigated in this study is presented in the following paragraphs.

2.4.1 Microbial quality

Microbial safety is essential for food products. According to the Food Safety Authority of Ireland (2003), some 53% of Irish consumers are concerned with the safety of food that they buy and eat. The degree to which a particular food

product can be considered microbially safe depends on the number, as well as type, of microbial contaminants it contains. Spoilage and pathogenic microorganisms are of particular concern in food production. Spoilage microorganisms cause disagreeable changes in taste, texture smell and sight of foods, while pathogenic microorganisms can result in disease.

The primary function of microorganisms in nature is self-perpetuation. They achieve this by converting organic matter into energy and inorganic matter (Jay, 2000). In order to survive, food-borne microorganisms require nutrients, as well as favourable physical (e.g. temperature) and chemical (e.g. pH) conditions. Microorganisms can be grouped, according to temperature ranges at which their growth is optimal, as follows: psychrophiles, psychrotrophs, mesophiles and thermophiles. Psychrophiles are capable of growth around 0 °C, and experience optimal growth between 15 and 20 °C. Psychrotrophs can grow at 7 °C, and experience optimal growth between 20 and 30 °C. Mesophiles prefer moderate temperatures; they can grow within a range between 20 and 45 °C, and thermophiles can grow at temperatures above 45 °C.

Microbial growth can be classified into four phases (Fig. 2.6). During the "lag" phase, growth is slow, as the bacteria adjust to their new environment. This is followed by a period of rapid cell division, known as the "exponential" phase. After the supply of nutrients becomes depleted, cell division ceases and the number of cells remains nearly constant; this is known as the "stationary" phase. Cell numbers subsequently decrease, as cells die during the "death" phase.

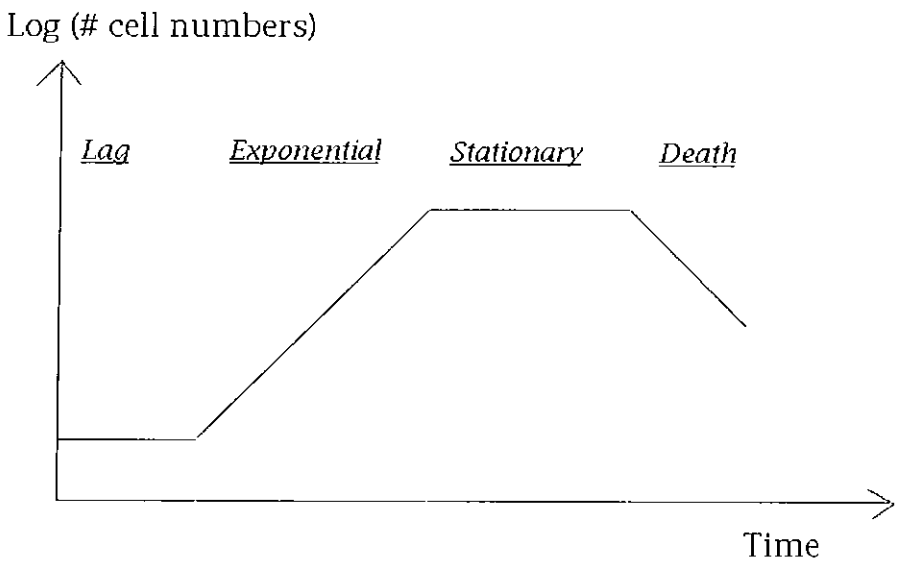


Fig. 2.6. Phases of microbial growth.

Food processing and storage conditions can be utilised to limit microbiological growth. Dehydration, one of the oldest methods of food preservation, works by decreasing the amount of water available for microbial growth. Chilling and freezing exploit the fact that microbial growth is slower at low temperatures.

2.4.1.1 Legume microbiology

Bacteria causing legume spoilage include: *Curtobacterium* (cause of bacterial wilt), *P.marspuriorum* (cause of halo blight) and *Erwinia carotovora* (cause of bacterial soft rot). Yeasts and mould such as grey mycelium and anthracnose can also cause bean spoilage (Adams & Moss, 2000). Dehydrated legumes are shelf stable because they contain insufficient water to promote microbial growth. However, subsequent handling and processing of dry legumes can compromise their microbial safety. Legumes are especially susceptible to microbial growth

during the soaking stage, when water is in plentiful supply. Typical industrial practises of soaking beans for long times (up to 18 h) at room temperature provide conditions favourable for proliferation of psychrotrophic and mesophilic microbes. In order to limit growth during the soaking stage, it is therefore desirable to minimise the amount of time spent in the soaking stage.

2.4.1.2 Chilled foods microbiology

Chilled foods depend mainly on refrigeration for preservation. Decreasing storage temperature increases the lag phase, thus slowing down the microbial growth rate. The microbiology of chilled foods (Walker & Betts, 2000) depends on a number of factors. The quantity of initial microflora present is important, as it affects future proliferation. Initial microflora depends on the raw material, aswell as processing techniques used in chilled food production. Psychrotrophs and psychrophiles are of particular concern during low temperature storage, and some microorganisms have been reported to grow at temperatures as low as 0 °C (Michener & Elliot, 1964).

Many foods destined for the chill cabinet are first subjected to pasteurisation, followed by packaging, then cooling (Snyder, 1997). The pasteurisation step involves heat treatment for sufficient time so that most microorganisms are killed. Increasing the severity of the pasteurisation process, by using high temperatures and long pasteurisation times, generally increases the shelf life of the chilled product, by destroying more microorganisms. It is essential that subsequent packaging be carried out under aseptic conditions, to minimise the risk of microbial invasion. After packaging, rapid cooling is usually achieved by

blast chilling. It is important to note that microbial growth is retarded, not stopped, during chilled storage. Therefore, the utmost care must be taken, during each stage of production and transport, to minimise the risk of growth.

2.4.1.3 Frozen foods microbiology

Frozen foods should be stored at temperatures below −18 °C (Blond & Le Meste, 2004), at which microbial growth is extremely unlikely. Consequently, they enjoy long shelf lives (6 –18 months) when compared with chilled foods. The shelf life of any particular frozen product depends upon the following factors: raw material, pre-freezing processing, packaging and storage. Raw material selection is important to ensure subsequent product quality. Pre-freezing processes, such as cleaning and pasteurization, can be used to minimize microbial contamination prior to freezing and packaging prevents the introduction of new microorganisms. Rapid freezing, achieved by use of blast-freezers, is desirable for maximum efficacy in destroying microbial contaminants. Although freezing stops microbial growth temporarily and microorganisms tend to decrease in number with frozen storage time, the microorganisms contained in frozen foods are never completely destroyed. Accordingly, it is essential to monitor the storage temperature of frozen products to prevent accidental thawing.

2.4.2 Water activity

The concept of water activity has enjoyed widespread use in the estimation of food quality since the 1970s, when it was found that water activity, rather than moisture content, could explain many of the deteriorative reactions occurring in

foods (Labuza, 1980). Water activity (a_w) is a dimensionless measure of the free water in a food system, available to support biological, physical and chemical reactions. It is related to the concept of vapour pressure, i.e. the pressure exerted by a vapour held in equilibrium with its solid or liquid state. More precisely, water activity can be defined as the ratio of vapour pressure of water (in a food or otherwise) to that of pure distilled water at the same temperature. Therefore, the water activity of pure, distilled water is equal to 1. Water activity generally increases with temperature and moisture content (Roos, 2002).

Figure 2.7 shows how the major deterioration reactions in foods are affected by water activity. High a_w foods tend to support microbial growth. Pathogenic microorganisms require $a_w > 0.86$, while yeasts and moulds are more tolerant, requiring $a_w > 0.62$ (Labuza, 1980). Many other deteriorative reactions, such as lipid oxidation and browning are related to water activity (Fig. 2.7). Lipid oxidation reactions can lead to rancidity, loss of nutrients, colour change and formation of toxic compounds, depending on the type of food concerned. Lipid oxidation of foods is generally minimal for a_w between 0.2 and 0.5 (Troller, 1989). However, Priestly and co-workers (1985) found that with a moisture range of 5 – 16% (corresponding to a_w range 0.4 – 0.8), dry soybeans varied little in vulnerability to lipid oxidation.

The water activity of a food system is subject to change, depending on storage and processing conditions. During dehydration, the majority of free water contained in the food is removed, and a_w subsequently decreases, inhibiting the onset of undesirable reactions such as microbial growth. Consequently, reducing

the water activity of a product is an important step in microbial control. Labuza and Saltmarch (1981) found that browning rate during storage reaches a maximum in the 0.6 – 0.9 a_w range (Fig. 2.7). Accordingly, drying food products to a final a_w level between 0.2 – 0.5, should ensure microbial safety, while preventing lipid oxidation and browning during storage.

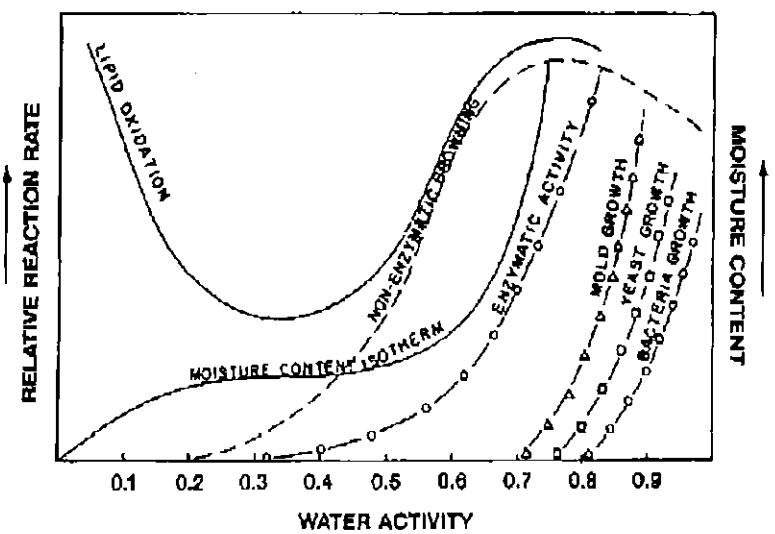


Fig. 2.7. Relationship of food deterioration rate as a function of water activity *(adapted from* Labuza, 1980).

2.4.2.1 Glass transition

There are limitations to the use of the concept of water activity in describing the stability of food systems. For example, water activity is temperature dependent, and variations in water activity may occur within food microstructure (Roos, 2002). Somewhat related to the concept of water activity is that of glass transition, which was proposed around 40 years ago to explain the stability of low moisture foods (White & Cakebread, 1966). Glass transition refers to the change in state of a solid matrix from the rubbery, amorphous state to the glassy state. Glass transition can occur during cooling or heating, and by the removal or

sorption of a plasticizer, e.g. water (Roos, 2002). A glass transition temperature (T_g) can be associated with any particular food matrix at a constant moisture content, above which the food matrix enters the mobile rubbery state. Water activity is not dependent on glass transition: however, high water activity foods cannot be glassy (Roos, 2002).

In the glassy state molecular mobility is very low; consequently, the speed of deteriorative reactions is slow. Ling and co-workers (2005) found that colour stability of dehydrated pears was related to onset on glass transition: by drying pear slices to moisture levels low enough such that glass transition occurred, colour remained stable during storage. Shrinkage during drying is also related to T_g. Significant volume changes can only occur when a product is in the rubbery state, so that volume stability is achieved when the product encounters temperatures lower than T_g at any particular moisture content (Ratti, 2001).

2.4.3 Texture quality

Texture is a mechanical property of foods that can be evaluated subjectively by means of sensory analysis, or objectively by instrumental measurement: the scientific study of the deformation and flow of matter is known as rheology. Human perception of food texture is a complex phenomenon, and can vary greatly from person to person. However, many fundamental, empirical and imitative rheological tests are available to the food scientist (Rosenthal, 1999). Fundamental tests measure texture in terms of well-defined mechanical properties, such as Young's modulus and Poisson's ratio. Empirical tests measure texture in more vaguely defined terms, such as hardness, firmness and

brittleness. In contrast, imitative tests, such as texture profile analysis, aim to imitate conditions of human mastication, involving measurement of parameters such as cohesiveness and chewiness.

Empirical tests, such as compression and puncture tests, are popular in the study of food texture (Murthy & Bhattacharya, 1998; Deshpande, 2001; Borges & Peleg, 1997), because empirical test parameters correlate well with sensory evaluation of texture (Bourne, 1978). The deformation rate, i.e. the speed at which the instrumental apparatus interacts with the test sample, is a much-debated issue. Deformation rates ranging from 10mm min^{-1} (Borges & Peleg, 1997) to 300 mm min^{-1} (Soliva-Fortuny *et al.*, 2003) have been cited in the literature. Human mastication occurs at high deformation rates, around 150 cm min^{-1} and it has been shown that the arbitrary low rates used in instrumental tests can lead to erroneous results (Voisey, 1975). This is because the rate of change of force with time increases as higher deformation speeds are used. However, in a study of the influence of compression rate on the rheological parameters and sensory texture of cooked potatoes, Thybo and co-workers (2000) found that performing compression tests on cooked potatoes at deformation rates resembling the mastication rate did not improve correlation to the sensory texture profile.

Textural properties of food products depend on inherent physical characteristics. In particular, water content has a substantial influence on food texture. The influence of water content, or water activity, on texture is complex. Increasing water content can have a softening (plasticizing) effect or a hardening (anti-

plasticizing) effect on foods (Chang *et al.*, 2000). Another important issue in the evaluation of foods is non-uniformity of samples. Borges and Peleg (1997) reported considerable variance between replicates, in a study of kidneybean and chickpea texture as a function of water activity, due to the size, shape and structural variability within each sample group.

The maximum force applied to a food product before breakage correlates well with the sensory evaluation of hardness (Collinson *et al.*, 1980) and is therefore commonly used to describe texture of foods. A typical force-deformation curve for chickpeas in the early stage of soaking is shown in Fig. 2.8. As the applied force increases, deformation of the product increases, until the product starts to break. Hardness corresponds to the peak of the force-deformation curve. The harder a product is, the higher the force it can support before breakage. Brittle foods are characterised by requiring little work to fracture (Dobrazczyk & Vincent, 1999), and rapid decrease in force after breakage has occurred, whereas non-brittle foods show a gradual decline in force after fracture.

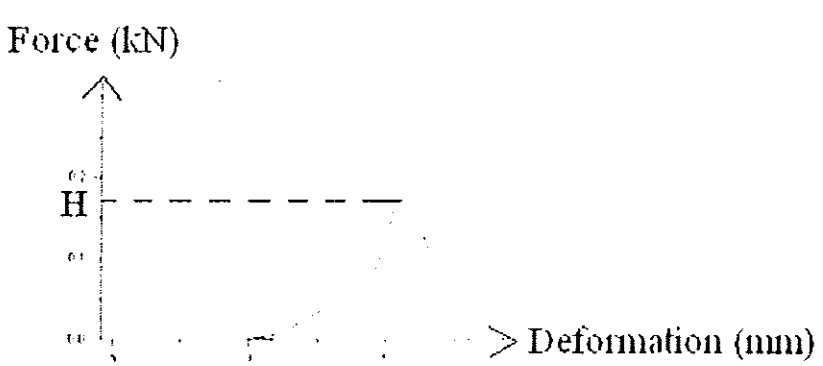


Fig. 2.8. Typical force deformation curve for chickpeas during early stage of soaking, showing hardness (H).

2.4.3.1 Texture during soaking

During soaking of legumes, water penetrates the seed coat, travelling through the cotyledons towards the centre of the bean. Such water absorption causes the bean to become softer and uniform in texture (Abu-Ghannam, 1998a; Abu-Ghannam, 1998b; Deshpande & Bal, 2001). It has been recommended that in studies of textural degradation at constant temperature, heating time should be long enough such that the textural property no longer changes with time (Rizvi & Tong, 1997). In a study on the force-deformation curves of kidneybeans during soaking, it was reported (Abu-Ghannam 1998b) that after a certain amount of soaking time, the deformation curves became uniform, corresponding to the attainment of an equilibrium texture. Changes in hardness may be correlated with water intake: Deshpande & Bal (2001) found that dry soybean hardness decreased as soaking time and temperature were increased; in another study, a first order model was proposed to describe kidneybean hardness during soaking (Abu-Ghannam, 1998a).

2.4.3.2 Texture during cooking

During cooking, starch gelatinisation and protein denaturation cause softening in legumes. Texture measurements are often used to determine the degree to which foods are cooked (Collinson *et al.*, 1980; Sangronis *et al.*, 2002): determination of cooking quality of pulses is often done by heating in water followed by texture measurement. The Mattson cooker can be used to estimate the cooking times required for beans (Mattson, 1946). Taiwo and co-workers (1997) found that penetration depth (inversely related to hardness) for cowpeas increased with cooking time. Quast and Da Silva (1977) reported that maximum shear force of

lima beans during cooking decreased linearly with cooking time.

2.4.3.3 Texture during drying

Reducing moisture content generally raises the glass transition temperature, T_g (Kasapis, 2006); therefore drying foods to sufficiently low moisture contents can result in glassy, dry product. Similarly, reducing the water activity of products to sufficiently low levels can allow the glass transition temperature to occur at room temperature. For example, some powders enter the glassy state below a_w of 0.3 (Labuza *et al.*, 2004), and bread enters the glassy state between a_w 0.32-0.56 (Chang *et al.*, 2000). When in the glassy state, foods can be hard or brittle in texture, depending largely on the dehydration conditions. Slow drying, sun drying of legumes being one example, leads to a dense dehydrated structure, which is very hard. Fast dehydration, such as vacuum microwave drying of carrots, can lead to a porous dehydrated product, with softer texture (Lin *et al.*, 1998)

2.4.3.4 Texture and storage

Food softening during storage is a major problem for food technologists (Soliva-Fortuny *et al.*, 2003). In the case of dehydrated foods, softening can occur if foods are stored in high humidity surroundings within unsuitable packaging: moisture could be absorbed by the dry product from the surrounding air, causing the water activity to increase, which usually leads to softening (Chang *et al.*, 2000). One of the main problems with frozen, and to a lesser extent chilled, foods is softening during low temperature storage. This is especially problematic in the case of high moisture foods. The freezing, and subsequent expansion of

water molecules within foods can result in damage to the cellular structure, leading to a soggy product when thawed (Kerr, 2004). Improvements in the processing of frozen goods may preserve textural quality. For example, Delgado and Rubiolo (2005) found that tissue damage of frozen strawberries could be minimised by using high freezing and thawing rates.

2.4.4 Colour quality

Colour is fundamental to visual quality, the primary quality attribute available to the consumer when making purchasing decisions (Marsili, 1996). Colour can also affect the flavour perception of foods. For example, in one study, it was reported that dark-coloured breakfast cereal tasted burnt compared with normal-coloured samples (Good, 2004). The sensation of colour arises from the interaction of light, object and observer. When light is incident on an object, it can be reflected, refracted or absorbed, depending on the optical properties of the object. Light rays coming from the object are sensed in the human eye, by rods (sensitive to low light) and cones (sensitive to colour) in the retina, and passed as electrical signals, via the optic nerve, to the brain for interpretation.

Colour can be measured subjectively by human observation, or objectively by scientific instruments. The human eye contains receptors (cones) for short (S), middle (M), and long (L) light wavelengths, also known as blue, green, and red receptors. Consequently, three parameters are required to describe a colour sensation. Tristimulus colorimetry attempts to imitate the analysis of the human eye in terms of responses to three stimuli. One of the first mathematically defined colour spaces was the CIE XYZ colour space, created by the International

Commission on Illumination (CIE) in 1931. The CIE parameter Y describes brightness and colour is described by transformation of the CIE X and Y components (Nave, 2005).

Two instruments frequently used to measure colour are the spectrophotometer and the tristimulus colorimeter. The spectrophotometer contains a diffraction grating, which splits light into component wavelengths. It then measures reflectance for each wavelength, from which tristimulus values can be calculated. The tristimulus colorimeter contains a light source from which light incident on an object is reflected and then passed through a number of band filters, and a photodiode which converts the light reflected to electrical signals (Good, 2004). Tristimulus colorimeters operate over a wider spectral band than spectrophotometers, and produce readings that correlate better with what the human eye actually sees (Good, 2004). Tristimulus colorimeters are often cheaper than spectrophotometers and are frequently employed for research on the colour of foods.

The tristimulus colorimeter transforms colour data into CIELAB colour space. The CIELAB colour measurement system was recommended by CIE in 1976, to provide a standard method for comparing colours, and is now the most widely used method for measuring colour in quality control (Datacolour, 2002). The CIELAB system (Fig. 2.9) has three components: Lightness (L*), Redness/Greeness (a*) and Yellowness/Blueness (b*). L* ranges in value from 100 (white) to 0 (black); a* ranges from positive values (red) to negative values (green); b* ranges from positive values (yellow) to negative (blue). Total colour

change can be determined by comparing CIELAB values of a test sample with a standard.

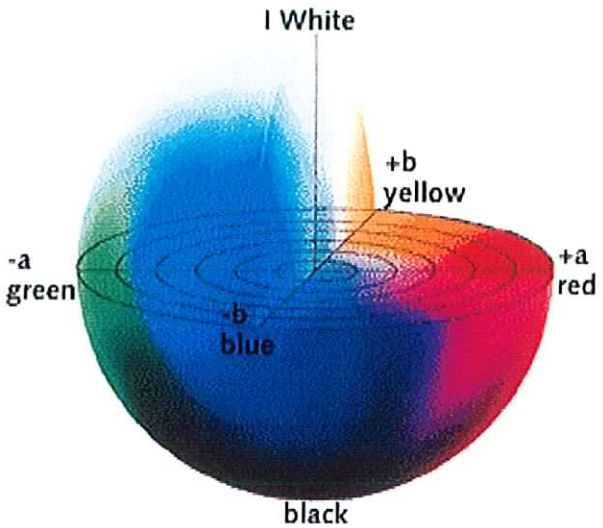


Fig. 2.9. 3-dimensional visualisation of CIELAB colour space.

During processing and storage, a number of physical and chemical reactions in food can cause undesirable colour change. These include pigment degradation, browning reactions, changes in ingredient distribution and re-crystallisation of compounds (Bayram *et al.*, 2004). Browning of foods during processing and storage is a major issue of concern for food producers, while pigment degradation can occur when foods are exposed to high temperatures. The Maillard reaction, involved in non-enzymatic browning (NEB), involves a network of complex chemical reactions. It is responsible for the surface browning of bakery products and meats, while also contributing to the production of off-colours on foods during processing and storage.

2.4.4.1 Colour and hydrothermal treatment

The colour change during soaking of soybeans was investigated by Bayram and

co-workers (2004), who reported that during the soaking process, lightness and yellow colour in soybeans increased, while redness value decreased. The decrease in redness, and corresponding increase in yellowness was attributed to the thermal breakdown of long chain carotenoids, which are reddish in colour, into shorter chain carotenoids, which are more yellow in colour. The increase in lightness was attributed to water intake, combined with the breaking down of long carotenoid chains.

2.4.4.2 Colour and dehydration

Colour change during drying is one of the most challenging aspects of dehydration process design. Usually, the producer wishes for the colour of the dried product to resemble as closely as possible that of the fresh product. However, a certain degree of colour change during dehydration is inevitable: reduction in water content causes luminosity of foods to decrease and browning is often an undesirable result of dehydration. The extent of browning during drying depends on water activity, processing temperature (Martins *et al.*, 2001) and time (Pott *et al.*, 2005). Eichner and co-workers (1985) reported that although decreasing water activity controls food browning, reducing temperature during the final stages of drying is even more important. Microwave drying has been shown to cause minimal colour change in foods (Maskan, 2000; Lin *et al.*, 1998) compared with air-drying. This has been attributed to the considerable reduction in drying time arising from microwave utilisation.

2.4.4.3 Colour and storage

The main reactions that affect foods colour during storage are non-enzymatic

browning (NEB) and pigment degradation. Redmond and co-workers (2004), found that freeze-chilling and chilling had a paling effect on green beans. Rodriguez-Amaya (1993) linked the loss of colour in carrots during chilled storage to the degradation of carotene, while no such colour loss was reported during the storage of pre-cooked, chilled/frozen carrots (Redmond *et al.*, 2004). NEB is influenced by water activity (Fig. 2.7). It has been reported that maximum browning of foods occurs at water activity levels within the intermediate range, i.e. 0.6 – 0.9 (Fig. 2.7). NEB occurs prominently during storage of dry products (Pott *et al.*, 2005); therefore, it is essential that storage temperature and relative humidity be controlled, and that packaging be moisture resistant.

2.4.5 Sensory quality

Sensory quality, although difficult to measure, is essential for the successful introduction of new food products into the marketplace. Sensory trials can be useful, both for gauging quality and in discriminating between the effects of different processing conditions on product quality. Typical sensory analysis involves three elements: preparation of samples, construction of a taste sheet and recruitment of a taste panel. Preparation of samples is fairly straightforward, in that the samples included in the study can be determined by preliminary laboratory experiments and samples can be presented in a random manner, using random number identifiers. Construction of a taste sheet is one of the most important steps in sensory analysis. The taste sheet should include all of the questions pertinent to the study, from which consumer preferences can be established. Questions involved in the taste sheet usually ask the taster to rate a

certain attribute on a scaled response. For example, a scaled response for texture evaluation could range in scale from very soft (bottom of scale) to very hard (top of scale). Although the number of divisions in a response scale can vary in number, it has been reported that five point scales are more amenable to statistical analysis (Cloninger *et al.*, 1976). Taste panel recruitment is another important consideration: if tests are to be repeated, it is important to ensure that the panellists can attend further tasting sessions; if specific product attributes are to be tested then panellist-training may be necessary.

Sensory analysis of bean texture was investigated by Calvo and del-Rey (1999), who used five point sensory scales to rate cooked bean texture. They measured the following characteristics: visual appearance, surface characteristics, texture and structural characteristics. Visual appearance was evaluated by observation of the cooked sample; tasters were asked to rate visual appearance on a five point scale where 1 = broken and 5 = whole. Surface characteristics were evaluated by the sensation of the bean on the tongue, and rated from smooth (= 1) to wrinkled (= 5). Texture was evaluated by behaviour of the bean towards deformation in the mouth, and rated from soft (= 1) to hard (= 5). Tasters were also asked to identify structural characteristics, such as flouriness and graininess, on a five point scale, where 1 = nothing and 5 = very. The researchers reported a high degree of variability in response, even among samples of the same variety.

CHAPTER 3

MATERIALS AND METHODS

An explanation of experimental methodology employed throughout the thesis

3.1 Raw material

Dry samples of Kabuli-Chickpeas *(Cicer arietinum.,* L.*)* and soybeans *(Glycine max)* were purchased from an Irish wholesaler of legumes (supplier: Munster Wholefoods; origin: Turkey (chickpea), Canada (soybean); harvest year: 2000; product code: 51 (chickpea), 34 (soybean)). Dry samples (Fig. 3.1) were stored in hermetically sealed bags at room temperature, in a dark room.

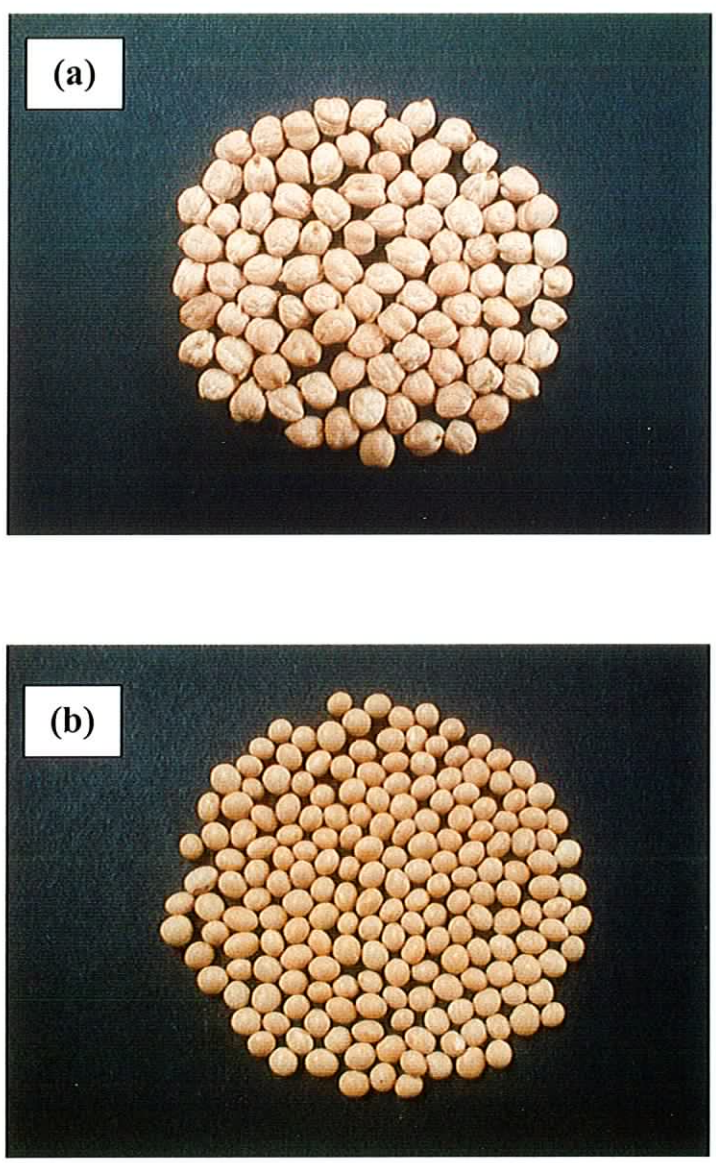


Fig. 3.1. Samples of dry Kabuli-chickpeas **(a)** and soybeans **(b)** used in the study.

3.2 Blanching procedure

Dry bean samples were placed in a wire basket and immersed into a 2 l beaker, containing 1 l of tap water (pH: 7.5 ± 0.2) heated to 100 °C, for 1.5 min. After blanching, the sample was removed from the boiling water, drained, superficially dried, allowed to equilibrate with room temperature for 15 min, and subsequently weighed.

3.3 Texture evaluation

Compression tests were performed using an Instron Universal Testing Machine (model 4301), attached to Series IX data acquisition control and analysis software for materials testing with a 500 N load cell (Fig. 3.2). A cutter with a circular molar end (diameter 10 mm, Fig 3.3) was used in compression tests (unless otherwise stated). The shape of the end of this implement resembles the shape of the molar tooth in the human mouth, and can grip the bean sample with ease throughout the cutting operation, preventing sample slippage. An aluminium plate with dimensions of 10 x 10 cm^2 and thickness 1.3 cm was supported on the Instron base.

The cutter was lowered at the maximum compression speed of 500 mm min^{-1}. This compression rate was chosen to approximate the high rates of deformation experienced during human mastication of food (Voisey, 1975). During operation, the orientation of each sample was kept uniform: chickpeas and soybeans were placed on their side, with the hilium pointing away from the observer (Fig. 3.4). The cutting implement was allowed to travel the height of the bean, cutting

through the sample, stopping 2 mm away from the plate. Hardness was defined as the peak of the force-deformation curve, recorded in kN per sample.

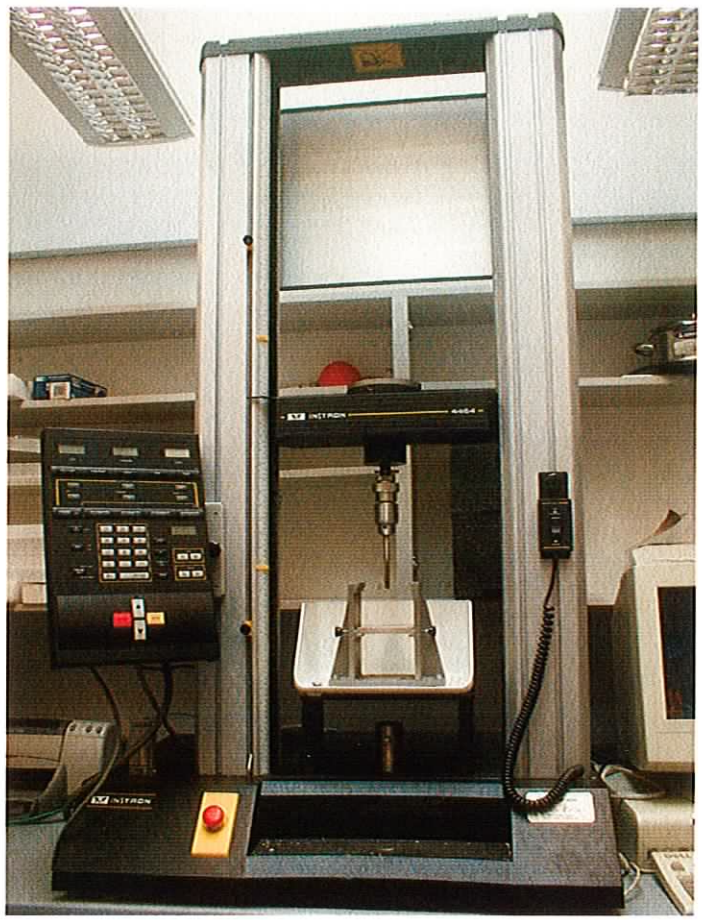


Fig. 3.2. Instron Universal materials testing machine, model 4301.

Fig. 3.3. Molar-end cutting implement.

Fig. 3.4. Sample orientation during compression testing.

3.4 Sample preparation for dehydration experiments

In preparation for dehydration experiments, samples were blanched for 1.5 min by immersion in boiling water, soaked at 40 ± 0.5 °C for 4 h in a thermostatically controlled water bath, then cooked by immersion in boiling water for 60 min. Preliminary experimental work showed that a cooking stage was necessary prior to drying in order to produce a rehydrated product with acceptable colour and texture (Appendix B). After cooking, samples were packed in 40 g units and stored at 4 °C. Soybean skin was removed (by hand) before drying, as it was found to crack in preliminary drying experiments. Prior to drying, samples were taken out of storage and allowed to equilibrate with the surrounding air for 16 h.

3.5 Drying equipment

A 600 W, 2450 MHz, combined microwave-hot air oven with 1.33 kW heater (Belling Triplette, Belling & Co., UK, magnetron: Sanyo 2M218J) was used for drying experiments carried out in Ireland, described in Chapters 7 and 9 (Fig. 3.5). Microwave power (operating range: 210 - 560 W), air temperature

(operating range: 160 °C – 250 °C) and processing time were varied using a digital display panel and a rotating turntable enabled more uniform drying.

The power output at each microwave level was measured calorimetrically, by measuring the temperature change of 1 l distilled water during 1 min heating at that level (Cui *et al.*, 2004). Prior to drying experiments, a glass beaker containing 1 l tap water was placed in the microwave and heated for 10 min at the required setting. Air velocity was measured using a digital hot wire anemometer (TSI air velocity transducer model no. 8455-300) connected to a data logger (Grant Squirrel meter 1000 Series) to be 1 ± 0.05 m/s.

3.6 Moisture content determination for dehydration experiments

Moisture content was determined before dehydration, after dehydration and after rehydration by drying in a convective oven for 24 h at 120 °C. Moisture loss during drying was measured by method of weight loss, unless otherwise stated.

3.7 Calculation of moisture ratio during drying

Moisture ratio (MR) was calculated from the following equation:

$$MR = \frac{M - M_e}{M_0 - M_e} \qquad ...(3.1)$$

Where M_0 refers to sample moisture content prior to drying, and M_e refers to dehydrated sample moisture content. In cases where M_e was almost zero, Eq. 3.1 becomes M divided by M_0.

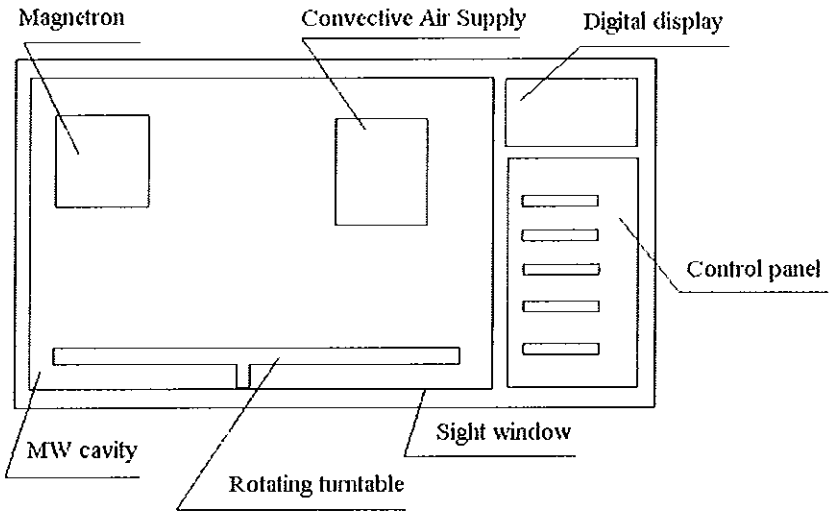


Fig. 3.5. Schematic diagram of combination microwave – hot air oven used in drying experiments.

3.8 Rehydration procedure

Approximately 20 g (weighed exactly) of dried sample was rehydrated in 1 l boiling water. Samples were removed every minute and weighed until difference in successive weightings was insignificant. Weight gain on rehydration was calculated from the equation below:

$$WGR = \left(\frac{W_t - W_d}{W_d} \right) \times 100 \qquad ...(3.2)$$

Rehydration ratio (RR) was defined as equilibrium rehydrated mass divided by initial dry sample mass.

3.9 Colour measurement

The colour of samples was measured using a colorimeter (Hunter Lab ColorQuest XE). The colorimeter was calibrated with a standard white tile (L^* =

93.97, a^* = -0.88, b^* = 1.21). The colour values were represented in CIELAB colour space as L^* (lightness/darkness), a^* (redness/greenness) and b^* (yellowness/blueness). Total colour change (DE^*) was then calculated from Eq. 3.3, where L^*_0, a^*_0 and b^*_0 refer to the CIELAB colour values for cooked chickpeas, before drying.

$$DE^* = \sqrt{(L^* - L^*_0)^2 + (a^* - a^*_0)^2 + (b^* - b^*_0)^2} \quad \ldots(3.3)$$

3.10 Modeling food dehydration and rehydration

Food hydration and dehydration are complex processes, in which simultaneous heat and mass transfer result in a net gain or loss of moisture. Mathematical models for dehydration and rehydration processes in foodstuffs can be divided into two broad categories: fundamental and empirical. Fundamental models describe water absorption in foods in terms of real physical phenomena and most are based on the diffusion of water through a porous medium, often coupled with heat transfer. Empirical models, which do not account for the fundamental physical processes occurring during water absorption, are often preferred to fundamental ones, due to their ease of computability and interpretation. Descriptions of the fundamental and empirical models employed in this work are given in the following paragraphs.

3.10.1 Fickian diffusion model

Moisture migration involves a number of transport phenomena, such as capillary motion, molecular diffusion, liquid diffusion, vapour diffusion and Knudsen flow (Senadeera *et al.*, 2003; Zogzas & Maroulis, 1996; Brennan *et al.*, 1990), all of

which are present, to different extents, during the drying process. Liquid diffusion is generally regarded to be the dominant mechanism during soaking of dry foods, and during the falling rate period (see section 2.3) of food drying. Ficks 2nd Law of diffusion (Eq. 3.4), where C represents the concentration of water within the drying body, is assumed to govern the process of diffusion. To account for the different types of diffusion occurring during drying or hydration, a lumped effective diffusivity parameter (D_{eff}) is usually employed (Arévalo-Pinedo & Murr, 2006; Gastón *et al.*, 2004; Ramesh, 2003; Zogzas & Maroulis, 1996; Karathanos *et al.*, 1990; Bakshi & Singh, 1980).

$$\frac{\partial C}{\partial t} = D_{eff} \nabla^2 C \qquad ...(3.4)$$

Analytical solutions of Eq. 3.4, with appropriate boundary conditions, can be obtained for a variety of geometries. To obtain an analytical solution, it is necessary to impose various assumptions, such as: moisture is initially uniformly distributed in the drying body, the food surface instantaneously attains equilibrium with the surrounding air or soaking medium and that volume changes are negligible. The general form of such analytical solutions is shown in Eq. 3.5, where the terms A, B_n and C_n depend on the geometry of the sample, and MR is the dimensionless moisture content.

$$MR = \frac{M - M_e}{M_0 - M_e} = A \sum_{n=0 or 1}^{\infty} B_n e^{(-C_n D_{eff} t)} \qquad ...(3.5)$$

3.10.1.1 Fickian diffusion: solution for spherical geometry with no external resistance

Different forms of Fick's second law of diffusion for spherical geometries have been used to describe the process of moisture diffusion in soybeans (Hsu, 1983),

chickpeas (Sayar *et al.*, 2001), faba beans (Kader, 1995) and rice (Bakshi & Singh, 1980). An analytical solution of Eq. 3.4 for spherical geometry can be derived by making the following assumptions:

1. Volume change during hydration/dehydration is negligible
2. The diffusion coefficient (D_{eff}) is concentration independent
3. Surface film resistance against water transfer is negligible

Moisture content at any time (Eq. 3.7) can then be calculated using Eq. 3.4 and the following initial and boundary conditions (Eq. 3.6):

$$M\big|_{t=0} = M_0 \qquad \left.\frac{\partial M}{\partial t}\right|_{r=0} = 0 \qquad M\big|_{r=a} = M_s \qquad ...(3.6)$$

$$MR = \frac{(M - M_e)}{M_0 - M_e} = \frac{6}{\pi^2}\sum_{n=1}^{\infty}\frac{\exp\left(\frac{-\pi^2 n^2 D_{eff} t}{a^2}\right)}{n^2} \qquad ...(3.7)$$

Where M_e represents the equilibrium moisture content and a represents the sphere radius.

3.10.1.2 Fickian diffusion: solution for infinite slab

The analytical solution of Ficks 2nd law of diffusion (Eq. 3.4) for an infinite slab has been used to describe the dehydration of garlic (Sacilik & Unal, 2005) and kiwi fruit (Simal *et al.*, 2005). The solution (Eq. 3.8) can be obtained by making the following assumptions:

1. Water is initially uniformly distributed in the slab
2. Surface film resistance against water transfer is negligible
3. Shrinkage during drying is negligible
4. The effective diffusion coefficient (D_{eff}) is concentration independent

Moisture ratio at any time (Eq. 3.9) can then be calculated using the following initial and boundary conditions (Eq. 3.8), where h is the half-thickness of the sample:

$$M|_{t=0} = M_0 \qquad \left.\frac{\partial M}{\partial t}\right|_{y=h/} = 0 \qquad M|_{y=2h} = M_s \qquad \text{...(3.8)}$$

$$MR = \frac{M - M_e}{M_0 - M_e} = \frac{8}{\pi^2}\sum_{n=0}^{\infty}\frac{1}{(2n+1)^2}\exp\left(\frac{-(2n+1)^2\pi^2 D_{eff}t}{4h^2}\right) \qquad \text{...(3.9)}$$

3.10.2 Empirical models

3.10.2.1 Asymptotic model

An empirical first order asymptotic model has been used to describe the hydration of kidneybeans (Abu-Ghannam & McKenna, 1997a) and faba beans (Haladjian *et al.*, 2003):

$$M = M_e + (M_0 - M_e)e^{-kt} \qquad \text{...(3.10)}$$

Where M is the moisture content at any time, t, M_e is the asymptotic moisture content, and M_0 is the initial moisture content. This is a three-parameter model, where k, the hydration rate constant, is representative of the rate of moisture intake.

The Henderson & Pabis model (Henderson & Pabis, 1961), shown in Eq. 3.11, is similar to Eq. 3.10: the moisture content variables are expressed jointly as moisture ratio (MR), and a multiplicative term (a_H) is joined to the exponent. Eq. 3.11 is also equivalent to the first term of Eq. 3.5.

$$MR = a_H e^{-k_H t} \qquad \text{...(3.11)}$$

This model has been used to describe drying of garlic (Sacilik & Unal, 2005), kiwis (Simal *et al.*, 2005), kale (Mwithiga & Olwal, 2005) and green beans (Doymaz, 2005). Parameter a_H in the Henderson & Pabis model therefore corresponds to the initial value of MR (which is assumed to be 1 in Eq. 3.10).

A special case of the Henderson & Pabis model (Eq. 3.11), when $a_H = 1$, is widely known in drying as the Lewis model (Eq. 3.12) and has been used to model the dehydration of bananas (Maskan, 2000), kiwis (Maskan, 2001) and green beans (Doymaz, 2005). This model is equivalent to Eq. 3.10.

$$MR = e^{-k_1 t} \qquad ...(3.12)$$

3.10.2.2 Bi-exponential model

Taking the first two terms of the series solution (Eq. 3.5) yields the bi-exponential model (Eq. 3.13). This model has been used to describe the drying kinetics of many foods, including garlic (Madamba *et al.*, 1996), potato (Akpinar *et al.*, 2003) and apricot (Toğrul & Pehlivan, 2003).

$$MR = a_{Bi} e^{-k_1 t} + b_{Bi} e^{-k_2 t} \qquad ...(3.13)$$

3.10.2.3 Page model

Semi-empirical models such as Eq. 3.11– Eq. 3.13, based on approximations of the series solutions (Eq. 3.5) of Ficks second law (Eq. 3.4) are often inadequate to describe drying, especially when heat transfer and shrinkage are significant. To overcome this, an empirical modification of the Lewis model, known as the Page model (Eq. 3.14), was proposed (Page, 1949). This empirical model has been successfully used to model the dehydration behaviour of garlic (Sacilik &

Unal, 2005; Sharma & Prasad, 2001), cherry tomatoes (Azoubel & Murr, 2004) and gooseberry flake (Methakhup *et al.*, 2005).

$$MR = e^{-k_p t^{n_p}} \quad \ldots(3.14)$$

3.10.2.4 Peleg model

The empirical Peleg model (Peleg, 1988), which has been used to describe the soaking kinetics of kidneybeans (Abu Ghannam & McKenna, 1997b) and chickpeas (Hung *et al.*, 1993; Turhan *et al.*, 2002), is shown below:

$$M = M_o + \frac{t}{k_{p1} + k_{p2} t} \quad \ldots(3.15)$$

This is a three-parameter model, where k_2 is inversely related to the equilibrium moisture content and k_1 is inversely related to the initial rate of water absorption.

3.11 Statistical analysis

Anova tables, t-tests, Log-likelihood ratio tests, nonlinear regressions and Monte-Carlo simulations were performed using R software (R development core team, 2005). Candidate models were compared in terms of pooled standard error, log-likelihood ratio tests, Akaike information criterion (AIC) and residual plots (Bates, 1988). The AIC is defined as follows:

$$AIC = -2*LogLik + 2*npar, \quad \ldots(3.16)$$

Where *LogLik* is the log-likelihood of a fitted model, and npar refers to the number of parameters in that model. The AIC can therefore be used to compare models in their suitability in describing datasets, taking into account different degrees of freedom. The model building strategy employed throughout the work is summarised in Fig. 3.6.

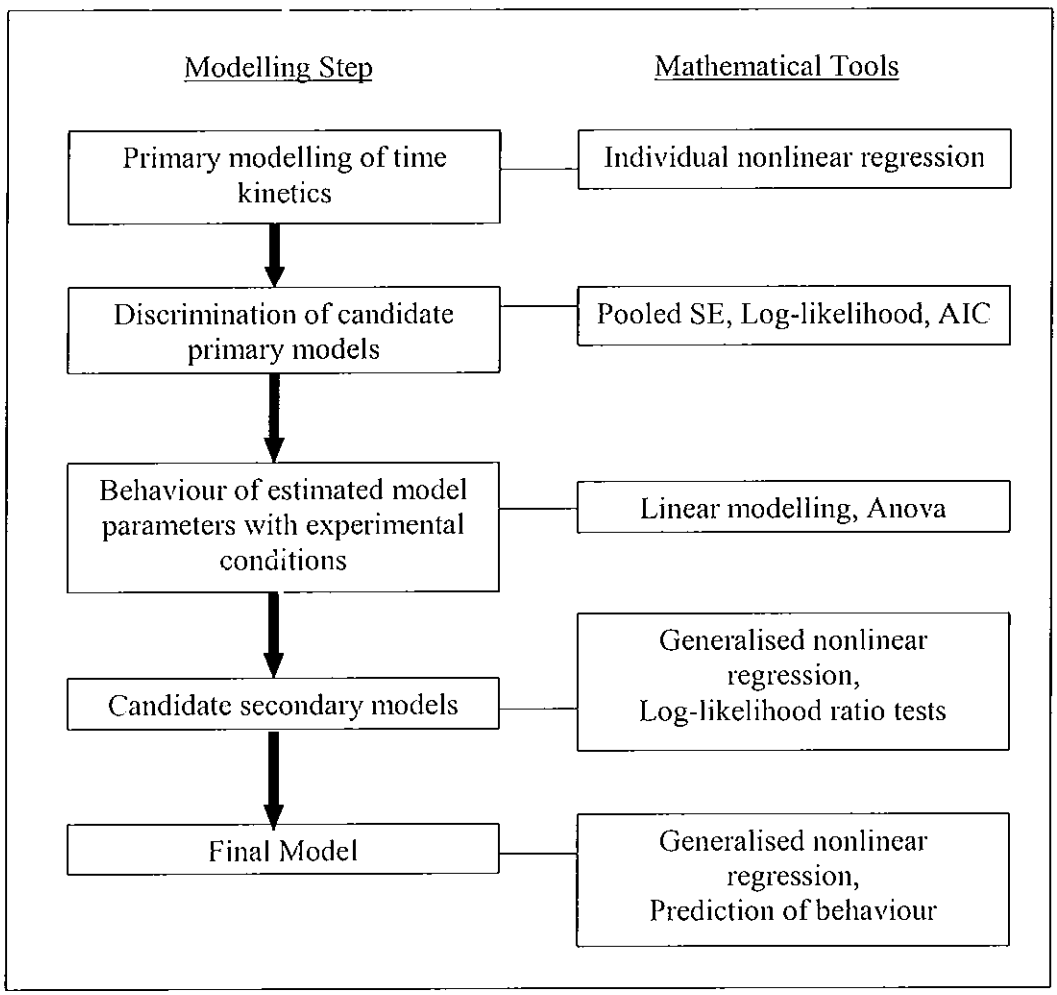


Fig. 3.6. Model building strategy applied throughout the work.

Initially, candidate primary kinetic models were fitted to experimental data by individual nonlinear regression, and discriminated in terms of their resultant pooled standard error, log-likelihood and AIC. Model parameters for the most suitable primary model, estimated by the individual nonlinear regression, were then investigated, and their dependence on processing parameters, (e.g. temperature, microwave power) was estimated through linear modelling and Anova analysis. This allowed for the construction of candidate secondary models, which were compared by means of the log-likelihood ratio test.

Following the selection of the most appropriate secondary model, which was then fitted to the data by the generalised nonlinear regression procedure, the estimated model parameters were used to generate predictive curves for the data.

CHAPTER 4

INVESTIGATION OF WATER ABSORPTION PROCESS IN CHICKPEAS AND SOYBEANS

The effect of blanching pre-treatment on initial microbial levels, water intake and texture kinetic of chickpeas and soybeans

Some of the results from this chapter were published as peer-reviewed articles in the Journal of Food Engineering (see pages 289-292)

Summary

Water intake and texture properties of chickpeas and soybeans during soaking were evaluated for soaking within the temperature range of 25 - 60 °C. The effect of high temperature-short time (HTST) pre-blanching on initial microbial levels, soaking and texture kinetics was investigated. Pre-blanching at 100 °C for 1.5 min before soaking resulted in a significant decrease of chickpea and soybean surface microflora ($p < 0.05$). Mathematical models were proposed to describe water intake and texture as functions of soaking time and temperature. Sample hardness decreased during soaking, until reaching an equilibrium level. Both water intake and texture degradation accelerated as soak temperature was increased. Temperature dependence of kinetics was described using the Arrhenius equation. Pre-blanching increased the rates of hydration and texture change for samples soaked at temperatures below 50 °C, having the greatest effect on hydration rate and texture degradation rate at 40 °C for chickpeas and 35 °C for soybeans. Blanched chickpeas experienced a break in the Arrhenius curves for water absorption and texture kinetics at 37.5 ± 1.5 °C. An uncertainty analysis of chickpea and soybean texture during soaking was performed to assess the influence of natural product variability on texture.

4.1 Introduction

Dry beans require the addition of water and heat to render them digestible. This is traditionally achieved in a two-stage process: soaking followed by cooking. Soaking is generally inconveniently time consuming, taking up to 16 h at room temperature.

Mesophilic bacteria thrive at room temperature, especially in the presence of water. Therefore, to minimise the risk of microbial proliferation during soaking, it is desirable to shorten soaking times. Blanching usually refers to the immersion of foods in boiling water or steam for a short amount of time, and is typically applied to legumes after soaking for reasons of microbial safety. Blanching also affects water intake characteristics of legumes: Abu-Ghannam & McKenna (1997a) found that pre-blanching could enhance hydration rates of kidneybeans during soaking. The present work was carried out to investigate the possible benefits of applying a pre-blanching step to chickpeas and soybeans. With this in mind, the main aims of this chapter were as follows:

1. Measure the effect of blanching on the initial microbial profile of dry chickpeas and soybeans.
2. Investigate the water intake and textural properties of chickpeas and soybeans during soaking.
3. Build mathematical models to describe the effect of pre-blanching and soak temperature on water intake and texture of chickpeas and soybeans during soaking.
4. Assess influence of product variability on texture behaviour during soaking.

4.2 Materials and methods

4.2.1 Legume source

Raw material is described in section 3.1

4.2.2 Dry moisture content determination

Pulses were manually size graded by removal of small and split samples. Dry samples were ground into flour using an electric coffee bean mill and passed through a 1 mm sieve. 2 g well mixed test sample was dried at 100 °C to constant weight in a vacuum oven (Lane, 2000). Average moisture content was subsequently calculated on a percentage dry basis (% d.b.). Samples were analysed in triplicate.

4.2.3 Blanching procedure

Blanching procedure is described in section 3.2.

4.2.4 Determination of water intake during soaking

Soaking experiments were carried out separately for both blanched and unblanched chickpeas and soybeans. 20 g sample of either blanched or unblanched sample was placed in a wire basket and immersed into a 2 l beaker containing 1 l of tap water (pH: 7.5 ± 0.2) heated to the required soaking temperature (25, 30, 35, 40, 45, 50, 55 or 60 °C) in a thermostatically controlled water bath. The temperature of the soaking solution was continuously checked and maintained at the required level (± 1 °C) throughout the soaking period.

Sample weight was measured at predefined time intervals (increments varied from 20 min to 12 h, depending on soak temperature and time), up to a total soaking time, which ranged from 200 min (at 60 °C) to 1440 min (at 25 °C), depending on the

soaking temperature. Measurement intervals were extended approaching equilibrium, as the rate of water absorption declined considerably. After specified soaking times, the samples were removed from the soaking solution, drained, superficially dried and weighed. Water intake was calculated as the percentage difference between measured weight at a specific time and the original weight. The samples were then returned to the beakers via the mesh baskets and the process was repeated until the difference between any two consecutive weightings was insignificant. Each experiment was performed in duplicate.

4.2.5 Texture evaluation during soaking

Pulses were blanched and soaked as described above. At predefined time intervals, 25 individual beans were removed from the water bath to undergo compression tests, described in section 3.3.

4.2.6 Determination of initial microbial quality

20 g legume samples (either dry or blanched) were added to 20 ml Ringers solution in a 0.2 l bottle and vigorously swirled to make a neat washing. Volumes of the neat solution were aseptically diluted according to the following dilutions: 10^{-1}, 10^{-2}, and 10^{-3}. This procedure was followed for both blanched and non-blanched samples. The following agar solutions were prepared according to the manufacturers instructions: Nutrient Agar (NA), Sabouraud Dextrose Agar (SDA), Violet Red Bile Agar (VRBA), Baird Parker Medium (BPM) and Reinforced Clostridial Agar (RCA) and plates were prepared for each of them in triplicate. Total Viable Count (TVC) and

Anaerobic Viable Count (AVC) were determined on NA, Yeast and Mould Count (YMC) on SDA, Coliform Count on VRBA, *Staphylococcus aureus (S. aureus)* Count on BPA and *Clostridia* Count on RCA.

The standard pourplate method, using 1ml aquilots, was used in the determination of TVC, AVC, YMC and Coliform Count, and the standard spreadplate method using 0.1ml aquilots was used for *Clostridia* and *S. aureus* counts. The plates were incubated (TVC, AVC, Col.forms, *Clostridia* and *S. aureus* at 37 °C, YMC at 30 °C) for 48 h to determine mesophilic counts. After incubation, all colonies on plates containing less than 300 colonies were counted using a colony counter. The number of colony forming units per gram (cfu/g) was then calculated. Each experiment was repeated three times.

4.3 Results and discussion

4.3.1 Effect of blanching on initial microbial levels of dry chickpeas and soybeans

Microbial levels for unblanched chickpeas (Figure 4.1(a)) were relatively high (TVC = 143 ± 34 cfu/g, TAC = 51 ± 30 cfu/g, YMC = 54 ± 33 cfu/g) when compared to blanched chickpeas (TVC = 18 ± 15 cfu/g, TAC = 5 ± 4 cfu/g, YMC = 10 ± 8 cfu/g), although all counts (both before and after blanching) were within satisfactory levels of microbiological contamination for dry foods (Gilbert *et al.*, 2000). After blanching, TVC, TAC and YMC decreased significantly ($p < 0.05$). Coliforms,

Clostridia and *S. aureus* were not found to be present in either unblanched or blanched chickpeas.

The average microbial profile for dry soybeans (Figure 4.1(b)) was as follows: TVC = 884 ± 217 cfu/g, AVC = 119 ± 11 cfu/g, YMC = 250 ± 31 cfu/g, Coliform Count = 95 ± 23 cfu/g. TVC, AVC and YMC for dry soybeans were all within satisfactory microbial levels for dry foods (Gilbert *et al.*, 2000). However, the dry soybeans average coliform count was just below the acceptable microbial level for dry foods (Acceptable level is < 100 cfu/g (Gilbert *et al.*, 2000)). TVC, AVC, YMC and coliform count for soybeans (Figure 4.1(b)) were all significantly reduced by blanching ($p < 0.05$). *S. aureus* and *Clostridia* were not present in either unblanched or blanched soybean samples. The use of blanching as a pre-treatment therefore substantially removes the majority of surface microflora on chickpeas and soybeans and would therefore inhibit further bacterial growth during soaking.

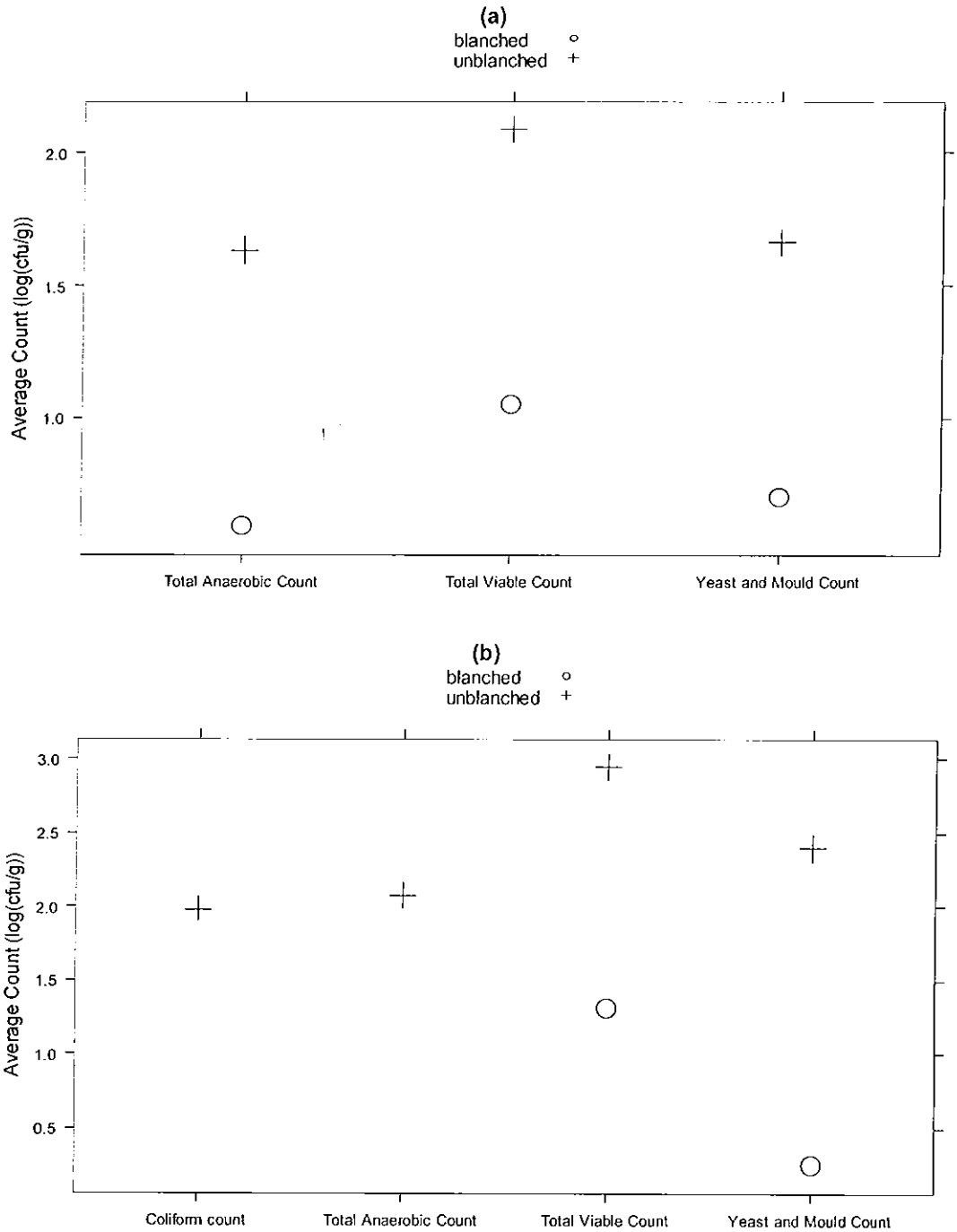


Fig. 4.1. Effect of pre-blanching on initial microflora of dry chickpeas **(a)** and soybeans **(b)**

Note: No growth was observed in tests for coliforms on chickpeas, and for coliforms and anaerobic colonies for blanched soybeans.

4.3.2 Water absorption behaviour of chickpeas and soybeans during soaking

4.3.2.1 General description of water absorption curves

Chickpea (Fig. 4.2(a)) and soybean (Fig. 4.2(b)) water absorption curves are characterised by an initial phase of rapid water pickup followed by an equilibrium phase, during which the legume approaches its full soaking capacity. As the moisture content of the legume increases, the speed at which water is absorbed decreases and water intake is minimal when the equilibrium phase is approached.

Pre-blanching dry samples at 100 °C for 1.5 min resulted in rapid uptake of water. Chickpea moisture content increased from an initial dry value of 9 ± 2 % (d.b.) to 25 ± 3 % (d.b.) after blanching, while soybean moisture content increased from an initial dry value of 12 ± 2 % (d.b.) to 32 ± 5 % (d.b.).

Results indicated that increasing soaking temperature enhanced water pick-up in the initial phase, increasing the slope of the soaking curve, thereby leading to faster attainment of the equilibrium phase, and this was in agreement with previously published data for the soaking of chickpeas (Turhan *et al.*, 2002), soybeans (Pan & Tangratanavalee, 2003) and kidneybeans (Abu-Ghannam & McKenna, 1997a).

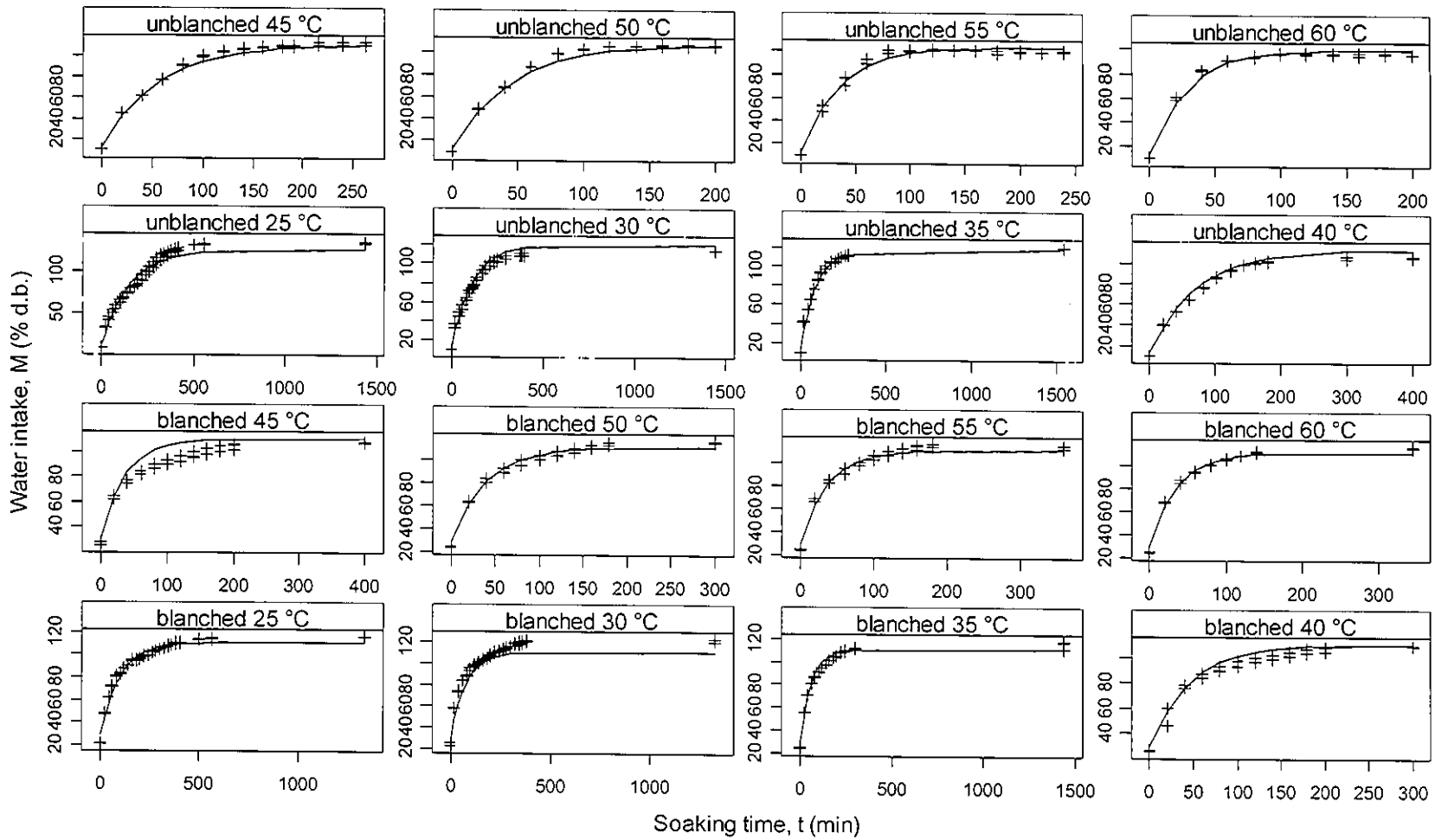


Fig. 4.2.a Water intake curves for blanched and unblanched chickpeas.

Solid lines indicate predictive curves generated by regression of Eq. 4.2 on chickpea soaking data.

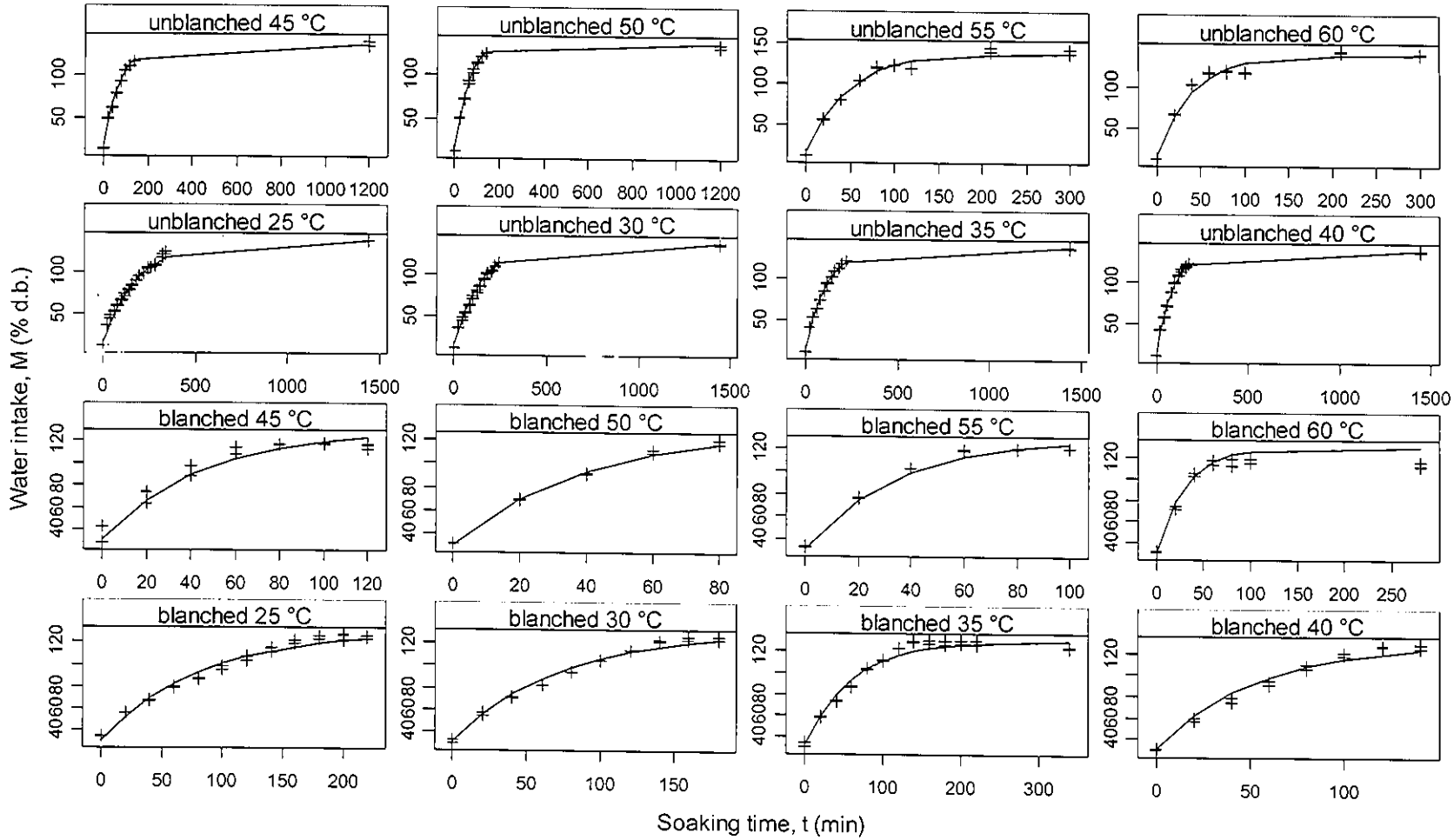


Fig. 4.2.b Water intake curves for blanched and unblanched soybeans.

Solid lines indicate predictive curves generated by regression of Eq. 4.3 on soybean soaking data.

4.3.2.2 Primary modelling of time dependence of chickpea and soybean water intake

In order to predict water intake as a function of soaking time, three models commonly used to describe water absorption in legumes were fitted to the data. The first model to be chosen was the series solution of Ficks second law of diffusion for spherical geometry (Eq. 3.7). An asymptotic model (Eq. 3.10) (which is equivalent to the first term of Eq. 3.7) and Peleg's model for water absorption (Eq. 3.15) were also fitted to the data. Peleg's model (Eq. 3.15) is only applicable to what is called the 'clearly curved' part of the sorption curve (Peleg, 1988). An objective method for determining the experimental points for inclusion in the model fitting is not suggested by Peleg (1988) and it is assumed that visual approximations were employed.

Pan & Tangratanavalee (2003) recommended that soybeans should be soaked to 120 % d.b. before further processing, for optimal textural quality. The 120 (% d.b.) moisture content was therefore chosen as an objective cut-off point for comparing the fitting of models 1-3 to soybean soaking data, so that data for $M < 120$ % were included in the regression analysis. No such limit for chickpea soaking was found in the literature, and so visual approximations were employed. By observation, the clearly curved part of the chickpea water intake curve (Fig 4.2(a)) occurred for moisture contents below 120 % d.b. Therefore, chickpea soaking data for $M < 120$ (% d.b.) were included in the regression analysis to compare each model under consideration.

The data from each individual experiment for each soaking temperature/pre-treatment combination was fitted by nonlinear regression (see section 3.11) to each model using the statistical software R (R development core team, 2005). For the series solution (Eq. 3.7), the first 50 terms of the sum were evaluated (series convergence was assumed). Each model has the same degrees of freedom, therefore the models could be discriminated by comparing the pooled standard error (S.E.) arising from their fits (Table 4.1). For both chickpeas and soybeans, the asymptotic model (Eq. 3.10) resulted in the lowest S.E., suggesting that it was best suited to the primary modelling of the data. Therefore, in order to build a general model to describe moisture content as a function of time, temperature and pre-treatment, the parameters of the asymptotic model (Eq. 3.10) were further investigated.

Table 4.1. Pooled Standard Error (SE) for nonlinear regression of Diffusion model (Eq. 3.7), First-order Asymptotic model (Eq. 3.10) and Peleg model (Eq. 3.15) on chickpea and soybean soaking data.

Eq.	Model	Standard Error (SE)	
		Chickpeas	Soybeans
3.7	$M = M_s + (M_0 - M_s)\frac{6}{\pi^2}\sum_{n=1}^{\infty}\frac{e^{\left(\frac{-\pi^2 n^2 D_{eff} t}{a^2}\right)}}{n^2}$	3.75	6.12
3.10	$M = M_e + (M_0 - M_e)e^{-kt}$	3.24	3.35
3.14	$M = M_o + \frac{t}{k_{p1} + k_{o2}t}$	7.64	5.17

Predicted initial water intake (M_0) was higher for blanched samples than for unblanched samples, due to the influx of water during blanching. Asymptotic water intake (M_e) for unblanched chickpeas decreased with increasing soak temperature ($p < 10^{-4}$). Similar temperature dependence was found in the literature for both kidneybeans (Abu-Ghannam & McKenna, 1997a) and chickpeas (Turhan *et al.*, 2002). It has been postulated that increasing soak temperature promotes leaching of water-soluble components, resulting in lower asymptotic moisture content (Abu-Ghannam & McKenna, 1997a). Blanched chickpeas, however, did not demonstrate a clear temperature dependence of M_e over the range of temperatures studied ($p > 0.05$). This may have been due to plasticization of the seed coat during blanching, which seemed to diminish the effect of temperature on the asymptotic moisture content. In the case of blanched and unblanched soybeans, M_e was not significantly dependent on soak temperature over the range of temperatures studied ($p > 0.05$). However, M_e for unblanched soybeans was higher than that for blanched soybeans ($p < 0.05$).

Hydration rate constant, k_h, generally increased with soaking temperature for both unblanched and blanched samples (Table 4.2). Since k_h represents the rate of water intake during soaking, the increase of k_h with temperature means that water intake accelerated as soak temperature was increased. This result was expected from visual inspection of the soaking curves (Fig. 4.2). Blanching resulted in an increase in k_h for both chickpeas and soybeans soaked at temperatures less than 50 °C and caused the greatest rise in k_h for chickpeas soaked at 40 °C and for soybeans soaked at 35 °C

(Table 4.2). Such an increase in k_h following blanching has also been observed in the soaking of kidneybeans (Abu-Ghannam & McKenna, 1997a). However, blanching followed by soaking at temperatures greater than 50 °C was ineffective in terms of increasing the hydration rate of both chickpeas and soybeans. It appears that high temperature soaking made the blanching step redundant, possibly due to the promotion of leaching of solutes through the thermally affected seed coat.

Table 4.2. Hydration rate constant, k_h, for chickpeas and soybeans soaked within the range 25 – 60 °C.

	Chickpeas k_h. ($x10^3$ min^{-1})		Soybeans k_h. ($x10^3$ min^{-1})	
T (°C)	Unblanched	Blanched	Unblanched	Blanched
25	4.7 ± 0.2	10.6 ± 0.7	5.1 ± 0.3	8.5 ± 1.3
30	8.8 ± 0.5	13.3 ± 0.9	6.5 ± 0.3	10.5 ± 1.6
35	12.4 ± 0.9	15.5 ± 1.3	8.1 ± 1.1	18.2 ± 1.3
40	14.7 ± 1.1	21.8 ± 2.1	11 ± 1.5	15.9 ± 1.1
45	19 ± 1.3	22.4 ± 2.3	12.8 ± 0.9	28.7 ± 4
50	25.5 ± 2	24.1 ± 2.2	15.2 ± 0.7	21.3 ± 4.9
55	33.2 ± 2.6	26.5 ± 2.4	20.5 ± 1.4	34.3 ± 4.6
60	45 ± 4.1	26.6 ± 2.8	28.9 ± 2.1	40.5 ± 4.6

The dependence of k_h on temperature (T) was fitted to the Arrhenius equation (Eq. 4.1), which has been used previously to describe the temperature dependent

hydration kinetics of a number of legumes (Abu-Ghannam & McKenna 1997a; Turhan, *et al.*, 2002).

$$k_h = k_{ref\_h} e^{\frac{-E_{a\_h}}{R}\left(\frac{1}{T}-\frac{1}{T_{ref}}\right)} \quad \ldots(4.1)$$

Where k_{ref_h} is a reference hydration rate constant, T and T_{ref} represent soaking and reference temperatures (in Kelvin) respectively, E_{a_h} is the activation energy for the hydration process and R is the gas constant (8.314 $x10^{-3}$ kJ/mol.K). In order to minimise the co-linearity of k_{ref_h} and E_{a_h}, T_{ref} was chosen as 40 °C, the average experimental soaking temperature (Haralampu *et al.*, 1985).

The suitability of applying the Arrhenius equation to a set of data can be examined by observing the Arrhenius curve, a graph of the natural logarithm of k_h against the inverse of T (Fig. 4.3). The slope of this graph is indicative of the temperature dependence of $\ln(k_h)$, and is related to the activation energy, E_{a_h}. For unblanched chickpeas, $\ln(k_h)$ decreased linearly with T^{-1} ($r^2 > 0.99$). However, for blanched chickpeas, a break seemed to occur at a certain soak temperature in the Arrhenius curve.

To locate the temperature at which the break was situated, the estimated natural log of k_h was fitted to a linear model with break point (Muggeo, 2003), and the break temperature was estimated (by likelihood maximization) to be 37 ± 1°C ($r^2 > 0.95$).

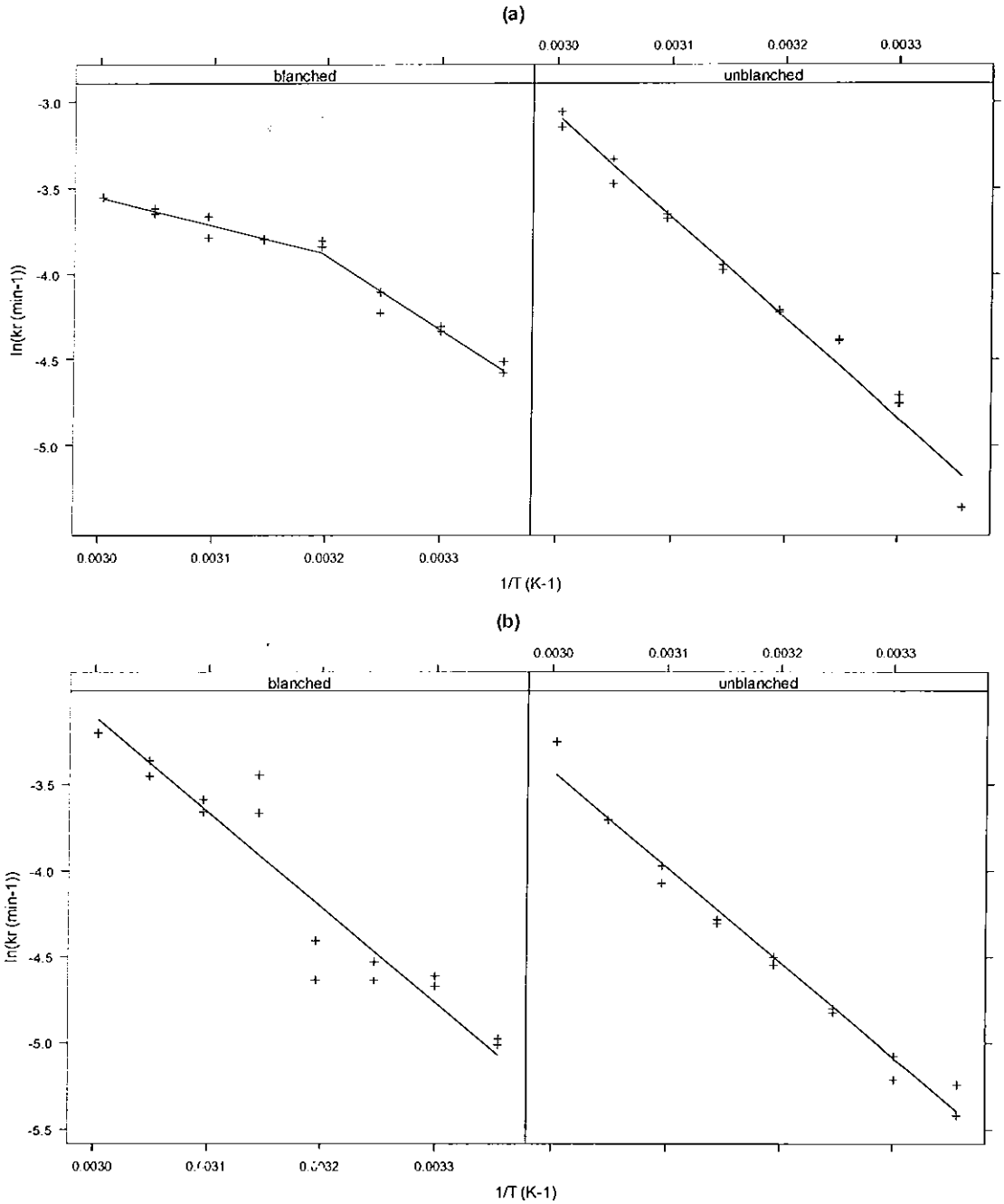


Fig. 4.3. Natural logarithm of hydration rate, k_h plotted against inverse of soak temperature (in Kelvins) for chickpea **(a)** and soybean **(b)** soaking.

Lines represent linear regression of $\ln(k_h)$ on T^{-1} ($r^2 > 0.99$) on data for unblanched chickpeas, unblanched soybeans and blanched soybeans, and linear regression of k_h on T^{-1} with break at 37 °C ($r^2 = 0.98$) for blanched chickpeas.

To confirm the validity of applying a linear model with a break to the blanched chickpea data, the following approach was taken. Firstly, a linear model without break was applied to the data ($r^2 = 0.92$), and then a linear model with a break at 37 °C was applied ($r^2 = 0.98$). The two models were compared using the log-likelihood ratio test, and the inclusion of the break was shown to significantly improve the model ($p < 10^{-4}$). This break in the kinetics may have been related to structural changes occuring in the sample, perhaps due to partial starch gelatinisation or protein denaturation within the cellular structure. In the case of soybeans, $\ln(k_h)$ decreased linearly with T^{-1} ($r^2 > 0.99$) for both unblanched and blanched samples (Fig. 4.3(b)). The slope of the Arrhenius curve for blanched soybeans appeared to be slightly flatter than that for unblanched soybeans. This indicated that changing the soak temperature has a greater effect on soaking for unblanched soybeans than for blanched ones.

4.3.2.3 General model to describe water intake as a function of pre-treatment, soak temperature and time

In the previous section, the effects of pre-blanching and increasing soak temperature on the parameters of the asymptotic model (Eq. 3.10) for the soaking of chickpeas and soybeans were examined. In the case of chickpeas, initial moisture content (M_0) was higher for blanched than for unblanched samples, asymptotic moisture content (M_e) decreased with increasing soak temperature for unblanched samples, while it remained constant for blanched samples and the hydration rate constant (k_h) demonstrated Arrhenius-type temperature dependence, with a break occurring at 37

°C for blanched samples. These features are encapsulated in the following model (Eq. 4.2).

$$M_i = M_{ei} + (M_{0i} - M_{ei})e^{-k_{ref\_h\_i}e^{\frac{-E_{a\_h\_i}}{R}\left(\frac{1}{T}-\frac{1}{T_{ref}}\right)}t} \; ; \; M_{e1} = M_{e1\_0} + cT \qquad ...(4.2)$$

Where i = 1, 2, 3 for unblanched, blanched and blanched (with $T \geq 37$ °C) chickpeas, respectively and c is a constant. To estimate the model parameters directly from the experimental data, a one-step non-linear regression (see section 3.11) of Eq. 4.2 was performed on the entire dataset for chickpea soaking (Table 4.3).

A reduced form of Eq. 4.2, which is Eq. 4.3, was proposed to describe the soaking kinetics of soybeans, which displayed Arrhenius-type temperature dependence of k_h, pre-treatment dependent M_o and M_e.

$$M_i = M_{ei} + (M_{0i} - M_{ei})e^{-k_{ref\_h\_i}e^{\frac{-E_{a\_h\_i}}{R}\left(\frac{1}{T}-\frac{1}{T_{ref}}\right)}t} \qquad ...(4.3)$$

Where i = either 1 or 2 for unblanched or blanched soybeans respectively. Model parameters were estimated by performing a one-step non-linear regression (see section 3.11) of Eq. 4.3 on the entire dataset (Table 4.3).

The rapid influx of water, experienced by both chickpeas and soybeans during blanching, was reflected in the higher estimated value of initial moisture content for blanched samples (Table 4.3). There was little difference between the activation energy (E_{a_h}) for unblanched chickpeas (42.45 ± 1.24 kJ.mol^{-1}) and that for blanched chickpeas soaked below 37 °C (41.79 ± 4.83 kJ.mol^{-1}). For blanched samples soaked above 37 °C, E_{a_h} was 8 kJ.mol $^{-1}$, representing more than 80% decrease in

activation energy. In the case of soybeans, E_{a_h} was 37.18 ± 1.57 kJ/mol for unblanched soybeans and was reduced by more than 37% to 23.16 ± 0.99 kJ/mol by blanching. The model parameters were significant with 95% confidence and the predictive curves arising from the models (see Fig. 4.2) adequately described the experimental data. The residual and quantile-quantile plots for the fitting of Eq. 4.2 and 4.3 to chickpea and soybean soaking data (respectively) are displayed in Fig. 4.4 and the residual points seem to be randomly distributed, with most residuals lying within 2 standard deviations.

Table 4.3. Estimated parameters for nonlinear regression of Eq. 4.2 and 4.3 on chickpea and soybean soaking data respectively. *All values significant ($p < 0.05$).*

Chickpeas (Eq. 5)			Soybeans (Eq. 6)		
Parameter (units)		Value ± SE	Parameter (units)		Value ± SE
M_{o1}	(% d.b.)	11.92 ± 0.99	M_{o1}	(% d.b.)	15.33 ± 1.60
M_{o2}	(% d.b.)	28.72 ± 1.77	M_{o2}	(% d.b.)	31.04 ± 0.97
M_{e1}	(% d.b.)	354.26 ± 15.52	M_{e1}	(% d.b.)	137.12 ± 1.75
M_{e2}	(% d.b.)	110.65 ± 0.58	M_{e2}	(% d.b.)	130.16 ± 1.08
$k_{ref\_h\_1}$	(min^{-1})	0.014 ± 0.001	k_{ref_1}	($x\ 10^{-2}\ min^{-1}$)	1.08 ± 0.04
$k_{ref\_h\_2}$	(min^{-1})	0.023 ± 0.001	k_{ref_2}	($x\ 10^{-2}\ min^{-1}$)	1.90 ± 0.06
$E_{a\_h\_1}$	(kJ/mol)	42.45 ± 1.24	E_{a_1}	(kJ/mol)	37.18 ± 1.57
$E_{a\_h\_2}$	(kJ/mol)	41.79 ± 4.83	E_{a_2}	(kJ/mol)	23.16 ± 0.99
$E_{a\_h\_3}$	(kJ/mol)	8.14 ± 3.27			
c	(K^{-1})	-0.77 ± 0.05			
RSE		4.5 on 460 dof	RSE		4.18 on 318 dof

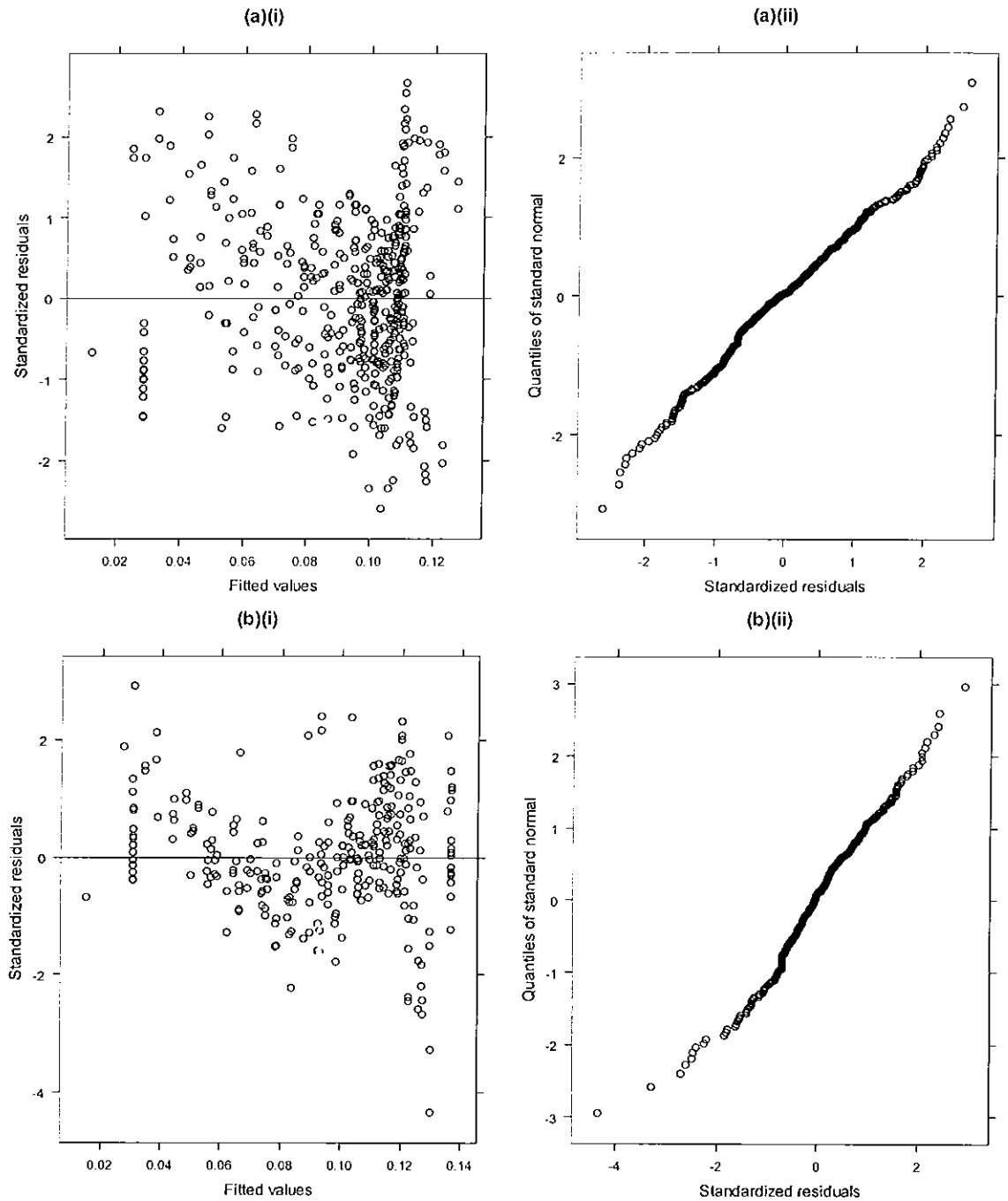


Fig. 4.4. Residual **(i)** and quantile – quantile **(ii)** plots for nonlinear regression of Eq. 4.2 & 4.3 on chickpea **(a)** and soybean **(b)** soaking data respectively.

4.3.3 Texture of chickpeas and soybeans during soaking

The general pattern of texture change during soaking can be observed in the curves of chickpea (Fig. 4.5a) and soybean (Fig. 4.5b) hardness (H) as a function of soak time and temperature. Although blanching caused initial soybean hardness to decrease (from 261 ± 31 N to 177 ± 22 N), no significant change in hardness was seen in the chickpea samples after blanching ($p > 0.1$). Average chickpea hardness actually increased upon blanching, from 346 ± 95 N to 358 ± 61 N, although this effect was insignificant.

As soaking time proceeded, the average hardness of both chickpeas and soybeans decreased, approaching a constant value corresponding to the asymptotic attainment of equilibrium hardness. The average value for equilibrium hardness was 38 ± 6 N for chickpeas, and 29 ± 4 N for soybeans. The soak time required to reach equilibrium hardness was dependent on both soak temperature and blanching pre-treatment.

Variability of hardness was large among samples, especially at early stages of hydration. This reflects the natural variability inherent in the dry bean sample and in its soaking and softening properties. As soaking proceeded, water was absorbed, resulting in a more uniform texture, and the variability between beans tested consequently decreased. Such a pattern of decreasing variability as soak time proceeded (see Fig. 4.5) was observed for all soaking temperatures studied.

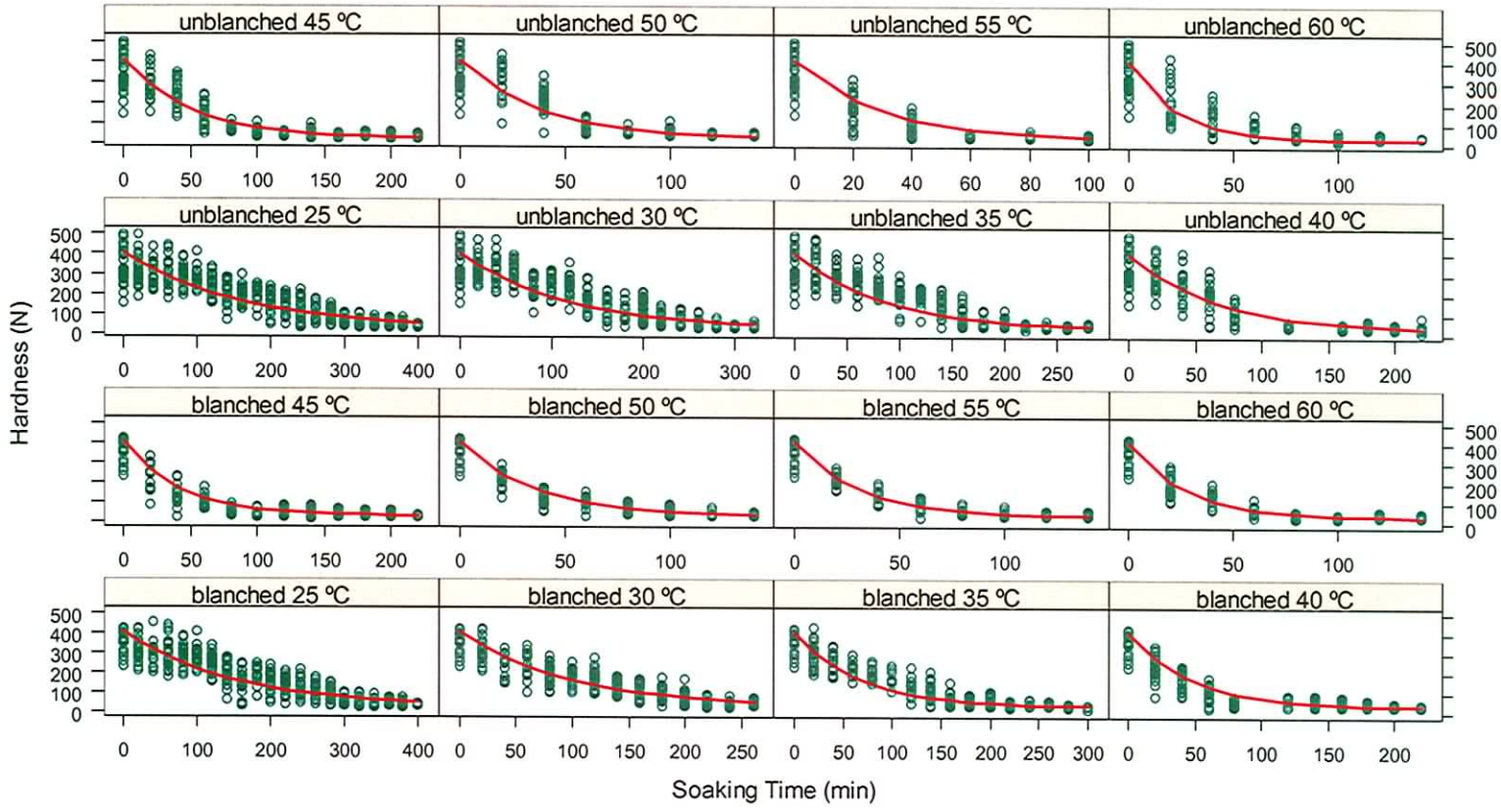


Fig. 4.5. (a) Chickpea hardness as a function of pre-treatment, soak temperature and time.

Solid lines represent predictive curves for nonlinear regression of Eq. 4.6 on chickpea texture data.

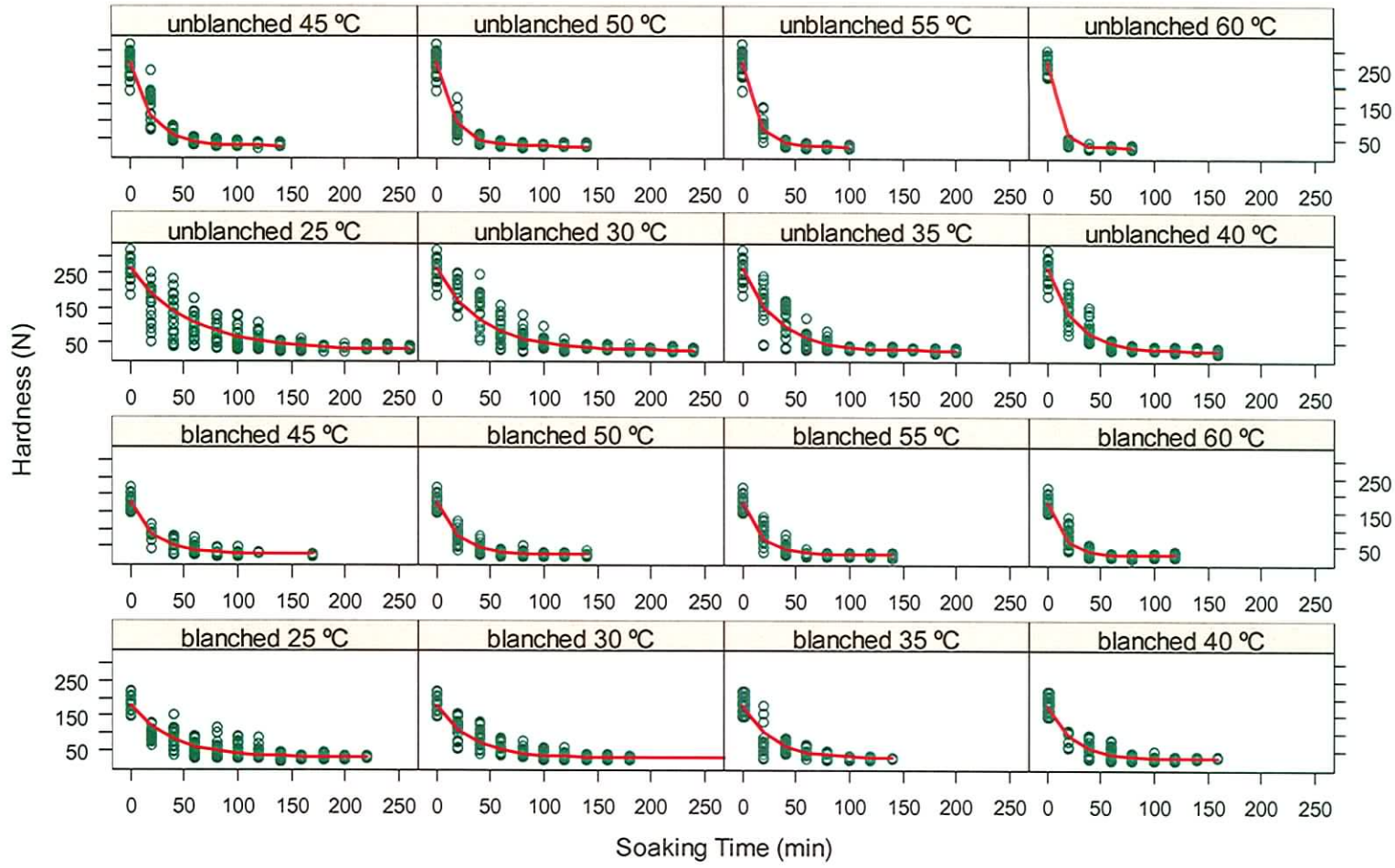


Fig. 4.5(b) Soybean hardness as a function of pre-treatment, soak temperature and time.

Solid lines represent predictive curves for nonlinear regression of Eq. 4.7 on soybean texture data respectively.

4.3.3.1 Primary modelling of chickpea and soybean hardness as a function of soaking time

Both chickpea and soybean hardness (H) decreased from initial hardness (H_0) towards an asymptotic equilibrium value (H_e) during soaking and the general shape of the textural degradation curves (Fig. 4.5) resembled the inverse shape of the soaking curves (Fig. 4.2). Therefore, for symmetry and simplicity, the following primary model, in which k_F represents the rate of chickpea or soybean softening, was chosen for application to the data to describe the decrease of both chickpea and soybean hardness as a function of soaking time.

$$H = H_e + (H_0 - H_e)e^{-k_F t} \qquad \ldots(4.4)$$

Initially, non-linear regression of Eq. 4.4 was performed on the texture data, for each temperature/pre-treatment combination (see section 3.11). Residual curves for the primary regression of Eq. 4 4 on the chickpea and soybean data (Fig. 4.6) displayed heteroscadastic fanning-out of the residuals. This indicated that variance was high at large values of hardness, reflecting the high variability of the dry sample. During the soaking process, as the chickpea texture became more uniform, intra-bean variability consequently decreased: this is also evidenced in Fig. 4.5.

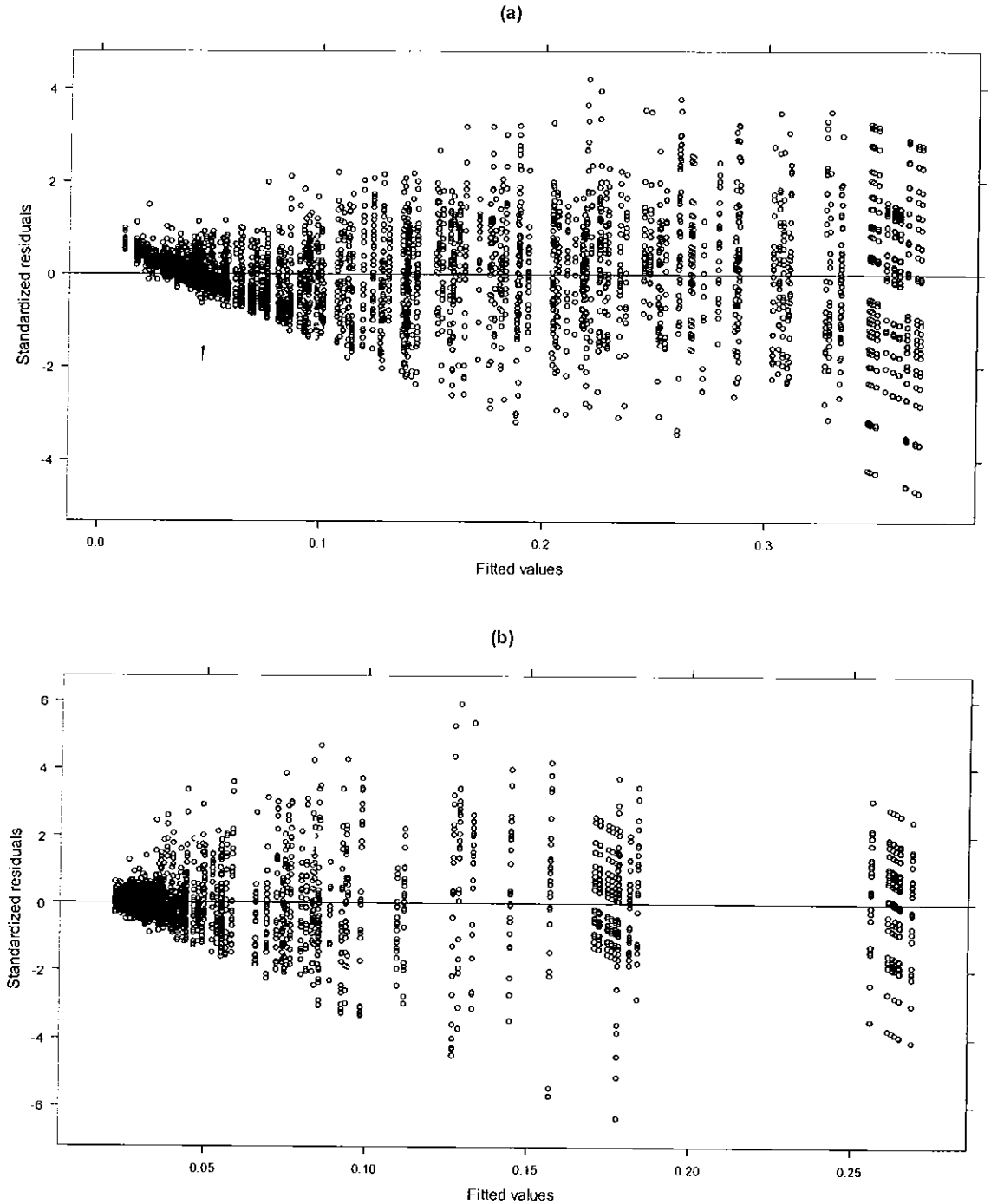


Fig. 4.6. Residual plots for primary regression of asymptotic model (Eq. 4.4) regressed on chickpea **(a)** and soybean **(b)** texture data.

With the aim of building a general model to describe chickpea and soybean hardness as a function of soaking time, temperature and pre-treatment, the estimated model parameters were investigated. The predicted values for asymptotic hardness, H_e, were fairly constant for both chickpeas and soybeans over the range of experimental conditions studied. The predicted values for initial hardness, H_0, were constant for both unblanched and blanched chickpeas. However, H_0 was statistically ($p < 0.05$) larger for unblanched soybeans than for blanched soybeans. In general, both blanching and increasing the soak temperature caused an increase in the rate of softening (k_F). Blanching caused the greatest increase in k_F when followed by soaking at 40 °C for chickpeas, and 35 °C for soybeans (Table 4.4), which was in agreement with the effect of blanching on the soaking kinetics.

Table 4.4. Texture degradation rate constant (k_F) for soaking within 25 – 60 °C.

	Chickpeas k_F. ($x10^3$ min^{-1})		Soybeans k_F. ($x10^3$ min^{-1})	
T (°C)	Unblanched	Blanched	Unblanched	Blanched
25	1.5 ± 0.4	2.1 ± 0.4	21.6 ± 0.9	29.3 ± 2.0
30	2.2 ± 0.5	5.4 ± 0.8	21.4 ± 0.8	27.5 ± 2.0
35	4.4 ± 0.6	8.6 ± 0.8	29.7 ± 1.2	49.5 ± 4.2
40	11.7 ± 1.1	25.1 ± 1.8	34.9 ± 1.5	41.6 ± 3.5
45	17.2 ± 1.3	28.2 ± 2.2	40.6 ± 1.9	43.5 ± 4.1
50	16 ± 1.8	29 ± 2.5	75.3 ± 4.2	50.3 ± 3.7
55	41.8 ± 4.1	28.2 ± 2.6	73.2 ± 4.6	46.3 ± 3.5
60	24.6 ± 2.8	31.7 ± 2.8	141.3 ± 22.2	53.2 ± 4

The dependence of k_F on temperature was fitted to the Arrhenius equation (Eq. 4.5):

$$k_F = k_{ref\_F} e^{\left(\frac{-E_{a\_F}}{R}\left(\frac{1}{T}-\frac{1}{T_{ref}}\right)\right)} \quad \ldots(4.5)$$

Where k_{ref_F} is the reference hydration rate constant, T and T_{ref} are the soaking and reference temperatures (in Kelvin) respectively, E_{a_F} is the activation energy for the softening process and R is the gas constant (8.314 $x10^{-3}$ kJ/mol.K). In order to minimise the co-linearity of k_{ref_F} and E_{a_F}, T_{ref} was chosen as 40 °C, the average experimental soaking temperature (Haralampu *et al.*, 1985).

The slope of the Arrhenius (i.e. $\ln(k_F)$ vs. 1/T) curve is related to the activation energy E_{a_F}, for the process of bean softening (Fig. 4.7). Unblanched chickpeas displayed an approximately linear Arrhenius curve (r^2 = 0.84). However, for blanched chickpeas, a break in the Arrhenius curve was apparent, similar to that observed in the soaking kinetics, after which the slope, or activation energy, changed.

In order to find where this break occurred, the natural log of k_F was fitted to a linear model with break point (Muggeo, 2003), and the break temperature was estimated to be 38 ± 1 °C ($r^2 > 0.95$). This is in agreement with the break temperature estimated for the water intake kinetics (37 ± 1 °C). Therefore, the change in chickpea water intake kinetics for blanched chickpeas was related to a change in the texture, as has been suggested in previously published data (Sayar *et al.*, 2001).

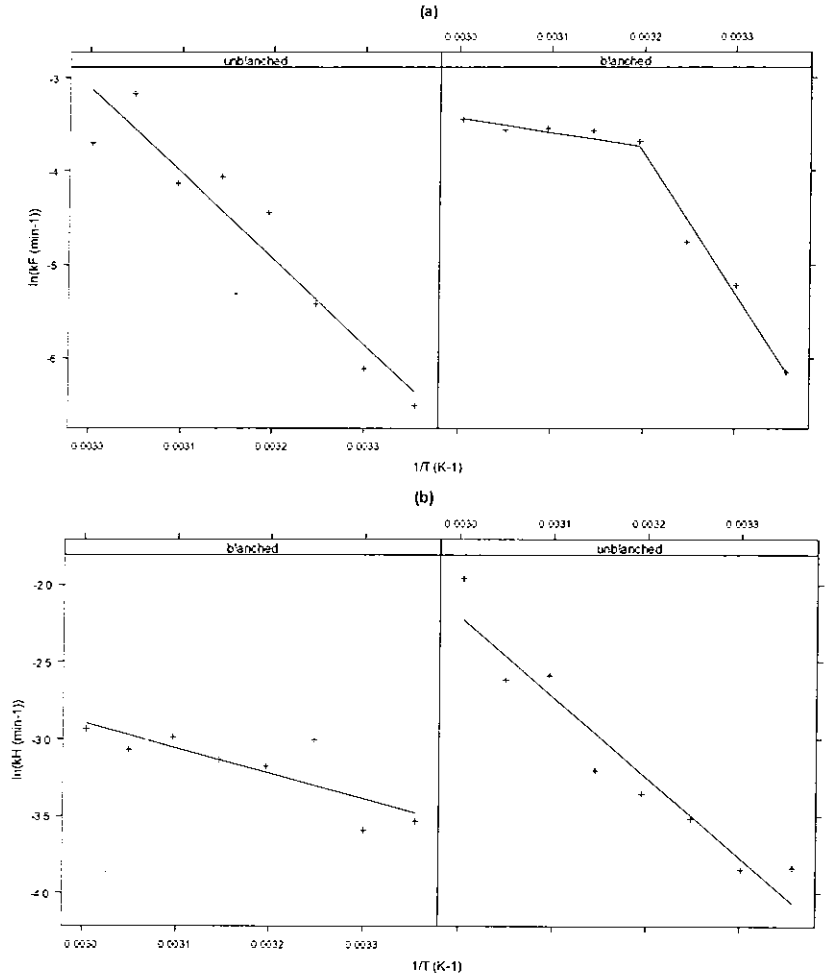


Fig. 4.7. Arrhenius plot for texture degradation rate constant, k_F, for chickpeas **(a)** and soybeans **(b)** over the temperature range 25 – 60 °C.

Lines represent linear regression of $ln(k_F)$ on T^{-1} ($r^2 > 0.99$) for unblanched chickpeas, unblanched soybeans and blanched soybeans, and linear model with break at 38 °C ($r^2 = 0.98$) for blanched chickpeas

To confirm the validity of applying a linear model with a break to the blanched chickpea texture data, a method similar to that in section 4.3.2 was applied. Firstly, a linear model without break was applied to the blanched chickpea texture data (r^2 = 0.78), and then a linear model with a break at 38 °C was applied (r^2 = 0.98). The two

models were compared using the log-likelihood ratio test and inclusion of the break was shown to significantly improve the model ($p < 0.05$). In the case of soybeans, the natural logarithm of the estimated value of k increased linearly with the inverse of soaking temperature for both unblanched and blanched samples ($r^2 > 0.99$).

4.3.3.2 General model to describe chickpea and soybean hardness as a function of pre-treatment, soak temperature and time

In the previous section, the effect of pre-blanching and soak temperature on the parameters of the asymptotic model (Eq. 4.4) for the hardness of chickpeas and soybeans during soaking were examined. In the case of chickpeas, initial hardness (H_0) was the same for blanched as for unblanched samples, asymptotic hardness (H_e) was constant, and the softening rate constant (k_F) demonstrated Arrhenius-type temperature dependence, with a break occurring at 38 °C for blanched samples. These features are encapsulated in Eq. 4.6, in which a power variance error term, ε, was included to account for the heteroscadastic behaviour displayed by sample hardness during soaking (Fig. 4.6).

$$H_{ij} = H_e + (H_{oi} - H_e)e^{-k_{ref\_F\_i}e^{\frac{-E_{a\_F\_i}}{R}\left(\frac{1}{T}-\frac{1}{T_{ref}}\right)}t} + \varepsilon_j \;,\; \varepsilon_j \sim N(0, \sigma_{ij}{}^2 H_i{}^{2\delta}) \qquad ...(4.6)$$

Where i = 1, 2, 3 for unblanched, blanched (T < 38 °C) and blanched (T ≥ 38 °C). A slight modification of Eq. 4.6, results in Eq. 4.7, which was proposed to describe the soaking kinetics of soybeans, incorporating the Arrhenius temperature dependence of k_F, constant H_e and pre-treatment dependence of H_0.

$$H_{ij} = H_e + (H_{oi} - H_e)e^{-k_{ref\_F\_i}e^{\frac{-E_{a\_F\_i}}{R}\left(\frac{1}{T}-\frac{1}{T_{ref}}\right)}t} + \varepsilon_j \;,\; \varepsilon_j \sim N(0, \sigma_{ij}{}^2 H_i{}^{2\delta}) \qquad ...(4.7)$$

Where i = 1, 2 for unblanched, blanched soybeans respectively, and $j \in [1, n]$, where n represents the experimental data points.

To estimate the model parameters, one-step non-linear regressions (see section 3.11) of Eq. 4.6 & 4.7 were performed on the entire dataset for chickpea and soybeans (Table 4.5). Activation energy for the softening process during soaking (E_{a_F}) was estimated to be 46 kJ mol $^{-1}$ for unblanched chickpeas, increasing to 54 kJ mol $^{-1}$ for blanched chickpeas soaked at temperatures below 38 °C. For blanched chickpeas soaked at temperatures above 38 °C, E_{a_F} decreased to 24 kJ mol $^{-1}$, representing nearly a 50% drop in temperature dependence. E_{a_F} for unblanched soybeans was 38.98 ± 0.76 kJ mol $^{-1}$ and decreased to 23.11 ± 0.03 after blanching, representing greater than 40% drop in temperature dependence.

Table 4.5. Estimated parameters for nonlinear regression of Eq. 4.6 and 4.7 on chickpea and soybean texture data respectively. All values significant ($p < 0.05$).

Chickpea					Soybean			
Parameter	(units)	Value	±	Std. Error	Parameter	(units)	Value	± Std. Error
H_o	(kN)	0.393	±	0.004	H_{o_1}	(kN)	0.264	± 0.003
H_c	(kN)	0.029	±	0.001	H_{o_1}	(kN)	0.180	± 0.003
$k_{ref\_F\_1}$	(min^{-1})	0.016	±	0.004	H_c	(kN)	0.0280	± 0.0002
$k_{ref\_F\_2}$	(min^{-1})	0.019	±	0.005	$k_{ref\_F\_1}$	(min^{-1})	0.041	± 0.006
$E_{a\_F\_1}$	(kJ/mol)	46.04	±	0.66	$k_{ref\_F\_2}$	(min^{-1})	0.040	± 0.005
$E_{a\_F\_2}$	(kJ/mol)	53.49	±	1.39	$E_{a\_F\_1}$	(kJ/mol)	38.98	± 0.76
$E_{a\_F\_3}$	(kJ/mol)	24.04	±	2.95	$E_{a\_F\_2}$	(kJ/mol)	23.11	± 0.03

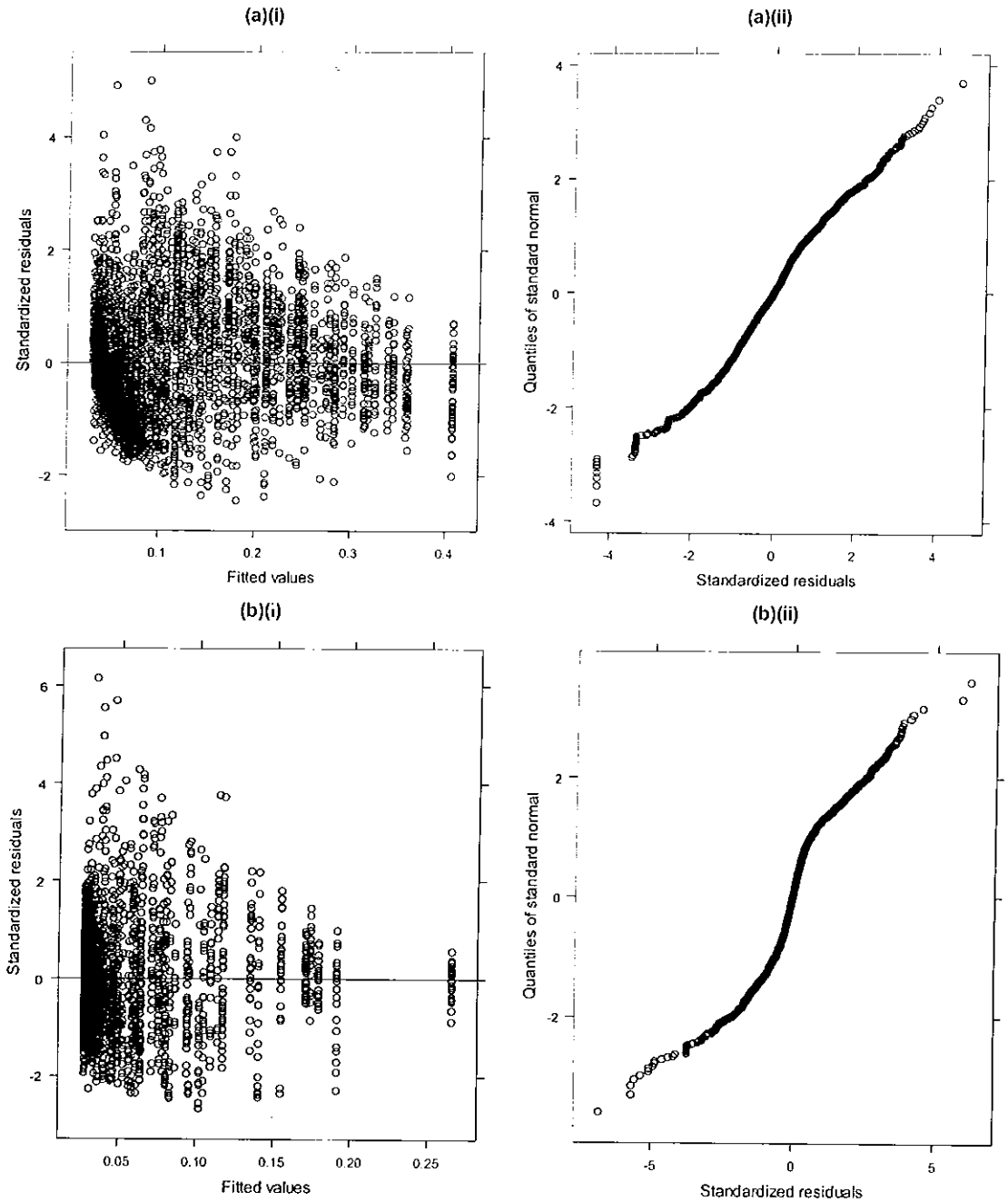


Fig. 4.8. Residual **(i)** and quantile – quantile **(ii)** plots for nonlinear regression of Eq. 4.6 & 4.7 on chickpea **(a)** and soybean **(b)** texture data respectively.

The model parameters were significant with 95% confidence and the predictive curves arising from the general model (see Fig. 4.5) adequately described the

experimental data. The residual and quantile-quantile plots for the general model regressed on the data are displayed in Fig. 4.8 and the residual points seem to be randomly distributed, with most residuals lying within 2 standard deviations. The quantile-quantile plot was close to linear, indicating reasonable model fit.

4.3.3.3 Effect of blanching on predicted time taken to reach equilibrium hardness

4.3.3.3.1 Average calculation

By rearranging Eq. 4.6 and 4.7, the average soaking time required to reach any particular value of hardness can be predicted. The average experimental equilibrium value of hardness was 38 ± 6 N for chickpeas and 29 ± 4 N for soybeans. The average soak time taken to reach these equilibrium values was predicted for both unblanched and blanched chickpeas and soybeans (Table 4.6). In Fig. 4.9, the predicted average time difference between unblanched and blanched chickpeas and soybeans to reach texture equilibrium is plotted over the range of temperatures studied. The model predicted that the effect of blanching was greatest for chickpeas near the break point at 40 °C, where the application of a pre-blanching step reduced the average soaking time required by just over 35 min, from 231 (for unblanched chickpeas) to 195 min (for blanched chickpeas). For soybeans soaked at 35 °C, average soak time was reduced by 25 min, from 170 to 145 min. Blanching was not beneficial (in terms of time to reach equilibrium texture) for soaking at temperatures above 50 °C, as was also observed for the process of water absorption.

Table 4.6. Average predicted soaking time (min) required to reach equilibrium hardness for chickpeas (38 N) and soybeans (29 N).

	Chickpeas		Soybeans	
Temperature (°C)	unblanched	blanched	unblanched	blanched
25	564	549	284	197
30	415	384	219	168
35	308	272	170	145
40	231	195	133	126
45	175	168	105	109
50	134	146	84	95
55	103	128	67	84
60	80	112	54	74

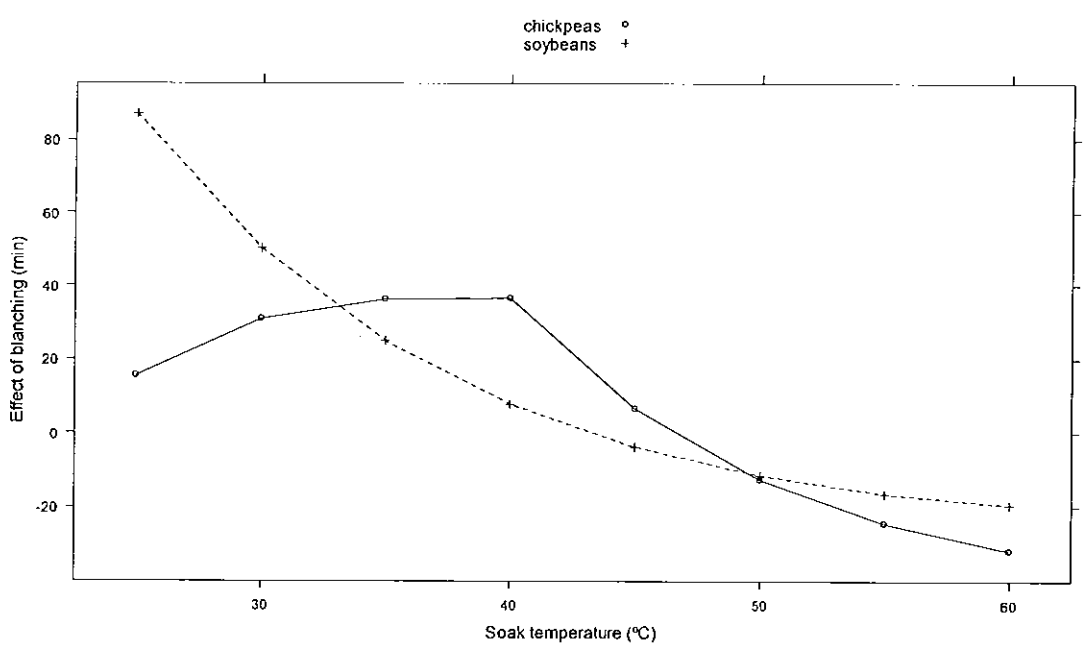


Fig. 4.9. Benefit of blanching in terms of soaking time required to reach equilibrium hardness for chickpeas and soybeans.

4.3.3.3.2 Stochastic calculation

As can be seen from the experimental texture data, the variability associated with this process is important enough to influence the kinetics. In order to define operating conditions and to assess the influence of product texture variability, an uncertainty analysis of the texture during soaking was performed (Vose, 2002). Assuming normally distributed model parameters (Eq. 4.6 & 4.7, Table 4.5) and including the uncertainty power variance function in the model error term, a bootstrap simulation of soaking time required to reach any particular hardness was performed (Davidson & Hinckley, 1997).

The simulation was performed on a grid of 10 temperatures by 10 forces by 2 pre-treatments in the experimental range considered (25-60 °C, 38-100 N for blanched and unblanched chickpeas; 29 – 100 N for blanched and unblanched soybeans, 999 simulations). A conservative prediction envelope for the maximum soaking time ($p < 0.05$) was estimated from the quantiles of the simulated soaking time distributions resulting for each individual temperature, forecasted final force and pre-treatment point in the simulation grid.

Figure 4.10(a) displays the 5% quantile, which represents the amount of time required to ensure that at least 95% of given batch of chickpeas has reached a certain level of texture during soaking within the range of temperatures studied. The benefit of blanching is evident from the contour plot (Fig. 4.10(a)). For example, when soaking at 40 °C, the time required for a given batch of chickpeas to reach a final

hardness of 38 N (Fig. 4.10(a)) was 210 min, compared to 250 min for unblanched chickpeas. Compared to the predicted average time to reach 38 N (see previous section), an extra 15-20 min soaking time would be required for 95% of chickpeas in a given batch to reach equilibrium hardness.

Similarly, the time required for a given batch of soybeans (Fig. 4.10(b)) to reach a final hardness of 29 N, when soaked at 35 °C, was predicted to be 195 min for unblanched samples, while it was just 160 min for blanched samples. Compared to the average prediction (see previous section), an extra 15-25 min soaking is required for 95% of soybeans in a given batch to reach equilibrium levels of hardness.

The stochastic calculation shows that the addition of a pre-blanching step can reduce soak time by 35 min for soybeans (when followed by soaking at 35 °C), and can reduce chickpea soaking time by 40 min (when followed by soaking at 40 °C), but still ensuring that most of the batch will achieve a uniform level of texture, while this level of texture would not be achieved if soaking had not been preceded by a blanching step.

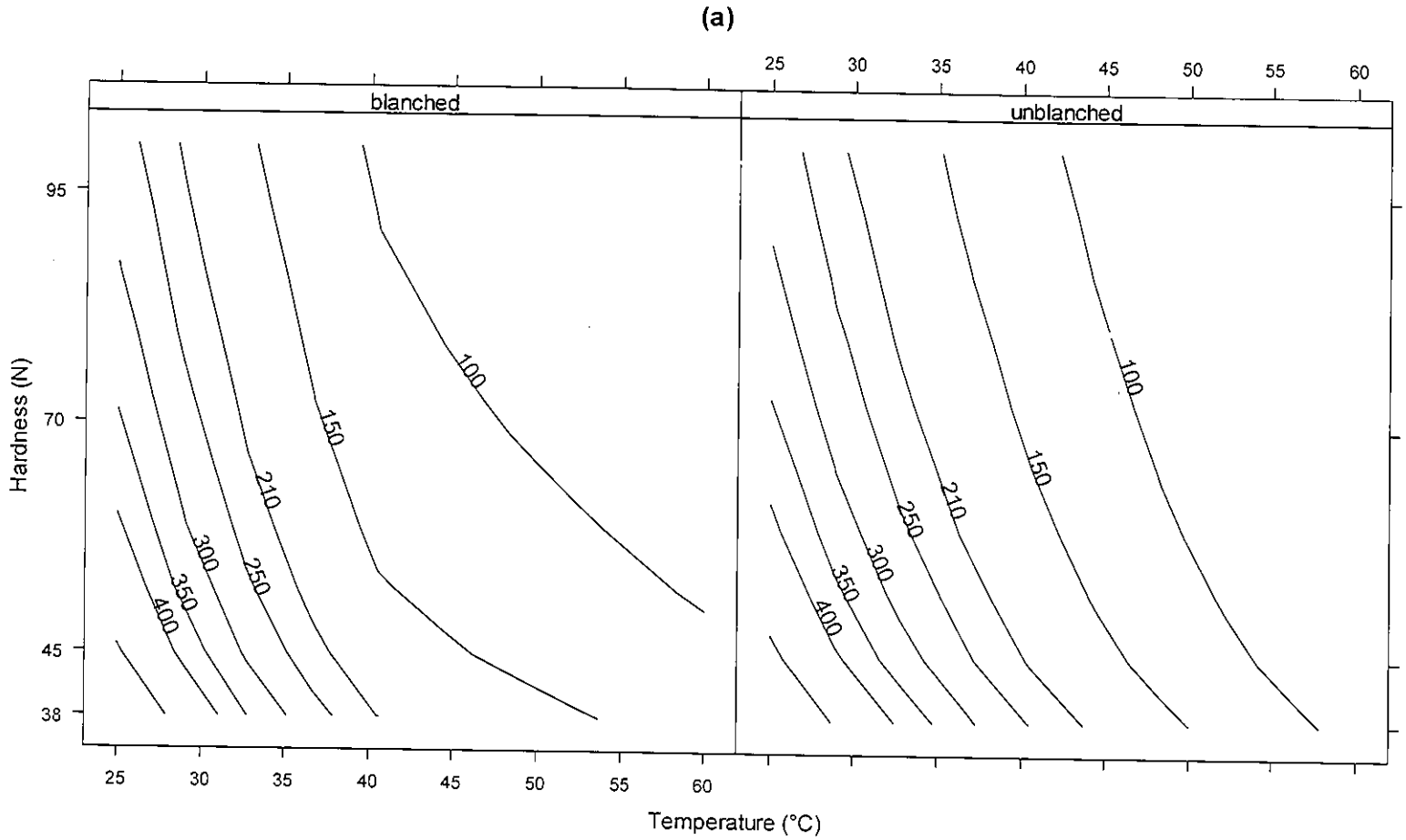


Fig. 4.10.(a) Contour plot of the soaking time needed to ensure (with a 95% confidence) that a batch of chickpeas will be processed up to a certain texture for the range of soaking temperatures studied.

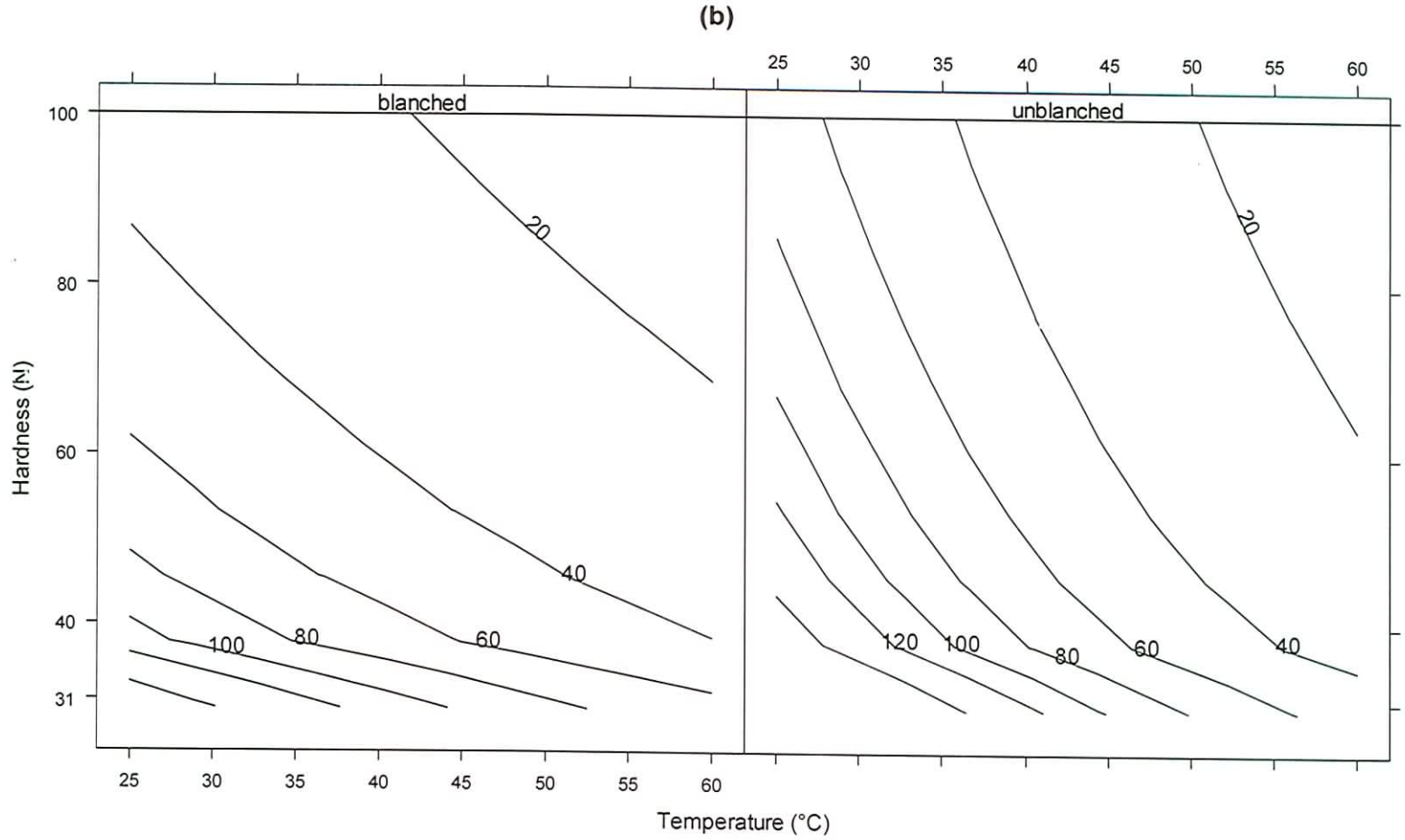


Fig. 4.10.(b) Contour plot of the soaking time needed to ensure (with a 95% confidence) that a batch of soybeans will be processed up to a certain texture for the range of soaking temperatures studied.

4.3.3.4 Water intake level corresponding to equilibrium hardness

For blanched chickpeas, the water intake corresponding to 210 min soaking, predicted from Eq. 4.2 is 110 (% d.b.), which is not significantly different from the asymptotic water intake level for blanched chickpeas (=110.65 ± 0.58 (% d.b.); see Table 4.3). This indicates that chickpeas need to be soaked to equilibrium water intake level to reach equilibrium level of hardness. For blanched soybeans, the water intake corresponding to 160 min soaking is 123 (% d.b.), which is significantly lower than the asymptotic water intake level for blanched soybeans (=130.16 ± 1.08 (% d.b.); Table 4.3). This indicates that soybeans reach texture equilibrium prior to reaching the constant phase of water intake. Similar findings were reported by Abu-Ghannam & McKenna (1997a), who found that kidneybeans enter a state of equilibrium texture prior to the attainment of equilibrium water absorption. Furthermore, the 123 % d.b. level of water intake is very close to the level (120 % d.b) to which soybeans should be soaked to before further processing, for optimal texture, as recommended by Pan & Tangratanavalee (2003).

4.4 Conclusions

Blanching is conventionally applied to legumes after soaking. However, the results show that it would be beneficial to apply blanching prior to soaking. Pre-blanching at 100 ^{o}C for 1.5 min significantly reduced initial microbial counts on dry chickpeas and soybeans. This would decrease the risk of further microbial proliferation during the soaking process. Application of blanching prior to soaking enhanced rates of water absorption, and therefore decreased the time required to reach textural

equilibrium, for the soaking of chickpeas and soybeans at temperatures under 50 °C. Asymptotic models were used to describe the processes of water intake and texture change as a function of soak time, temperature and blanching pre-treatment for blanched and unblanched samples. A change in the water absorption dynamics of chickpeas was reflected in the texture: activation energies for both the water intake and texture degradation processes in blanched chickpeas were found to change at around 37.5 °C, when a break in the Arrhenius curves occurred. After the break temperature (37.5 ± 1.5 °C) was reached, the Arrhenius curves for both water absorption and texture kinetics of blanched chickpeas became flatter, corresponding to a decrease in the activation energy. Essentially, this means that increasing soak temperature above 37 °C for blanched chickpeas resulted in less significant changes in water absorption kinetics when compared to unblanched samples. Since the temperature dependence of k (rate constant) was stronger for unblanched samples than for blanched samples above 37 °C, there existed a point (50 °C) after which blanching was ineffective, actually resulting in a decrease in chickpea hydration rates. Similarly, for soybeans, the temperature dependence of k, reflected in the activation energy, was stronger for unblanched samples than for blanched ones, and soaking above 50 °C was ineffective. Stochastic simulations of soaking time showed that soak time should be lengthened so that 95% of a given batch of chickpeas or soybeans would attain a certain texture. Simulations such as these can be used to establish processing conditions required in industry, taking in account the variability and effectively assessing the risk of finding hard chickpeas or soybeans after the soaking process.

CHAPTER 5

COOKING OF PRE-SOAKED CHICKPEAS AND SOYBEANS

Effect of boiling and microwave cooking treatments on sample hardness and sensory quality

Some of the results from this chapter were presented at 'Foodchain 2004' International Food Conference, University College Dublin, Ireland (see pages 289-292)

Summary

Texture of pre-soaked chickpeas and soybeans during cooking was investigated for two cooking modes: boiling only and boiling followed by microwave treatment. Sample hardness was measured at regular time intervals during boiling (20, 40, 60 min) and microwave (0, 5, 10 min) treatments. Bean hardness decreased as boil time was increased. Hardness also decreased during the first 5 min microwave treatment. The cooking treatment resulting in the softest bean samples was 60 min boiling followed by 5 min microwave cooking. A sensory trial was designed, in which panellists were asked to judge the appearance, texture and liking of samples for a selection of different cooking treatments. The sensory score for chickpea texture correlated well with instrumental hardness. The addition of 5 min microwave treatment after 60 min boil had no significant effect on panellist response ($p > 0.05$). Based on average panellist response, the optimal cooking treatment was estimated to be 60 min boiling.

5.1 Introduction

Cooking is an essential step in legume processing, which involves hydrothermal deactivation of anti-nutritional factors within the bean (Rehman & Shah, 2005). During cooking, legume digestibility is improved via starch gelatinisation and protein denaturing reactions, which also tenderise the legume, making it edible. The amount of boiling time required to cook legumes typically ranges from 50 min to 3 h (Sabapathy, 2005; Kabbara *et al.*, 1987; Williams *et al.*, 1983). Microwave cooking has been associated with shorter cooking times (Marconi *et al.*, 2000) and reduced leaching of nutritional components (El-Adawy, 2002) in legumes.

In the present study, the possibility of reducing the cooking time of legumes, by application of a microwave step, was investigated. Preliminary results showed that microwave cooking alone was not sufficient for cooking soaked legumes. A pre-boiling step was required before microwave treatment to ensure acceptable texture. Consequently, this study comprised an investigation into the effects of applying microwave cooking after boiling, compared to boiling alone, to pre-soaked chickpeas and soybeans. Therefore, the aims of the research described in this chapter were as follows:

1. Investigate effect of boiling treatment on sample texture
2. Investigate effect of adding microwave treatment after boiling on sample texture
3. Optimise cooking conditions with regard to instrumental and sensory quality.

5.2 Materials and methods

5.2.1 Soaking

Raw material is described in section 3.1. 20 g legume samples were soaked to equilibrium water intake levels, by immersion in tap water (pH: 7.5 ± 0.2) heated to the required temperature, in a thermostatically controlled water bath. Based on analysis of water intake data (see Ch. 4), chickpeas were pre-blanched (see section 3.2) and then soaked for 240 min at 40 °C; soybeans were pre-blanched (see section 3.2) and then soaked at 35 °C for 200 min.

5.2.2 Cooking

After soaking, 20 g samples were cooked by immersion in 1l boiling tap water for 20, 40 and 60 min, followed by microwave treatment at full power (750W) in 300ml tap water for 0, 5, and 10 min. All experiments were performed in triplicate, following a fully randomised experimental design (Fig. 5.1).

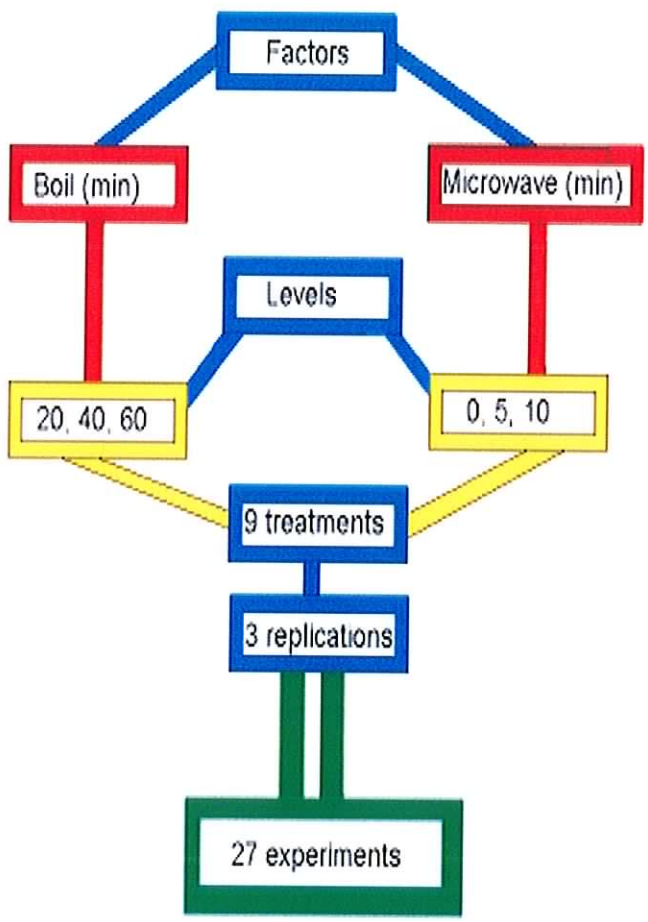


Fig. 5.1. Experimental design for cooking experiments.

5.2.3 Texture measurement

Texture of 25 samples at each sampling point during cooking was evaluated as described in section 3.3.

5.2.4 Sensory evaluation

Optimal cooking treatment (in terms of instrumental texture: see section 5.3.1) was estimated from preliminary cooking experiments to be 60 min boil time followed by 5 min microwave time. To investigate the sensory attributes of cooked samples, a sensory trial was constructed to include the optimal treatment (Fig. 5.2). Five cooking treatments (numbered 1-5 on Fig. 5.2) were investigated. A tasting panel of 6 people was recruited. *Compusense 5* software for sensory analysis was employed in the sensory study.

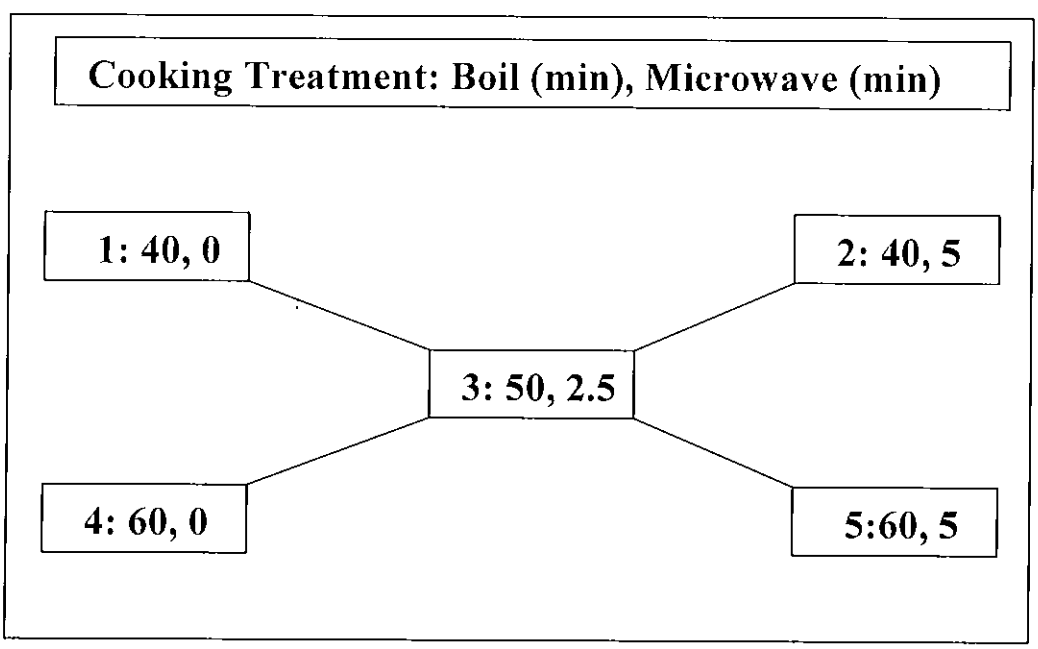


Fig. 5.2. Experimental design for sensory trial.

Based on the recommendations of Cloninger and co-workers (1976), a five point hedonic scale was employed in this study. Members of the tasting panel were asked to evaluate the cooked samples in terms of appearance (1 = Highly unacceptable, 5 = Highly acceptable), texture (1 = Too soft, 5 = Too hard) and

liking (1 = Dislike extremely, 5=Like extremely). Further details of the sensory trial are presented in Appendix A.

5.3 Results and discussion

5.3.1 Effect of boiling & microwave cooking treatments on hardness of pre-soaked chickpeas and soybeans

Average chickpea hardness (Fig. 5.3(a)) decreased significantly as boiling time increased ($p < 0.05$). Chickpea hardness demonstrated quadratic dependence on microwave cooking time: average chickpea hardness decreased significantly ($p < 0.05$) during the first 5 min of microwave treatment and increased significantly ($p < 0.05$) between 5 - 10 min microwave cooking treatment (Fig. 5.4(a)). The increase in chickpea hardness after 10 min microwaving may be related to the observation that some samples floated to the water surface step after 10 min: this may have caused them to dry out and become harder.

Microwave treatment after boiling could reduce cooking time required for chickpeas to reach a given level of softness. For example, chickpeas boiled for 20 min followed by 5 min microwave treatment achieved an average hardness of 25 ± 2 N, equivalent to that achieved by chickpeas boiled for 40 min (25 ± 2 N); chickpeas boiled for 40 min followed by 5 min microwave treatment achieved an average hardness value of 22 ± 1 N, equivalent to that achieved by chickpeas boiled for 60 min (22 ± 2 N). A multiple order regression model (Eq. 5.1) was determined ($r^2 = 0.77$) to predict chickpea hardness as a function of boil time (t_B) and microwave time (t_{MW}).

$$H = 31.6 - 0.2t_B - 1.3t_{MW} + 0.1t_{MW}^2 \quad \ldots(5.1)$$

Predictive plots were generated from Eq. 5.1 and fitted the data adequately (Fig. 5.3(a) & Fig. 5.4(a)). From the plots of chickpea hardness during cooking (Fig. 5.3(a) & Fig. 5.4(a)) it is clear that the softest texture was achieved for chickpeas boiled for 60 min, followed by 5 min microwave cooking.

Soybean hardness decreased significantly ($p < 0.05$) as boiling time was increased (Fig. 5.3(b)). During the first five minutes of microwave cooking treatment, average hardness decreased significantly ($p < 0.05$) (Fig. 5.4(b)). There was no significant change in soybean hardness ($p > 0.05$) between 5 and 10 min microwave treatment, except in the case of soybeans that had been pre-boiled for 20 min, for which average hardness decreased significantly ($p < 0.05$) during the 10 minutes of microwave treatment (Fig. 5.4(b)).

The addition of a microwave step after boiling could reduce cooking time required for soybeans. For example, soybeans that were boiled for 20 min followed by 10 min microwave treatment achieved an average hardness value of 15 ± 2 N, equivalent to that achieved by soybeans after 40 min boiling (16 ± 1 N); soybeans that were boiled for 40 min followed by 5 min microwave treatment achieved an average hardness value of 14 ± 2 N, equivalent to the hardness of soybeans that were boiled for 60 min boiling (13 ± 1 N). A multiple order regression model (Eq. 5.2) was determined ($r^2 = 0.91$) to predict soybean hardness as a function of boil time (t_B) and microwave time (t_{MW}).

$$H = 32.9 - 0.58t_B + 0.004t_B^2 - 0.99t_{MW} + 0.016t_{MW}t_B \quad \ldots(5.2)$$

Predictive plots generated from Eq. 5.2 fitted the data adequately (Fig. 5.3(b) & 5.4(b)). From the plots of soybean hardness against cooking treatment (Figs. 5.3(b) & 5.4(b)) it is clear that the softest texture for soybeans was achieved after 60 min boiling, followed by 5 min microwave cooking, as was also observed for chickpeas.

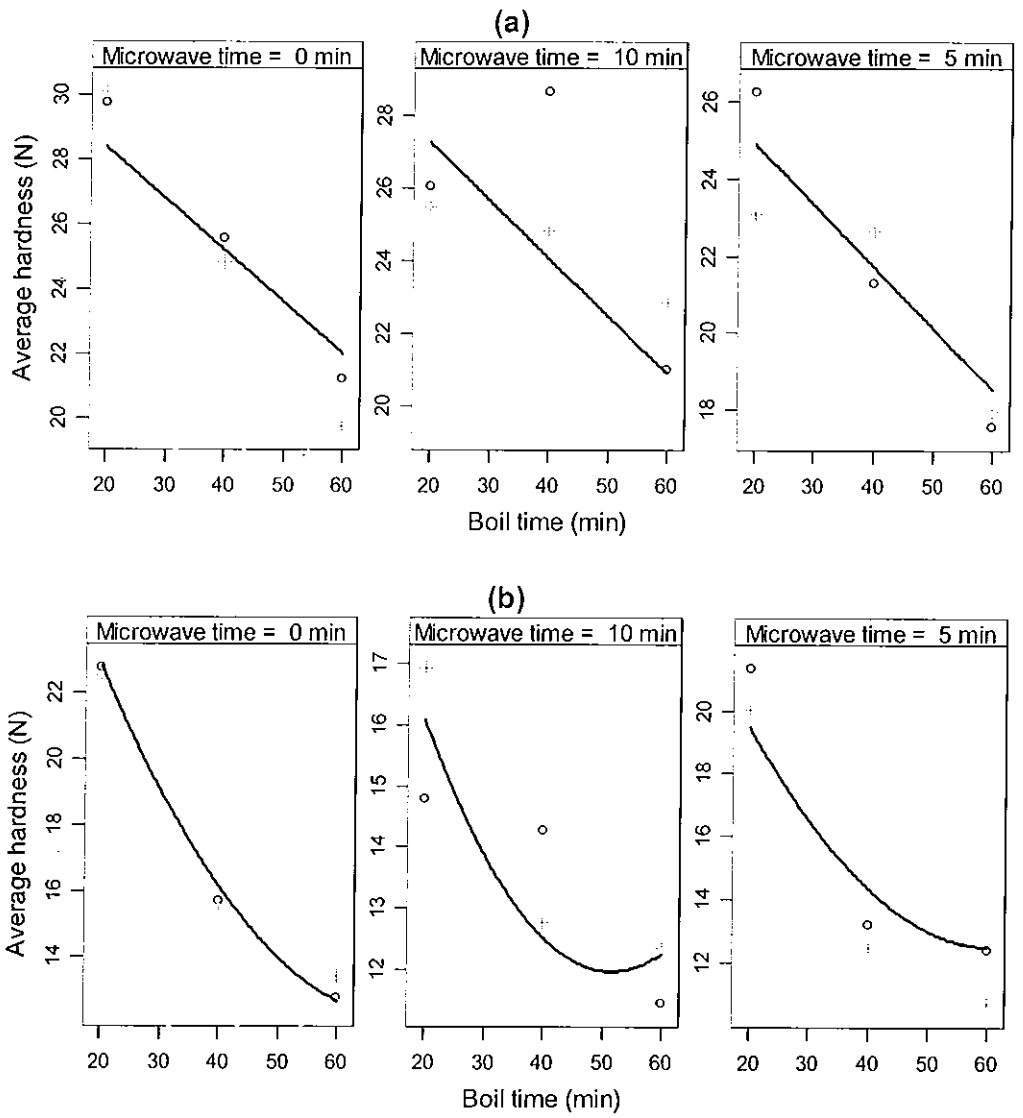


Fig. 5.3. Average hardness (N) of chickpeas **(a)** and soybeans **(b)** as a function of boiling time.

Solid lines represent predictive plots generated from Eq. 5.1 on chickpea data and Eq. 5.2 on soybean data.

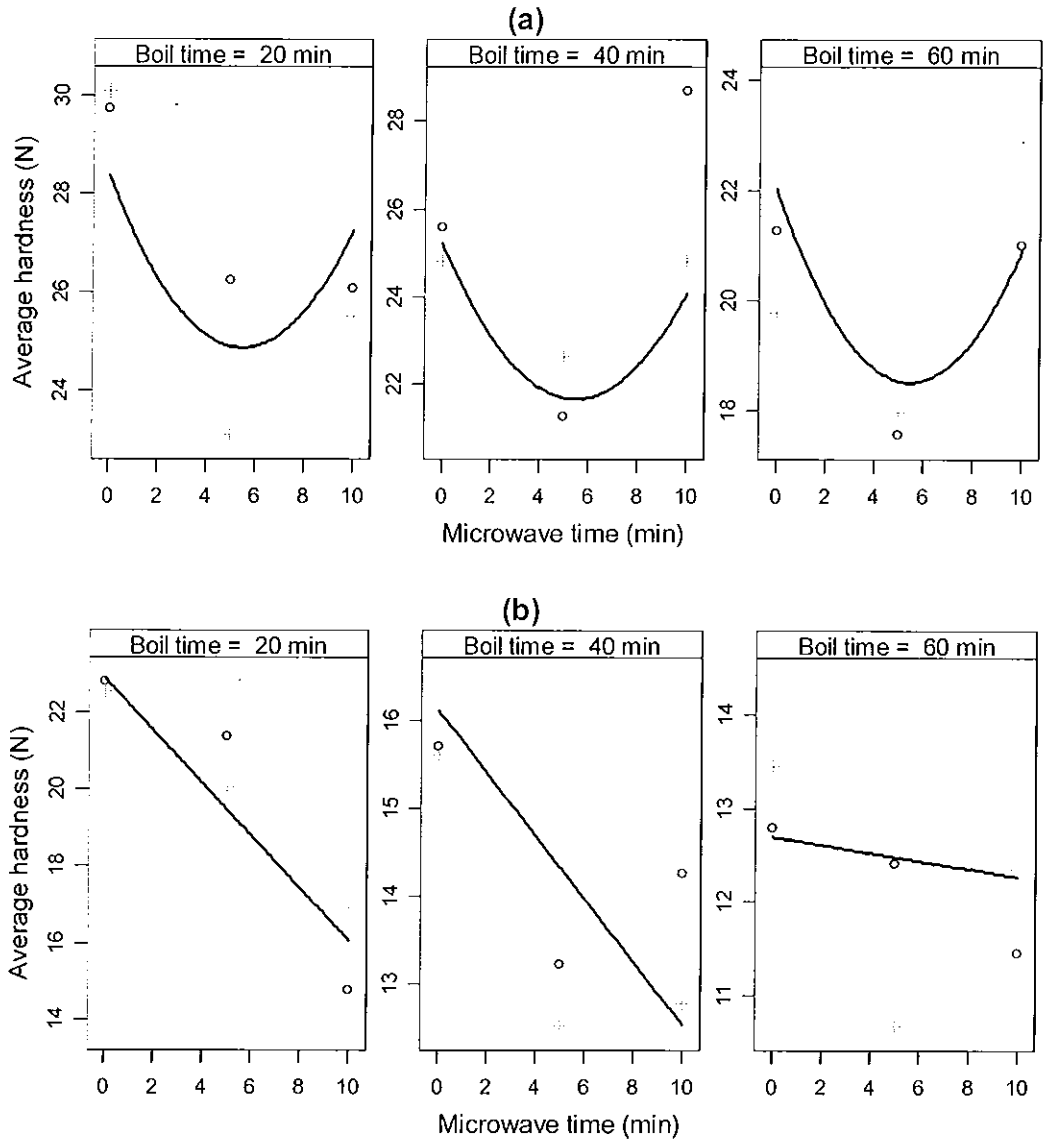


Fig. 5.4. Average hardness (N) of chickpeas **(a)** and soybeans **(b)** as a function of microwave cooking time.

Solid lines represent predictive plots generated from Eq. 5.1 on chickpea data and Eq. 5.2 on soybean data.

5.3.2 Sensory evaluation of cooked chickpeas and soybeans

5.3.2.1 Chickpea sensory evaluation

Average panellist scores for chickpea appearance (Fig. 5.5(a)) were within the range of 1 ("highly unacceptable") to 4 ("acceptable"). Treatment 3 (50 min boil & 2.5 min microwave) received the lowest average score, while treatment 4 (60 min boil) received the highest average score for appearance. Treatment 3 received statistically lower response for appearance than treatment 4. However, differences in panellist response for appearance for treatments 1, 2, 4 and 5 were statistically insignificant ($p > 0.05$).

Average sensory score for texture (Fig. 5.5(b)) ranged between 3 ("just right") and 4 ("hard"). Treatment 1 (40 min boil) was perceived, on average, as being the hardest, while treatment 3 was perceived, on average, as being the softest. However, due to the large variation in responses, the differences in texture perception were statistically insignificant.

Average sensory score for chickpea liking (Fig. 5.5(c)) ranged between 3 ("neither like nor dislike") to 4 ("like"). Treatment 1 (40 min boiling) received the lowest score for liking, while treatment 4 (60 min boiling) received the highest average response. Treatment 1 was significantly less liked than the other samples ($p < 0.1$). However, due to the large variation in responses, the differences in liking scores for treatments 2 – 5 were statistically insignificant. Therefore, the average sensory panel results indicate that those samples boiled for 60 min were the most popular.

5.3.2.2 Soybean sensory evaluation

Average panellist scores for soybean appearance (Fig. 5.5(a)) were within the range of 2 ("unacceptable") to 3 ("don't know"). Treatment 5 (60 min boil & 5 min microwave) got the lowest score, while treatments 1 (40 min boil) and 4 (60 min boil) received the highest average scores for appearance. However, differences in panellist response for appearance were statistically insignificant ($p > 0.05$).

Average sensory score for texture (Fig. 5.5(b)) ranged between 3 ("just right") and 4 ("hard"). Treatments 2 (40 min boil & 5 min microwave) and 4 (60 min boil) were perceived, on average, as being the hardest, while treatment 5 was perceived, on average, as being the softest. Due to the large variation in responses, the differences in texture perception were statistically insignificant.

Average sensory score for soybean liking (Fig. 5.5(c)) ranged between 3 ("neither like nor dislike") to 4 ("like"). Treatment 1 (40 min boiling) received the lowest score for liking, while treatment 4 (60 min boiling) received the highest average response. However, due to the large variation in responses, the differences were statistically insignificant. Therefore, the average sensory panel results indicate that those samples boiled for 60 min were the most popular.

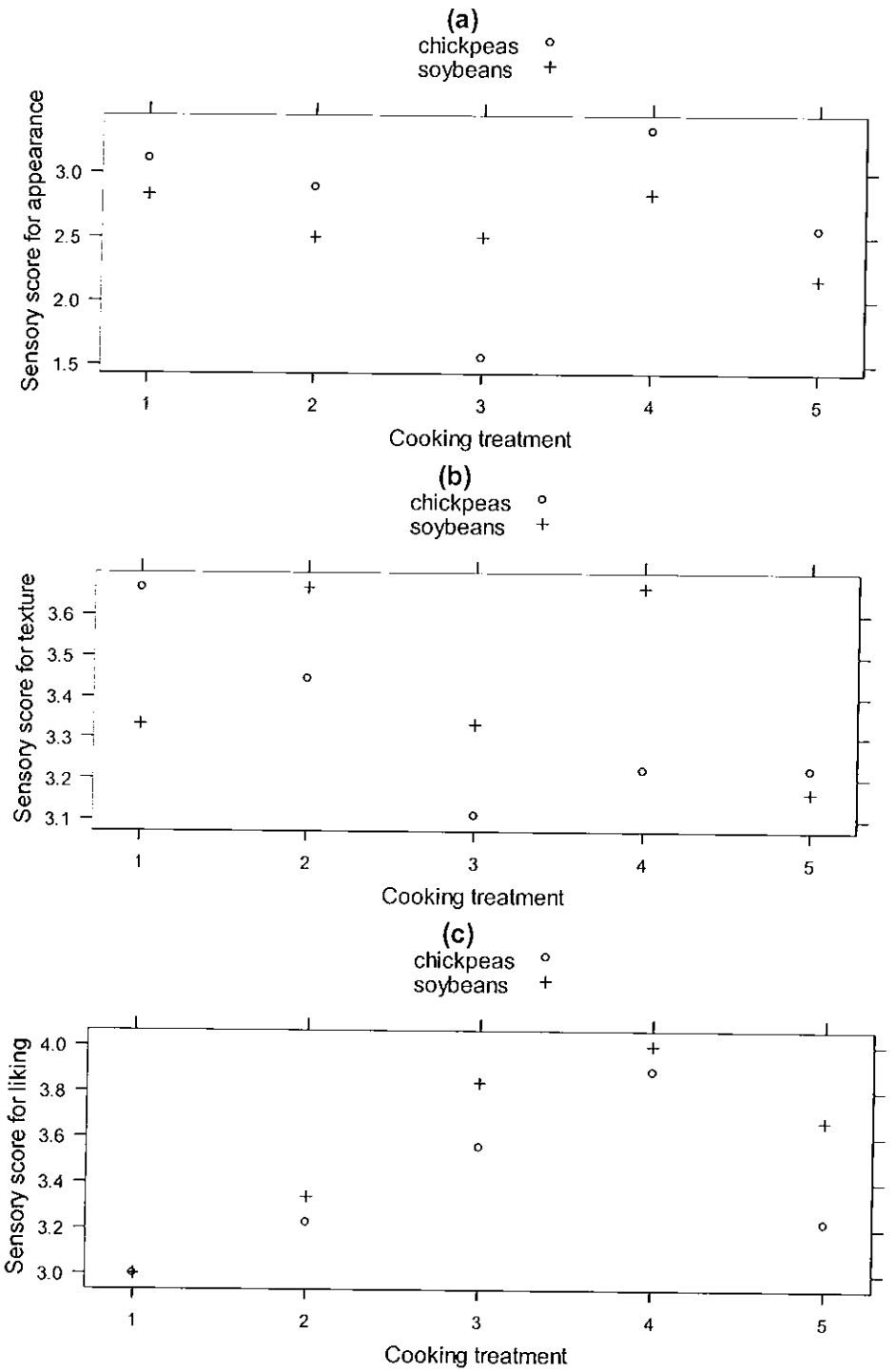


Fig. 5.5. Taste panel scores for **(a):** appearance *(1 = Highly unacceptable, 5 = Highly acceptable);* **(b):** texture*(1 = Too soft, 5 = Too hard)* and **(c):** liking *(1 = Dislike extremely, 5 = Like extremely)* for cooked chickpeas and soybeans.

Cooking treatments codes are explained in Fig. 5.2.

The average sensory response for chickpea texture was correlated ($r^2 > 0.9$) with the instrumental value of hardness (Fig. 5.6 (a)), while average sensory response for soybean texture was not correlated ($p > 0.05$) with the instrumental value of hardness (Fig. 5.6(b)).

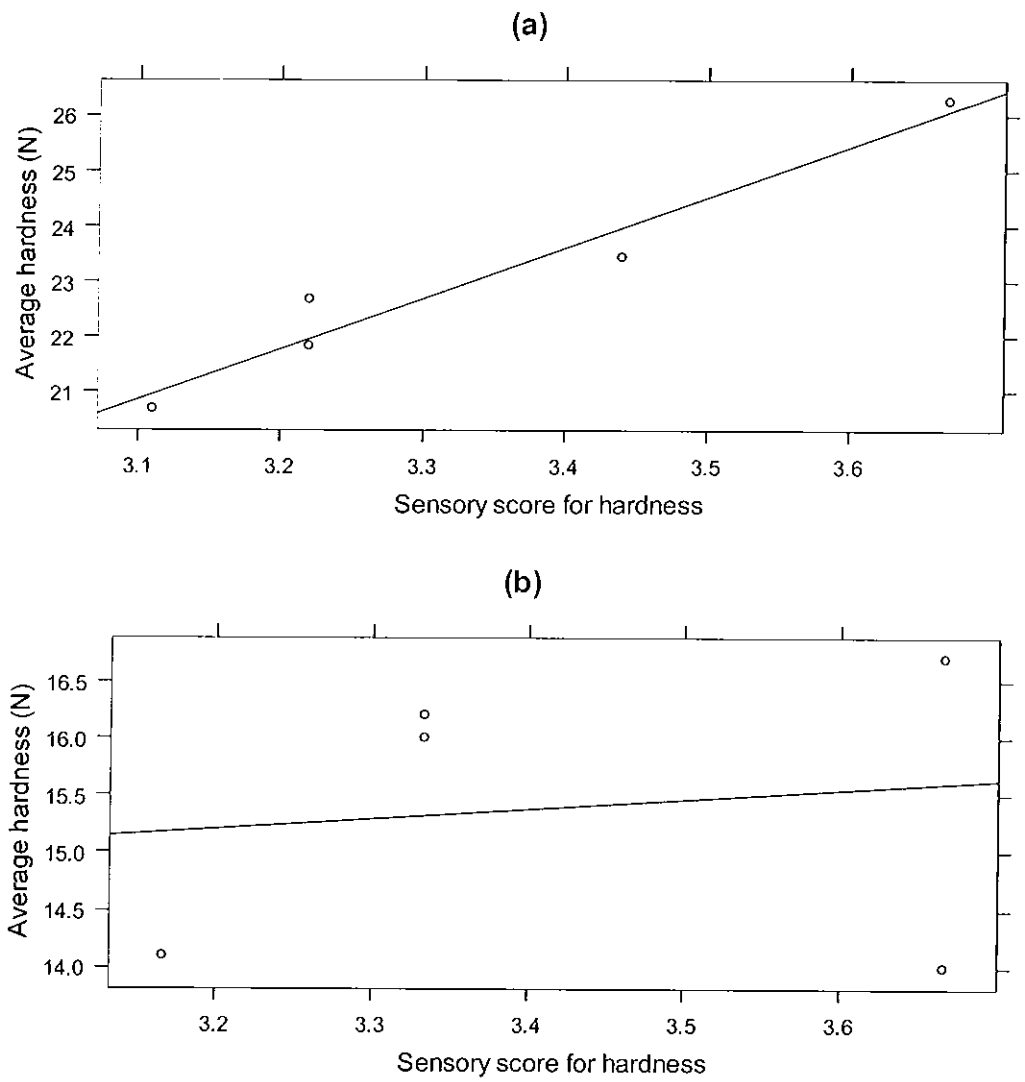


Fig. 5.6. Average instrumental score for hardness as a function of sensory score for hardness for cooked chickpeas (a) and soybeans (b).

It has been reported (Harker, 2000), that a difference in instrumental texture of 6N was the minimum required before panellists could differentiate between the texture of apples. This may explain why, on average, sensory interpretation of chickpea hardness was highly correlated to instrumental hardness (the maximum difference in instrumental texture between chickpea samples was 6N), while sensory interpretation of soybean hardness was not significantly correlated to instrumental hardness (the greatest measured difference in soybean texture was 2.6 N).

5.4 Conclusions

Chickpea hardness decreased with the boiling time and displayed quadratic dependence on microwave treatment time. Soybean hardness decreased with boiling time and an interactive effect between boil time and microwave time was significant. The softest sample texture was achieved for 60 min boil followed by 5 min microwave. Although adding five min microwave treatment to the cooking process resulted in lower hardness for all samples, the differences in sensory score between samples that were boiled for 60 min and those boiled for 60 min followed by 5 min microwave treatment were insignificant. Samples undergoing 60 min boiling treatment were the most popular, in terms of average sensory score for liking. Therefore, it was concluded that the optimum cooking method for chickpeas and soybeans was 60 min treatment in boiling water. There was a high degree of correlation between panellist score for chickpea texture and instrumental score for hardness. This was not the case with soybeans, indicating that the differences in soybean texture were less identifiable than those in chickpea texture.

CHAPTER 6

SHELF LIFE STUDY

Investigation of short-term and long-term shelf life of pre-cooked chickpeas and soybeans during chill, freee-chill and frozen storage

Summary

The shelf life of pre-cooked chickpeas and soybeans was investigated in terms of total viable count (TVC), colour and texture. Three storage methods were examined: chill storage (4 °C), frozen storage (-52 °C) and freeze-chill storage (-52 °C, followed by 7 d at 4 °C). A short-term (14 d) trial was carried out to study the effect of storage method and time on the shelf life, and a long-term (48 wk) trial, to investigate the effects of long-term freezing, as well as the potential application of a freeze-chill cycle. TVC for both chickpeas and soybeans was less than 10^5 in all cases, demonstrating the microbial safety of these products over the storage periods examined. Chickpeas experienced significant softening and loss of luminosity over the first two weeks of storage, after which changes in texture and colour were insignificant, whereas soybeans experienced an increase in Hue angle over the first two weeks of storage, after which changes in texture and colour became insignificant.

6.1 Introduction

The lack of convenient legume products available to the consumer (see section 1.1) has motivated the current research work: whole, pre-cooked chickpeas and soybeans were proposed as a convenient alternative to either canned or dry products. These products could also potentially be used as components for ready meals. Storage possibilities for such ready–to–heat products include chill, freeze and freeze-chill methods. While chilled foods are generally perceived to be healthier than frozen or canned (Mintel, 2003; Dennis & Stringer, 2000), their shelf life is comparatively shorter. Frozen foods enjoy long shelf life (up to 12

months) and superior nutritional quality, compared to canned products (Makhlouf *et al.*, 1995). The freeze-chill approach, in which frozen food samples are thawed prior to release, could potentially combine the extended shelf-life of frozen foods with the healthy image associated with chilled foods (Redmond *et al.*, 2003).

Quality control of a new food product is a multi-faceted problem. The main factor of concern is microbial safety. Chill injury due to inappropriate storage can accelerate microbial growth, so it is essential that storage temperature is monitored throughout the storage period. Apart from microbiological concerns, it is essential that the product be of high visual quality, as this is the main factor that will influence initial consumer choice (Hutchings, 1999). Maintenance of other sensorial aspects of the new product, such as texture, will determine whether the consumer continues to buy the product.

A major factor that limits the long-term storage of foods is textual degradation during storage. During freezing of foods, water molecules expand, causing cell walls to rupture. This is why many frozen vegetables, when re-heated, have a softer texture than their fresh counterparts. Blast freezing minimizes the amount of cell wall rupture, by producing a large number of small ice crystals.

The aim of this study was to investigate the short- and long-term shelf life of whole, pre-cooked chickpeas and soybeans. Microbial safety was estimated through investigation of total viable counts (TVC) of samples during the storage period. Colour and texture of samples during storage were chosen to represent

the sensory aspects of the products. The effect of storage method and time on TVC, colour and texture was examined.

6.2 Materials and methods

6.2.1 Sample preparation

Raw material is described in section 3.1. Based on findings in Ch. 4 and Ch. 5, chickpeas and soybeans were prepared as described in Table 6.1. After cooking treatment, 40 g samples were packed in polyethylene bags, which then were sealed using a heat-sealer.

Sample	Chickpeas	Soybeans
Blanching Pretreatment	1.5min @100 °C	1.5 min @ 100 °C
Soak Treatment	4 h @ 40 °C	4 h @ 40 °C
Cook Treatment	1 h @ 100 °C	1 h @ 100 °C

Table 6.1. Sample preparation for shelf life experiments.

6.2.2 Freezing and chilling treatments

6.2.2.1 Short-term shelf life trial

Three freezing/chilling storage methods were investigated:

I. Chill storage: Cooked samples were blast frozen to –20 °C for 2 h and then placed in chill storage at 4 °C. Samples were tested at 7 & 14 days of storage.

II. Frozen storage: Cooked samples were blast frozen to –20 °C for 2 h and then stored at –52 °C. Samples were thawed overnight at 4 °C prior to the day of analysis, and were tested at 7 & 14 days of storage.

III. Freeze-chill storage: Cooked samples were blast frozen to –20 °C for 2 h and then stored at -52 °C. Samples were thawed overnight at 4 °C and kept at 4 °C for 7 days prior to analysis. Samples were tested at 7 & 14 days of storage.

6.2.2.2 Long-term shelf life trial

Two storage methods were investigated:

I Frozen storage: Samples were blast frozen to –20 °C for 2 h and then stored at -52 °C. Samples were thawed overnight at 4 °C prior to the day of analysis and were tested at 12, 24, 36 and 48 weeks of storage.

II Freeze-chill storage: Samples were blast frozen to –20 °C for 2 h and then stored at –52 °C. Samples were thawed overnight at 4 °C and kept at 4 °C for 7 days prior to analysis. Samples were tested at 12, 24, 36 and 48 weeks of storage.

Samples were also analyzed on the day after preparation (day 0) and each treatment was repeated three times.

6.2.3 Total viable count evaluation

20 g chickpea sample was diluted with 180 ml Ringers solution and then stomached to make a 10^{-1} dilution. 10^{-2} and 10^{-3} dilutions were made, plated in triplicate on Plate Count Agar using the standard pourplate method with 1ml

aquilots. Samples were incubated at 37 °C for 48 h and the number of colony forming units per gram was calculated.

6.2.4 Colour measurement

The colour of whole samples during the shelf life study was measured by the method described in section 3.9. Hue angle, which can be used to measure the intensity of colour in foods (Redmond *et al.*, 2002), was calculated (Eq. 6.1)..

$$H^* = \tan^{-1}(b^*/a^*) \quad \ldots(6.1)$$

6.2.5 Texture evaluation

The texture of 10 samples for each treatment/replication was evaluated by the method described in section 3.9.

6.3 Results and discussion

6.3.1 Short term shelf life trial

6.3.1.1 Total Viable Count (TVC)

TVC was calculated to evaluate microbiological quality of the samples during storage (Fig. 6.1). In the case of chickpeas, TVC decreased significantly with storage time for both frozen ($p < 0.05$) and freeze-chill ($p < 0.05$) samples. TVC for soybeans decreased significantly with time for both frozen ($p < 0.05$) and freeze-chill ($p < 0.05$) soybeans.

TVC was significantly affected by storage method: TVC for chilled samples was significantly ($p < 0.05$) higher than that for freeze-chill samples and frozen samples, and TVC for freeze-chill samples was significantly ($p < 0.05$) higher than that for frozen samples. According to the Food Safety Authority of Ireland (Anonymous, 2001), the TVC values obtained in this study are within acceptable levels ($\log_{10}$cfu < 5) for cooked vegetable meals at the point of sale.

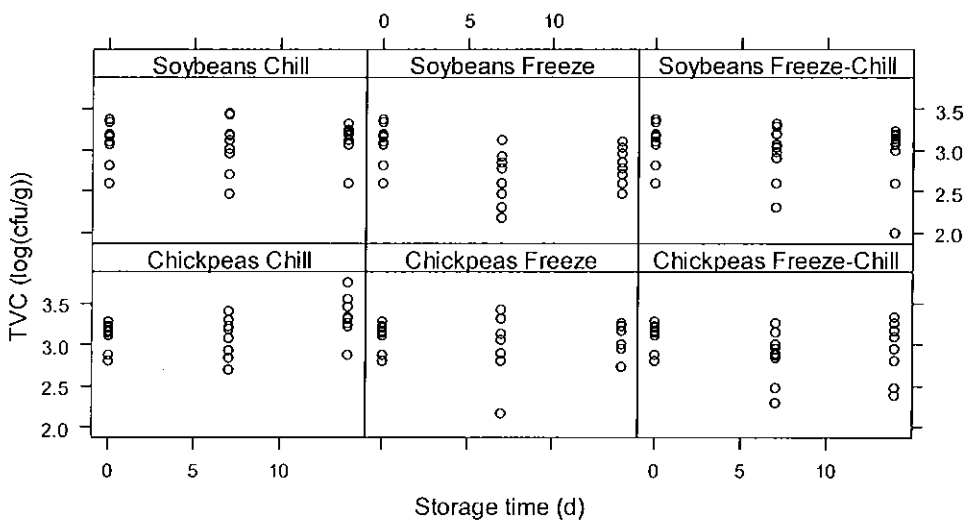


Fig. 6.1. TVC for cooked chickpeas and soybeans during short-term storage.

6.3.1.2 Colour

CIELAB Lightness value (L^*) as a function of storage is shown in Fig. 6.2. In the case of chickpeas, L^* decreased significantly between days 0 and 7 of storage ($p < 0.05$), regardless of storage method, but did not change significantly between days 7 and 14. Chickpea lightness value was not significantly affected by storage method ($p > 0.05$). Soybean lightness was not significantly affected by either storage method or storage time.

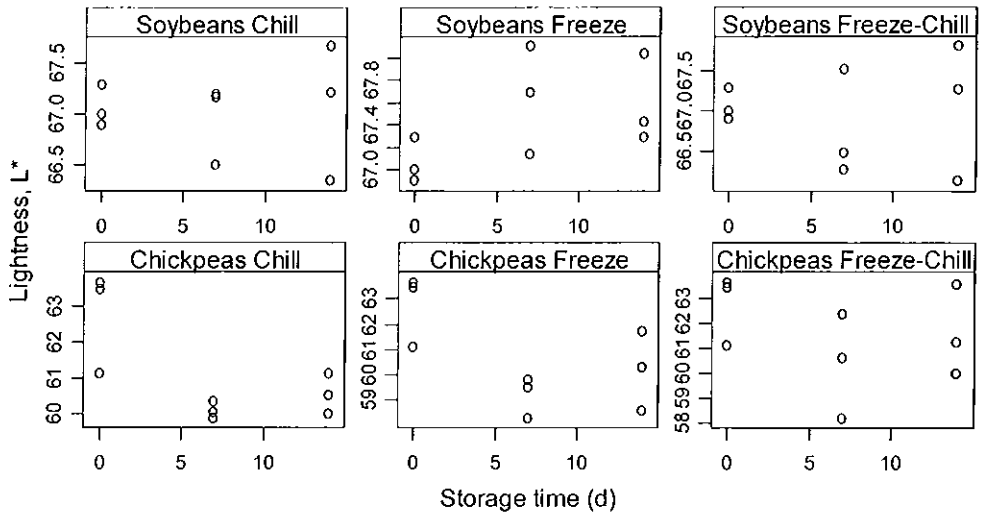


Fig. 6.2. Lightness for cooked chickpeas and soybeans during short-term storage.

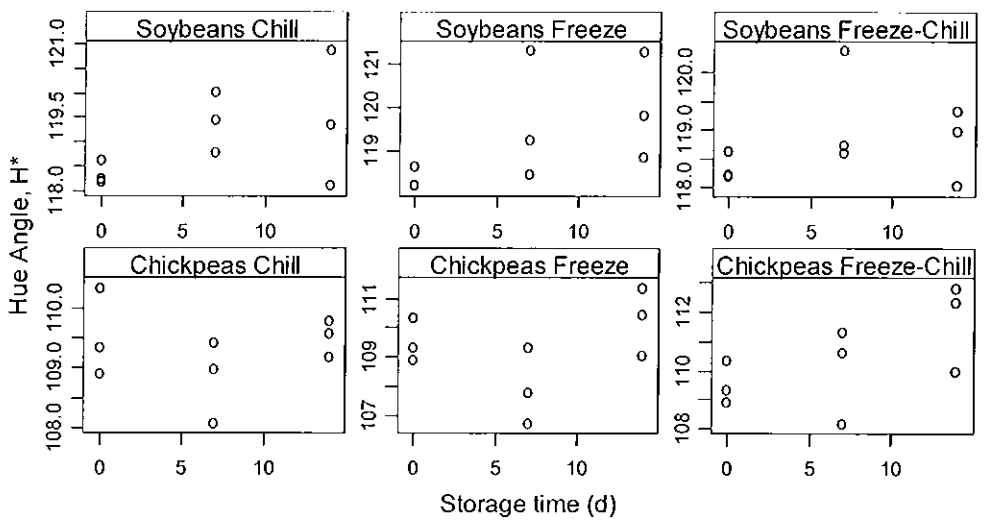


Fig. 6.3. Hue angle for cooked chickpeas and soybeans during short-term storage.

CIELAB Hue value (H^*) is plotted as a function of storage time in Fig. 6.3. In the case of chickpeas, H^* did not significantly change with storage time or storage

method. Hue angle for soybeans increased significantly during the storage period, regardless of storage method, indicating an increase in the intensity of yellow colour during storage. Soybean hue was not significantly dependent on storage method.

6.3.1.3 Texture

Hardness of samples was measured during the storage period (Fig. 6.4). In the case of soybeans, hardness did not significantly change over the 14 days of chilled storage ($p > 0.05$). However, frozen and freeze-chill soybeans were significantly softer than chilled soybeans ($p < 0.05$). Regardless of storage method, chickpea hardness decreased ($p < 0.05$) with storage time over the short-term trial period.

Chilled samples decreased from 18 ± 2 N on day 0 to 15 ± 2 N on day 14. Frozen and freeze-chill samples decreased from 18 ± 2 N on day 0 to 12 ± 2 N on day 14. Chickpeas that were frozen and freeze-chilled (H = 14 ± 3 N) were significantly ($p < 0.05$) softer than those that were chilled (H = 17 ± 2 N). This may have been due to cell rupture, caused by the expansion of water molecules during freezing. However, it has been reported (Harker, 2000), that a difference of 6N in instrumental texture was the minimum amount required before panellists could differentiate between the texture of apple samples. Therefore, the differences in chickpea texture during short-term storage may not be detectable by consumers.

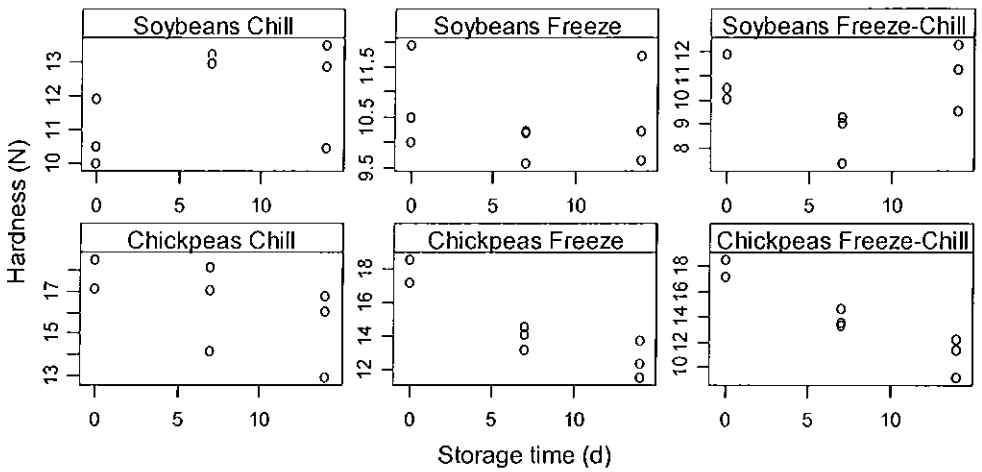


Fig. 6.4. Average hardness for cooked chickpeas and soybeans for different methods of short-term storage.

6.3.2 Long term shelf life trial

6.3.2.1 Total Viable Count (TVC)

TVC for each treatment in the long-term trial is shown in Fig. 6.5. TVC was significantly ($p < 0.05$) higher for freeze-chill samples than for frozen ones and TVC did not change significantly with storage time ($p > 0.05$). Similar findings were reported in a study of the shelf life of carrots and green beans (Redmond *et al.*, 2004).

The TVC values obtained in the long-term study are within acceptable levels ($\log_{10}$cfu < 5) for cooked vegetable meals at the point of sale, according to the Food Safety Authority of Ireland (Anonymous, 2001).

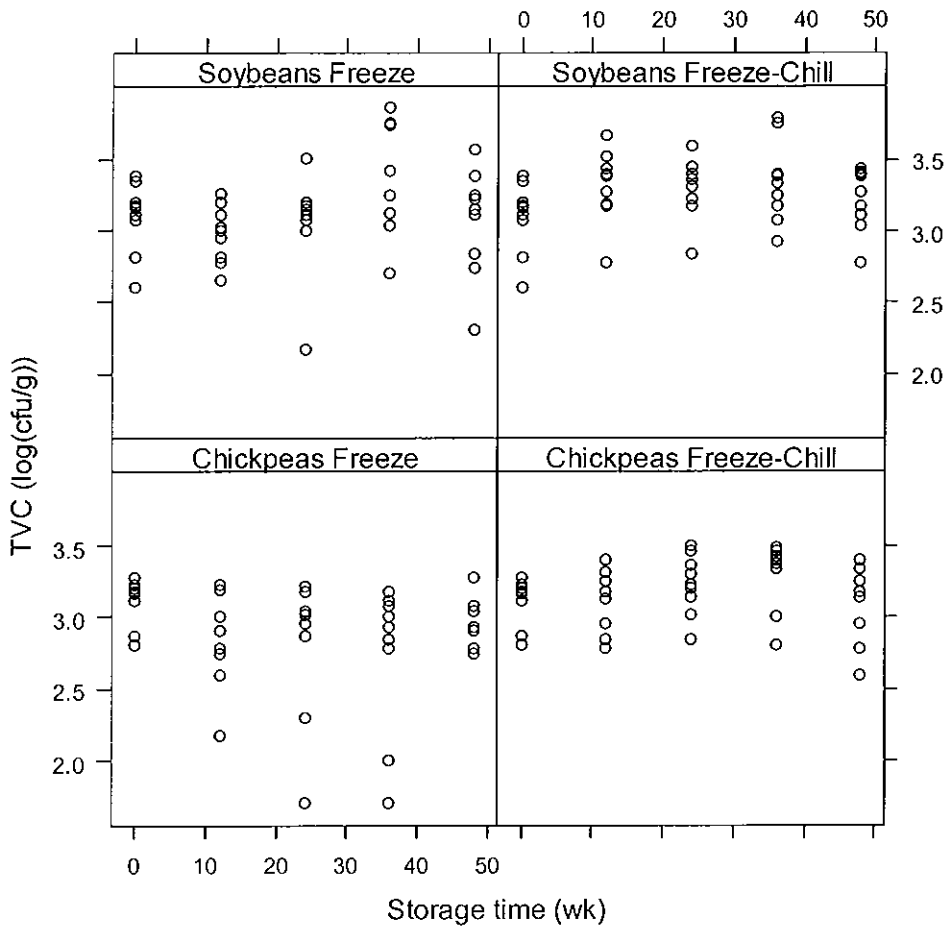


Fig. 6.5. TVC for cooked chickpeas and soybeans during long-term storage.

6.3.2.2 Colour

Lightness of both chickpeas and soybeans (Fig. 6.6) did not change significantly ($p > 0.05$) over the long-term trial. Hue angle, (Fig. 6.7) and consequently colour retention, was not significantly dependent on either storage time ($p > 0.05$) or storage method ($p > 0.05$).

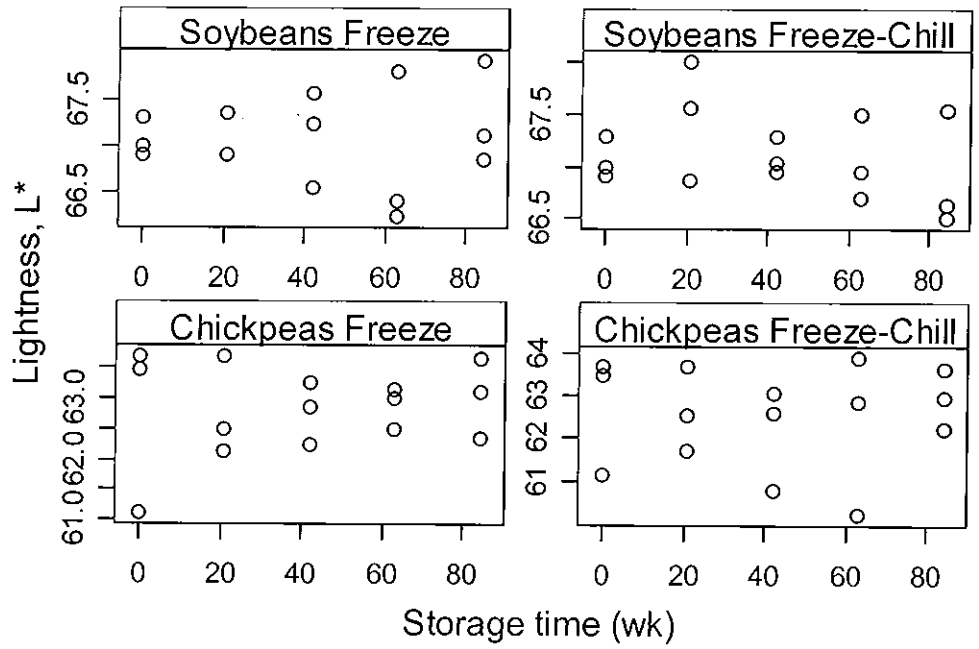


Fig 6.6. Lightness, L^*, of chickpeas and soybeans during long-term storage.

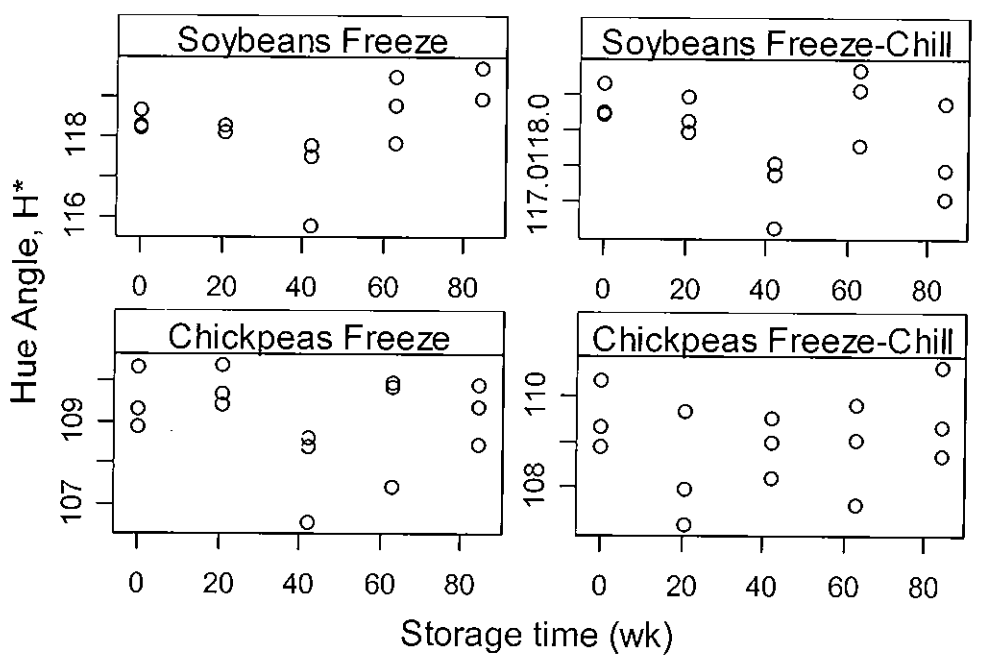


Fig. 6.7. Hue angle for cooked chickpeas and soybeans for different methods of long-term storage.

6.3.2.3 Texture

Hardness of samples during long-term storage, for each of the treatments studied, is shown in Fig. 6.8. Soybeans that underwent freeze-chill storage were significantly ($p < 0.05$) harder than frozen soybeans, and storage method did not affect the long-term texture of chickpeas ($p > 0.05$). Analysis of variance indicated that sample hardness over the long-term trial was not significantly affected by storage time ($p > 0.05$). Therefore, it seems that the majority of cell wall softening occurred during the first two weeks of frozen storage, after which changes in texture were insignificant.

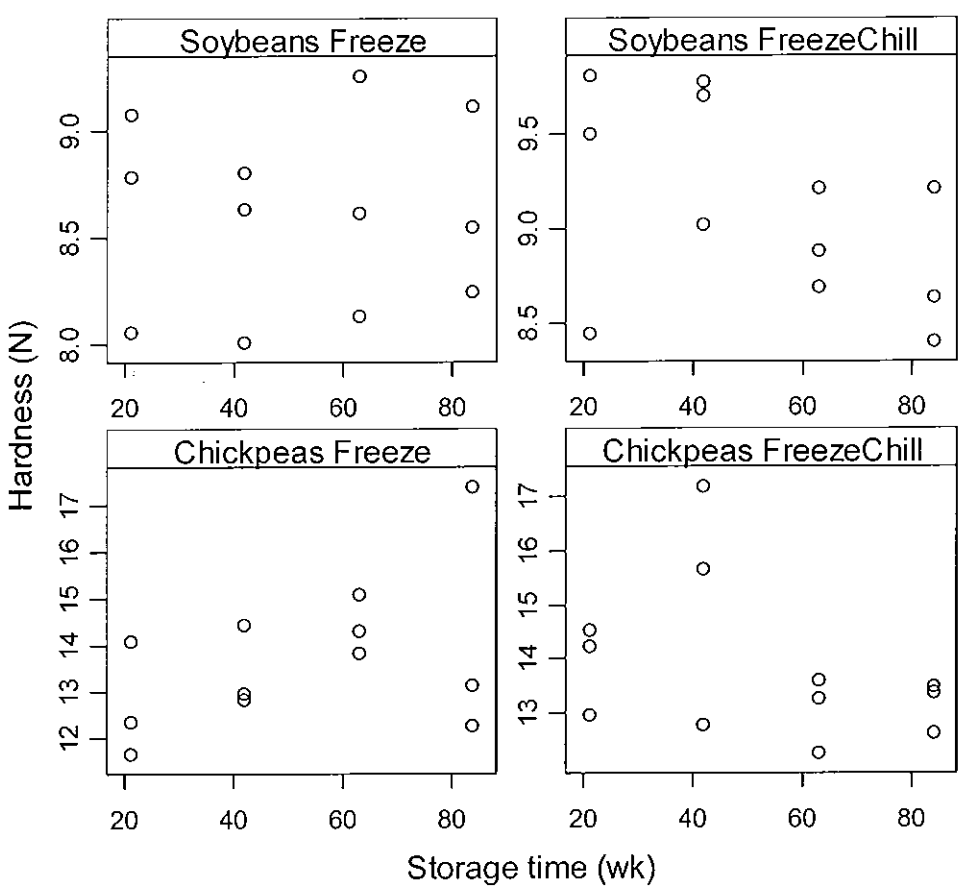


Fig. 6.8. Average hardness for cooked chickpeas and soybeans during long-term storage.

6.4 Conclusions

Microbial results show that pre-cooked chickpeas and soybeans can be consumed for up to 2 weeks when stored at 4 °C and for up to 48 weeks when held in either frozen or freeze-chill storage. Chickpea colour and texture quality experienced small but significant changes during the first two weeks of storage. However, changes in chickpea quality were insignificant during the long-term storage period, suggesting that chickpea quality stabilised after the first two weeks. Soybeans experienced an increase in Hue angle during the first two weeks of storage: apart from this, no significant changes in soybean colour and texture quality were observed during storage. Results suggest that long-term freezing of cooked chickpea and soybean products is viable, as changes in TVC, colour and texture were not significant over the long-term storage period. Application of a freeze – chill cycle is another viable long-term storage option for chilled chickpeas and soybeans, providing an alternative to frozen storage while maintaining microbial safety, colour quality and texture. The shelf life of pre-cooked chickpea and soybean products was 14 days for chilled storage and 48 weeks for frozen or freeze-chill storage.

CHAPTER 7

OPTIMISATION OF PROCESS CONDITIONS FOR DEHYDRATION OF COOKED CHICKPEAS AND SOYBEANS: HIGH TEMPERATURE/MICROWAVE POWER PROCESSING

Comparison of the effects of convective hot air-drying, microwave drying and combined microwave- convective hot air drying on dehydration and rehydration properties of pre-cooked chickpeas and soybeans within temperature range 160 – 200 °C and microwave power range 210 – 560 W.

Some of the results from this chapter were presented at the CIGR Section VI International Symposium on the FUTURE OF FOOD ENGINEERING, Warsaw, Poland, and have been submitted for publication in the Journal of Food Engineering *(see pages 289-292)*

Summary

Convective hot air, microwave and combined microwave-convective hot air drying of pre-cooked, whole chickpeas and soybeans were investigated. Three microwave levels (210, 400, 560 W) and three air temperatures (160, 180, 200 °C) were examined. Drying kinetics, rehydration kinetics and colour change were investigated with relation to microwave level and air temperature. Combined microwave – hot air drying decreased the drying time required for both chickpeas and soybeans, when compared to drying with either hot air or microwave energy alone. Predictive models were developed to describe dehydration and rehydration kinetics. Dehydration rate, rehydration rate and total colour change of rehydrated product increased with microwave level and air temperature. Optimal drying, in terms of processing time and rehydrated product quality occurred for combined drying at the lowest levels of microwave power and air temperature studied, i.e. microwave power = 210 W, air temperature = 160 °C. Lumped effective diffusivity (D_{eff}) of water and water vapour during the drying process was estimated by fitting a series solution of Ficks 2nd law of diffusion to the data. D_{eff} ranged from 10^{-7} – 10^{-8} m^2/s increasing with both increasing temperature and microwave power. The high values of D_{eff} reflect the rapidity of the drying process when high drying temperatures and microwave powers were employed.

7.1 Introduction

Preliminary experimental results showed that drying of cooked chickpeas by combination of microwave and convective hot air is a promising method, which

could produce highly rehydratable products in short drying times (see Appendix C). In the present study, an extensive investigation of the dehydration properties of cooked chickpeas and soybeans was conducted within a temperature range of 160-200 °C and microwave power range of 210-560 W. Samples were subjected to three different drying conditions: convective hot-air drying, microwave drying and combined microwave – convective hot air drying and quality of the resultant rehydrated product was examined. Samples were dried until no significant variation in weight was observed and then used for rehydration experiments. This was to allow each drying process to impose its characteristic structure on the dry sample. In this way, relevant rehydration properties specific to each process (colour, rehydration rate, etc.) could be examined and compared.

The main aims of this chapter can be summarised as follows:

1. Study the benefit of combined microwave-hot air drying compared to hot air and microwave drying alone.
2. Investigate the effect of microwave power and air temperature on drying and rehydration kinetics of cooked chickpeas and soybeans.
3. Estimate optimal drying conditions with respect to processing time and quality.

7.2 Materials and methods

7.2.1 Material

Raw material is described in section 3.1. Preparation of samples for dehydration is described in section 3.4.

7.2.2 Drying equipment

Drying equipment is described in section 3.5.

7.2.3 Experimental design

Three types of drying were studied:

1. *Convective hot air drying:* Three temperature settings (160 °C, 180 °C, 200 °C) were investigated (air velocity = 1 ± 0.05 m/s).

2. *Microwave drying:* Three microwave levels (210 W, 300 W, 560 W) were investigated. Air temperature was measured to be 23 ± 1°C (natural convection).

3. *Combined Microwave-hot air-drying:* Nine levels of combined drying (comprised of the three convective and three microwave settings described above) were investigated ((160 °C, 180 °C, 200 °C) x (210 W, 300 W, 560 W)) (air velocity = 1 ± 0.05 m/s).

Each experiment was performed in triplicate, in a random order; therefore the total number of experiments for each chickpea or soybean sample was 45.

7.2.4 Dehydration procedure

A single layer of 40 g pre-cooked chickpea or soybean sample was spread over a glass petri dish, which was then placed in the centre of the oven cavity. Drying conditions were then set on the display panel. The oven (see section 3.5) was altered, so that an attachment could be fitted between the plate of the oven and an electronic balance, attached to a PC (Fig. 7.1). This allowed for the continuous measurement of sample weight during drying. In order to avoid experimental noise and therefore improve the accuracy of weight measurements, it was necessary to disconnect the rotating mechanism within the oven, so that the sample remained stationary throughout drying. After dehydration, samples were stored in sealed bags over a desiccator in darkness at 23 ± 2 °C, for further use in rehydration experiments. Storage of dehydrated samples was never longer than 7 days prior to rehydration experiments.

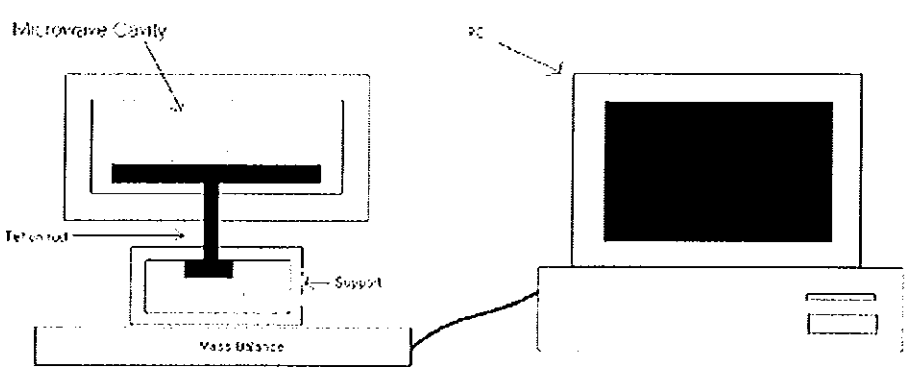


Fig. 7.1. Schematic diagram of combination microwave – hot air oven, mass balance and PC used for online measurement of sample weight during dehydration.

7.2.5 Moisture content determination

Moisture content determination is described in section 3.6.

7.2.6 Calculation of moisture ratio

Moisture ratio calculation is described in section 3.7.

7.2.7 Rehydration procedure

Rehydration procedure is described in section 3.8.

7.2.8 Colour measurement

The colour of the surface of five individual rehydrated samples for each drying treatment was measured. Colour measurement apparatus is described in section 3.9.

7.2.9 Synthetic evaluation index

In order to compare each of the drying methods investigated using a single process indicator, a synthetic evaluation index (S) was built (Liu, 1998; Hu *et al.*, 2005), taking into account the relative product colour (Y_1), relative rehydration rate (Y_2), relative rehydration ratio (Y_3) and relative dehydration rate (Y_4). The quality parameters measured in the study were ranked in order of decreasing significance (presumed from a consumer's point of view) as follows: colour, rehydration rate, rehydration ratio, dehydration rate. They were assigned weights (λ_1, λ_2, λ_3, λ_4) of 0.4, 0.3, 0.2, 0.1, respectively. Synthetic evaluation index was

then calculated for each of the experimental conditions from the equations below (Eq. 7.1).

$$S = \sum_{i=1}^{4} \lambda_i Y_i$$

$$Y_1 = 1 - \frac{DE^* - DE^*_{\min}}{DE^*_{\max} - DE^*_{\min}} \quad ; \quad Y_2 = \frac{RR - RR_{\min}}{RR_{\max} - RR_{\min}} \quad ;$$

$$Y_3 = \frac{k_r - k_{r\min}}{k_{r\max} - k_{r\min}} \quad ; \quad Y_4 = \frac{k_d - k_{d\min}}{k_{d\max} - k_{d\min}} \qquad ...(7.1)$$

7.3 Results and discussion

7.3.1 Characteristics of drying rate curves

Drying rate was plotted as a function of moisture content for chickpea (Fig. 7.2(a)) and soybean (Fig. 7.2(b)) drying. Drying rates generally increased as microwave power was increased. In all cases, drying rate increased during the early stages of drying, reaching a maximum value corresponding to moisture ratio between 0.7 and 0.9.

For convective drying, following the attainment of maximum drying rate, a falling rate was observed, during which drying rate decreased with decreasing moisture content. Compared with convective drying, combination microwave-convective drying resulted in a clear increase in drying rates, for all drying temperatures studied.

Considering microwave drying, the following characteristics were observed: after reaching a peak value (corresponding to moisture ratio between 0.7 and 0.9)

drying rate decreased to a minimum value (corresponding to a moisture ratio value of approximately 0.5), after which the drying rate experienced another increase, until reaching a second peak (corresponding to moisture ratio value of 0.2-0.3), after which drying rate decreased with decreasing moisture content.

Rate curves for combined drying displayed similar shape to those for microwave drying, described above. Rate curves for the drying of chickpeas and soybeans (Fig. 7.2) are comparable, in terms of shape, to those reported by Andres and co-workers (2004), who described the drying rate behaviour of apple slices. The initial increase in drying rate is due to "warming-up" of the sample during the early drying stages, when mass losses are small: the subsequent decrease in drying rate could be attributed to drying out of the sample surface caused by evaporation of water.

The size of the second peak in the drying curve generally increased as microwave power was increased. This may be related to the fast formation of an internal porous structure, by volumetric heating of the source, facilitating vapour diffusion. Water vapour, driven by the application of microwave power, is then forced through the sample, expanding its structure. This behaviour is important for the creation of a highly porous dehydrated structure and would affect the subsequent rehydration behaviour. The second peak in the drying rate curves (occurring at moisture content between 13-20 %) may be related to textural changes within the sample, which are further explored in Chapter 9. The final "falling rate" period in the curve could be attributed to expulsion of the remaining highly bound moisture contained within the sample (Brennan, 1990).

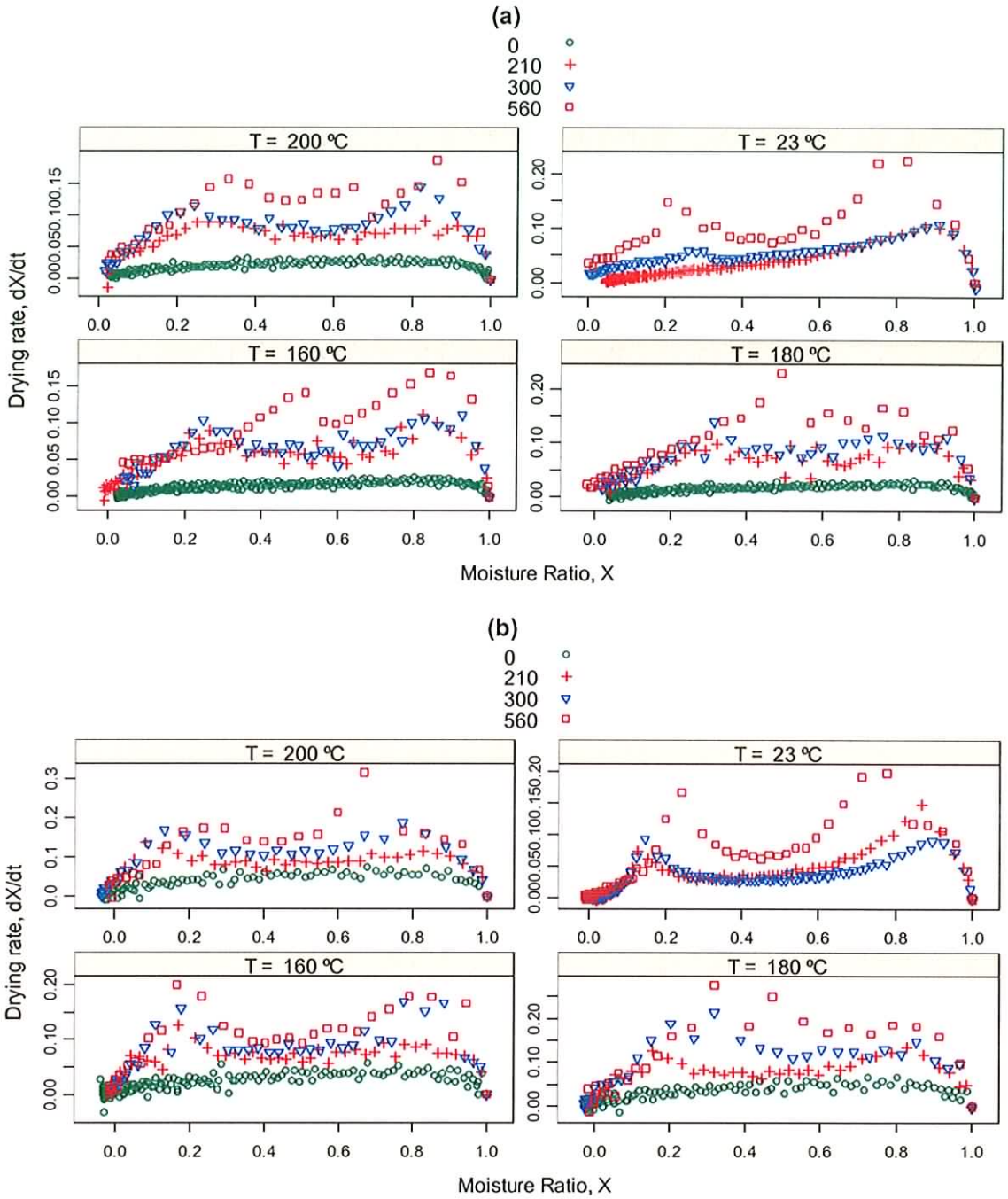


Fig. 7.2. Drying rate behaviour of chickpeas **(a)** and soybeans **(b)** subjected to convective hot-air, microwave and combined microwave – hot-air drying.

7.3.2 Dehydration kinetics

Moisture ratio, MR, was plotted as a function of drying time for cooked chickpeas (Fig. 7.3(a)) and soybeans (Fig. 7.3(b)) over the range of experimental conditions studied. As the drying time increased, MR decreased, approaching an equilibrium value close to zero.

The drying time required to reach equilibrium was clearly dependent on the drying method used. In the case of chickpeas, air-drying was the slowest method, taking up to 80 min; microwave drying was more than twice as fast, taking up to 40 min. Combined drying was faster again, ranging from 10 - 20 min. For soybeans, air-drying took up to 40 min, microwave drying required up to 25 min and combined microwave-hot air drying required just 15 min to reach a constant moisture level.

Each of the empirical drying models discussed in section 3.10.2 (Eq. 3.11 – 3.14) was fitted to the drying data, to find which one was best suited to describing the dehydration data. Nonlinear regression of each model was performed on the chickpea and soybean data sets (see section 3.11) and the pooled standard error (SE) and Akaike information criterion (AIC) were estimated (Table 7.1).

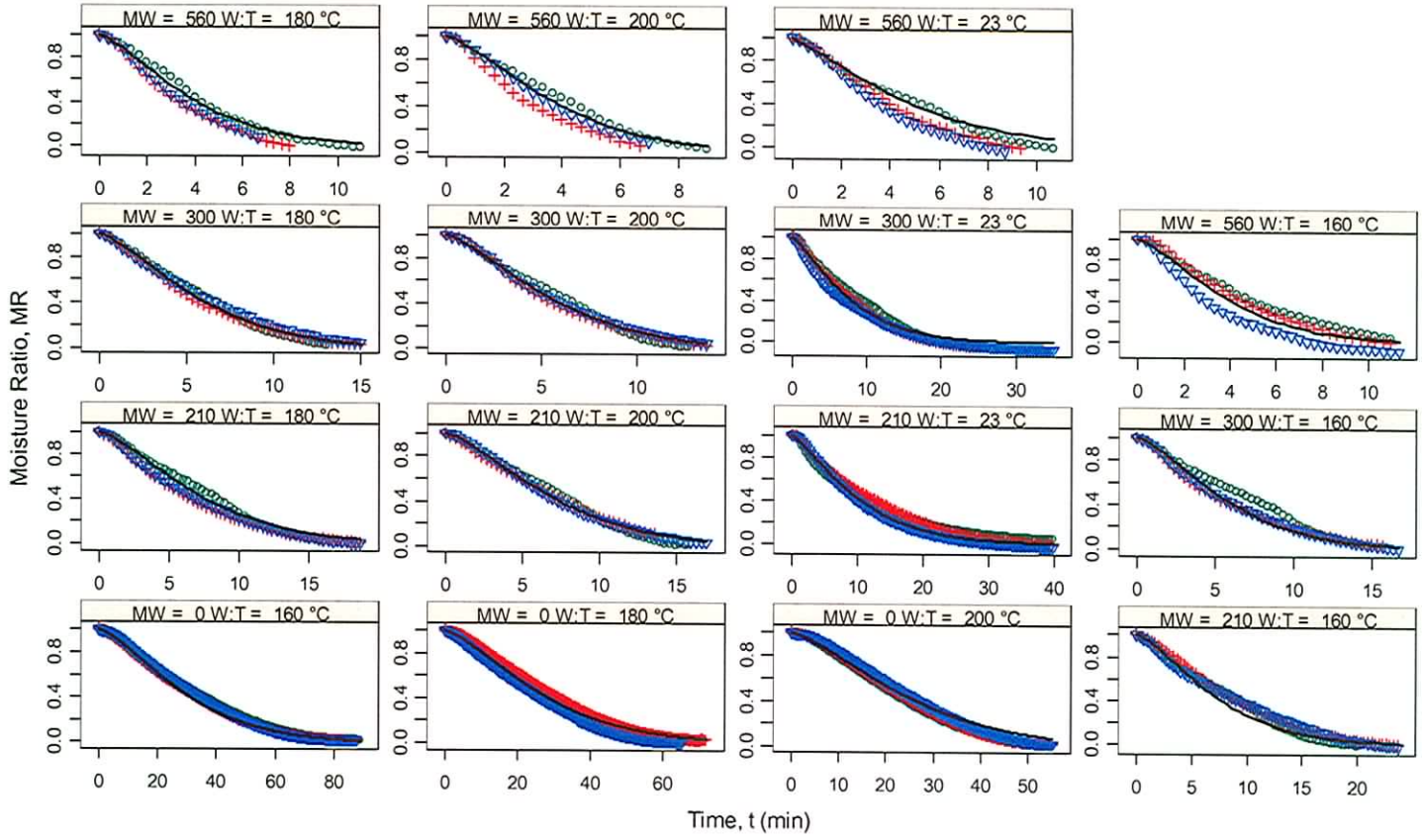


Fig. 7.3 (a). Moisture Ratio (MR) as a function of drying method and time for pre-cooked chickpeas.

Solid lines indicate predictive plots for nonlinear regression of Eq. 7.3 on the data.

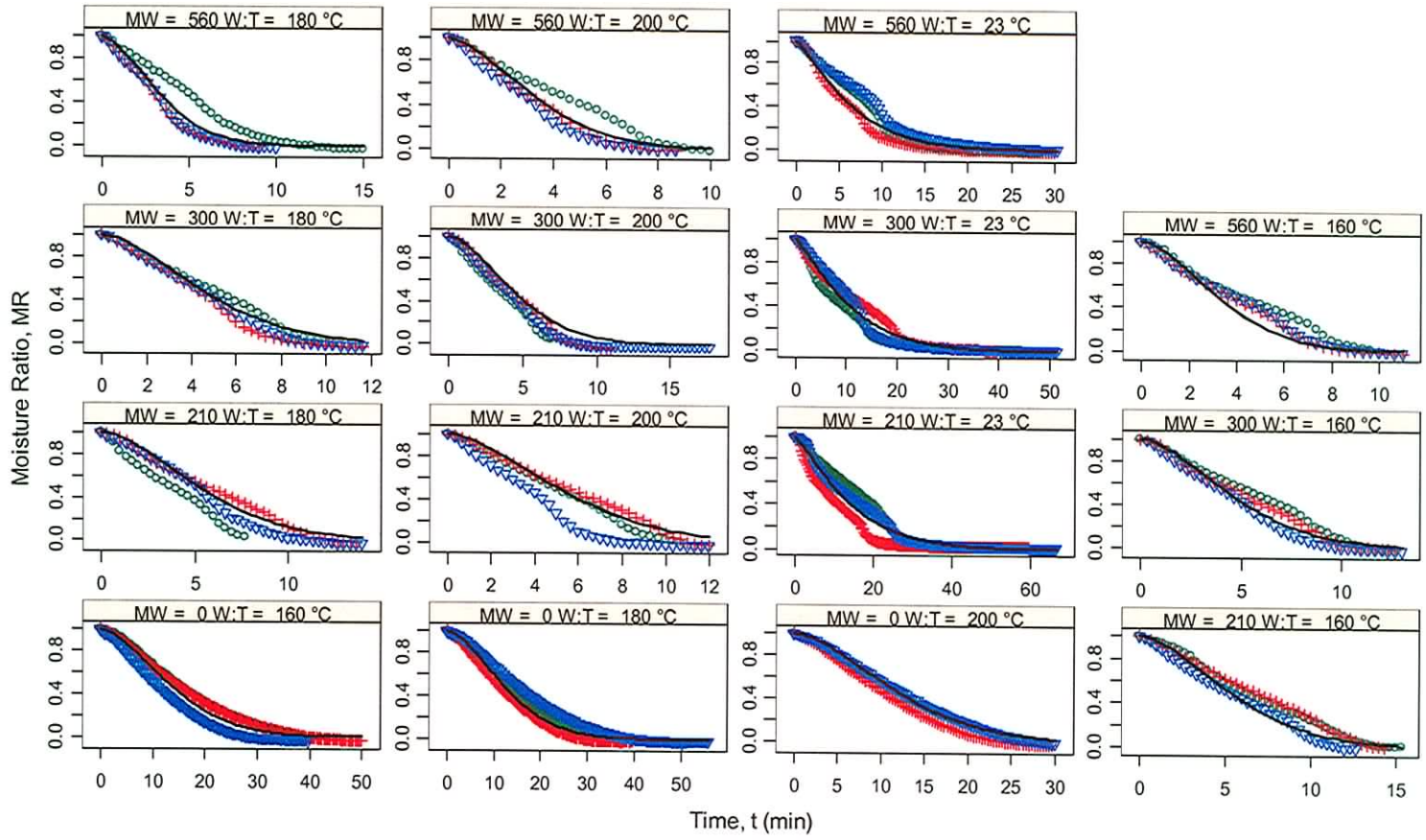


Fig. 7.3 (b). Moisture Ratio (MR) as a function of drying method and time for pre-cooked soybeans.

Solid lines indicate predictive plots for nonlinear regression of Eq. 7.3 on the data.

Table 7.1. Pooled Akaike Information Criterion (AIC) for nonlinear regression of Henderson & Pabis model (Eq. 3.11), Lewis model (Eq. 3.12), Bi-exponential model (Eq. 3.13) and Page model (Eq. 3.14) on chickpea and soybean drying data.

	SAMPLE	CHICKPEAS		SOYBEANS	
	Equation	**SE**	**AIC**	**SE**	**AIC**
3.11	$MR = a_H e^{-k_d t}$	0.052	-12108.96	0.065	-8855.41
3.12	$MR = e^{-k_d t}$	0.069	-10106.70	0.079	-7634.737
3.13	$MR = a_{Bi} e^{-k_1 t} + b_{Bi} e^{-k_2 t}$	0.130	-5053.636	0.110	-5659.239
3.14	$MR = e^{-k_p t^{n_p}}$	0.018	-21041.86	0.030	-14152.88

The Page model (Eq. 3.14) resulted in the lowest SE and AIC for both chickpea and soybean drying data and was therefore the best suited to model the dehydration data. This result was in agreement with the findings of Doymaz (2005) and Simal and co-workers (2005) who reported that the Page model gave the best model fit for dehydration of green beans and kiwi fruit respectively. In order to build a model to describe MR as a function of drying time and method, the influence of processing parameters (i.e. microwave power and air temperature) on the coefficients of the Page model were investigated.

Average Page constant k_p was plotted as a function of microwave power (MW) and air temperature (T), for both chickpeas (Fig. 6.4(a)) and soybeans (Fig. 6.4(b)). In the case of chickpeas, k_p increased significantly with both MW ($p < 10^{-12}$) and T ($p < 0.05$). Similarly, for soybeans, k_p increased significantly with

both MW ($p < 10^{-6}$) and T ($p < 10^{-3}$). After careful inspection of a number of different candidate models, which were compared using log-likelihood ratio tests, a linear model (Eq. 7.2) was found to best describe the overall effect of increasing MW and T on k_p for both chickpeas and soybeans ($r^2 > 0.95$). The coefficients a_p and b_p were estimated by linear regression (Table 7.2).

$$k_p = a_p MW + b_p T \quad \ldots(7.2)$$

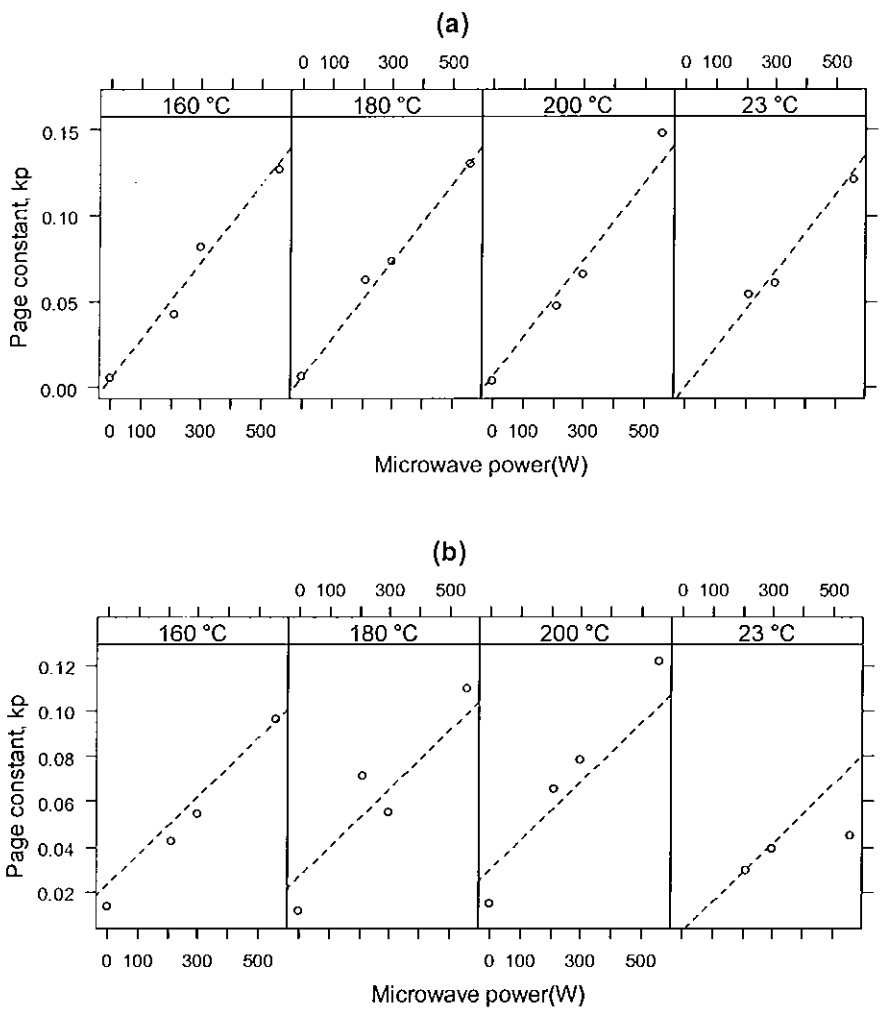


Fig. 7.4. Estimated page constant (k_p) as a function of microwave power and air temperature for chickpeas **(a)** and soybeans **(b)**.

Dashed lines represent linear prediction plots arising from fitting Eq. 7.2 to the data.

Table 7.2. Estimated regression parameters for linear regression of Eq. 7.2 on chickpea and soybean dehydration data.

SAMPLE	a_p ($W^{-1}.min^{-1}$)	b_p ($°C^{-1}.min^{-1}$)	r^2
CHICKPEAS	2.25e-04 ± 0.08e-04	3.25e-05 ± 1.75e-05	0.99
SOYBEANS	1.28e-04 ± 0.15e-04	1.50e-04 ± 0.33e-04	0.95

Page model parameter n_p (Table 7.3) was significantly smaller for microwave-dried samples than for combined or convective-dried samples for both chickpeas ($p < 0.05$) and soybeans ($p < 10^{-3}$). This indicates that the shape of the drying curves is quite different when microwave drying is the dominant drying mechanism.

Table 7.3. Average Page constant, n_p, as a function of drying method.

Drying Method	CHICKPEAS	SOYBEANS
Convective	1.56 ± 0.1	1.61 ± 0.09
Microwave	1.32 ± 0.1	1.37 ± 0.11
Combined	1.41 ± 0.06	1.59 ± 0.05

The dehydration rate, related to the product of k_p and n_p, increased significantly with both microwave power and air temperature ($r^2 > 0.95$). The following model was therefore constructed to describe MR for both chickpeas and soybeans as a function of drying time, air temperature, microwave power and drying method.

$$MR = e^{-(a_p MW + b_p T)t^{(n_{p1} - I_m \cdot n_{p2})}} \quad \ldots(7.3)$$

Where I_m = 1 for microwave drying and zero otherwise. Eq. 7.3 was fitted to the entire drying datasets for each of the legumes studied, by one-step non-linear regression (see section 3.11) and the model parameters were estimated (Table 7.4).

Predictive plots were generated from the model, which adequately describe the drying data (Fig. 7.3). Residual and quantile-quantile plots for Eq. 7.3 fitted to the chickpea and soybean-drying data are displayed in Fig. 7.5. The residual points seem to be randomly distributed, with most residuals lying within 2 standard deviations. An intrinsic residual correlation (as evidenced in Fig. 7.5(i)) is inevitable due to the continuous weight monitoring, but it is believed that this effect did not affect parameter estimation or model fit significantly.

Table 7.4. Estimated regression parameters for nonlinear regression of Eq. 7.3 on chickpea and soybean drying data.

SAMPLE	CHICKPEAS	SOYBEANS
Parameter	**Value ± Std.Error**	**Value ± Std.Error**
a_p ($W^{-1}.min^{-1}$) x 10^4	2.16 ± 0.03	1.64 ± 0.04
b_p ($^oC^{-1}.min^{-1}$) x 10^5	4.61 ± 0. 09	6.38 ± 0. 03
n_{p1}	1.54± 0.01	2.08 ± 0.02
n_{p2}	0.14 ± 0.01	0.43 ± 0.01

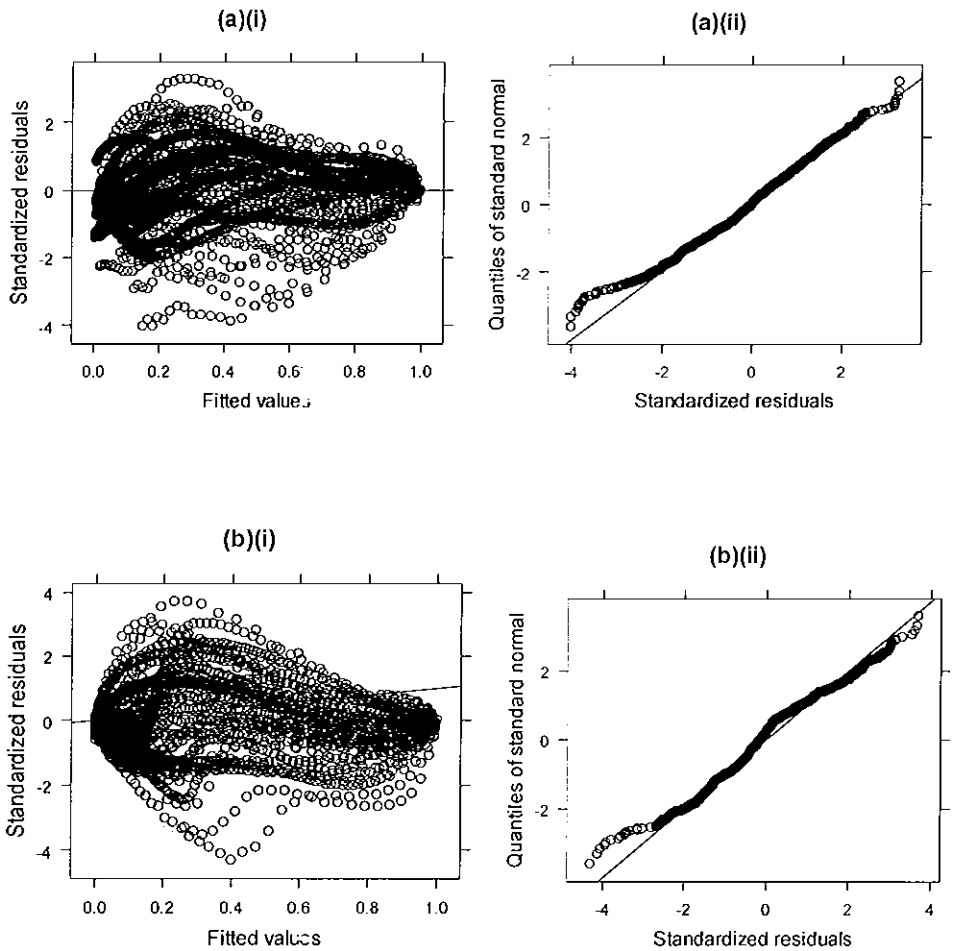


Fig. 7.5. Residual **(i)** and quantile-quantile **(ii)** plots for nonlinear regression of Eq. 7.3 on dehydration data for chickpeas **(a)** and soybeans **(b)**.

7.3.3 Rehydration kinetics after drying treatment

Weight gain upon rehydration (WGR) as a function of rehydration time is shown in Fig. 7.6. Rehydration curves for both chickpeas (Fig. 7.6(a)) and soybeans (Fig. 7.6(b)) followed a general pattern of bounded growth, characteristic of a first order process. Therefore the following equation was applied for primary modelling of the rehydration data:

$$WGR = WGR_e - WGR_e e^{-k_r t} \qquad \ldots(7.4)$$

The experimental data for each rehydration experiment was fitted by nonlinear regression (see section 3.11) to Eq. 7.4. The regression coefficients for Eq. 7.4 were estimated by minimising the residual sum of squares and were significant within a 95% confidence level. In order to build a secondary model to predict WGR as a function of time, temperature and microwave power, further analysis of the estimated parameters was required.

Asymptotic weight gain on rehydration (WGR_e) was constant over the range of experimental conditions studied (no significant change at the 0.05 level). However, rehydration rate, k_r, increased significantly ($p < 0.01$) with both microwave power and air temperature. After careful inspection of a number of different candidate models, a linear model (Eq. 7.5) was chosen to describe the dependence of k_r on microwave power and air temperature for both chickpeas and soybeans ($r^2 > 0.94$) (Table 7.5).

$$k_r = a_r MW + b_r T \qquad \ldots(7.5)$$

Table 7.5. Estimated regression coefficients for linear regression of Eq. 7.5 on chickpea and soybean rehydration rate constant.

SAMPLE	a_r ($W^{-1}.min^{-1}$)	b_r ($^oC^{-1}.min^{-1}$)	r^2
CHICKPEAS	4.5e-04 ± 7.2e-05	7.7e-04 ± 1.5e-04	0.94
SOYBEANS	8e-04 ± 9.3e-05	1.1e-03 ± 2e-04	0.95

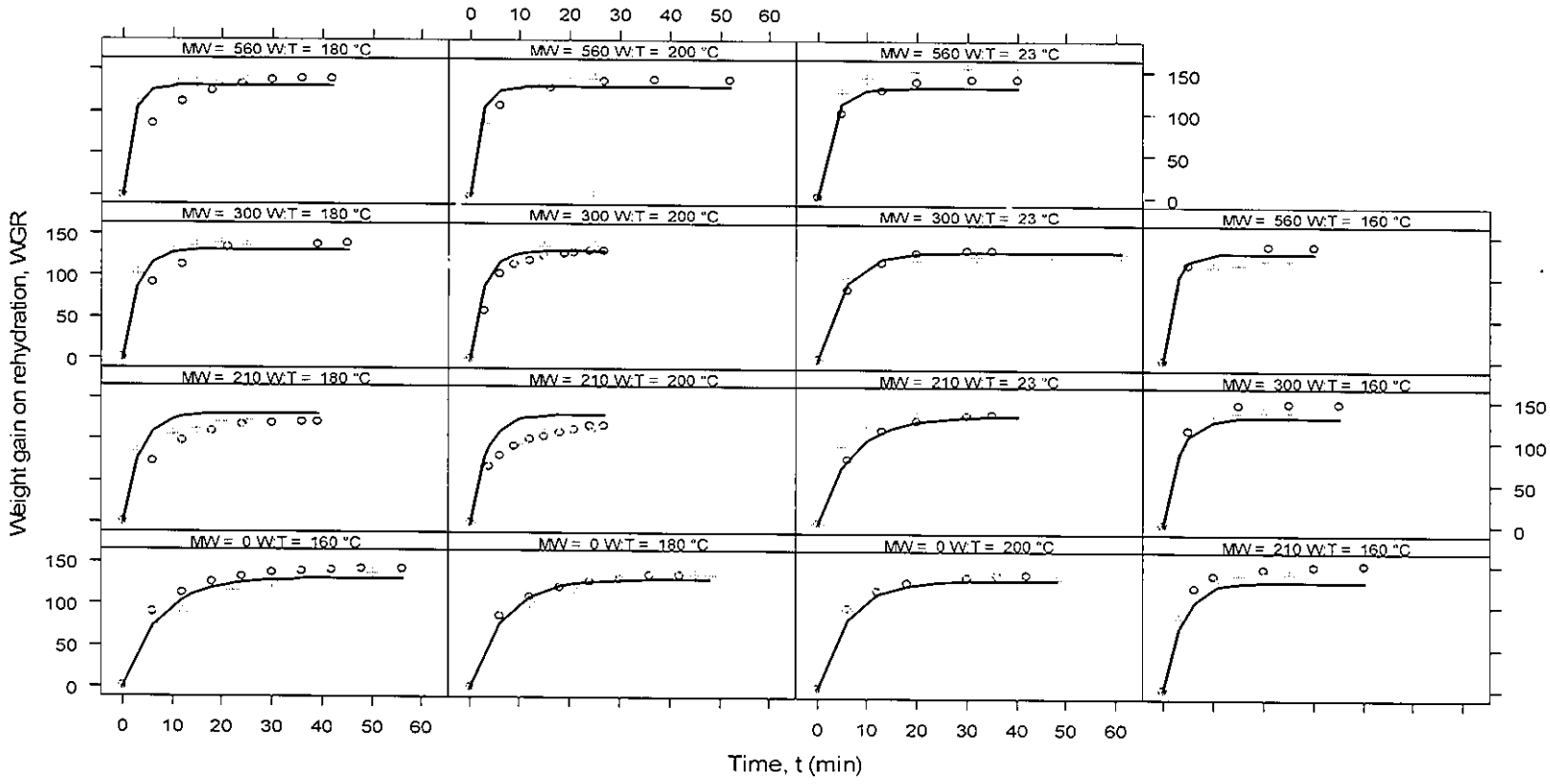


Fig. 7.6(a). Weight gain on rehydration (WGR) as a function of drying method and time for chickpeas.

Solid lines indicate predictive plots for nonlinear regression of Eq. 7.6 on rehydration data.

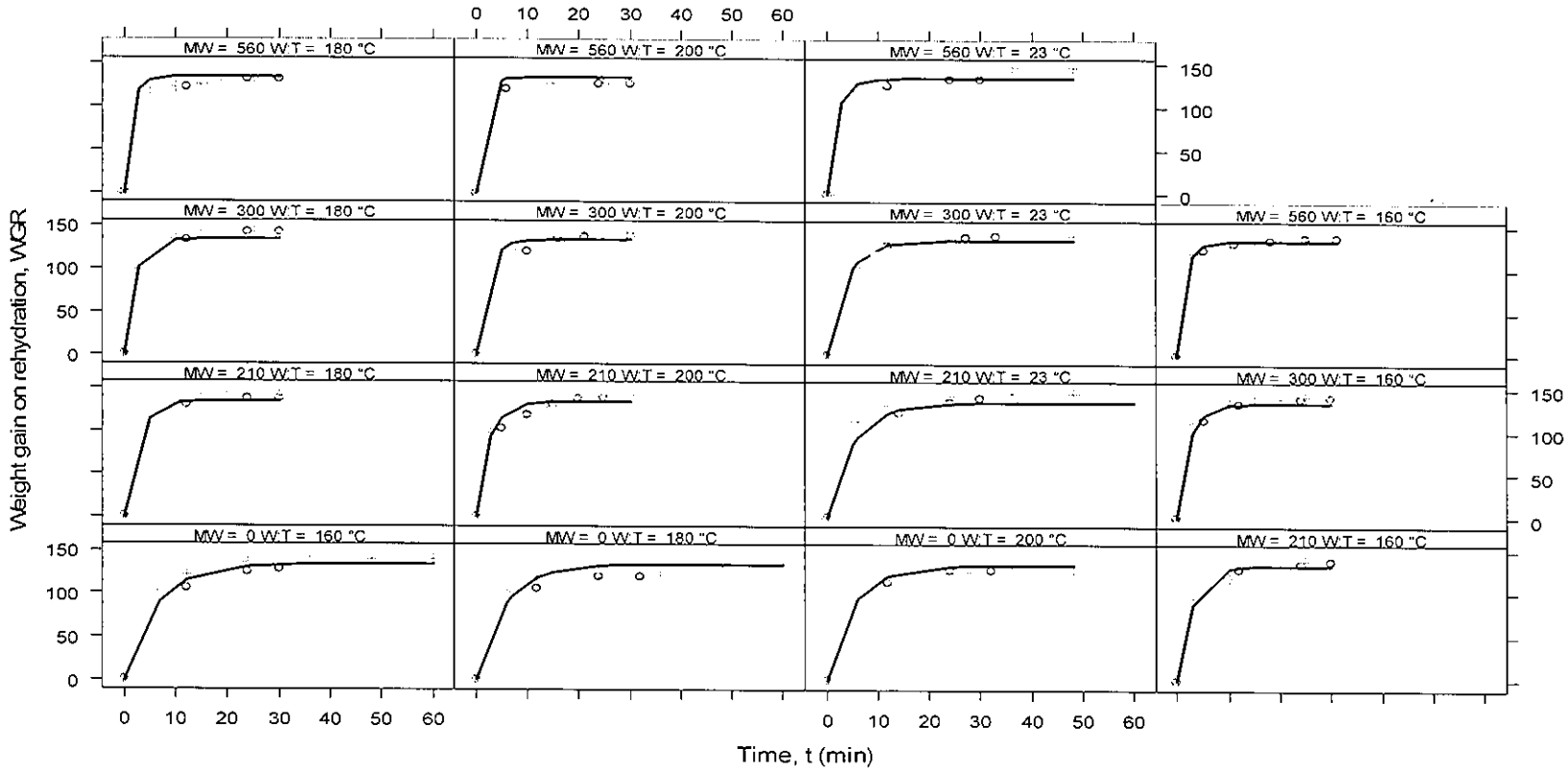


Fig. 7.6(b). Weight gain on rehydration (WGR) as a function of drying method and time for soybeans.

Solid lines indicate predictive plots for nonlinear regression of Eq. 7.6 on rehydration data.

The following model (Eq. 7.6) was then constructed to describe WGR for both chickpeas and soybeans as a function of drying time, air temperature, and microwave power.

$$WGR = WGR_e - WGR_e e^{-(a_r MW + b_r T)t} \quad \ldots(7.6)$$

Eq. 7.6 was fitted to the rehydration data from each of the pulses, by one-step nonlinear regression (see section 3.11) and the model parameters and their standard errors were estimated (Table 7.6).

Table 7.6. Estimated regression parameters for nonlinear regression of Eq. 7.6 on chickpea and soybean rehydration data.

SAMPLE	CHICKPEAS	SOYBEANS
Parameter	**Value ± Std.Error**	**Value ± Std.Error**
WGR_e	130 ± 1	134 ± 1
a_r ($W^{-1}.min^{-1}$) x 10^4	7.0 ± 0. 4	9.6 ± 0. 4
b_r ($^oC^{-1}.min^{-1}$) x 10^4	8.4 ± 0.01	10.1± 0.4

Predictive plots were generated from the model, which adequately describe the rehydration kinetics (Fig. 7.6). The residual and quantile-quantile plots for Eq. 7.6 regressed on the chickpea & soybean rehydration data are displayed in Fig. 7.7. The residual points seemed to be randomly distributed, with most residuals lying within 2 standard deviations.

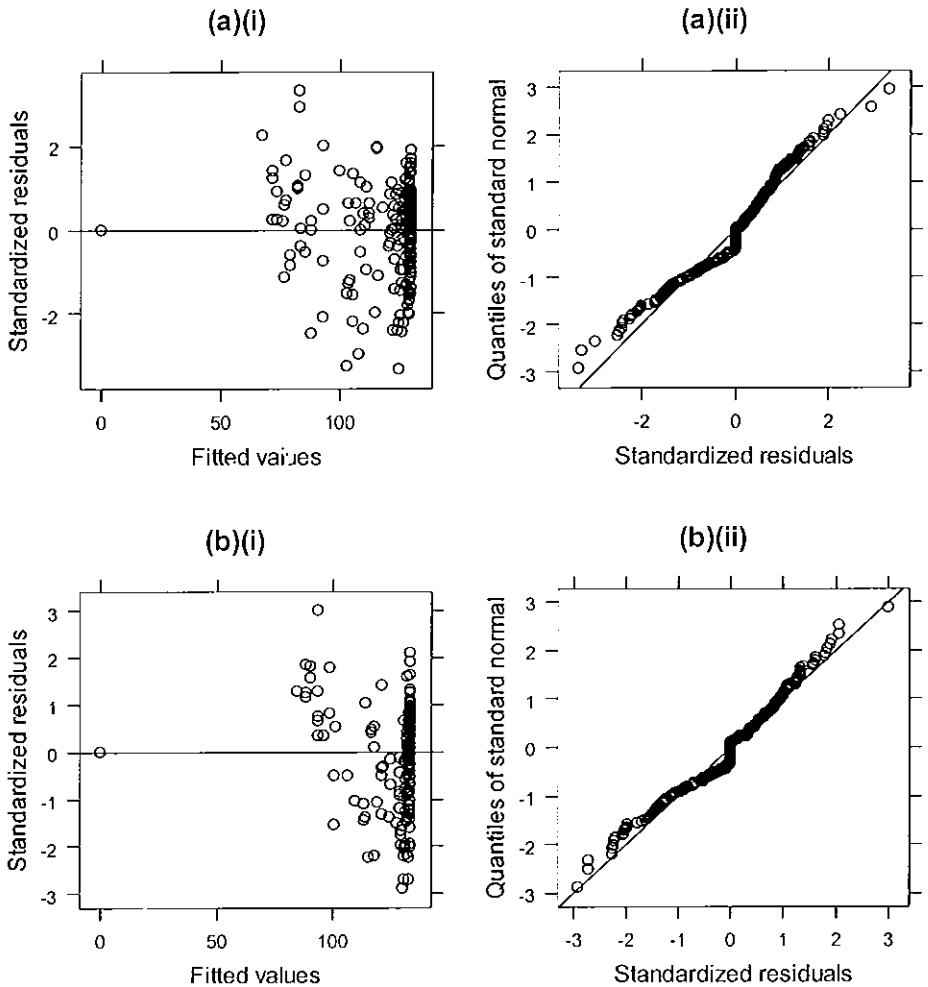


Fig. 7.7. Residual **(i)** and quantile-quantile **(ii)** plots for nonlinear regression of Eq. 7.6 on rehydration data for chickpeas **(a)** and soybeans **(b)**.

The amount of rehydration time required to reach the 95% lower level of asymptotic moisture content was estimated from the Eq. 7.6 (Table 7.7). The 95% lower level of WGR_e was considered as the final point at which the rehydration process attained moisture content "not different" from the asymptotic level. The time taken to reach this level was fastest for samples that had been dried by combination of microwave and hot air. For example, at the highest level of combination drying (MW = 560 W, T = 200 °C), rehydration time to reach the

95% lower level of asymptotic moisture content took just under eight minutes for both chickpeas and soybeans (Fig. 7.7). Rehydration time was slowest for the samples that had been dried using hot air alone. For example, at the lowest level of air drying (T = 160 °C), time to reach the 95% lower level of asymptotic moisture content was just over 30 min.

Table 7.7. Amount of rehydration time (in minutes) required to reach the 95% lower level of asymptotic moisture content estimated from Eq. 7.6.

SAMPLE		CHICKPEAS	SOYBEANS
MW (W)	T (°C)	t (min)	t (min)
210	23	25.3	21.8
300	23	18.3	15.7
560	23	10.2	8.7
0	160	31.3	30.3
210	160	14.9	13.5
300	160	12.2	10.9
560	160	8.0	7.0
0	180	27.8	26.9
210	180	14.1	12.8
300	180	11.6	10.4
560	180	7.7	6.8
0	200	25.0	24.2
210	200	13.3	12.1
300	200	11.1	10.0
560	200	7.5	6.6

7.3.4 Colour change upon rehydration

Fig. 7.8 shows CIELAB lightness value (L*) as a function of microwave power (MW) and air temperature (T) for rehydrated chickpeas (Fig. 7.8(a)) and soybeans (Fig. 7.8(b)). When the datasets for microwave and combined drying (i.e. MW ≥ 210 W) were considered, L* decreased significantly ($p < 0.01$) with increases in MW and T, for both chickpeas and soybeans. This indicates that significant darkening of samples occurred during drying, which increased as the applied microwave power was increased. However, when the colour data for T = 160 °C and MW ≤ 210 W were considered, L* for chickpeas was not significantly ($p > 0.1$) dependent on microwave power, while L* for soybeans actually increased ($p < 0.05$) as microwave power increased from 0 W to 210 W.

Total colour change (DE*) of rehydrated chickpeas (Fig. 7.9(a)) and soybeans (Fig. 7.9(b)) was also examined. When the datasets for microwave and combined drying (i.e. MW ≥ 210 W) were considered, DE* increased significantly ($p < 0.01$) with increases in MW and T, for both chickpeas and soybeans. However, when the colour data for T = 160 °C and MW ≤ 210 W were considered, DE* for both chickpeas and soybeans was not significantly ($p > 0.1$) dependent on microwave power.

Therefore, the addition of 210 W microwave power to air-drying at 160 °C would produce dehydrated chickpeas or soybeans in a fraction of the time required by air drying, without causing significant colour deterioration.

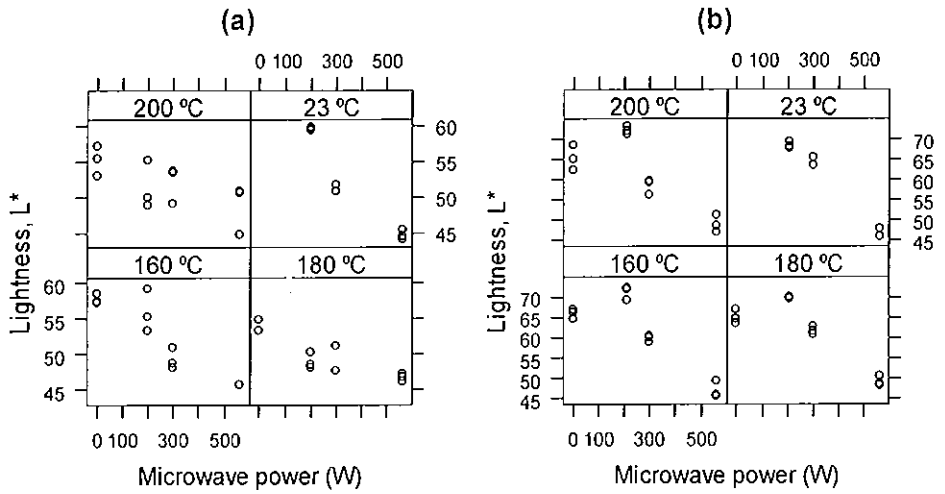


Fig. 7.8. Lightness (L*) as a function of microwave power and air temperature for rehydrated chickpeas **(a)** and soybeans **(b)**.

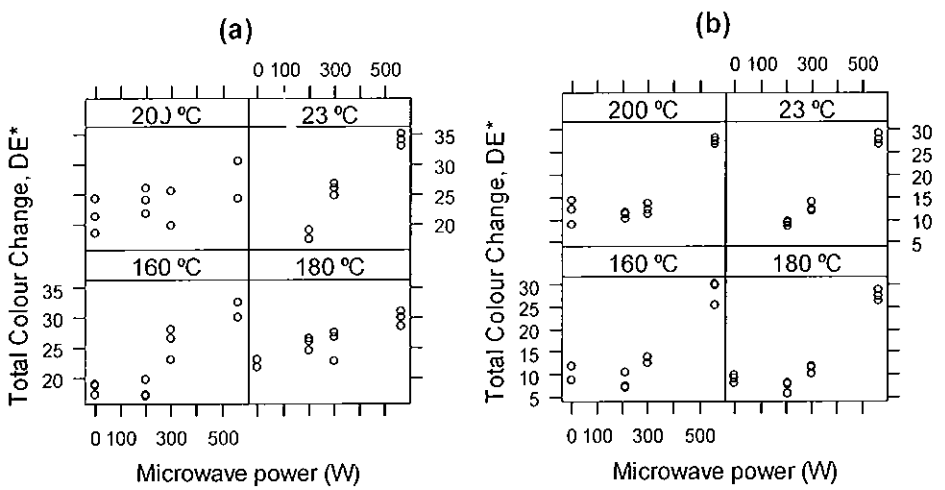


Fig. 7.9. Total colour change (DE*) as a function of microwave power and air temperature for rehydrated chickpeas **(a)** and soybeans **(b)**.

7.3.5 Evaluation of optimal drying conditions

Synthetic evaluation index (S), as presented in Eq. 7.1, was calculated for each of the drying methods examined (Table 7.8). The dehydration rate constant (k_d in

Eq. 7.1) was estimated by the product of Page constants k_p and n. For both chickpeas and soybeans, the drying method resulting the highest S-value was the lowest level of combination drying, i.e. MW = 210 W, T = 160 °C. This means that combination drying at this level is optimal (within the experimental range examined) in terms of rehydrated-product quality, while also producing a dehydrated product with relatively fast rehydration and dehydration properties.

Table 7.8. Synthetic evaluation index (S) for chickpeas and soybeans for each drying microwave power level (MW) and air temperature level (T) examined.

SAMPLE		CHICKPEAS	SOYBEANS
MW (W)	T (°C)	S	S
0	160	0.55± 0.05	0.55± 0.14
0	180	0.50± 0.05	0.51± 0.15
0	200	0.53± 0.12	0.48± 0.13
210	23	0.64 ± 0.07	0.59 ± 0.13
210	160	0.79 ± 0.07	0.80 ± 0.10
210	180	0.51 ± 0.07	0.78 ± 0.05
210	200	0.52 ± 0.05	0.73 ± 0.08
300	23	0.48 ± 0.15	0.59 ± 0.11
300	160	0.58 ± 0.08	0.68 ± 0.03
300	180	0.61 ± 0.02	0.7 ± 0.07
300	200	0.67 ± 0.10	0.71 ± 0.08
560	23	0.41 ± 0.10	0.34 ± 0.10
560	160	0.46 ± 0.05	0.42 ± 0.07
560	180	0.54 ± 0.15	0.43 ± 0.08
560	200	0.61 ± 0.24	0.40 ± 0.05

7.3.6 Effective diffusivity estimation

Estimation of effective diffusivity (D_{eff}) of water and water vapour through cooked chickpeas and soybeans during convective hot air drying, microwave drying and combined microwave-convective hot air drying was carried out by fitting the solution of Ficks 2nd law of diffusion for an infinite slab (see section 3.10.1.1) to the drying data. A similar method for estimating D_{eff} was used in describing the drying behaviour of green beans by Doymaz (2005), who used the first term of the series solution, which is equivalent to the Henderson-Pabis model (see section 3.10.2.1).

In the present case, the first 100 terms of the sum were calculated. D_{eff} (Fig. 7.10) was very large, ranging from 1.5 x 10^{-8} m^2/s to 1.9 x 10^{-7} m^2/s for chickpeas (Fig. 7.10(a)) and from 3.0 x 10^{-8} m^2/s to 1.8 x 10^{-7} m^2/s for soybeans (Fig. 7.10(b)), reflecting the rapidity of the drying, due to the high temperatures and microwave powers used. After careful inspection of a number of different candidate models, a linear model (Eq. 7.7) was chosen to describe the dependence of D_{eff} on microwave power and air temperature for both chickpeas and soybeans ($r^2 > 0.95$) (Table 6.9).

$$D_{eff} = a_D MW + b_D T \quad \ldots(7.7)$$

Table 7.9. Estimated regression coefficients for linear regression of Eq. 7.7 on chickpea and soybean effective diffusivity.

SAMPLE	a_D($W^{-1}.m^2.s^{-1}$)	b_D ($^oC^{-1}.m^2.s^{-1}$)	r^2
CHICKPEAS	1.5e-10 ± 1.3e-11	3.0e-10 ± 2.8e-11	0.97
SOYBEANS	2.2e-10 ± 8.9e-12	1.0e-10 ± 1.9e-11	0.95

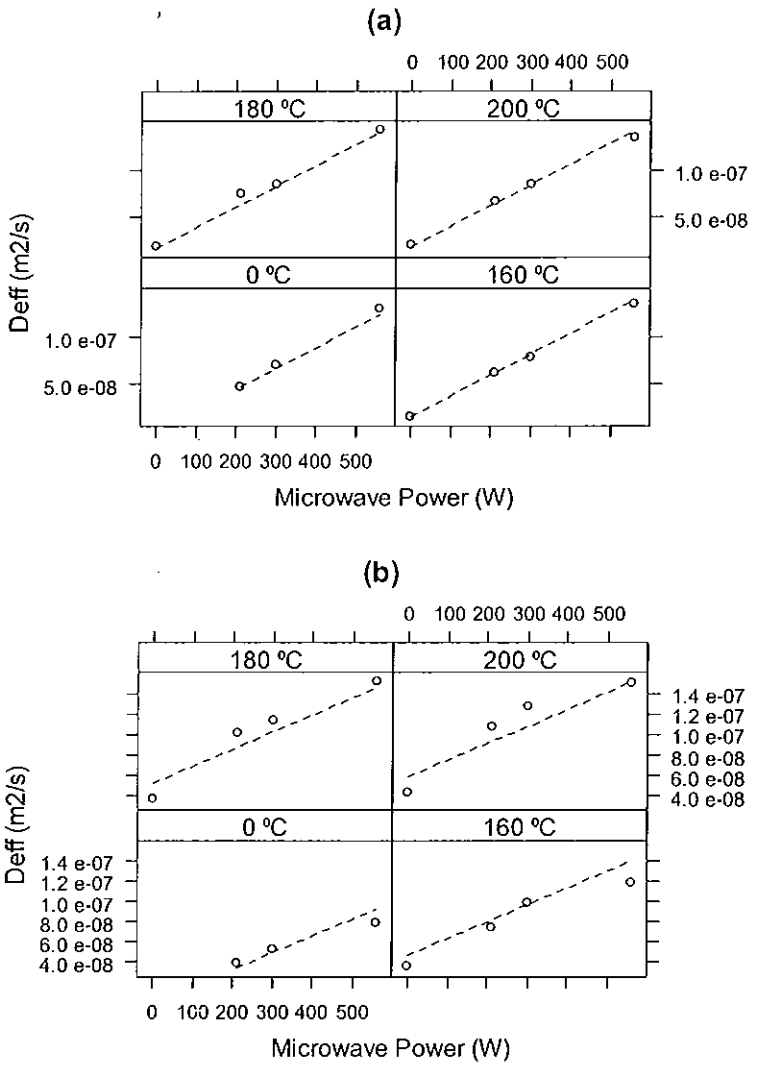


Fig. 7.10. Effective diffusivity (D_{eff}) as a function of microwave power and air temperature for drying of chickpeas (**a**) and soybeans (**b**).

7.4 Conclusions

Dehydration and rehydration kinetics of cooked chickpeas and soybeans were influenced by drying method, microwave power and air temperature. Combined microwave – convective hot air drying was up to four times faster, when

compared to convective drying alone and up to twice as fast, when compared to microwave drying alone. Lumped effective diffusivity of water and water vapour for the drying process increased in a linear fashion with microwave power and air temperature. Rehydration time for chickpeas and soybeans that underwent combined drying was 50-60% less than for legumes subjected to either convective or microwave drying alone. Total colour change of the rehydrated pulses generally increased with increasing levels of microwave power and air temperature, although the colour change was insignificant between convective drying at 160 °C and combined drying at 160 °C and 210 W. Simultaneous combination of microwave and convective drying at microwave power of 210 W and air temperature of 160 °C, resulted in a rehydrated product with optimal quality within the range of experimental conditions studied.

CHAPTER 8

OPTIMISATION OF PROCESS CONDITIONS FOR DEHYDRATION OF COOKED CHICKPEAS: LOW TEMPERATURE/MICROWAVE POWER PROCESSING

Comparative study of quality and structural changes occurring upon dehydration and rehydration of cooked chickpeas (Cicer Arietinum L.) subjected to combined microwave-convective hot-air dehydration and convective hot-air dehydration for air temperature 100 °C and microwave powers 100-200W

Some of the results from this chapter have been accepted for publication as a peer-reviewed article in the Journal of Food Science (see pages 289-292)

Summary

Convective hot air dehydration (100 °C) of cooked chickpeas was compared with combination hot-air microwave dehydration, in terms of microstructure, density, colour, texture, dehydration and rehydration kinetics. In the combined drying experiments, two levels of microwave energy (100 W & 200 W) were investigated, combined continuously with convective air-drying at 100 °C. Compared with convective hot-air drying, combination drying led to a considerable reduction in dehydration time. Combination drying also improved the porosity of the finished dehydrated product, leading to faster rehydration kinetics. Cold stage scanning electron microscopy (cryo-SEM) micrographs showed that chickpeas subjected to combined drying experienced less shrinkage than those dried by convective air currents. Combination drying at the higher (200 W) level produced a darker ($p < 0.05$) rehydrated product with significantly lower relative rehydrated moisture content ($p < 0.05$) when compared with the lower (100 W) level of combination drying. Effective diffusivity (D_{eff}) of water and water vapour through samples during the drying process, estimated by fitting a series solution of Ficks 2nd law of diffusion to the data, was compared with values obtained for higher temperature/microwave processing (Ch. 7), confirming the earlier finding that D_{eff} increased linearly with air temperature and microwave power.

8.1 Introduction

Experimental work presented in this chapter was carried out under the supervision of Dr. Jose Barat at the Department of Food Technology, in the Polytechnic University of Valencia, Spain, where the author had access to a pilot

scale oven, specifically designed to facilitate precise control of operating parameters (temperature, microwave power, air velocity) as well as on-line measurement of mass change during dehydration (Andres *et al.*, 2004). In the preceding chapter (Ch. 7), it was reported that pre-cooked chickpeas, dried by combined microwave-convective hot air at 160 °C and 210 W, had optimal quality, among the experimental range studied (160-200 °C; 210-560 W). In the present study, air temperature of 100 °C and microwave power levels 100 W and 200 W were chosen, in order to investigate the effects of lower temperature/microwave power on product quality. Bearing this in mind, the aims of this study were as follows:

1. Comparison of quality, drying kinetics and rehydration kinetics of cooked chickpeas subjected to combined microwave-convective hot air drying and convective hot air drying;
2. Investigation of the effects of processing treatments on product microstructure;
3. Comparison of results from drying experiments conducted in Ireland (high temperature/microwave processing; Ch. 7) with those conducted in Spain (low temperature/microwave processing).

8.2 Materials and methods

8.2.1 Material

Raw material is described in section 3.1. Preparation of samples for dehydration is described in section 3.4.

8.2.2 Drying equipment

All drying experiments were carried out in a specially designed hot air-microwave oven, equipped with adjustable-temperature/velocity convective mode and adjustable-power continuous-output microwave mode (Fig. 8.1).

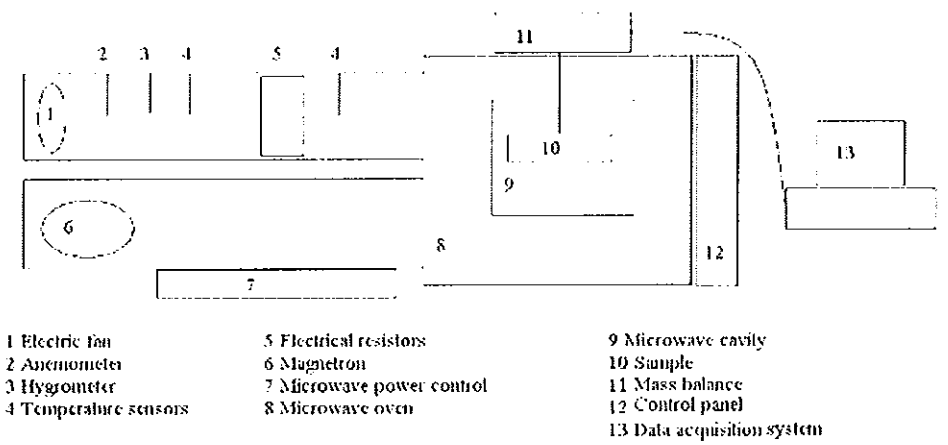


Fig. 8.1. Drying equipment used in dehydration experiments.

8.2.3 Experimental design

Three drying regimes were investigated:

(1) *Convective drying:* Convective air temperature was set to 100 °C.

(2) *Combined Convective-Microwave drying (Level 1):* Microwave power was set to 100 W and convective air temperature was set to 100 °C.

(3) *Combined Convective-Microwave drying (Level 2):* Microwave power was set to 200 W and convective air temperature was set to 100 °C.

Air velocity was set at 1.6 ± 0.1 m/s (measured at a fixed location inside the air inlet) in all experiments, representing an average of the values found in the literature (Khraisheh *et al.*, 2004; Cui *et al.*, 2003; Ruíz Díaz *et al.*,2003).

Laboratory air temperature was 23 ± 2 °C and its relative humidity was measured to be 49 ± 2 % during drying experiments.

8.2.4 Dehydration procedure

40 g cooked chickpea sample was placed inside the oven cavity, in a plastic mesh container suspended from a balance attached to a PC, allowing for continuous weighing of the sample during drying. Samples were dried to approximately 0 % moisture content (d.b.) to enable kinetic modelling of dehydration and rehydration processes. Each experiment was performed in triplicate, in a random order.

After dehydration, samples were stored in sealed bags over a desiccator, in darkness, at 23 ± 2 °C, for further analysis. Storage of dehydrated chickpeas was never longer than 7 days before rehydration experiments.

8.2.5 Moisture content determination

Moisture content was determined before drying, after drying and after rehydration by drying in a vacuum oven at 60 °C until constant weight was achieved (AOAC, 2000).

8.2.6 Calculation of moisture ratio

Moisture ratio calculation is described in section 3.7.

8.2.7 Apparent density measurement

Apparent density of dehydrated chickpeas was measured using a glass pycnometer containing olive oil (in principle, any oil of uniform density could be used). Density of 5 dehydrated chickpeas was measured for each drying regime.

Pycnometer volume (V_p) was calculated (in cm^3) from Eq. 8.1, where m_p is the mass of the empty pycnometer (in g) and m_{p+w} is the mass (in g) of the pycnometer when completely filled with distilled water.

$$V_p = \frac{(m_{p+w} - m_p)}{1} \quad ...(8.1)$$

Olive oil density (ρ_o (in g/cm^3)) was then calculated from Eq. 8.2, where m_{p+o} is the mass (in g) of the pycnometer when completely filled with olive oil.

$$\rho_o = \frac{m_{p+o} - m_p}{V_p} \quad ...(8.2)$$

A dehydrated chickpea of known mass (m_{cp} (in g)) was then added to the oil filled pycnometer (excess oil was allowed to pour out and pycnometer surface was carefully cleaned), which was then weighed (m_{p+o+cp} (in g)) and the volume of oil displaced (V_{cp} (in cm^3)) was calculated (Eq. 8.3).

$$V_{cp} = V_p - (m_{p+o+cp} - m_p - m_{cp})\rho_o^{-1} \quad ...(8.3)$$

Chickpea apparent density (ρ_{cp} (in g/cm^3)) was then calculated from Eq.8.4.

$$\rho_{cp} = \frac{m_{cp}}{V_{cp}} \quad ...(8.4)$$

8.2.8 Rehydration procedure

Rehydration procedure is described in section 3.8. Relative rehydrated moisture content (RRM) was calculated from Eq. 8.5 by dividing the moisture content of the rehydrated sample (M_r), by the moisture content of the cooked sample (M_c).

$$RRM = \frac{M_r}{M_c} \quad ...(8.5)$$

8.2.9 Colour measurement

The surface colour of five individual rehydrated samples for each drying treatment was measured. Colour measurement apparatus is described in section 3.9.

8.2.10 CryoSEM observations

Microstructure of dry, blanched, soaked, cooked, dehydrated and rehydrated chickpeas was examined using a cryogenic scanning electron microscope (CryoSEM). Cooked samples were dried to 2.6 ± 0.4 % moisture content (w.b.), by applying different drying conditions (convective drying: 480 min @ 100 °C, combined convective-microwave drying: 70 min @ level 1; 40 min @ level 2) to observe the effect of drying treatment on microstructure. Dehydrated samples were rehydrated, in boiling distilled water to 62 ± 1 % moisture content (w.b.), to observe the effect of drying treatment on microstructure of rehydrated samples (rehydration times: convective dried sample 50 min, combined convective-microwave drying (level 1 & level 2): 30 min). Samples were fractured, using a microtome blade, from the middle part of the central chickpea cross sectional axis, attached to the specimen holder of a CT-1000C Cryo-transfer system

(Oxford Instruments, Oxford, UK), interfaced with a JEOL JSM-5410 scanning electron microscope (SEM), and frozen in slush nitrogen. The sample was then fractured and transferred from cryostage to the microscope sample stage, where the condensed surface water was sublimed by controlled warming to −85 °C. Afterwards, the sample was transferred again to the cryostage in order to gold coat it by sputtering. Finally the sample was put back to the microscope sample stage to be viewed at an accelerating voltage of 10 keV and at different magnifications. Three images were acquired at different locations on the sample for each magnification level studied (x150, x500, x2000).

8.2.11 Texture measurement

For each drying regime investigated, the texture of 10 randomly selected rehydrated samples was evaluated. Equipment for texture measurement is described in section 3.3. Each sample was compressed to 10 % of its original thickness. The method of texture evaluation used in the present study was a 1-cycle test, adapted from the method described by Bourne (1978). Hardness was defined as the average maximum force required to compress 10 samples, and was calculated as the peak force at first compression.

8.3 Results and discussion

8.3.1 CryoSEM observations of chickpeas prior to dehydration

Micrographs of dry chickpea (prior to soaking and cooking) displayed tightly packed cells, containing embedded (non-gelatinised) starch globules (Fig. 8.2(i)).

Upon blanching, the space between cells increased, due to rapid intake of water and expansion caused by high temperature blanching (Fig. 8.2(ii)). After soaking, the space between cells was observed to increase again, due to imbibing of water: starch granules were still in the non-gelatinised state, and cell walls were visibly intact (Fig. 8.2 (iii)). Major micro-structural changes were evident in the chickpea after cooking (Fig. 8.2(iv)). Starch fractions within cells became gelatinised, (due to high temperatures experienced during cooking) and cell wall damage was apparent, with evidence of some cell wall separation. Extra cellular spaces appeared to be filled with solutes that had leaked from cells during cooking probably as a consequence of cell wall damage.

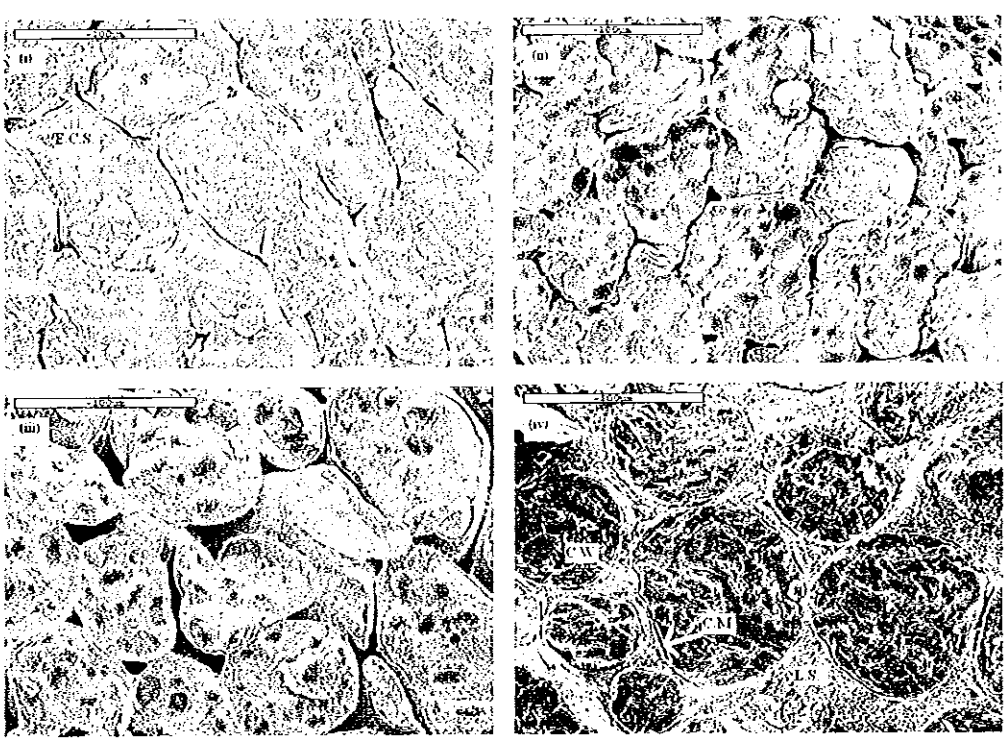


Fig. 8.2 CryoSEM images for dry **(i)**, blanched **(ii)**, soaked **(iii)**, cooked **(iv)**, chickpeas (S = starch globule, G.S. = gelatinised starch, E.C.S. = extra cellular space, C.W. = cell wall, C. M. = cell membrane, L.S. = leached solutes).

8.3.2 Drying rate curves

Drying rate curves for cooked chickpeas dried at lower temperature and microwave powers (Fig. 8.3) were similar in shape to those obtained at higher temperatures and microwave powers (Fig. 7.2), described in Ch.7.

For convective drying, an initial rise in drying rate was observed, until reaching a maximum value corresponding to moisture ratio between 0.8 and 0.9. This was followed by a falling rate period, during which drying rate decreased with decreasing moisture content. This behaviour is characteristic of the relationship between dehydration rate and moisture content for vegetables upon application of convective hot-air.

For combined microwave-convective drying, an initial rise in drying rate was observed, until reaching a maximum value corresponding to moisture ratio between 0.8 and 0.9. This was followed by a decrease in drying rate until reaching moisture ratio between 0.5 and 0.6, after which drying rate increased to a second peak value, corresponding to a moisture ratio between 0.3-0.5, which was followed by another decrease in drying rate with decreasing moisture content. These curves are comparable to those reported by Andres and co-workers (2004), who described the drying rate behaviour of apple slices. The second peak is probably due to the fast formation of a porous structure, upon vaporisation of water within the sample, caused by application of microwave power during drying (for further explaination, please see section 7.3.1).

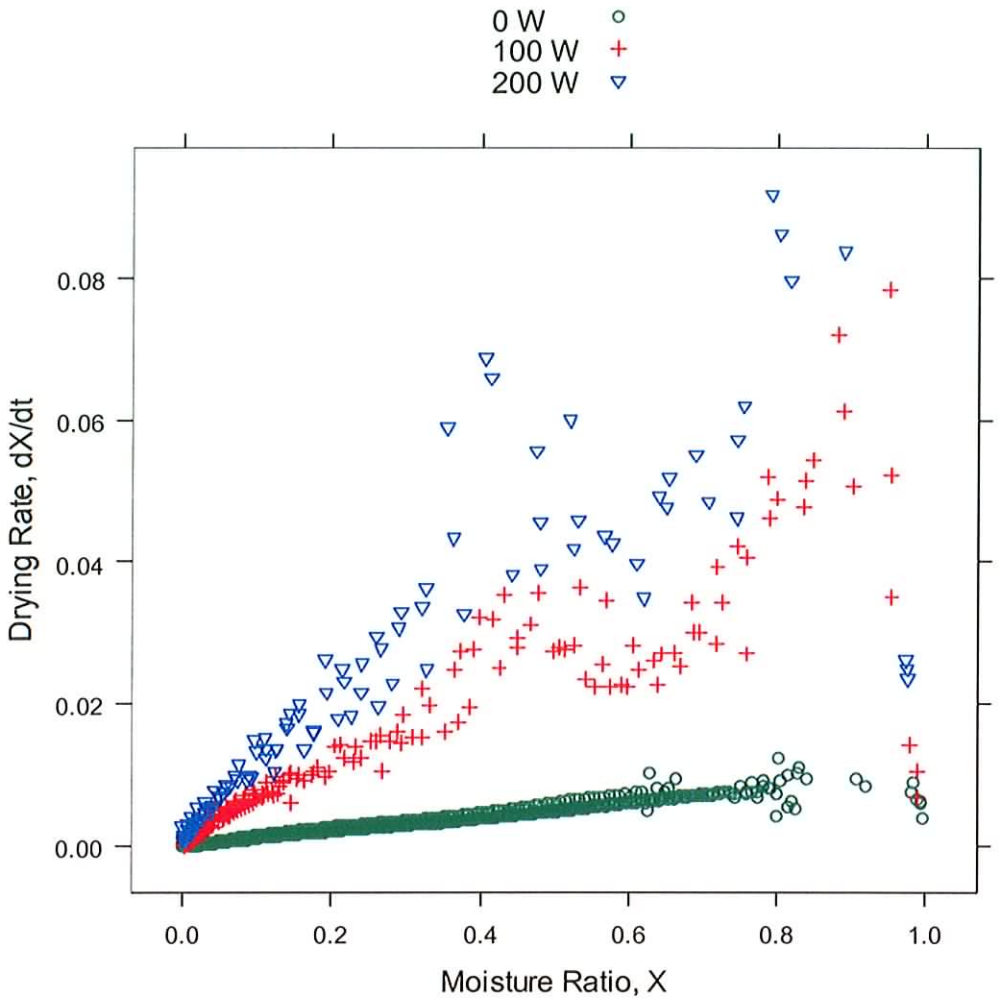


Fig 8.3. Drying rate behaviour for cooked chickpeas subjected to convective hot-air drying (100 °C) and combined microwave-convective hot-air drying (100-200W).

8.3.3 Dehydration kinetics

Pre-cooked chickpeas (moisture content = 64 ± 1 % w.b.) were dried until reaching constant weight, corresponding to approximately 0% moisture content. Moisture ratio (MR) was plotted against drying time (Fig. 8.4). Combining microwave power with hot air drying dramatically accelerated the drying process. Drying with hot air alone required up to 10 h to reach the constant phase, while combined drying at the highest level (200 W) took only 50 min.

Following the analysis of drying kinetics in Ch. 7, in order to predict MR as a function of microwave power and drying time, the Page model (Eq. 8.6) was fitted to the entire dataset (Table 8.2). Predictive curves were generated from Eq. 8.6 and fitted the experimental data well, as seen in Fig. 8.4.

$$MR = e^{-(a_p \lambda_i W) t^{n_p}} \quad ...(8.6)$$

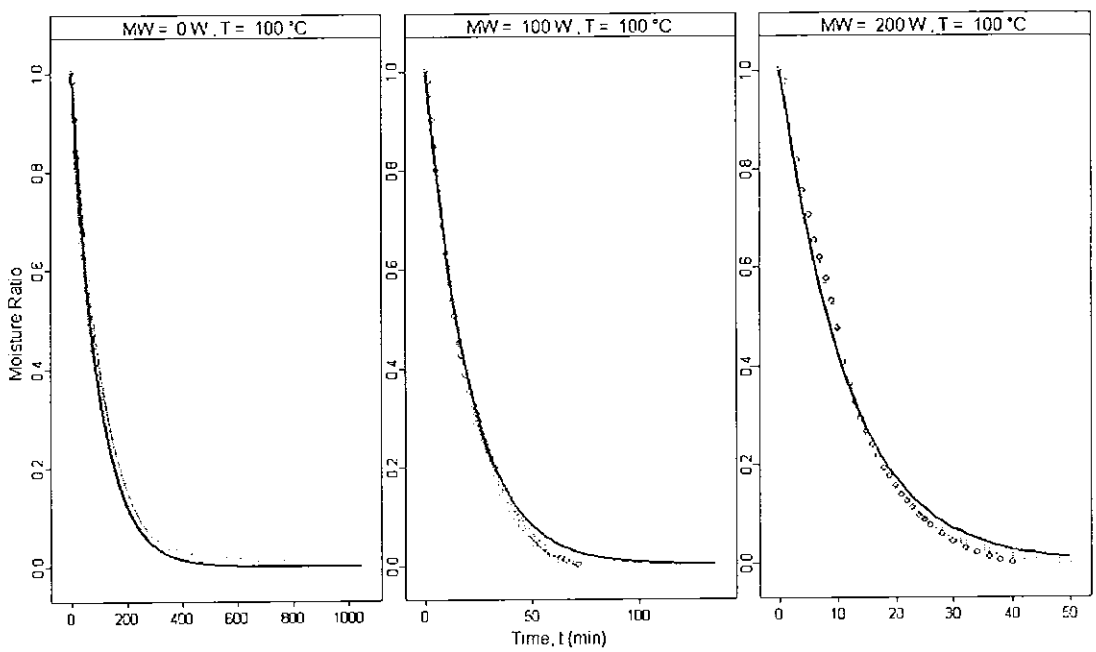


Fig. 8.4. Dehydration curves for chickpeas undergoing hot air and combined microwave-hot air drying.

Solid black line indicates predictive plot generated from Eq. 8.6.

8.3.4 CryoSEM observations of dehydrated chickpeas

Dehydration of cooked chickpeas caused their cells to shrivel and shrink, becoming amorphous glassy structures (Fig. 8.5(i)-(iii)). Leached solutes that were visible in the extra cellular spaces of cooked chickpea (Fig. 8.2(iv)) were no

longer present, having adhered to the cell surface during the drying process. Dehydrated structure was totally different to that of the dry chickpea before processing (Fig. 8.2(i)). For dehydrated samples (Fig. 8.5(i)-(iii)) non-gelatinised starch was not visible and cell structure was amorphous.

Air-dried chickpeas (Fig. 8.5(i)) displayed smaller cells that were more tightly packed than samples dried by microwave-air combination. Larger extra cellular spaces and cell sizes observed in combination-dried samples may have been due to high internal temperatures reached during microwave application: volumetric heating causes vaporisation of internal water, which in turn leads to expansion of the internal cell structure. Cell size and spacing did not seem to be substantially different when samples dried at 200 W (Fig. 8.5(iii)) and those dried at 100 W (Fig. 8.5(ii)) were compared.

Rapid drying of foods is generally associated with lower levels of shrinkage (Brennan, 1990). The substantial time difference between air drying (480 min) and combined drying (40-70 min) is reflected in the cryo-SEM observations: cellular shrinkage was more pronounced for air drying. The much-smaller difference in drying time between the 100 W (70min) and 200W (40min) levels of combined drying could explain why structural differences were not apparent between them.

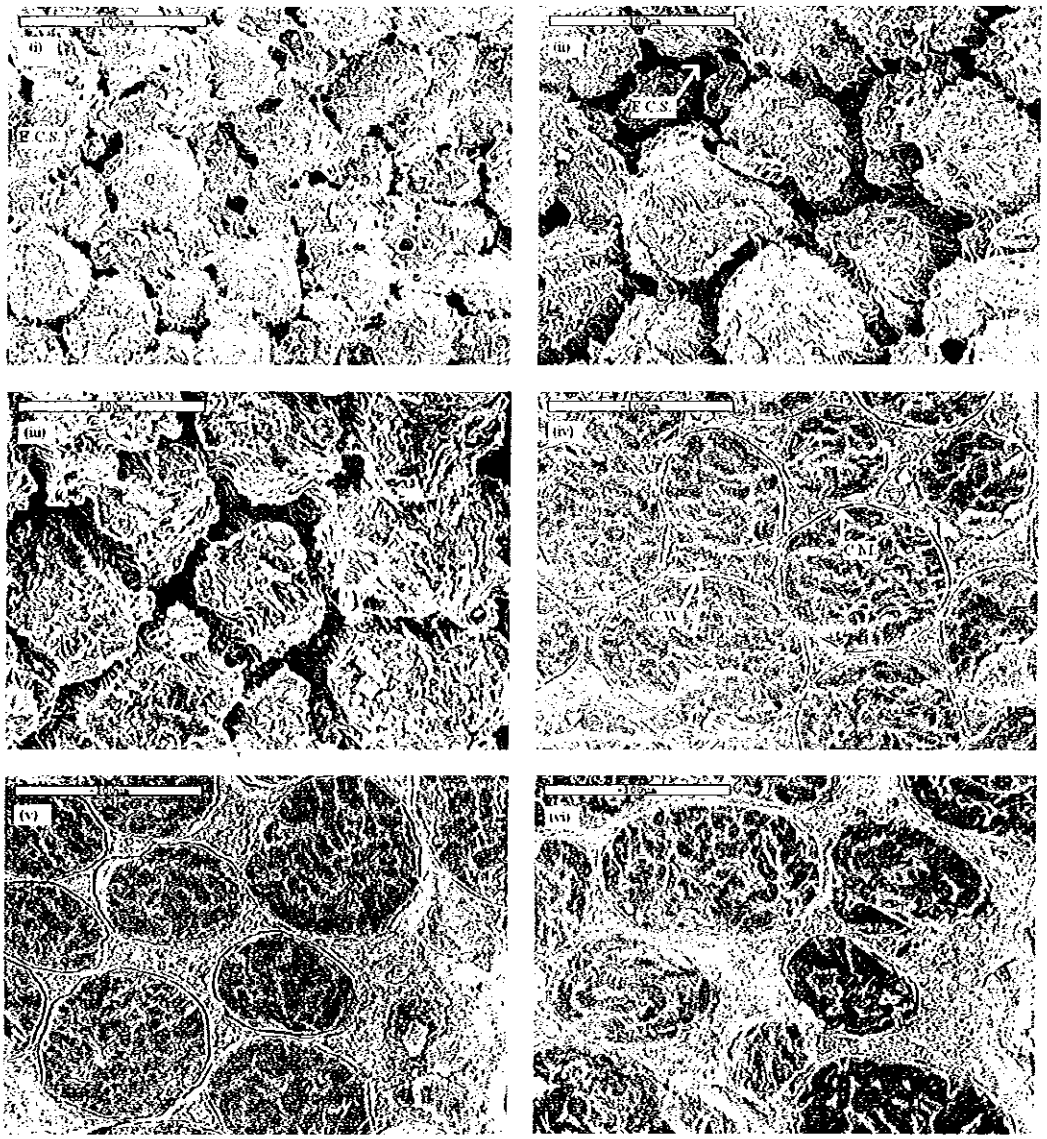


Fig. 8.5. CryoSEM images for dehydrated ((i) = air dried, (ii) combination dried at 100W, (iii) = combination dried at 200W) and rehydrated ((iv) = air dried, (v) combination dried at 100W, (vi) = combination dried at 200W) chickpeas (C = cell, G.S. = gelatinised starch, E.C.S. = extra cellular space, C.W. = cell wall, C. M. = cell membrane).

8.3.5 Apparent density of dehydrated samples

Air-dried chickpeas had significantly ($p < 0.05$) higher apparent density (ρ_{air} = 0.99 ± 0.06 g/cm^3), compared with combination-dried samples (Table 8.1). In the case of combination-dried samples, the differences in apparent density between those dried at the higher (200 W) microwave level (ρ_{200W} = 0.79 ± 0.05 g/cm^3) and those dried at the lower (100 W) microwave level (ρ_{100W} = 0.82 ± 0.06 g/cm^3) were statistically insignificant ($p > 0.05$). The density measurements therefore confirmed Cryo-SEM observations, in that air-dried chickpea cells were smaller in size and more closely packed than combination-dried samples. The compaction would influence the subsequent rehydration kinetics, as discussed below.

8.3.6 Rehydration kinetics

Rehydration curves (Fig. 8.6) show that weight gain on rehydration (WGR) increased asymptotically to an equilibrium value (WGR_e) for each of the drying conditions studied. Samples that had been dehydrated with hot air alone were slower, taking up to 60 min to reach equilibrium, than the combination-dried samples, which took up to 25 min. The shape of the rehydration curves led to the selection of an asymptotic model (Eq. 8.7) for modelling purposes, in a similar fashion to the method of modelling rehydration in the preceding chapter. Eq. 8.7 was fitted to the rehydration data by nonlinear regression.

$$WGR = WGR_e - WGR_e * e^{-k_r t} \quad ...(8.7)$$

Rehydration rate, k_r, was significantly ($p < 0.05$) faster for combined drying than for air-drying alone ($k_{r\_air} = 0.18 \pm 0.02$ min^{-1}) (Table 8.1). This is in agreement with the cryo-SEM observations, in that air-dried samples experienced more shrinkage during drying and were therefore slower to rehydrate. Although on average, k_r was slightly higher for the combined drying at the higher (200 W) microwave level ($k_{r\_200W} = 0.32 \pm 0.02$ min^{-1}), when compared to the lower (100 W) level ($k_{r\_100W} = 0.30 \pm 0.02$ min^{-1}), the difference was statistically insignificant ($p > 0.05$). Equilibrium weight gain on rehydration (WGR_e) was significantly ($p < 0.05$) smaller for samples dried at the 200 W level of combined drying ($WGR_{e\_200W} = 149.8 \pm 3.2$ % d.b.) when compared to the samples that underwent convective drying ($WGR_{e\_air} = 157.1 \pm 2.5$ % d.b.) or combined drying at the 100 W level ($WGR_{e\_100W} = 161.9 \pm 3.2$ % d.b.) (Table 8.1). Therefore the following general model (Eq. 8.8) was used to describe the rehydration kinetics as a function of rehydration time and drying method:

$$WGR = (WGR_e - I_{200W} * w_1) - (WGR_e - I_{200W} * w_1) * e^{-(k_{r,air} + I_{comb} w_2)t} \quad \ldots(8.8)$$

$$I_{200W} = \begin{cases} 1, \textit{for combined drying at } 200W \\ 0, otherwise \end{cases} ; I_{comb} = \begin{cases} 1, \textit{for combined drying} \\ 0, otherwise \end{cases}$$

Where the subscript *200W* refers to combined drying at 200 W, the subscript *air* refers to convective hot air drying, and the subscript *comb* refers to combined drying at either 100 W or 200 W. Eq. 8.8 was fitted to the entire data set by nonlinear regression (Table 8.2). The estimated rehydration rate constant, k_r, for air drying was 0.18 min^{-1}, while k_r for combined drying was 0.31 min^{-1}, indicating that the rehydration kinetics for chickpeas dried by combination of microwaves and convective hot air were more than 40 % faster than for those

subjected to air drying alone. Predictive curves were generated from Eq. 8.8, and fitted the experimental data adequately, as seen in Fig. 8.6.

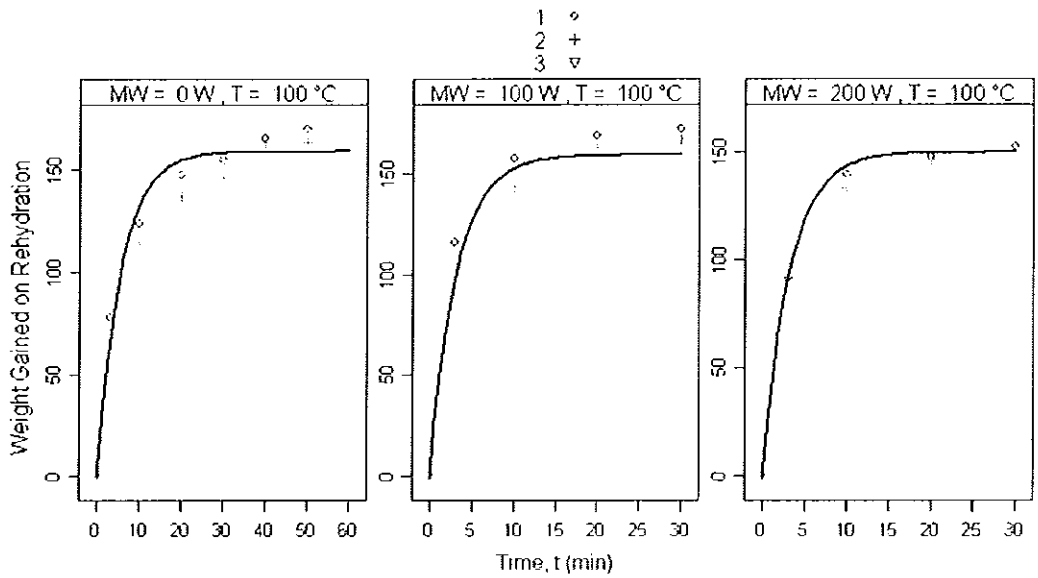


Fig. 8.6. Rehydration curves for chickpeas undergoing hot air and combined microwave-hot air drying. Sample replications are denoted by numbers above the plot. Solid black line indicates predictive plot generated from Eq. 8.6.

8.3.7 Rehydration ratio (RR) and relative rehydrated moisture content (RRM)

Rehydration ratio (RR) was significantly ($p < 0.05$) lower for chickpeas dried at the 200 W level ($RR_{200W} = 2.55 \pm 0.04$), when compared with those dried by combination at the 100 W level and those dried by hot air alone (Table 8.1). The difference between RR for air-dried samples ($RR_{air} = 2.67 \pm 0.04$) and that for combination-dried samples at 100 W ($RR_{100W} = 2.66 \pm 0.06$) was insignificant ($p > 0.05$). Analysis of variance showed that RRM for air-dried chickpeas was not significantly different to that for chickpeas dried by hot air - microwave combination at 100 W ($p > 0.05$). However, RRM for chickpeas that were

combination dried at the higher (200 W) microwave level was significantly ($p < 0.05$) lower than that for those dried using hot air alone, or the lower (100 W) level of combination drying (Table 8.1). Lower values of RR and RRM for chickpeas combination-dried at the 200 W level could be due to cellular damage caused by the rapid vaporisation of water upon application of high microwave power, affecting the chickpeas ability to retain water.

8.3.8 CryoSEM observations of rehydrated chickpeas

Rehydrated chickpeas that were dried using hot air alone (Fig. 8.5(iv)) and at the lower (100 W) level of combination drying (Fig. 8.5(v)) displayed microstructure strikingly similar to that of cooked chickpea (Fig. 8.2(iv)). Cell walls were clearly visible, gelatinised starch was contained within the cells and intracellular spaces were filled with leached solutes. However, for samples dried at the higher (200 W) level of combination drying (Fig. 8.5(vi)), some cell wall damage was apparent. The space between the cell wall and membrane (for those samples dried at 200 W) was not clearly visible, as it had been for cooked chickpeas (Fig. 8.2(iv)), rehydrated chickpeas that were dried using hot air alone (Fig. 8.5 (iv)), and at the lower (100 W) level of combination drying (Fig. 8.5(v)). It is hypothesised that the cell wall was damaged due to large internal forces exerted on cell during vaporisation of water, caused by the application of the higher (200 W) level of microwave power. This could have created cracks through which intracellular material leaked, filling the space between the cell wall and membrane and therefore adhering to the cell membrane. Such structural damage may have been responsiole for the lower rehydration ratio and relative rehydrated moisture content of the chickpeas that were dried at 200W.

8.3.9 Rehydrated texture

Average rehydrated hardness (H) was greatest for air-dried chickpeas (H_{air} = 24.9 ± 3.3 N), and lowest for combination dried chickpeas at the 200 W microwave level (H_{200W} = 22.2 ± 5.7 N) (Table 8.1). This may be related to case hardening, or the observation that air-dried samples had a higher apparent density than those dried by combination of microwave with convective drying. However, analysis of variance showed that differences in rehydrated texture between samples dried by each method examined in the study were insignificant at the 0.05 level ($p > 0.05$).

8.3.10 Rehydrated colour

Cooked chickpeas are light yellow in colour, which is represented by the following CIELAB values: L_0^* = 62.8 ± 1.4, a_0^* = 8.8 ± 1.4, b_0^* = 23.8 ± 3.2. Regardless of drying method, chickpeas experienced colour change during drying (Table 8.1). Rehydrated chickpeas dried at the higher (200 W) level of combined drying (L_{200W} * = 57.1 ± 2.4) were significantly ($p < 0.05$) darker than both those dried at 100 W (L_{100W} * = 61.5 ± 2.1) and those dried by hot air alone (L_{air}^* = 62.8 ± 3.2) (Table 3). However, chickpeas that were dried by hot air alone were not significantly ($p > 0.05$) lighter than those dried at the lower (100 W) level of combination drying. Loss of moisture is generally associated with loss of luminosity, so differences in luminosity may be related to RRM, which was significantly lower for chickpeas that were combination-dried at 200 W. Redness, represented by the a* value and yellowness, represented by the b* value were not significantly dependant upon drying method at the 0.05 level. Average total colour change (DE*) was least for chickpeas dried at the lower (100 W)

level of combined drying, although differences in DE* were insignificant at the 0.05 level.

8.3.11 Effective diffusivity estimation

Estimation of effective diffusivity (D_{eff}) of water and water vapour in cooked chickpeas during convective hot air drying and combined microwave-convective hot air drying was carried out by fitting the solution of Ficks 2nd law of diffusion for an infinite slab (see section 3.10.1.1) to the drying data. A similar method for estimating D_{eff} was used by Doymaz (2005), who used the first term of the series solution, which is equivalent to the Henderson-Pabis model (see 3.10.2.1). In the present study case, the first 100 terms of the sum were calculated.

D_{eff} values obtained from experiments carried out at low temperature/ microwave powers (in Spain, see Fig. 8.7) were compared with those obtained for drying at higher temperatures and microwave powers (in Ireland, see Ch. 7), as seen in Fig. 8.7. When no microwave power was applied (Fig. 8.7(a)), D_{eff} increased linearly with drying temperature ($r^2 > 0.98$). When microwave power was applied at the 200-210 W level (Fig. 8.7(b)), D_{eff} increased linearly with drying temperature ($r^2 > 0.93$). Moreover, D_{eff} increased linearly with increasing microwave power and air temperature ($r^2 > 0.99$) (Fig 8.7 (c)). This confirms the finding reported in Ch. 7 (see section 7.3.6), i.e. that D_{eff} increased in a linear fashion with both microwave power and air temperature, and that there was no significant interactive effect noticed when microwave and air drying were combined simultaneously.

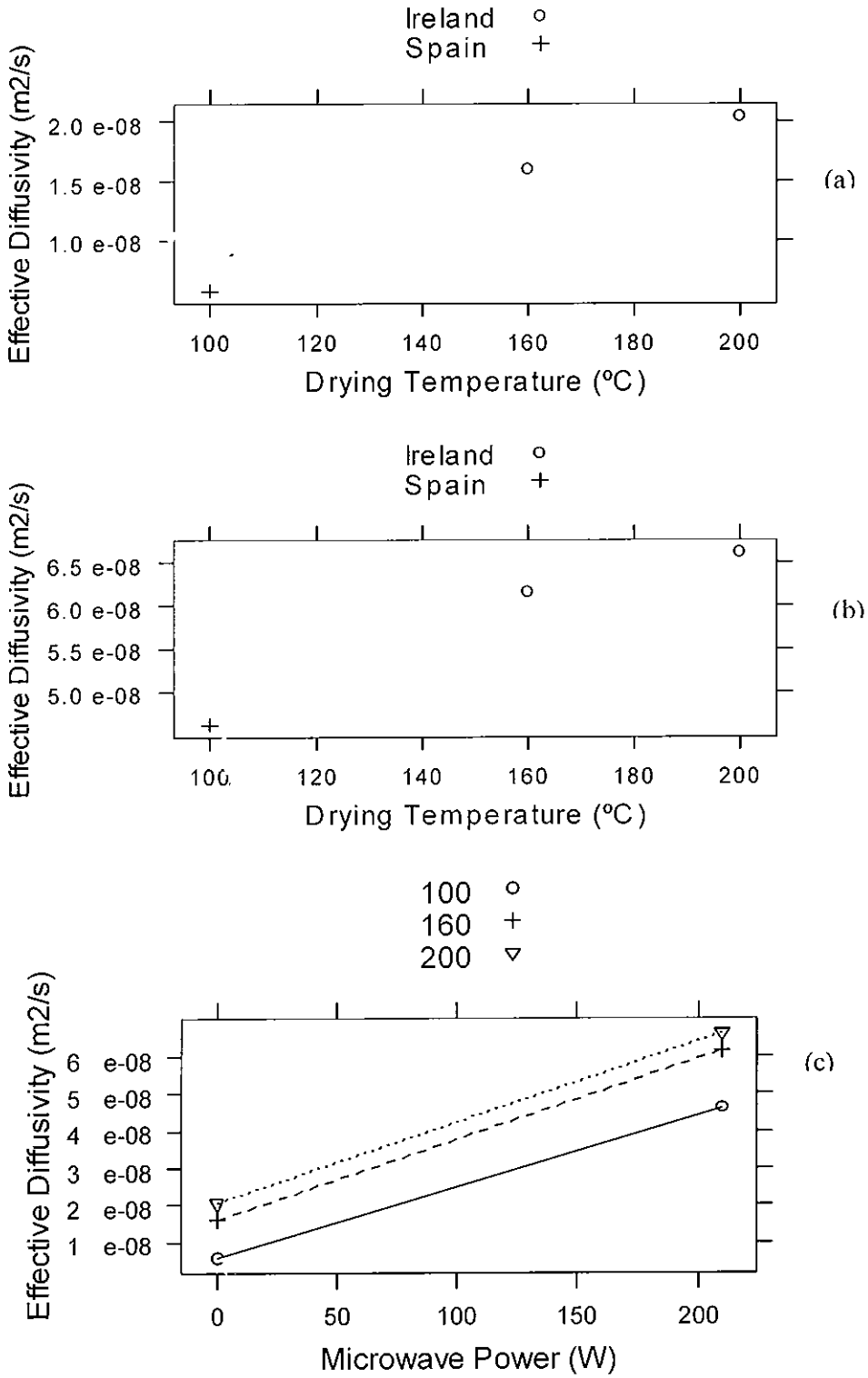


Fig. 8.7. Effective diffusivity (D_{eff}) as a function of drying temperature for convective drying **(a)**; combined drying at the 200-210 W level **(b)**; and Deff as a function of drying temperature and microwave power **(c)**.

Table 8.1. Apparent density (ρ (g/cm^3)), rehydration rate (k_r (min^{-1})), rehydration ratio (RR), relative rehydrated moisture content (RRM), hardness (H (N)) and colour parameters (L*, a*, b*, DE*) for dehydrated chickpeas undergoing hot air and combined microwave-hot air drying. Values within a column sharing the same letter are not significantly different ($p > 0.05$).

MW (W)	T (°C)	ρ(g/cm^3)	k_r (min^{-1})	RR	RRM	H (N)	L*	a*	B*	DE*
0	100	0.99 ± 0.06 a	0.18 ± 0.02 a	2.67 ± 0.04 a	0.98 ± 0.01 a	24.9 ± 3.3 a	62.8 ± 3.2 a	6.6 ± 1.2 a	17.2 ± 3.9 a	7.0 ± 2.1 a
100	100	0.82 ± 0.06 b	0.30 ± 0.02 b	2.66 ± 0.06 a	0.97 ± 0.02 a	22.4 ± 3.7 a	61.5 ± 2.1 a	6.9 ± 0.6 a	17.9 ± 2.3 a	5.6 ± 1.9 a
200	100	0.79 ± 0.05 b	0.32 ± 0.02 b	2.55 ± 0.05 b	0.94 ± 0.01 b	22.2 ± 5.7 a	57.1 ± 2.4 b	6.6 ± 0.6 a	15.2 ± 1.7 a	8.0 ± 2.1 a

Table 8.2. Estimated regression parameters for general models of dehydration (Eq. 8.6) and rehydration (Eq. 8.8) kinetics.

Dehydration kinetics model (Eq. 8.6)		Rehydration kinetics model (Eq. 8.8)	
Parameter	Values	Parameter	Values
a_d (min^{-1})	0.010371 ± 1.85E-05	WGR_e (% d.b.)	158.97 ± 1.90
b_d ($min^{-1}.W^{-1}$)	0.000383 ± 1.63E-06	w_1 (% d.b.)	8.96 ± 3.31
RSE	0.015	$k_{r,air}$ (min^{-1})	0.18 ± 0.01
AIC	-18134.7	w_2(min^{-1})	0.13 ± 0.02
BIC	-18116.4	RSE	8.49
LogLik	9070.36	AIC	375.84
		BIC	385.59
		LogLik	-182.92

8.4 Conclusions

Continuous application of microwave energy during air-drying of pre-cooked chickpeas was beneficial in terms of reducing the processing times required. Samples subjected to combined microwave – convective hot air drying could be dried in approximately 10 % of the time required by air dried samples and rehydrated within approximately 60 % of the time required by air dried samples. Combination of microwave energy with convective air-drying also resulted in a more porous dehydrated chickpea. Cryo-SEM observations and apparent density measurement confirmed that, compared with combination-dried samples, air-dried samples were denser, and accordingly less porous. Increasing microwave power from 100 W to 200 W accelerated the dehydration kinetics, but had an adverse effect on the rehydrated sample's ability to hold water and consequently on its luminosity. In terms of drying time, rehydration time, colour, texture and yield, the lower level (100 W) of combined microwave – convective hot air drying was the optimal drying method. Effective diffusivity values were in agreement with those obtained for higher temperature/microwave processing, demonstrating linear dependence on processing temperature and microwave power.

CHAPTER 9

QUALITY CHARACTERISTICS OF COOKED CHICKPEAS AND SOYBEANS DURING DRYING

Moisture content, shrinkage, water activity, colour and texture of cooked chickpeas and soybeans during microwave drying, convective hot air drying and combined microwave-convective hot air drying

Some of the results from this chapter are currently under review for publication in the Journal of Food Processing and Preservation (see pages 289-292)

Summary

Quality of cooked chickpeas and soybeans during convective, microwave and combined microwave-convective drying was studied. Moisture content, shrinkage, water activity, colour and texture of samples during drying was investigated. Combined microwave-convective hot air drying was significantly ($p < 0.05$) faster than either convective or microwave drying and resulted in lower overall shrinkage of the dehydrated product. Rapid burning occurred when samples were dried below a water activity of 0.27 ± 0.07 for chickpeas ($p < 0.05$) and 0.13 ± 0.04 for soybeans ($p < 0.05$). Samples displayed a transitional behaviour in texture when dried to a water activity below 0.40 ± 0.10 ($p < 0.05$) for chickpeas and below 0.63 ± 0.15 ($p < 0.05$) for soybeans, where samples became brittle. Shelf stable dehydrated chickpea and soybean products with stable water activity ($a_w = 0.35$) and good visual quality could be obtained within 14 min combination drying.

9.1 Introduction

In Ch. 7, the drying of cooked chickpeas and soybeans was examined in terms of microwave power and air temperature. Within the range of experimental conditions studied (for high temperature/microwave power processing), rehydrated product quality was optimal for combined drying at 160 °C and 210 W. However, the process was not optimised in terms of the amount of drying time required.

Fresh legumes are usually dried to a final moisture content of 10-15% (d.b.), for commercial purposes (Hnatowich, 2000). It would be possible to choose the 10% (d.b.) level as a target moisture level for drying and then predict to the amount of time required to reach this level, from the drying models that were developed in Ch.7. However, the storage stability of pre-cooked dehydrated chickpeas and soybeans at this level of moisture content would not be certain.

In the present study, quality during dehydration was measured in terms of moisture content, water activity, shrinkage, colour and texture. Consequently, the main objectives of this chapter were as follows:

1. To measure the quality characteristics of cooked chickpeas and soybeans during drying;
2. To apply mathematical models to predict quality changes during drying;
3. To estimate the drying time required to produce shelf-stable products with optimal quality.

9.2 Materials and methods

9.2.1 Material

Raw material is described in section 3.1. Preparation of samples for dehydration is described in section 3.4.

9.2.2 Drying equipment

Drying equipment is described in section 3.5.

9.2.3 Experimental design

Three types of drying were studied:

(1) *Convective drying.* The oven was set to convective mode at 160 °C (air velocity = 1 m/s),

(2) *Microwave drying.* The oven was set to microwave mode at 210 W (natural convection (ambient temperature = 23 °C)).

(3) *Combined Convective-Microwave drying.* The oven was set to combination mode, with air temperature set to 160 °C (air velocity = 1 m/s) and microwave power at 210 W.

9.2.4 Dehydration procedure

20 g samples were dried for a specified time, depending on the drying method used: total drying time in each case was based on data from Ch. 7. After drying for a specified amount of time (Table 9.1), they were removed from the oven, and were stored in sealed bags over silica gel in a desiccator in darkness at 24 ± 1 °C for further analysis.

Each experiment was performed in triplicate, in a random order, and storage prior to analysis took no longer than 2 days.

Table 9.1. Sampling points (in min) for convective (Air), Microwave (MW) and combined (Comb) dehydration experiments.

Chickpeas			Soybeans		
Air	MW	Comb	Air	MW	Comb
0	0	0	0	0	0
11	5	1	11	5	1
21	11	3	21	11	3
25	17	5	32	17	5
32	21	7	40	21	6
40	25	9	50	25	9
50	32	12	60	30	12
60	35	15	70	35	14
70		17	80		15
		18			16

9.2.5 Moisture content determination

Determination of moisture content during drying (% w.b.) is described in section 3.6.

9.2.6 Apparent volume measurement

For evaluation of apparent volume during dehydration, the experiments described in Table 9.1 were repeated separately. Volume of five randomly selected samples was measured by the method of displacement of water. Measurement time was less than 15 seconds, to minimise water absorption (Maskan, 2001). Bulk shrinkage coefficient (S_b) was calculated (Eq. 9.1) as the ratio of sample volume (V) during drying to initial volume (V_0) (Khraisheh *et al.*, 2004).

$$S_b = \frac{V}{V_0} \qquad \ldots(9.1)$$

9.2.7 Water activity measurement

Water activity of dried samples, after storage in dessicator containing silica gel for 24-48 h at 24 ± 1 °C, was measured using an Aqualab Series 3 water activity meter for food quality. All water activity measurements were recorded at 24 ± 1 °C.

9.2.8 Colour measurement

The colour of crushed and then blended samples was measured at each sampling point during drying. Colour measurement apparatus is described in section 3.9.

9.2.9 Texture evaluation

At each sampling point, the texture of 10 samples was evaluated. Beans were compressed to 10 % of their original thickness (see section 8.2.11). Equipment for texture measurement is described in section 3.3.

9.3 Results and discussion

9.3.1 Moisture content during drying

For each of the drying methods examined, moisture content (M) decreased asymptotically with drying time (t) to an equilibrium value very close to zero (Figs 9.1 & 9.2). Drying was slowest for hot air drying, taking 50 – 60 min to

reach equilibrium. Compared with hot air drying, microwave drying alone resulted in up to 50 % reduction in drying time, taking 25 – 30 min. Overall, the method of combined microwave – hot air drying was fastest, taking just 15 – 17 min to dry samples to a constant weight. Based on the findings in Ch. 6-7, the Page model (Eq. 9.2) was chosen for primary modelling, to investigate the dependence of moisture content on drying time.

$$M = M_0 e^{-k_p t^{n_p}} \quad ...(9.2)$$

M_0 represents the initial moisture content for cooked samples, which was measured as 63 ± 1 (% d.b.) for chickpeas and 66 ± 1 (% d.b.) for soybeans.

Page constants, k_p and n_p, were estimated for each drying method by nonlinear regression of Eq. 9.2 on the data (see Table 9.2). Page constant k_p was significantly ($p < 0.05$) lower for convective drying than for combined or microwave drying. Page constant n_p was significantly lower for microwave drying than that for combined or convective drying (Table 9.2), which is in accordance with the findings from Ch. 7.

The product of k_p and n_p, which is related to the dehydration rate, was significantly greater for combined drying than either microwave or convective drying, and was significantly greater for microwave drying than for convective drying, for both chickpeas and soybeans (Table 9.2).

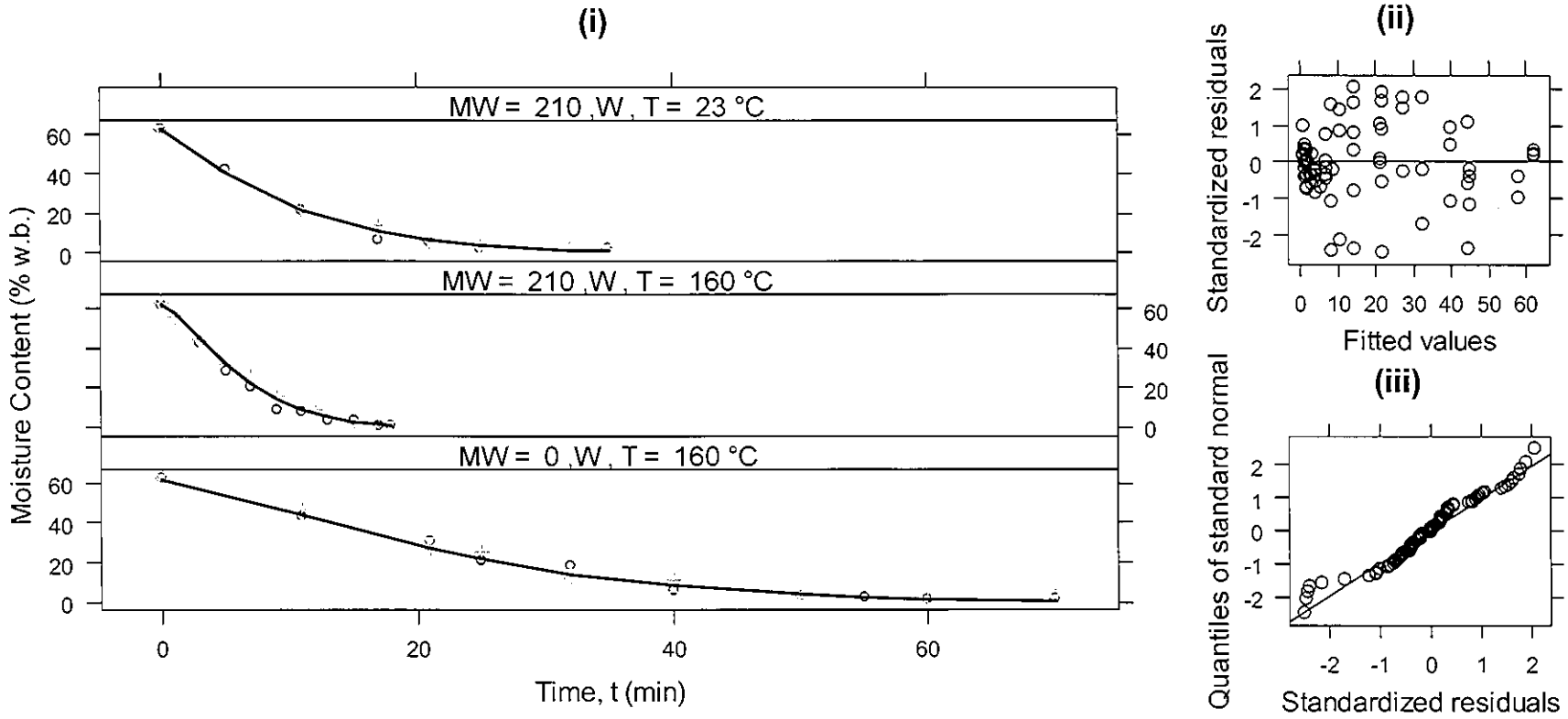


Fig. 9.1. Moisture content (M, % w.b.) as a function of drying method and drying time for cooked chickpeas(i) *solid lines indicate predictive plots for nonlinearregression of Eq. 9.3 on chickpea dehydration data.* Residual (ii) and quantile-quantile (iii) plot for nonlinear regression of Eq. 9.3 on chickpea dehydration data alsoshown.

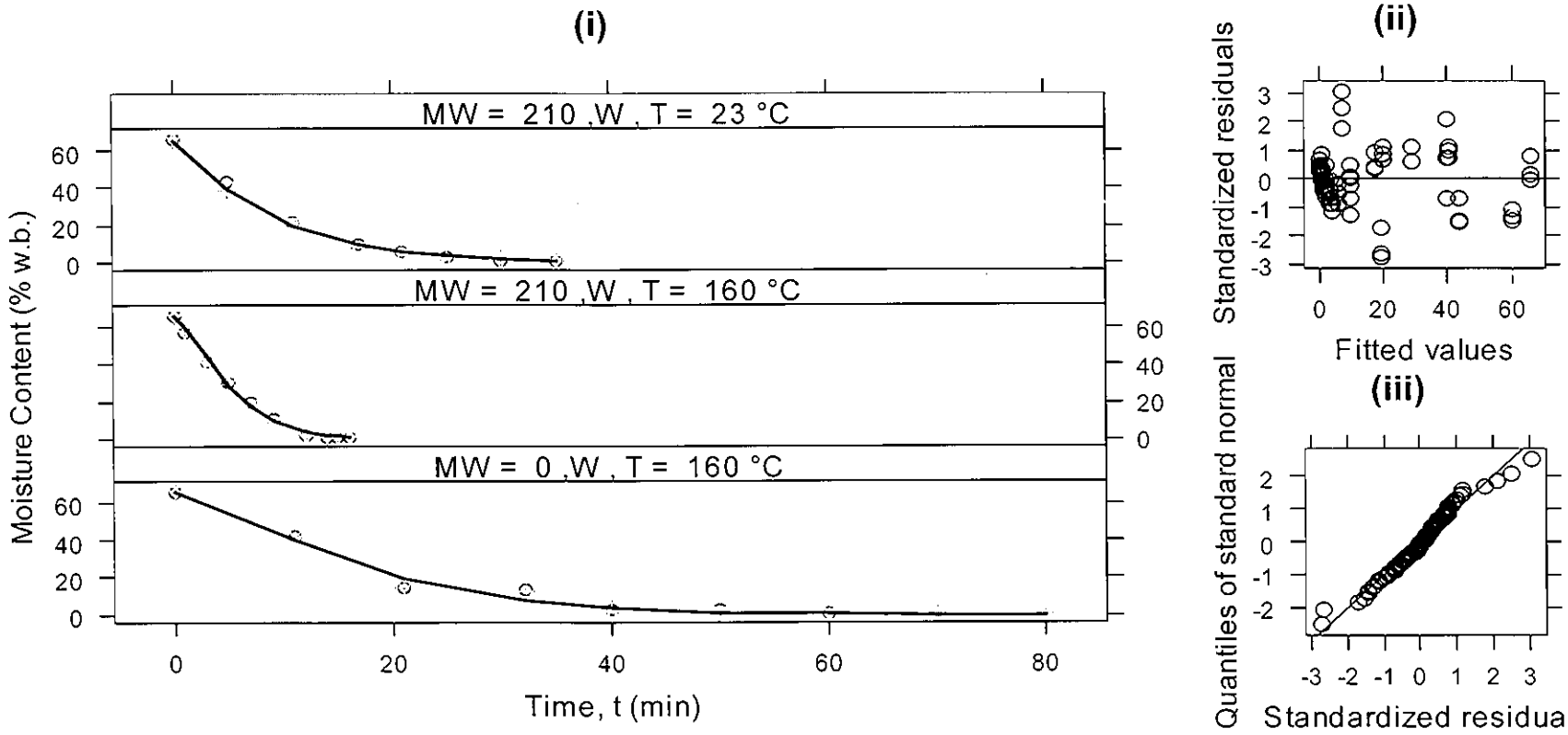


Fig. 9.2. Moisture content (M, % w.b.) as a function of drying method and drying time for cooked soybeans (i). *Solid lines indicate predictive plots for nonlinear regression of Eq. 9.3 on soybean dehydration data.* Residual (ii) and quantile-quantile (iii) plots for nonlinear regression of Eq. 9.3 on soybean dehydration data also shown.

Table 9.2. Page constants for cooked chickpeas and soybeans undergoing convective, microwave and combined microwave-convective drying. Values within a column sharing the same letter are not significantly different.

Sample	Drying method	Page k_p (min^{-np})	Page n_p	k_p*n_p (min^{-1})
Chickpeas	Convective	0.012 a	1.39 a	0.02 a
	Microwave	0.067 b	1.17 b	0.08 b
	Combined	0.071 b	1.38 a	0.10 c
Soybeans	Convective	0.018 a	1.31 a	0.02 a
	Microwave	0.068 b	1.17 b	0.08 b
	Combined	0.082 b	1.37 a	0.11 c

Based on the behaviour of the Page-model constants, k_p and n_p, described above, the following model was proposed to describe M for both chickpeas and soybeans as a function of drying time and drying method:

$$M = M_0 e^{-(k_{P1} - I_T * k_{P2}) t^{n_{P1} - I_{MW} * n_{P2}}} \quad ...(9.3)$$

Where I_T = 1 for convective drying, and zero otherwise, and I_{MW} = 1 for microwave drying and zero otherwise. Eq. 9.3 was regressed on each of the datasets, and the model parameters were estimated (Table 9.3).

Predictive plots were generated from the model, which adequately described the drying data (Figs 9.2(i) & 9.3(i)). The standardised residual plots (Figs 9.2(ii) & 9.3(ii)) for Eq. 9.3 regressed on the chickpea and soybean drying data showed that most residuals were within 2 standardised residuals, indicating reasonable model fit.

Table 9.3. Estimated regression parameters from nonlinear regression of Eq. 9.3 on cooked chickpea and soybean dehydration data.

	Chickpeas	Soybeans
M_0 (% d.b.)	62.03 ± 0.67	65.53 ± 0.59
k1 (min-1)	0.070 ± 0.006	0.087 ± 0.006
k2 (min-1)	0.058 ± 0. 005	0.070 ± 0. 005
n_{p1}	1.39 ± 0.05	1.40 ± 0.04
n_{p2}	0.25 ± 0.02	0.31 ± 0.02

9.3.2 Apparent volume change during drying

Drying of foods usually results in shrinkage, due to water loss. Soybeans shrank during drying, to reach a final apparent volume less than 50% of their original apparent volume, corresponding to a bulk shrinkage coefficient value of 0.46 ± 0.04 (Fig. 9.3). Chickpeas shrank to a lesser extent, reaching a final apparent volume of around 60% of their original apparent volume, corresponding to a bulk shrinkage coefficient value of 0.63 ± 0.07 (Fig. 9.3).

For each of the drying methods examined, the bulk shrinkage coefficient, S_b, decreased exponentially with drying time to a constant value (Fig. 9.3). Therefore, the following first-order asymptotic model was chosen to describe the shrinkage kinetics:

$$S_b = S_{be} + (S_{b0} - S_{be})e^{-k_s t} \qquad \ldots(9.4)$$

Where S_{b0} represents initial bulk shrinkage ratio, S_{bc} represents asymptotic bulk shrinkage ratio and k_s represents the bulk shrinkage rate constant.

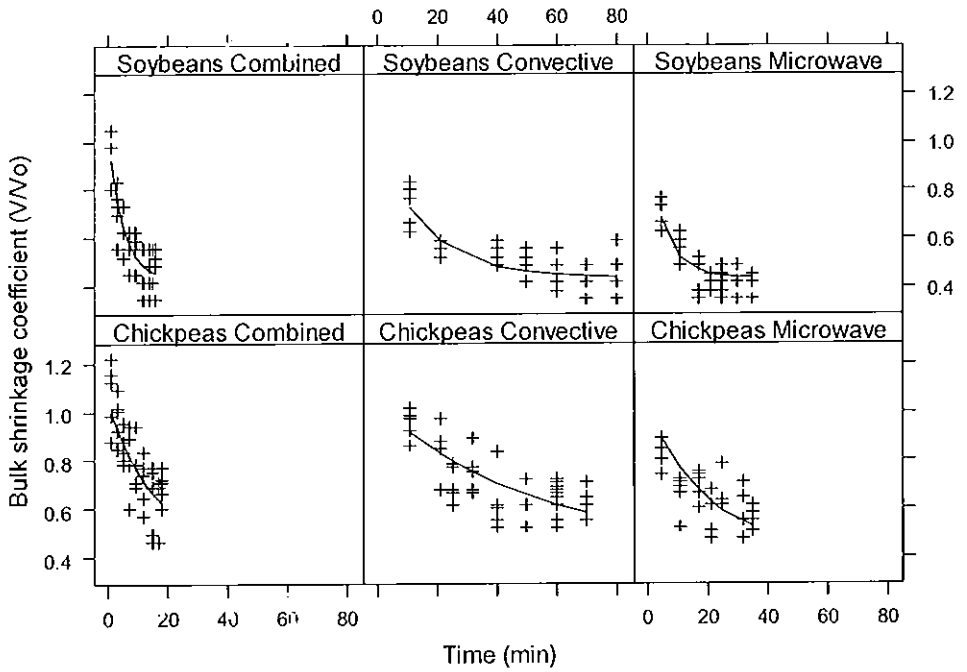


Fig. 9.3. Bulk Shrinkage coefficient (S_b) as a function of drying method and drying time for dehydration of cooked chickpeas and soybeans; solid lines indicate predictive plots for nonlinear regression of Eq. 9.4 on data.

The bulk shrinkage rate constant, k_s, was estimated by nonlinear regression of Eq. 9.4 on the data (Table 9.4). For both chickpeas and soybeans, k_s was greatest for combination drying, ($k_{s\_cp\_Comb}$= 0.16 ± 0.05, $k_{s\_sb\_Comb}$= 0.27 ± 0.06), and lowest for hot air drying ($k_{s\_cp\_Air}$= 0.06 ± 0.02, $k_{s\_sb\_Air}$= 0.07 ± 0.03). Microwave drying resulted in an intermediate k_s value ($k_{s\_cp\_MW}$= 0.13 ± 0.07, $k_{s\_sb\_MW}$= 0.14 ± 0.05). This result was expected, as combined drying resulted in the fastest drying (see section 9.3.1) and therefore should result in the fastest shrinkage rates.

The asymptotic bulk shrinkage ratio, represented by S_{be}, was, on average, greatest for combination-dried samples ($S_{be\_cp\_Comb}$ = 0.69 ± 0.06, $S_{be\_sb\_Comb}$ =

0.50 ± 0.09), and smallest for microwave-dried samples ($S_{be\_cp\_MW}$ = 0.56 ± 0.04, $S_{be\_sb\_MW}$ = 0.41 ± 0.04). Convective-dried samples had an intermediate average S_{be} value ($S_{be\_cp\_Air}$ = 0.63 ± 0.06, $S_{be\_sb\_Air}$ = 0.47 ± 0.09). Therefore, on average, convective drying resulted in more overall-shrinkage than combined drying, which is in agreement with the findings from Ch. 8. However, even more shrinkage occurred for samples that were dried by microwave power only. This was similar to the observation of Maskan (2001), who suggested that rapid shrinkage of kiwis undergoing microwave drying was due to extensive heat generation, accelerating the removal of water during microwave heating. S_{be} for soybeans subjected to microwave drying was significantly lower ($p < 0.05$) than that for soybeans subjected to either convective or combined drying. However, the differences in S_{be} for chickpeas among drying treatments were statistically insignificant ($p > 0.05$), probably due to the large variability among measurements (Fig. 9.3).

Predictive curves generated from the estimated model parameters (Fig. 9.3) indicated that Eq. 9.4 gave a good representation of the average behaviour of bulk shrinkage coefficient during drying. The drying time after which changes in volume became insignificant (t_{eq}) was estimated from Eq. 9.4 for each of the drying methods examined (Table 9.4). It was observed that sample volume became fixed before the end of the drying process: for example, chickpea volume ceased to change significantly ($p > 0.05$) after just 11 min combined drying. This may be due to the onset of glass transition during drying, after which changes in volume are expected to be minimal, since the legume sample had entered a state of low deformability.

Table 9.4. Asymptotic bulk shrinkage coefficient (S_{be}), shrinkage rate constant (k_s) and time at which changes in S_b became insignificant (t_{eq}) for drying of chickpeas and soybeans.

Sample	Drying method	S_{be} ± std. error	k_S ± std. Error	t_{eq} (min)
Chickpeas	Combined	0.69 ± 0.06	0.16 ± 0.05	11
	Microwave	0.56 ± 0.04	0.13 ± 0.07	15
	Convective	0.63 ± 0.06	0.06 ± 0.02	39
Soybeans	Combined	0.50 ± 0.09	0.27 ± 0.06	9
	Microwave	0.41 ± 0.04	0.14 ± 0.05	17
	Convective	0.47 ± 0.09	0.07 ± 0.03	35

9.3.3 Water activity during drying

The water activity (a_w) of dry samples (measured prior to blanching, soaking and cooking) was 0.54 ± 0.01 for chickpeas, and 0.67 ± 0.01 for soybeans. After soaking and cooking, the water activity of both chickpeas and soybeans was measured to be 0.99 ± 0.01. During the early stages of drying, water activity was almost constant (Fig. 9.4), close to 0.99. Towards the end of drying, at a certain time (dependant on drying method), a rapid decrease in a_w to a value between 0.2 and 0.4 was observed. Further drying caused a_w to decrease slowly to a minimum value less than 0.2 (Fig. 9.4). In all cases, the time at which water activity became lower than 0.4 corresponded to the time at which volume changes became minimal (see section 9.3.2), indicating a link between the onset of volume stability and storage stability (i.e. the state at which $a_w < 0.4$), probably due to glass transition.

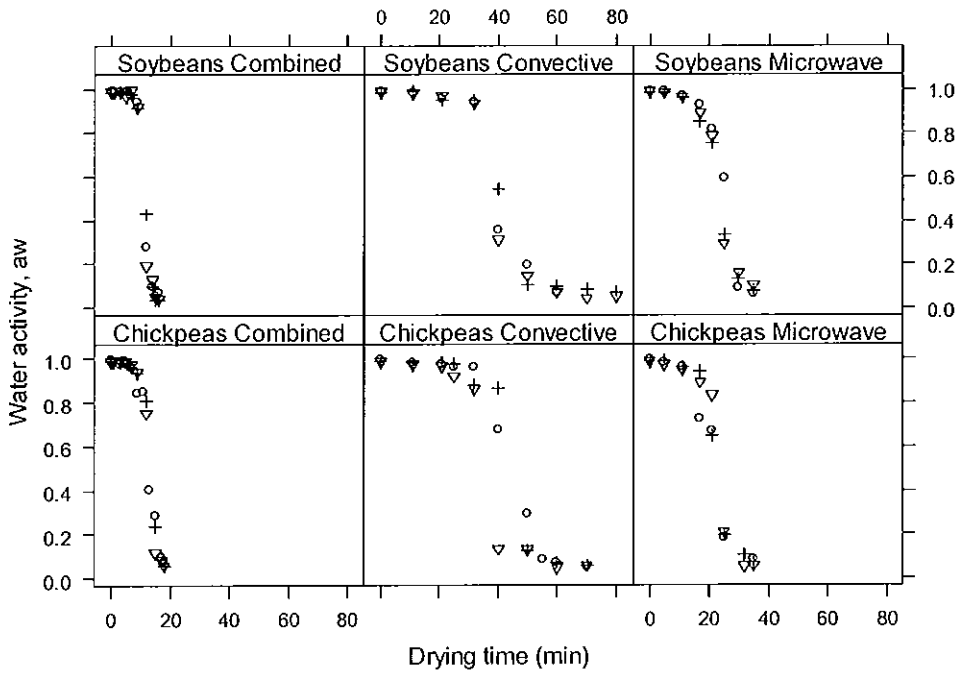


Fig. 9.4. Water activity (a_w) as a function of drying method and time for dehydration of cooked chickpeas and soybeans.

The relationship between water activity and moisture content (M) appeared to be independent of the drying method (Fig. 9.5). In the early-to-mid stages of drying, when moisture content decreased rapidly, water activity remained high (between 0.9 and 1). Only after a low moisture content was reached (approximatedly 15% (w.b.) for chickpeas and 10 % (w.b.) for soybeans) did water activity reach values below 0.9, decreasing with decreasing moisture content at a faster rate.

In order to predict water activity as a function of moisture content, a number of empirical models, commonly used to describe the relationship between water activity and moisture content, were fitted to the water activity data (Table 9.5). The pooled standard error (SE) and Akaike Information Criterion (AIC), arising from the fit of each model to the data, were calculated (Table 9.5). The Peleg

model (Eq. 9.5) resulted in both the lowest SE and AIC values, suggesting that it was the best model for describing the relationship between a_w and M, giving a reasonable fitting of the data without an excessive number of parameters.

$$M = k_1 a_w^{n1} + k_2 a_w^{n2} \quad \ldots(9.5)$$

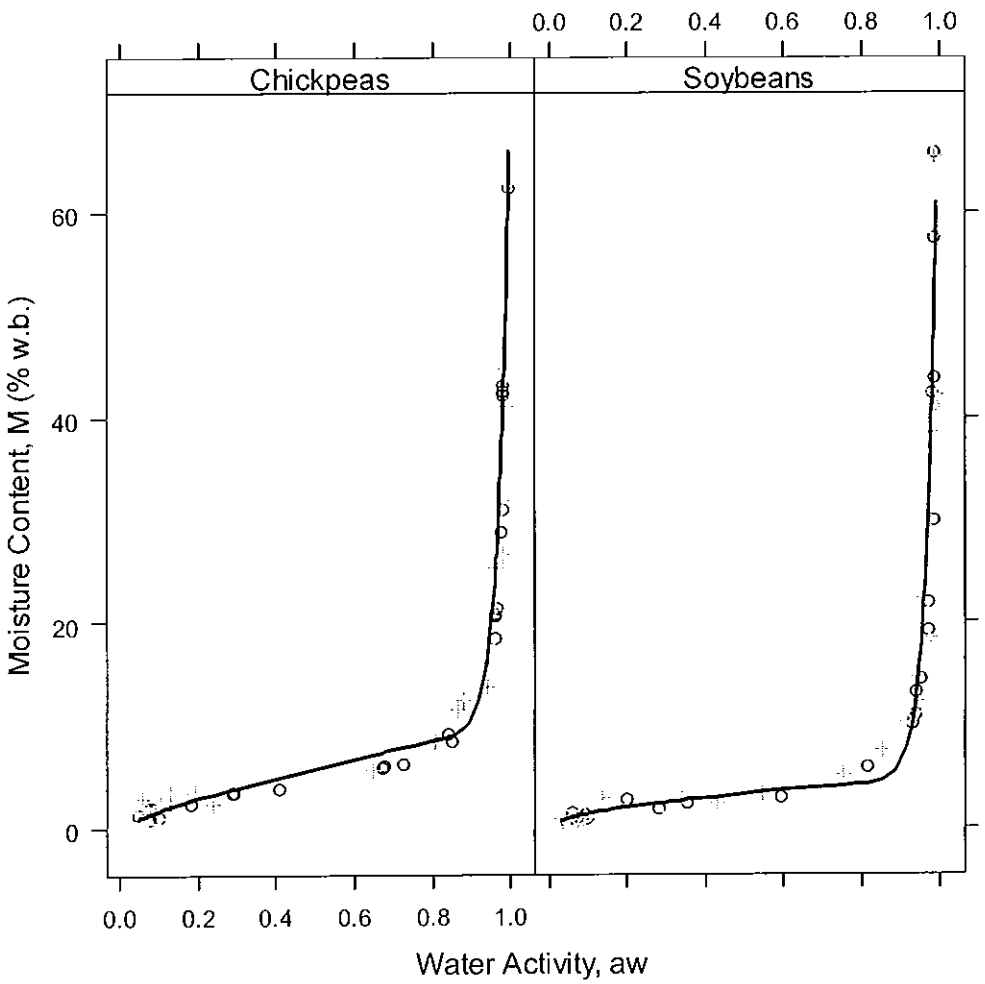


Fig. 9.5. Moisture content, M (% w.b.) as function of water activity (a_w); solid lines indicate predictive plots for nonlinear regression of Eq. 9.5 on data.

Table 9.5. Comparison of mathematical models applied to water activity of cooked chickpeas and soybeans during dehydration, showing pooled standard error (SE) and Akaike information criterion (AIC).

Model	Equation	SE	AIC
GAB	$M = \frac{M_o.C.K.a_w}{((1-K.a_w)(1-K.a_w+C.a_w)}$	18.5	1303.9
Henderson	$M = \left(\frac{\ln(1-a_w)}{A}\right)^{\frac{1}{B}}$	8.6	1136.0
Hasley	$M = \left(\frac{A}{\ln(a_w)}\right)^{\frac{1}{B}}$	9.1	1156.0
Smith	$M = A + b\ln(1-a_w)$	10.4	1198.3
BET	$M = \frac{M_0.C.a_w}{((1-a_w)+(C-1)(1-a_w)a_w)}$	13.5	1290.4
Peleg	$M = k_1 a_w^{n1} + k_2 a_w^{n2}$	7.9	1111.2

Peleg model parameters k_1, k_2, n_1 and n_2 were estimated by nonlinear regression of Eq. 9.5 on the drying data and are shown in Table 9.6. Predictive plots were generated from the estimated parameters. They were found to describe the data adequately (Fig. 9.5).

Table 9.6. Estimated parameters for nonlinear regression of Peleg model (Eq. 9.5) on water activity of cooked chickpeas and soybeans during drying.

Sample	Chickpeas	Soybeans
k_1	65.0 ± 5.1	71.9 ± 5.7
k_2	10.0 ± 3.0	4.7 ± 3.6
n_1	36.3 ± 5.9	35.0 ± 6.9
n_2	0.77 ± 0.45	0.55 ± 0.66

9.3.4 Colour change during drying

Before drying, both soybeans (with skin removed) and chickpeas were light yellow in colour. This was represented by relatively low redness values, (a_{0_cp}* = 8.55 ± 0.43, a_{0_sb}* = 7.60 ± 0.07) compared to high values of lightness (L_{0_cp}* = 69.88 ± 0.61, L_{0_sb}* = 68.81 ± 1.59) and yellowness (b_{0_cp}* = 29.20 ± 0.32, b_{0_sb}* = 29.21 ± 0.59). Sample colour changed during drying, irrespective of the drying method used (Fig. 9.6).

Lightness value, L*, decreased during drying (Fig. 9.6(a)), indicating that the samples became darker, due to loss of water during drying, which would have reduced the luminosity of the sample. In the case of convective drying, the L*-value decreased rapidly during the first 40 min of drying, after which time there was little change in the lightness or moisture content. For both combined and microwave drying, there was a rapid decrease in L* in the early drying stages, followed by a constant phase, after which another rapid decrease in L* was observed.

During the early stages of drying, the b*-value, representing yellowness, increased slightly to a maximum value (Fig. 9.6(b)), after which it decreased, indicating destruction of the yellow pigment. The a*-value, representing red colour, increased with drying time to an equilibrium value (Fig. 9.6(c)).

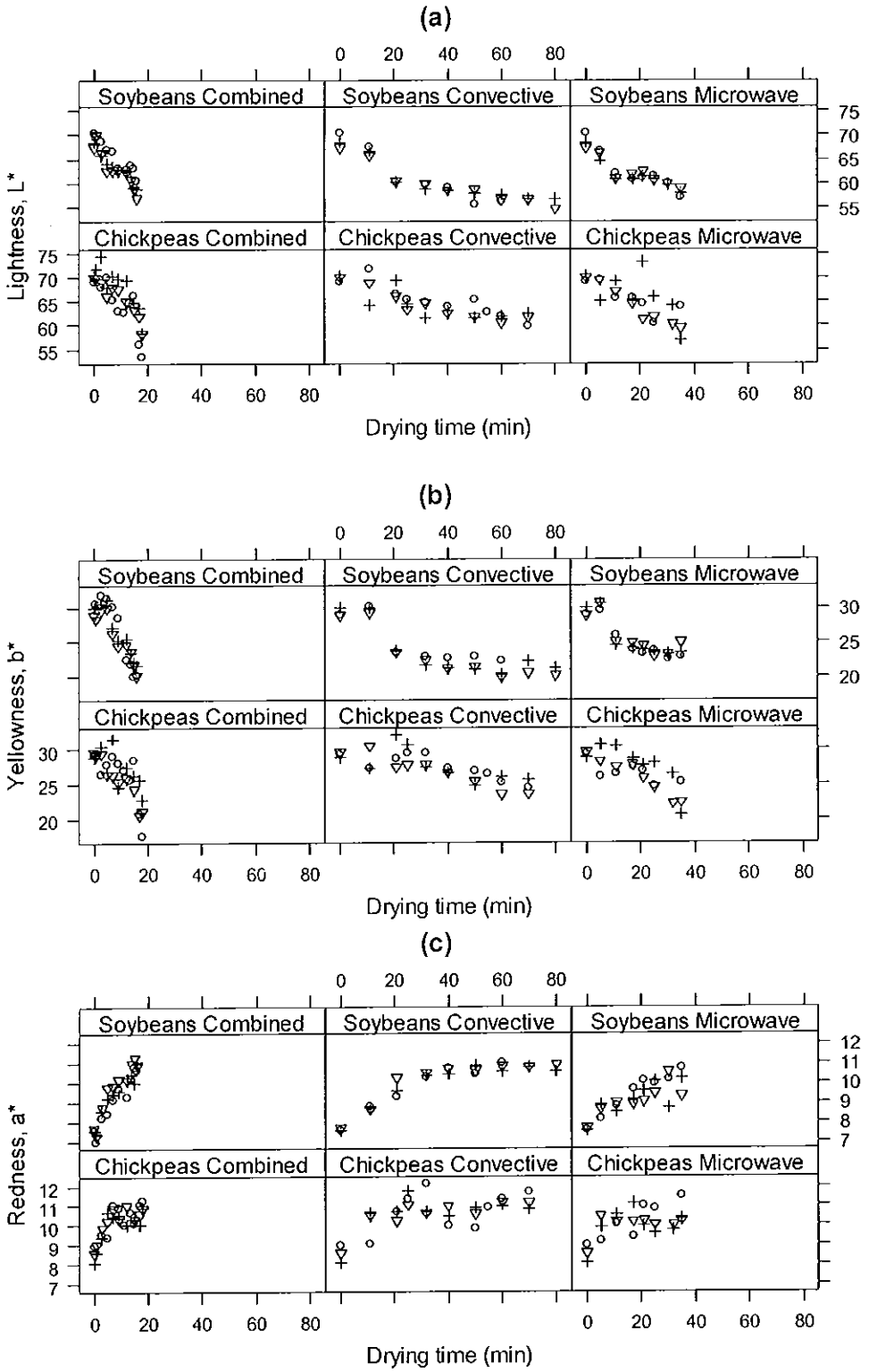


Fig. 9.6. CIE L* (a), b* (b) and a*(c) values as a function of drying method and time for dehydration of cooked chickpeas and soybeans.

As water activity decreased from 1 to 0.9, total colour change (DE*) increased rapidly (Fig. 9.7), corresponding to the rapid change in moisture content during the early - to - mid drying stages, when water activity was almost constant. DE* remained fairly constant while aw decreased, until reaching a water activity value less than 0.4, when a second increase in DE* occurred. At this stage, rapid browning of samples was observed, accelerated by a combination of the high drying temperatures and low water activity.

In order to estimate the water activity at which rapid browning occurred, DE* (a_w < 0.9) was fitted to a linear model with break point (Muggeo, 2003) and the break a_w was estimated to be 0.27 ± 0.07 for chickpeas ($p < 0.05$), and 0.13 ± 0.04 for soybeans ($p < 0.05$).

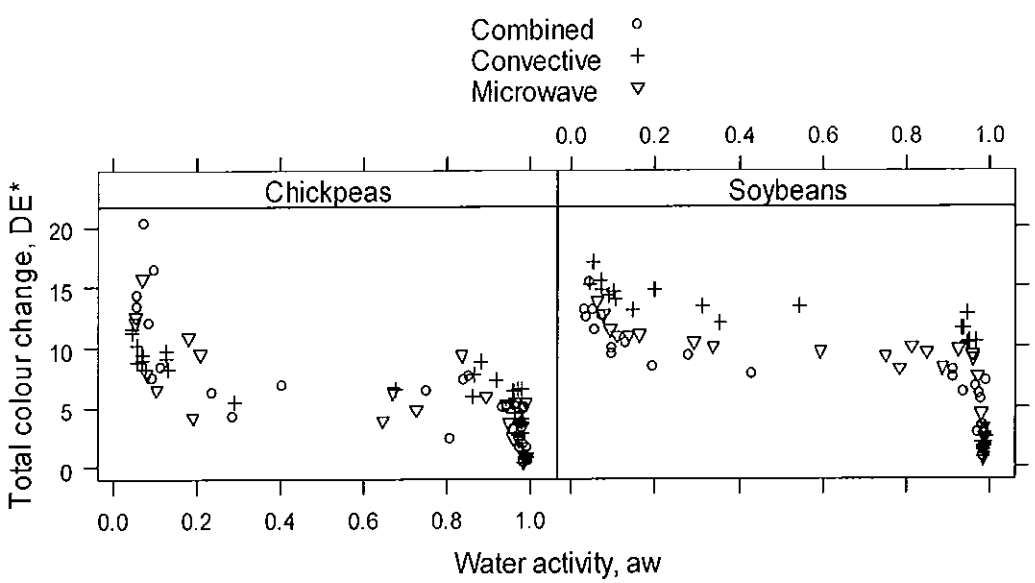


Fig. 9.7. Total colour change, DE*, as a function of water activity for dehydration of cooked chickpeas and soybeans.

9.3.5 Texture during drying

For each of the drying methods examined, sample hardness initially increased with drying time to a maximum value, after which it decreased rapidly, approaching an equilibrium value (Fig. 9.8). The initial increase in hardness was probably due to toughening of the samples crust or core due to initial water loss, when water activity was approximately constant. The subsequent rapid decrease in hardness may have been caused by the creation of a porous network, which affected the ability of the bean structure to support itself.

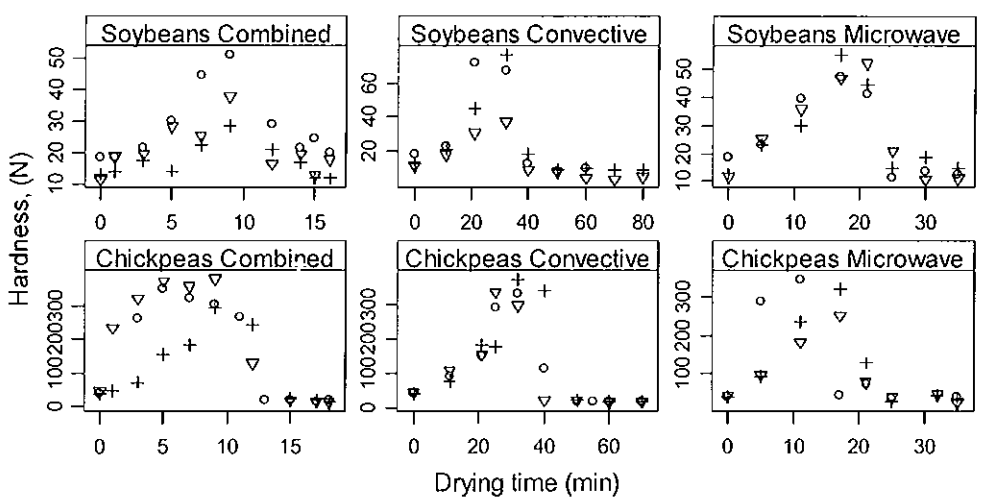


Fig. 9.8. Average hardness (N) as a function of drying method and time for dehydration of cooked chickpeas and soybeans.

Sample hardness increased as moisture content decreased (Fig. 9.9), until a critical moisture level (15-20% for chickpeas, 10-15% for soybeans) was reached. As moisture content decreased below these levels, a rapid decrease in hardness was observed. The situation is somewhat analogous to the concept of moisture toughening, in which water acts as an antiplasticiser of food at low

moisture contents. Antiplasticisation peaks in the compressive fracture stress of bread have been found at intermediate water contents of 9 –12 % (Fontanet *et al.*, 1997), similar to those seen in Fig. 9.9. However, such antiplasticisation peaks were seen during hydration, while the situation presented here is that of rapid dehydration.

The critical moisture levels (15-20% for chickpeas, 10-15% for soybeans) are close to those at which the second peak in the dehydration rate curve occurred (see section 7.3.1), aswell as the point at which water activity started to decrease below 0.9. It seems that at this level of dehydration, major structural changes occured, caused by rapid expulsion of water. The point at which sample hardness reached a constant value corresponds to the stage at which water activity decreased below 0.4, and when volume stability was reached, indicating storage stability of the dehydrated product, having entered the glassy state.

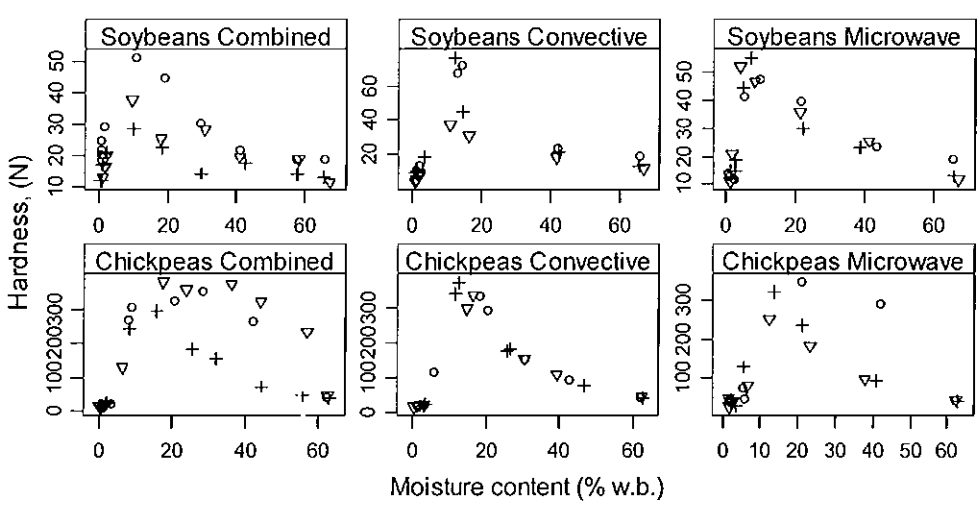


Fig. 9.9. Average hardness (N) as a function of drying method and moisture content for dehydration of cooked chickpeas and soybeans.

When water activity (a_w) decreased from 1 to a value of approximately 0.96, sample hardness increased to a maximum value (Fig. 9.10). After reaching maximum hardness, as a_w decreased from 0.96, hardness decreased towards an equilibrium value, changing little as a_w decreased below 0.4, which is assumed to correspond to the onset of glass transition. In order to estimate the water activity at which hardness (H) reached an equilibrium value, H for ($a_w < 0.96$) was fitted to a linear model with break point (Muggeo, 2003), and the break a_w was estimated to be 0.40 ± 0.10 for chickpeas ($p < 0.05$), and 0.63 ± 0.15 for soybeans ($p < 0.05$).

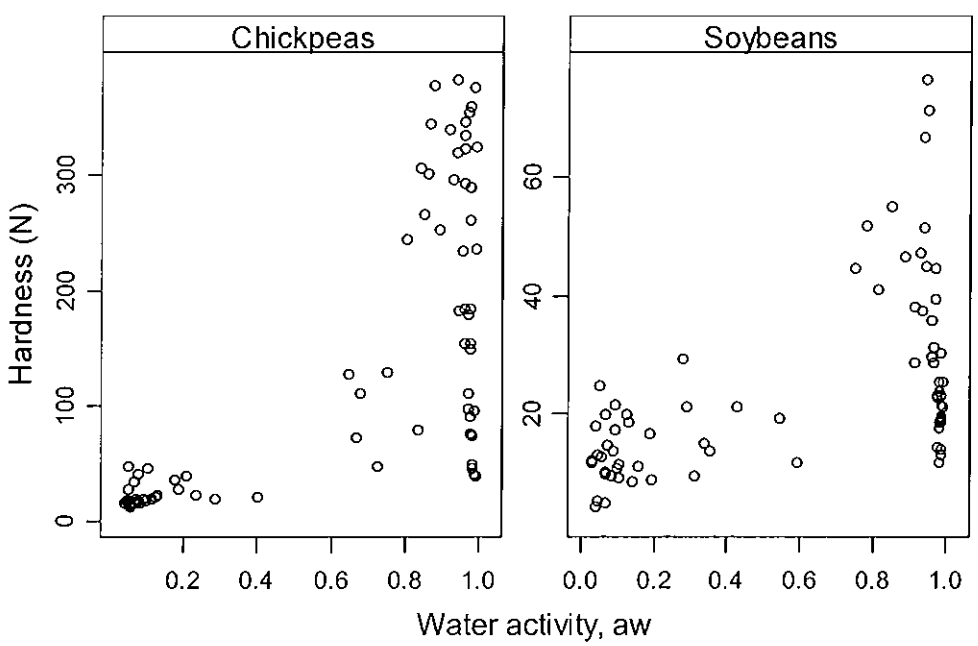


Fig. 9.10. Average hardness (N) as a function of water activity for dehydration of cooked chickpeas and soybeans.

9.3.6 Estimation of optimal drying time

In the previous sections, it was estimated that in order to avoid excessive browning, water activity should not be reduced during drying to a value below 0.27 ± 0.07 for chickpeas and 0.13 ± 0.04 for soybeans and that in order to reach glass transition, water activity should be decreased to a value below 0.40 ± 0.10 for chickpeas, and below 0.63 ± 0.15 for soybeans. In the introduction section, it was stated that foods dried to a final a_w level between 0.3 – 0.5 should not experience microbial growth, lipid oxidation, or browning during storage. Therefore, drying chickpeas and soybeans to a final water activity of 0.35 should prevent burning, allowing for glass transition, while also ensuring microbial safety, preventing lipid oxidation and browning during storage.

Using the Peleg model (Eq. 9.6), the moisture content corresponding to any particular water activity can be estimated for both cooked chickpeas and cooked soybeans during drying. For chickpeas, a_w = 0.35 corresponds to a moisture content of 4.43 %, while for soybeans, a_w = 0.35 corresponds to a moisture content of 2.65 %.

The drying time required by each drying method to reach this moisture content can then be estimated from Eq. 9.3 (Table 9.7). Combined drying would yield dehydrated chickpeas and soybeans with suitable water activity (a_w = 0.35) within 14 min drying, which is more than 1.7 times faster than microwave drying and more than 3.3 times faster than convective drying.

Table 9.7. Drying time required to reach a final moisture content (M) corresponding to a water activity of 0.35 for cooked chickpeas ($t_{M = 4.43\%}$) and soybeans ($t_{M = 2.65\%}$) during convective, microwave and combined microwave-convective drying.

Drying method	Chickpeas, $t_{M = 4.43\%}$ (min)	Soybeans $t_{M = 2.65\%}$ (min)
Convective	48.4	42.2
Microwave	24.1	27.4
Combined	13.6	13.2

9.3.7 Rehydrated product quality

After dehydration by combination of microwave power (210 W) and convective hot-air (160 °C) for 14 min, dry chickpeas and soybeans were rehydrated in boiling water. Moisture content was measured during rehydration (Fig. 9.11). Chickpea moisture content did not change significantly after 15 min rehydration, reaching a final moisture content of 60 ± 1 % (w.b.), which corresponds to 95% of their original, cooked moisture content (which is 63 ± 1 % (w.b.)). Similarly, soybean moisture content did not change significantly after 15 min rehydration, reaching a final moisture content of 60 ± 1 % (w.b.), which corresponds to 91% of their original, cooked moisture content (which is 66 ± 1 % (w.b.)). Using an approach similar to that taken in section 7.3.3, the amount of rehydration time required to reach the 95% lower level of asymptotic moisture content was estimated to be 9 min for both chickpeas and soybeans.

After 15 min rehydration, chickpea hardness was measured to be 15 ± 4 N, which is lower than the hardness of freshly cooked chickpeas (22 ± 4 N). Soybean hardness, after 15 min rehydration, was measured to be 10 ± 1 N, which is lower than the hardness of cooked soybeans (13 ± 3 N). This demonstrates the softening effect of high temperature drying followed by rehydration.

Surface colour of samples was measured after 15 min rehydration in terms of lightness (L*), redness (a*) and yellowness (b*). In the case of soybeans, rehydrated samples (L* = 61 ± 3, a* 7 ± 2, b* 20 ±1), were darker, redder and less yellow than cooked samples (L* = 68 ± 1, a* 5 ± 2, b* 23 ± 2). In the case of chickpeas, rehydrated samples (L* = 58 ± 3, a* = 9 ± 2, b* = 19 ± 2), were darker, slightly redder and less yellow than cooked samples (L* = 63 ± 2, a* = 8.8 ± 2, b* = 24 ± 2).

Sample appearance, after combined dehydration (MW = 210, T = 160 °C) for 14 min, and subsequent rehydration for 15 min in boiling water, is shown in Fig. 9.12. Dehydration caused cooked samples (also shown in Fig. 9.12) to become somewhat darker in colour. Nonetheless, the appearance of rehydrated samples was quite similar to cooked ones.

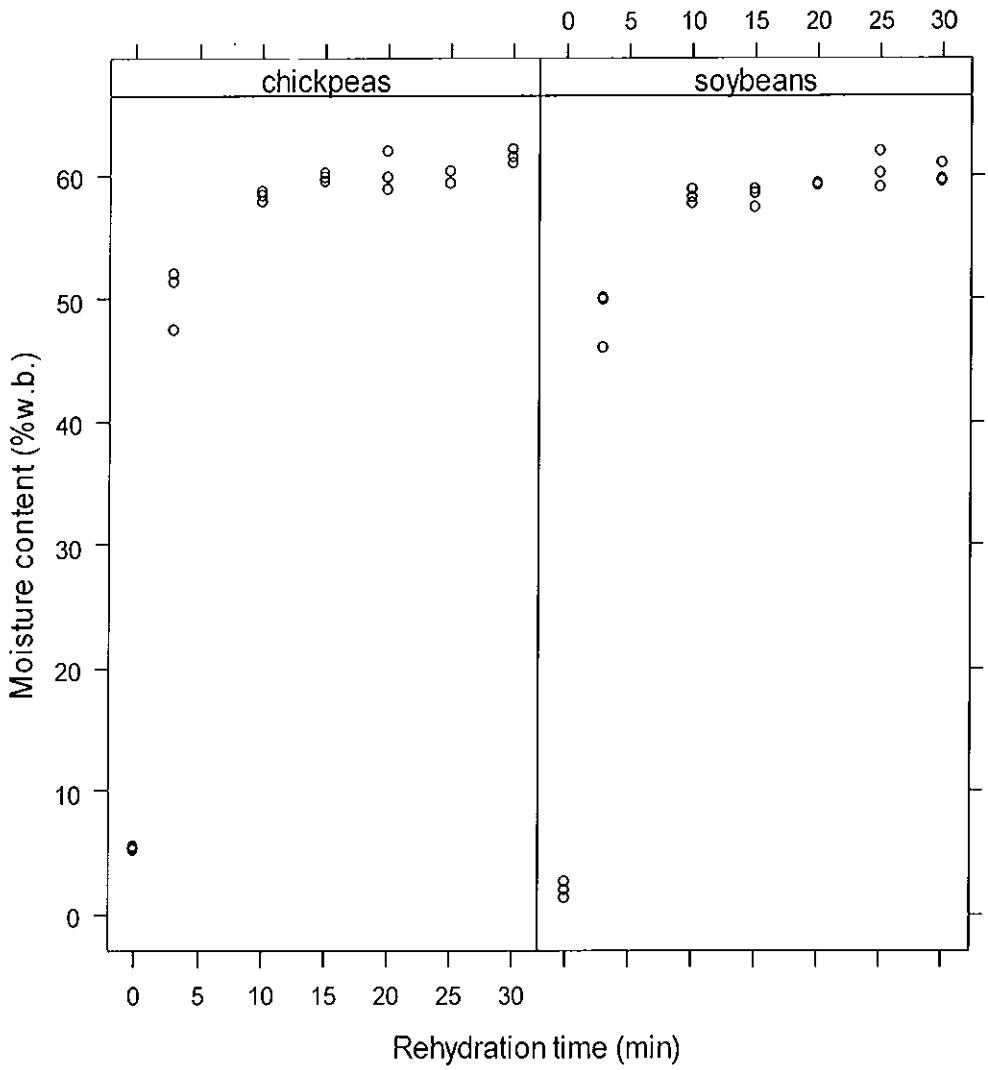


Fig. 9.11. Rehydration of chickpeas and soybeans that were previously dried by combination of microwave power (200W) and convective hot-air (160 °C) for 13 min.

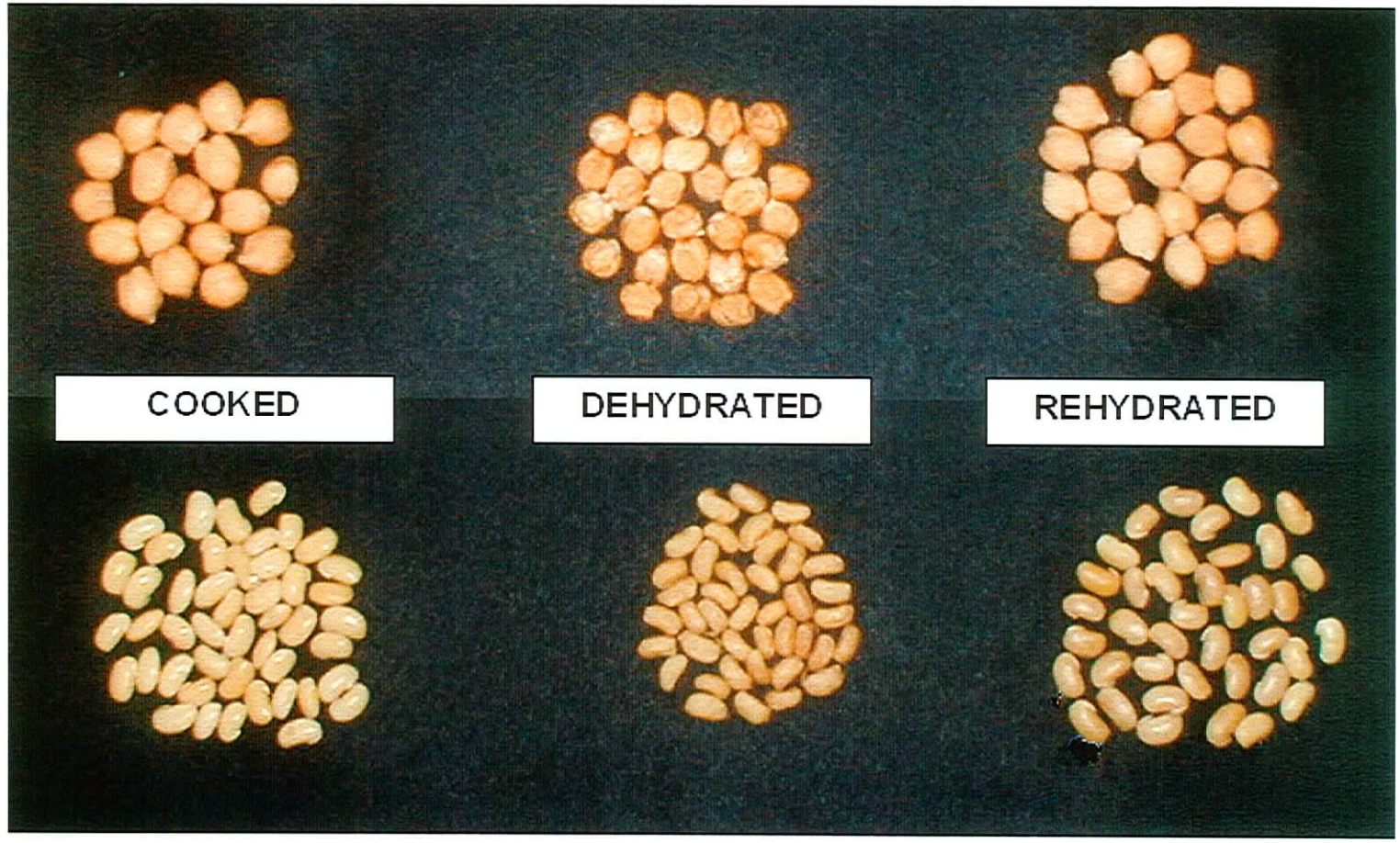


Fig 9.12. Cooked, dehydrated (by combination of microwave power (200W) and convective hot-air (160 °C) for 13 min) and rehydrated (by immersion in boiling water for 15 min) chickpea (upper half of picture) and soybean (lower half of picture) samples.

9.4 Conclusions

Combining microwave with hot air drying decreased the drying time, and the overall shrinkage encountered during drying, compared with convective drying and microwave drying, for cooked chickpeas and soybeans. Glass transition behaviour during drying was suggested by shrinkage and texture behaviour. Water activity was reduced during drying, for each of the methods examined. However, the onset of burning occurred when samples were dried to very low water activities (0.27 for chickpeas and 0.13 for soybeans), due to the high temperatures encountered in the processing. Drying chickpeas and soybeans to a water activity of 0.35 would produce shelf-stable dry products without severe discoloration. Results indicated that combined microwave-convective drying of cooked chickpeas and soybeans is viable, producing shelf stable products within relatively short processing times.

CHAPTER 10

GENERAL CONCLUSIONS

A summary of the main conclusions arising from the work, including suggestions for further research

10.1 General conclusions

Two types of legume product were developed in the research, namely: pre-cooked, ready-to-heat and quick-cook dehydrated products. The ready-to-heat product (Fig. 10.1) can be consumed from chilled or frozen storage within 1-2 min microwave heating, and the dehydrated product (Fig. 10.2) is rehydrated within 15 min boiling. Dry legumes generally require 12 h soaking, followed by 1 h cooking. Therefore, the products developed in this work represent timesavings to the consumer of up to 13 h. In the process of developing these products, a number of general conclusions, relating to hydration and dehydration properties of chickpeas and soybeans, arose. These are summarised in the following.

Predictive models were developed to describe water intake during soaking as a function of soaking time, temperature and pre-treatment. Increasing the soak temperature hastened water intake rate, and application of a blanching pre-treatment accelerated the soaking kinetics, for soaking at temperatures less than 50 °C. Changes in sample hardness during soaking were also modelled as a function of soak time, temperature and pre-treatment, and soaking conditions required to reach a given level of hardness were predicted. Boiling of pre-soaked samples for 60 min was the optimal cooking treatment. Although application of a microwave step following boiling resulted in softer texture, the difference was not distinguishable by a taste panel. Shelf life of pre-cooked samples under chilled and frozen storage was investigated: chilled samples could be consumed safely up for to 14 days of chilled storage and for up to 12 months in frozen storage. Application of a freeze – chill cycle is a viable long-term storage option

for chilled chickpeas and soybeans, providing an alternative to frozen storage while maintaining microbial safety, colour quality and texture

Fig. 10.1. Pre-cooked, ready-to-heat chickpeas **(a)** and soybeans **(b)**

Fig. 10.2. Quick-cook, dehydrated chickpeas **(a)** and soybeans **(b)**

The first stage of the work, described in Ch. 4 – 6, allowed for the setting up of general procedure for production of pre-cooked, ready-to heat chickpeas and

soybeans (Fig. 10.3) which could be produced in just over 7 hours. It should be noted that the blast freez ng procedure was not optimised in the work and it may have been possible to carry out the blast freezing/chillling step in a shorter time.

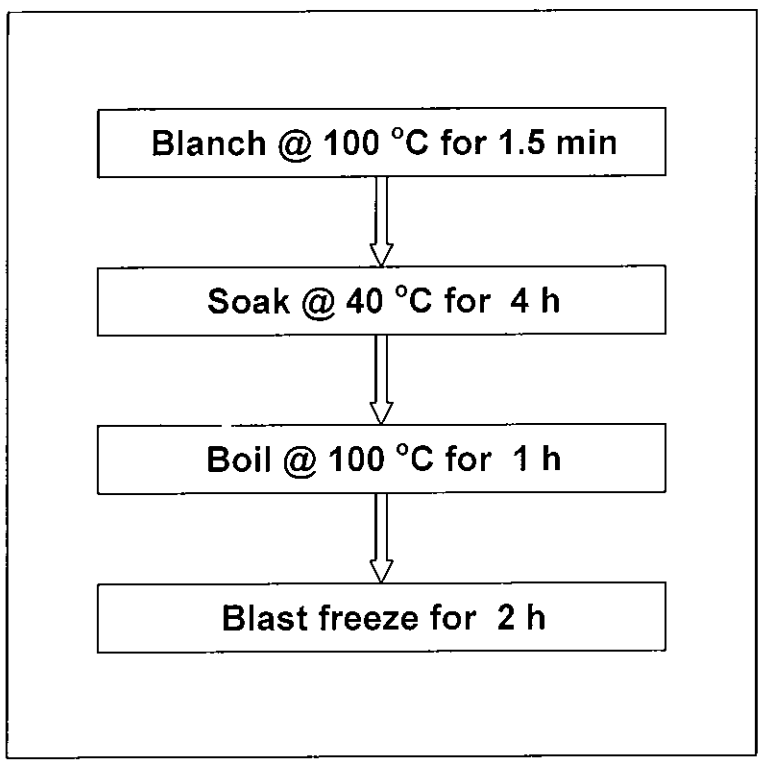


Fig. 10.3. Processing steps for production of pre-cooked chickpeas and soybeans

The application of combined microwave-convective hot air drying to cooked chickpeas and soybeans was investigated in the second stage of the project. Moisture loss during drying was modelled in terms of drying time, microwave power and drying temperature. Combined microwave-convective hot-air drying was more rapid, compared with convective hot-air or microwave drying alone. Drying kinetics increased linearly with microwave power and air temperature and no interactive effect between microwave power and temperature was observed. Lumped effective diffusivity during drying was estimated to range

from 10^{-9} m/s^2 to 10^{-7} m/s^2. These very high values indicate that the majority of moisture loss was due to evaporation of water, caused by the high air temperatures and microwave powers employed. Colour change due to drying became more extreme as microwave power and air temperature were increased, and increased with drying time, mainly due to browning of the sample surface. Rehydration was modelled as a function of rehydration time, microwave power and air temperature. Rehydration rate increased linearly with microwave power and air temperature without interactive effects, in a similar fashion to drying. Optimal drying conditions to produce shelf stable dehydrated chickpeas and soybeans were estimated as follows: application of 14 min combined drying at microwave power of 210 W and air temperature of 160 °C to pre-cooked (Fig. 10.1) chickpeas and soybeans.

10.2 Suggestions for further work

The innovative products developed in the work could potentially be marketed as novel food products that are convenient and healthy. However, the processing steps described for their production were estimated under laboratory conditions. Appropriate scaling up of the processes, using industrial-scale soaking and drying equipment, would be essential if these products were to be produced on an industrial scale. Once the effects of scaling-up were known, it would be possible to apply the processing steps to other legume varieties.

Pre-gelatinised dehydrated legume products, developed in the current work, have potential commercial use, in their dried form, as healthy snack-foods. Extensive

sensory analysis would be required to develop the taste and texture of such products to acceptable standards.

Prior to commercial marketing of the quick-cook products developed in this work, it would be essential to study the impact of processing conditions, i.e. soaking, cooking, dehydration, rehydration and storage, on nutritional factors, such as protein digestibility, vitamin retention levels and phtyochemical degradation.

Additionally, a fundamental study of structure formation in products during drying would facilitate the generation of new, highly dehydratable legume products.

References

Abd El-Hady, E., & Habiba, R. 2003. Effect of soaking and extrusion conditions on antinutrients and protein digestibility of legume seeds. *Lebensmittel-Wissenschaft und-Technologie*, 36: 285-293.

Abdel-Gawad, A., 1993. Effect of domestic processing on oligosaccharide content of some dry legumeseeds. *Food Chemistry*, 46: 25-31.

Abu-Ghannam, N., & McKenna, B. 1997a. Hydration Kinetics of Red Kidney Beans. *Journal of Food Science*, 62: 520-523.

Abu-Ghannam, N., & McKenna, B. 1997b. The Application of Peleg's Equation to Model Water Absorption During the soaking of Red Kidney Beans. *Journal of Food Engineering*, 32: 153-159.

Abu-Ghannam, N. 1998a. Modelling Textural Changes During the Hydration Process of Red Beans, *Journal of Food Engineering*, 28: 341-351.

Abu-Ghannam, N. 1998b. Interpretation of the force deformation curves of soaked red kidney beans (*Phaseolus vulgaris* L.), *International Journal of Food Science & Technology*, 33: 509-515.

Adams, M. & Moss, M. 2000. Food microbiology, 2nd ed. Royal Society of Chemistry.

Ahmad, S., Morga, M., & Okos, M. 2001. Effects of microwaves on the drying, checking and mechanical strength of baked biscuits, *Journal of Food Engineering*, 50: 63-75.

Akpinar, E., Midilli, A. & Bicer, Y. 2003. Single layer drying behaviour of potato slices in a convective cyclone dryer and mathematical modelling, *Energy Conversion and Management*, 44: 1689–1705.

Anderson, J., Smith, B., & Washnock, C. 1999. Cardiovascular disease and renal benefits of dry bean and soybean intake. *American Journal of Clinical Nutrition*, 70: 46S-74S.

Andres, A., Bilbao, C., & Fito, P. 2004. Drying kinetics of apple cylinders under combined hot air-microwave dehydration. *Journal of Food Engineering*, 63: 71-78.

Anonymous. 2001. Guidelines for the interpretation of results of microbiological analysis of some ready to eat foods sampled at point of sale. Guidance Note No. 3, Published by the Food Safety Authority of Ireland, Dublin, Ireland.

Anthony, M. 2000. Soy and Cardiovascular disease: Cholesterol lowering and beyond. *Journal of Nutrition*, 130: 662S-663S.

AOAC. 2000. Official methods of analysis. 17th ed. Association of Official Analytical Chemists

Arévalo-Pinedo, A., & Murr, F. 2006. Kinetics of vacuum drying of pumpkin (*Cucurbita maxima*): Modeling with shrinkage. *Journal of Food Engineering,* 76: 562-567.

Azoubel, P., & Murr, F. 2004. Mass transfer kinetics of osmotic dehydration of cherry tomato, *Journal of Food Engineering*, 61: 291-295.

Bakshi, A., & Singh, R. 1980. Kinetics of water diffusion and starch gelatinisation during rice parboiling. *Journal of Food Science*, 45: 1387-1392.

Bandyopadhyay, S., & Roy, N. 1978. A semi-empirical correlation for prediction of hydration characteristics of paddy during parboiling. *Journal of Food Technology*, 13: 91-98.

Barampama, Z., & Simard, R. 1995. Effects of soaking, cooking and fermentation on composition, in-vitro starch digestibility and nutritive value of common beans. *Plant Foods for Human Nutrition*, 48: 349-365.

Bates, D. 1988. Nonlinear regression analysis and its applications. Wiley. New York.

Bayram, M., Öner, M., & Kaya, A. 2004. Influence of soaking on the dimensions and colour of soybean for bulgur production. *Journal of Food Engineering*, 61: 331-339.

Bazzano, L., He, J., & Ogden, L. 2002. Legume consumption and risk of coronary heart disease in US men and women. NHANES I epidemiologic follow-up study. *ACC Current Journal Review,* 11: 31-32.

Berteli, M., & Marsaioli, A. 2005. Evaluation of short cut pasta air dehydration assisted by microwaves as compared to the conventional drying process. *Journal of Food Engineering*, 68. 175-183.

Bilbao-Sainz, C., Andres, A., & Fito, P. 2005. Hydration kinetics of dried apple as affected by drying conditions. *Journal of Food Engineering*, 68: 369-376.

Blond, G., & Le Meste, M. 2004. Principles of Frozen storage. In *Handbook of frozen foods* (Ed. Isabel Guerrero Legaretta). Marcel Dekker.

Bonazzi, C., Dumoulin, E., Raoult-Wack, A., Berk, Z., Bimbenet, J., Courtois, F., Trystram, G. Vasseur, J. 1996. Food drying and dewatering. *Drying Technology,* 14: 2135-2170.

Bordeleau, G., Myers-Smith, I., Midak, M., & Szeremeta, A. 2002. Food Quality: A comparison of organic and conventional fruits and vegetables. Ecological Agriculture Den Kongelige Veterinœr- og Landbohøjskole. URL: http://www.kursus.kvl.dk

Borges, A. & Peleg, M. 1997. Effect of water activity on the mechanical properties of selected legumes and nuts. *Journal of the Science of Food and Agriculture*, 75: 463-471.

Bourne, MC 1978. Texture profile analysis. *Food Technology*, 32: 62- 66.

Brennan, J., Butters, J., Cowell, N. & Lilly, A. 1990. *Food Engineering Operations, 3rd Edition*, Applied Science, London.

Calvo, M.S., & del Rey, J.A. 1999. Sensory analysis of beans. *Biotechnology, Agronomy, Society and Environment*, 3: 201-204.

Cai, T., & Chang, K. 1997. Processing to improve quality of dehydrated precooked pinto beans. *Journal of Food Science*, 62: 141-144.

Chang, Y., Cheah, P., & Seow, C. 2000. Variations in felxural and compressive fracture behaviour of a brittle cellular food (dried bread) in response to moisture sorption. *Journal of Texture Studies*, 31: 525-540.

CIE. 1931. International Commission on Illumination. URL: http://www.cie.co.at

CIE. 1976. International Commission on Illumination. URL: http://www.cie.co.at

Clemente, A., Vioque, J., Sanchez-Vioque, R., Pedroche, J., Bautista, J., & Millan, F. 1999. Protein quality of chickpea (*Cicer arietinum* L.) protein hydrolysates. *Food Chemistry*, 67: 269-274.

Cloninger, M., & Baldwin, R. 1976. Analysis of sensory rating scales. *Journal of Food Science*, 41: 1225 – 1228.

Collinson, R., Johnson, K., & West, A. 1980. Subjective and objective assessments of the degree of cooking of potatoes heated by different methods. *Journal of Food Technology*, 15: 1-8.

Cui, Z-W., Xu, S-Y., & Sun, D-W. 2003. Dehydration of Garlic Slices by combined microwave-vacuum and air drying. *Drying Technology*, 21: 1173-1184.

Cui, Z-W., Xu, S-Y., & Sun, D-W. 2004. Microwave-vacuum drying kinetics of carrot slices. *Journal of Food Engineering*, 65: 157-164.

Cummings, J., and Bingham, S (1998) Diet and the prevention of cancer, *British Medical Journal*, 317: 1636-1640.

Dai, Q., Shu, X., Jin, F., Potter, J., Kushi, L., & Teas, J. 2001. Population-based case-control study of soyfood intake and breast cancer risk in Shanghai. *British Journal of Cancer* , 85:372–8.

Davidson, A. & Hinckley, D. 1997. *Bootstrap Methods and Their Application.* Cambridge University Press, Cambridge.

Doll, R., & Peto, R. 1981. The causes of cancer. *Journal of the National Cancer Institute*, 66: 1191-1308.

De Leon, L., Elias, L., & Bressani, R. 1992. Effect of salt solutions on the cooking time, nutritional and sensory characteristics of common beans (Phaseolis vulgaris). *Food Research International*, 25: 131-136.

Delgado, A., & Rubiolo, A. 2005. Microstructural changes in strawberry after freezing and thawing process. *Lebensmittel-Wissenschaft und-Technologie,* 38: 135-142.

Dennis, C., & Stringer, M.F. 2000. *Chilled Foods: A Comprehensive Guide, Second Edition.* Woodhead Publishing in Food Science and Technology.

Deshpande, S.D. 1994. A study on diffusion of water by the soybean grain during cold water soaking. *Journal of Food Engineering*, 23: 121-127.

Deshpande, S.D. & Bal, S. 2001. Effect of soaking time and temperature on textural properties of soybean. *Journal of Texture Studies,* 32: 343-348.

Diabetes Federation of Ireland. 2006. URL: http://www.diabetesireland.ie

Dobrasczyck, B., & Vincent, J. 1999. Mechanical testing of foods, In *Food texture, measurement and perception* (Ed. A. Rosenthal). Aspen Publishers, Inc.

Dorsey, W., & Strashun, S. 1961. New continuous production facility for processing "instant" precooked beans. *Food Technology*, 15: 13-18.

Doymaz, I. 2005. Drying behaviour of green beans. *Journal of Food Engineering,* 69: 161-165.

Egounlety, M., & Aworh, O. 2003. Effect of soaking, dehulling, cooking and fermentation with Rhizopus oligosporus on the oligosaccharides, trypsin inhibitor, phytic acid and tannins of soybean (Glycine max Merr.), cowpea (Vigna unguiculata L. Walp) and groundbean (Macrotyloma geocarpa Harms). *Journal of Food Engineering*, 56: 249-254.

Eichner, K., Laible, R., & Wolf, W. 1985. The influence of water content and temperature on the formation of Malliard reaction intermediates during drying of plant products. In *Properties of water in Foods* (Eds. D. Simatos & J. Moulton). Martinus Nijhoff Publishers.

El-Adawy, T. 2002. Nutritional composition and antinutritional factors of chickpeas (*Cicer arietinum* L.) undergoing different cooking methods and germination. *Plant Foods for Human Nutrition* 57: 83-97.

Esaka, M., Suzuki, K., & Kubota, K. 1987. Effects of microwave heating on lipoxygenase and trypsin inhibitor activities, and water absorption of winged bean seeds. *Journal of Food Science*, 52: 1738-1739.

Estevez, A., & Luh, B. 1985. Chemical and physical characteristics of ready-to-eat dry beans. *Journal of Food Science*, 50: 777-781.

Fan, L., Chung, D., & Shellenberger, J. 1961. Diffusion coefficients of water in wheat kernels. *Cereal Chemistry*, 38: 540-548.

Feldberg, C., Fritzsche, H., Wagner, J. 1956. Preparation and evaluation of precooked, dehydrated bean products. *Food Technology*, 10: 523-525.

Fernandez, M., & Berry, J. 1989. The effect of germination on chickpea starch. *Starch*, 41: 17-21.

Flemming, S.E. 1981. A study of relationships between flatus potential and carbohydrate distribution in legume seeds. *Journal of Food Science*, 46: 794 -798.

Food products association. 2005. A Short History of Processed Foods. URL: http://www.fpa-food.org

Fontanet, S., Davidou, S., Dacremont, C. and Le Meste, M. 1997. Effect of water on the mechanical behaviour or extruded flat bread. *Journal of Cereal Science*, 25: 303-311.

Foster-Powell, K., Holt, S., & Brand-Miller, J. 2002. International table of glycemic index and glycemic load values. *American Journal of Clinical Nutrition*, 76: 5 - 56.

Food Safety Authority of Ireland. 2003.URL: www.fsai.ie

Funebo, T., & Ohlsson, T. 1998. Microwave-assisted air dehydration of apple and mushroom. *Journal of Food Engineering*, 38: 252-267.

Gastón, A., Abalone, R., Giner S., & Bruce, D. 2004. Effect of Modelling Assumptions on the Effective Water Diffusivity in Wheat. *Biosystems Engineering,* 88: 175-185.

Geervani, P. 1991. Utilization of chickpea in India and scope for novel and alternative uses. p. 47-54. In *Uses of Tropical Grain Legumes: Proceedings of Consultants' Meeting, 27-30 March, 1989.* ICRISAT Center, Patancheru, Andhra Pradesh, India.

Gilbert, R., Louvois, J., Donovan, T., Little, C., Nye, K., Ribeiro, C., Richards, J., Roberts, D., & Boiton, F. 2000. Guidelines for the microbiological quality of some ready-to-eat foods samples at the point of sale. *Communicable Disease and Public Health*, 3: 163-167.

Good, H. 2004. Color measurement of cereal and cereal products. *Cereal Foods World,* 47: 5-6.

Haladjian, N., Fayad, R., Toufeili, I., Shadarevian, S., Sidahmed, M., & Baydoun, E. 2003. pH, Temperature and Hydration Kinetics of Faba Beans. *Journal of Food Processing & Preservation,* 27: 9-20.

Guiné, R., & Fernandes, R. 2006. Analysis of the drying kinetics of chestnuts. *Journal of Food Engineering,* 76: 460-467.

Hnatowich, G. 2000. Pulse production manual 2000. Saskatchewan Pulse Growers, Saskatoon, SK, Canada.

Hafez, Y., Ali, M., Hewedy, F., Singh, G. 1985. Effects of Microwave Heating on Solubility, Digestibility and Metabolism of Soy Protein. *Journal of Food Science*, 50: 415-417.

Haralampu, S., Saguy, I., & Karel, M. 1985. Estimation of Arrhenius model parameters using three least square methods. *Journal of Food Processing and Preservation,* 9: 129-143.

Harker, F., Maindonald, J., Murray, S., Gunson, F., Hallet I., & Walker, S. 2002. Sensory interpretation of instrumental measurements 1: texture of apple fruit. *Postharvest Biology and Technology*, 24: 225-239.

Harland, B. F., & Morris, E. R. 1995. Phytate - a good or a bad food component. *Nutrition Research*, 15: 733-754.

Health Promotion Unit. 2005. Report of the National Taskforce on Obesity. URL: http://www.healthpromotion.ie

Heinen, E., & Van Twisk, P. 1976. Evaluering van droëbone. CSIR Research Report, no. 330. Pretoria.

Henderson, S.M., & Pabis, S. 1961. Grain drying theory. I. Temperature effect on drying coefficients, *Journal of Agricultural Engineering Research,* 6: 169–174.

Hsu, K. 1983. Effect of temperature on water diffusion in soybean. *Journal of Food Science,* 48: 1364-1365.

Hu, Q-g. , Zhang, M., Mujumdar, A., Xiao, G-n., & Jin-cai, S. 2005. Drying of edamames by hot air and vacuum microwave combination . *Journal of Food Engineering,* In Press.

Huang, M., Ferraro, T., Ho, C. 1994. Cancer chemoprevention by phytochemicals in fruits and vegetables, an overview. In *Food Phytochemicals for Cancer Prevention I: Fruits and Vegetables* (Eds. Mou-Tuan Huang, Chi-Tang Ho, Toshihiko Osawa, Robert T. Rosen). Wiley Publishers.

Hung, T., Liu, L., Black, R., & Trewhella, M. 1993. Water Absorption in Chickpea and Field Pea Cultivars using the Peleg model. *Journal of Food Science,* 58: 848-852.

Hutchings, J. 1999. Food color and appearance, 2nd ed. Aspen Publishers

Ibarz, A., González, C., & Barbosa-Cánovas, G. 2004. Kinetic models for water adsorption and cooking time in chickpea soaked and treated by high pressure. *Journal of Food Engineering*, 63: 467-472.

Irish Government. 1999. The Cardiovascular Health Strategy - Building Healthier Hearts. URL: http://www.healthpromotion.ie

Irish Universities Nutrition Alliance, 2000. North/South Ireland Food Consumption Survey. URL: http://www.safefoodonline.com.

Jay, J. 2000. Modern Food Microbiology. Springer Publishers.

Johnson, J., & Jimmerson, J. 2003. Chickpeas (Garbanzo beans). Agricultural Marketing Policy Center, Briefing No. 55.

Kabbara, S., Abbas, I., Scheerens, J., Tinsley, A., & Berry, J. 1987. Soaking and cooking parameters of tepary beans: effects of cooking time and cooking temperature on hardness and activity of nutritional antagonists. *Plant Foods for Human Nutrition*, 36: 295-307.

Kader, Z. 1995. Study of some factors affecting water absorption by faba beans during soaking. *Food Chemistry*, 53: 235-238.

Karathanos, V., Villalobos, G., & Saravacos, G. 1990. Comparison of two methods of estimation of the effective moisture diffusivity from drying data. *Journal of Food Science*, 55: 218-223.

Kasapis, S. 2006. Definition and applications of the network glass transition temperature. *Food Hydrocolloids,* 20: 218-228.

Kennedy, A. 1994. Prevention of carcinogenesis by protease inhibitors. *Cancer Research*, 54: 1999s-2005s.

Kerr, W. 2004. Texture in frozen foods. In *Handbook of Frozen Foods* (Ed.Y. Hui). Marcel Dekker.

Khatoon, N., & Prakash, J. 2004. Nutritional quality of microwave-cooked and pressure-cooked legumes. *International Journal of Food Science and Nutrition*, 55:441-8.

Khraisheh, M., McMinn, W., & Magee, T. 2004. Quality and structural changes in starchy foods during microwave and convective drying. *Food Research International,* 37: 497-503.

Kon, S. 1979. Effect of soaking temperature on cooking and nutritional quality of beans. *Journal of Food Science*, 44: 1329-1334.

Krokida, M., Karathanos, V., Maroulis, Z., & Marinos-Kouris, D. 2003 Drying kinetics of some vegetables. *Journal of Food Engineering,* 59: 391-403.

Labuza, T.P., Roe, K., Payne, C., Panda, F., Labuza, T.J., Labuza, P., Krusch, L., 2004. Storage Stability of Dry Food Systems: Influence of State Changes during

Drying and Storage. In *Drying 2004–Proceeding of the 14th International Drying Symposium* (Eds. M. Silva & S. Rocha), São Paulo, Brazil. URL: http://www.feq.unicamp.br/~ids2004/

Labuza, T., & Saltmarch, M. 1981. The nonenzymatic browning reaction as affected by water activity in foods. In *Water activity: influences on food quality* (Eds. L. Rockland & G. Stewart). Academic Press.

Labuza, T. 1980. The effect of water activity on reaction kinetics of food deterioration. *Food Technology,* 34: 36-42.

Lampe, J. 2003. Spicing up a vegetarian diet: chemopreventive effect of phytochemicals. *Americal Journal of Clinical Nutrition*, 78: 579S-583S.

Lane R. 2000. Official Method AOAC 925.10 for Moisture in Flour. Cereal Foods. In *Official Methods of Analysis of the Association of Official Analytical Chemists*, 17th ed (Ed. W Horwitz). Association of Official Analytical Chemists.

Leterme, P. 2002. Recommendations by health organizations for pulse consumption. *British Journal of Nutrition*, 88: S239–S242.

Lestienne, I., Icard-Vernière, C., Mouquet, C., Picq, C., & Trèche, S. 2005. Effects of soaking whole cereal and legume seeds on iron, zinc and phytate contents. *Food Chemistry*, 89: 421-425.

Lin, T., Durance, T., & Scaman, C. 1998. Characterization of vacuum microwave, air and freeze dried carrot slices. *Food Research International,* 31: 111-117.

Ling, H-I., Birch, J. and Lim, M. 2005. The glass transition approach to determination of drying protocols for colour stability in dehydrated pear slices. *International Journal of Food Science and Technology, 40*: 921-927.

Liu, K. 1998. Food research and data analysis. Chinese Light Industry Publisher. Beijing.

Luh, B., & Mickus, R. 1980. Parboiled rice. In *Rice: Production and Utilization* (Ed. B. Luh). AVI Publishing Co., Inc.

Madamba, P., Driscoll, R., & Buckle, K. 1996. The thin-layer drying characteristics of garlic slices, *Journal of Food Engineering,* 29: 75–97.

Makhlouf, J., Zee, J., Tremblay, N., Belanger, A., Michaud, M.-H., & Gosselin, A. 1995. Some nutritional characteristics of beans, sweet corn and peas (raw, canned and frozen) produced in the province of Quebec. *Food Research International*, 28: 253-259.

Maneepun, S. 2003. Traditional processing and utilization of legumes. In *Processing and Utilization of Legumes: report of the APO seminar on processing and utilization of legumes.* Asian Productivity Organisation.

Marconi, E., Ruggeri, S., Cappelloni, M., Leonardi, D., & Carnovale, E. 2004. Physicochemical, nutritional, and microstructural characteristics of chickpeas (*Cicer arietinum* L.) and common Beans (*Phaseolus vulgaris* L.) following microwave cooking. *International Journal of Food Sciences and Nutrition*, 55: 441-448.

Martins, S.,. Jongen, W., & van Boekel, M. 2001. A review of Malliard reaction in food and implications to kinetic modelling. *Trends in Food Science and Technology*, 11: 364-373.

Maskan, M. 2000. Microwave/air and microwave finish drying of banana. *Journal of Food Engineering*, 44: 71-78.

Maskan, M. 2001. Drying, shrinkage and rehydration characteristics of kiwifruits during hot air and microwave drying. *Journal of Food Engineering*, 48: 177-182.

Mattson, S. 1946. The cookability of yellow peas. A colloid-chemical and biochemical study. *Acta Universitatis Agriculturae Sueciae Agraria*, 2: 185-188.

May, B., Sinclair, A., Halmos, A., & Tran, V. 1999. Quantitative analysis of drying behaviour of fruits and vegetables. *Drying Technology*, 17: 1441-1448.

Marsili, R. 1996. Food colour: more than meets the eye. URL: www.foodproductdesign.com.

Márquez, M., & Alonso, R. 1999. Inactivation of trypsin inhibitor in chickpea. *Journal of Food Composition and Analysis*, 12: 211-217.

Messina, M. 1999. Legumes and soybeans: overview of their nutritional profiles and health effects. *American Journal of Clinical Nutrition*, 70: 439S-450S.

Methakhup, S., Chiewchan, N., & Devahastin, S. 2005. Effects of drying methods and conditions on drying kinetics and quality of Indian gooseberry flake. *LWT - Food Science and Technology*, 38: 579-587.

Michener, H., & Elliot, R. 1964. Minimum growth temperature for food-poisoning, fecal-indicator, and phychrophilic microorganisms. *Advances in Food Research*, 13: 349-396.

Migliori, M., Gabriele, D., De Cindio, B., & Pollini, C. 2005. Journal *of Food Engineering*, 71: 242-251.

Mintel. 2005. Frozen and Canned Fruit and Vegetables – UK. Mintel Reports – UK series. Mintel Group.

Mintel. 2003. Ready Meals – Ireland. Mintel Reports – Irish Series. Mintel Group.

Muggeo, V. M. 2003. Estimating regression models with unknown break-points. *Statistics in Medicine,* 22: 3055 – 3071.

Muehlbauer, F., & Tullu, A. 1997. *Cicer arietinum* L. NewCROP factsheet. URL: http://www.hort.purdue.edu/newcrop/cropfactsheets/Chickpea.html

Murthy, C., & Bhattachayra, S. 1998. Moisture dependent physical and uniaxial compression properties of black pepper. *Journal of Food Engineering*, 37: 193-205.

Mwithiga, G., & Olwal, J. 2005. The drying kinetics of kale (*Brassica oleracea*) in a convective hot air dryer. *Journal of Food Engineering,* 71: 373-378.

Nagata, C., Takatsuka, N., Kurisu, Y, & Shimizu, H. 1998. Decreased serum total cholesterol is associated with high intake of soy products in Japanese men and women. *Journal of Nutrition*. 128 , 209 – 213.

Nave, R. 2005. The C.I.E. Color Space. URL: http://hyperphysics.phy-astr.gsu.edu/hbase/vision/cie.html

Nijhuis, H., Torringa, E., Luyten, H., Rene, F., Jones, P., Funebo, T., & Ohlsson, T. 1996. Research need and opportunities in the dry conservation of fruits and vegetables. *Drying Technology*: 14, 1429 – 1458.

Nijhuis, H., Torringa, H., Muresan, S., Yuksel, D., Leguijt, C., & Kloek, W. 1998. Approaches tc improving the quality of dried fruit and vegetables. *Trends in Food Science and Technology*, 9: 13-20.

Ogwal, M., & Davis, D. 1994. Rapid rehydration methods for dried beans. *Journal of Food Science*, 59: 611-654.

Page, G. 1949 Factors ir fluencing the maximum of air drying shelled corn in thin layer. M.Sc. Thesis, USA. Purdue University, Indiana.

Pan, Z., & Tangratanavalee, W. 2003. Characteristics of soybeans as affected by soaking conditions. *Lebensmittel-Wissenschaft und-Technologie*, 36: 143-151.

Parker, R. 1998. Cereals, grains legumes and oilseeds. *In Food Science,* 5th ed (Eds. N. Potter & J. Hotchkiss). Springer.

Pathak, P., Srivastava, S., & Grover, S. 2000. Development of food products based on millets, legumes and fenugreek seeds and their suitability in the diabetic diet. *International Journal of Food Sciences and Nutrition*, 51: 409-414.

Peleg, M. 1988. An Empirical model for the description of Moisture Sorption Curves. *Journal of Food Science*, 53: 1249-1251

Pollini, C. 1996. Pasta drying: consolidation of VHT technology. In *Pasta and noodle technology* (Eds. J. Kruger, R. Matsuo, & J. Dick). American Association of Cereal Chemistry.

Pott, I., Neidhart, S., Mühlbauer, W., & Carle, R. 2005. Quality improvement of non-sulphited mango slices by drying at high temperatures. *Innovative Food Science and Emerging Technologies*, 6: 412-419.

Priestly, D., Werner, B., & Leopold, A. 1985. The susceptibility of soybean seed lipids to artificially-enhanced atmospheric oxidation. *Journal of Experimental Botany*, 36: 668-74.

Priestly, R., 1978. Processing and utilization of dry beans, Evaluation of new cultivars. CSIR Research Report, Document 2/10. Pretoria.

Prodanov, M., Sierra, I., & Vidal-Valverde, C. 2004. Influence of soaking and cooking on the thiamin, riboflavin and niacin contents of legumes. *Food Chemistry*, 84: 271-277.

Quast, D., & Silva, S. 1977. Temperature Dependence of Hydration Rate and Effect of Hydration on the Cooking Rate of Dry Legumes: *Journal of Food Science,* 42: 1299-1303.

R Development Core Team. 2005. R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. URL: http://www.R-project.org

Ramesh, M. 2003. Moisture transfer properties of cooked rice during drying. *Lebensmittel-Wissenschaft und-Technologie,* 36: 245-255.

Ratti, C. 2001. Hot air and freeze-drying of high-value foods: a review. *Journal of Food Engineering.* 49: 311-319.

Redmond, G., Gormley, T., & Butler, F. 2003. The effect of short- and long-term freeze-chilling on the quality of mashed potato. *Innovative Food Science and Emerging Technologies,* 4: 85–97.

Redmond, G., Gormley, T. & Butler, F. 2004. The effect of short- and long-term freeze-chilling on the quality of cooked green beans and carrots. *Innovative Food Sciences and Emerging Technologies*, 5: 65-72.

Rehinan, Z., Rashid, M., & Shah, W. 2004. Insoluble dietary fibre components of food legumes as affected by soaking and cooking processes. *Food Chemistry*, 85: 245-249.

Rehman, Z., & Shah, W. 2005. Thermal heat processing effects on antinutrients, protein and starch digestibility of food legumes. *Food Chemistry,* 91: 327-331.

Reuters Business Insight. 2003. Identifying the convenience consumer. URL: http://www.marketresearch.com.

Rizkalla, S., Bellisle, F., & Slama, G. 2002. Health benefits of low glycaemic index foods, such as pulses, in diabetic patients and healthy individuals, *British Journal of Nutrition*, Suppl. 3: 255-262.

Rizvi, A., & Tong, C. 1997. Fractional conversion for determining texture degradation kinetics of vegetables. *Journal of Food Science*, 62: 1-7.

Rodriguez-Amaya, D. 1993. Stability of carotenoids during the storage of foods. In *Shelf life studies of foods and beverages - chemical, biological, physical and nutritional aspects* (Ed. F. Charalambous). Elsevier Science.

Roos, Y. 2002. Glass transition and water activity. IFT's pre-meeting continuing education program: fundamentals of water activity. URL: www.wateractivity.org

Rosenthal, A. 1999. Food Texture: Measurement and Perception. Aspen Publishers Inc.

Ruíz Díaz G, Martínez-Monzó J, Fito P, Chiralt A, 2003. Modelling of dehydration-rehydration of orange slices in combined microwave/air drying. *Innovative Food Science and Emerging Technologies,* 4: 203-209.

Sabapathy, N. 2005. Heat and mass transfer during cooking of chickpea – measurements and computational simulation. M.Sc Thesis, Canada. University of Saskatchewan, Saskatoon, Saskatchewan.

Sacilik. K. & Unal, G. 2005. Dehydration Characteristics of Kastamonu Garlic Slices. *Biosystems Engineering,* 92: 207-215.

Sangronis, E., Ibarz, A., Barbosa-Canovas, G., & Swanson, B. 2002. Effect of high hydrostatic pressure on water imbibition, cooking times and microstructure of Phaseolus vugaris. *Archivos Latinoamericanos De Nutricion*, 52: 301-306.

Sarwar, G., & McDonough, F. 1990. Evaluation of protein digestibility-corrected amino acid score method for assessing protein quality of foods. *Journal of the Association of Official Analytical Chemists*, 73: 347-56.

Sayar, S., Turhan, M., & Guneskaran, S. 2001. Analysis of chickpea soaking by simultaneous water transfer and water-starch reaction. *Journal of Food Engineering*, 50: 91-98.

Schneider, A. 2002. Overview of the market and consumption of pulses in Europe. *British Journal of Nutrition*, 88: S243-50.

Senadeera, W., Bhandari, B.,Young, G. & Wijesinghe, B. 2003. Influence of shapes of selected vegetable materials on drying kinetics during fluidized bed drying. *Journal of Food Engineering,* 58: 277-283.

Sharma, G., & Prasad, S. 2001. Drying of garlic (*Allium sativum*) cloves by microwave-hot air combination. *Journal of Food Engineering*, 50: 99-105.

Shewfelt, R. 1999. What is quality? *Postharvest Biology and Technology*, 15: 197-200.

Silva, C., Bates, R., & Deng, J. 1981. Influence of pre-soaking on black bean cooking kinetics. *Journal of Food Science*, 46: 1721-25.

Silva, H., & Braga, G. 1982. Effect of soaking and cooking on the oligosaccharide content of dry beans. *Journal of Food Science*, 47: 924-925.

Simal, S., Femenia, A., Garau, M.C. & Rosselló, C. 2005. Use of exponential, Page's and diffusional models to simulate the drying kinetics of kiwi fruit. *Journal of Food Engineering,* 66: 323-328.

Singh, K. 1997. Chickpea (*Cicer arietinum* L.). *Field Crops Research*, 53: 161-170 .

Soliva-Fortuny, R., Lluch, M., Quiles, A., Grigelmo-Miguel, N., & Martín-Belloso, O. 2003. Evaluation of Textural Properties and Microstructure During Storage of Minimally Processed Apples. *Journal of Food Science*, 68:312-317.

Song, J., An, G., & Kim, C. 2003. Color, texture, nutrient contents, and sensory values of vegetable soybeans [*Glycine max* (L.) Merrill] as affected by blanching. *Food Chemistry*, 83: 69-74.

Sosulski, K & Sosulski, F. 2005. Legume: Horticulture, properties and processing. 18-1 – 18-14. In *Handbook of Food Science, Technology and Engineering,* Volume 3 (Ed. Y.H. Hui). CRC Press, UK.

Snyder, P. 1997. Safety of pasteurised-chilled food. Hospitality Institute of Technology and Management.

Steinhart, V., Reimers, C., Lecerf, J-M. 2002. Protein quality – methods for evaluating protein quality of food proteins. Dupont Protein Technologies. URL: www.dupont.com

.

Steinkraus, K., Van Beuren, J., LaBelle, R., & Hand, J. 1964. Some studies on the production of precooked dehydrated beans. *Food Technology*, 18: 121-126.

Strumillo, C., & Adamiec, J. 1996. Energy and quality aspects of food drying. *Drying Technology*, 14: 423-448.

Taiwo, K., Akanbi, C., & Ajibola, O. 1997. The effects of soaking and cooking time on the cooking properties of two cowpea varieties. *Journal of Food Engineering*, 33: 337-346.

Thybo, A., Nielsen, M., & Martens, M. 2000. Influence of uniaxial compression rate on rheological parameters and sensory texture prediction of cooked potatoes. *Journal of Texture Studies*, 31: 25-40.

Tijskens, L., Schijvens, E., & Biekman, E. 2001. Modelling the change in colour of broccoli and green beans during blanching. *Innovative Food Science and Emerging Technologies*, 2: 303-313.

Toğrul, İ., & Pehlivan, D. 2003. Modelling of drying kinetics of single apricot, *Journal of Food Enginee ing,* 58: 23–32.

Troller, J 1989. Water activity and food quality. In *Water and food quality* (Ed. T. Hardman) pp 1-31, Elsevier Applied Science, London.

Turhan, M., Sayar, S., & Gunasekaran, S. (2002). Application of Peleg model to study water absorption in chickpea during soaking. *Journal of Food Engineering.* 53: 153-159.

USFDA. 1999. Food labeling, health claims, soy protein, and coronary heart disease. Federal Regulations. 57: 699-733.

USDA. 2006. What's in the Foods You Eat - Search Tool. URL: http://www.usda.gov

Van der Poel, T., Blonk, J.,van Zuilichem, D., Van Doort, M. 1990. Thermal inactivation of lectins and trypsin inhibitor activity during steam processing of dry beans (Phaseolus Vulgaris) and effects on protein quality. Journal of the Science of Food and Agriculture, 53: 215-228.

Vega-Mercado, H., Góngora-Nieto, M., Barbosa-Cánovas, G. 2001. Advances in dehydration of foods. *Journal of Food Engineering*, 49: 271-289.

Verma, R., & Prasad, S. 1999. Kinetics of absorption of water by maize grains. *Journal of Food Engineering*, 39: 395-400.

Voisey, P. 1975. Selecting deformation rates in texture tests. *Journal of Texture Studies*, 6: 253 257.

Vidal-Valverde, C., Frias, J., & Valverde, S. 1993. Changes in the carbohydrate composition of legumes after soaking and cooking. *Journal of the American Dietetic Association*, 93: 547-550.

Vose, D. 2002. Risk Analysis: a Quantitative Guide, 2nd ed. J Wiley, Chichester, England.

Walker, S., & Betts, G. 2000. Chilled foods microbiology. In *Chilled Foods*, 2nd edition (Eds. M. Stringer & C. Dennis). Campden and Chorleywood Food Research Association, UK, Woodhead Publishing Limited, Abington Hall, Abington, Cambridge, CB1 6AH, England

Wang, S., & Toledo, M. 1987. Inactivation of soybean lipoxygenase by microwave heating: effect of moisture content and exposure time. *Journal of Food Science*, 52: 1344-1347.

White, G. and Cakebread, S. 1966. The glassy state in certain sugar- containing food products. *Journal of Food Technology*, 1: 73 – 82.

Willett, W. 1995. Diet, nutrition and avoidable cancer. *Environmental Health Perspectives,* 103: 165-170.

Williams, P., Nakoul, H., & Singh, K. 1983. Relationship between cooking time and some physical characteristics in chickpea (*Cicer arietinum*). *Journal of the Science of Food and Agriculture,* 34: 492-496.

Wu, A., Wan P., Hankin J., Tseng C., Yu M., Pike M. 2002. Adolescent and adult soy intake and risk of breast cancer in Asian-Americans. *Carcinogenesis*, 23: 1491–6.

Yongsawatdigul, J., & Gunaskeran, S. 1996. Microwave-vacuum drying of cranberries: part 1. Energy use and efficiency. *Journal of Food Processing and Preservation,* 20: 121-143.

Yoshida, H., & Kajimoto, G. 1988. Effects of microwave treatment on the Trypsin Inhibitor and molecular species of triglycerides in soybeans. *Journal of Food Science,* 53: 1756-1760.

Zink, D. 1997. The Impact of Consumer Demands and Trends on Food Processing. *Emerging Infectious Diseases,* 3: 467-469.

Zogzas, N., Maroulis, Z. 1996. Effective moisture diffusivity estimation from drying data: a comparison between various methods of analysis. *Drying Technology,* 14: 1543-1573.

APPENDIX A

SENSORY TRIAL FOR COOKED CHICKPEAS AND SOYBEANS

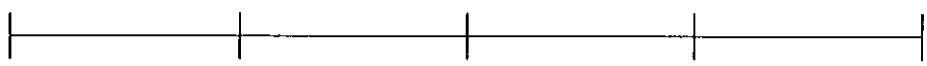
Sensory trial as presented to taste panel

Instructions

You will be comparing samples of beans in terms of taste, texture, and appearance. Please take your time and take a sip of water, if required, after tasting each sample.

Question 1

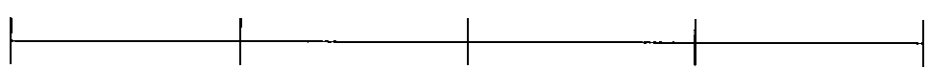
You will now evaluate the appearance of each sample. Examine the bean in terms of colour, appearance of skin (e.g. cracks, smoothness). Please mark your response on the scale below.



Highly unacceptable | Unacceptable | Don't know | Acceptable | Highly acceptable

Question 2

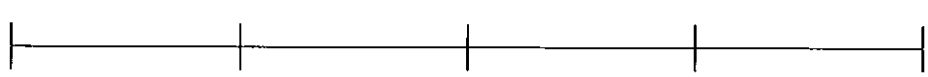
You will now taste 2-3 beans from each sample and compare the texture of each sample. Please mark your response on the scale below.



Too soft | Soft | Just right | Hard | Too hard

Question 3

You are now asked to judge your overall liking of each sample. Please mark your response on the scale below.



Dislike extremely | Dislike | Neither like nor dislike | Like | Like extremely

Random numerical codes were assigned to each cooking treatment (Table A1).

Table A1. Coding for sensory trial

Boil time (min)	Microwave time (min)	Code
40	0	120
50	2.5	978
40	5	784
60	5	851
60	0	560

APPENDIX B

EFFECT OF COOKING PRIOR TO DEHYDRATION ON DRYING, REHYDRATION AND QUALITY CHARACTERISTICS OF CHICKPEAS AND SOYBEANS

B.1 Introduction

This short study was performed to investigate the necessity to cook chickpeas and soybeans, as opposed to just soaking them, before dehydration. Colour and texture of rehydrated samples that had been soaked prior to drying, and those that had been soaked and cooked prior to drying, were compared.

B.2 Materials & methods

B.2.1 Materials

Chickpeas and soybeans were prepared as described in section 3.4.

B.2.2 Drying equipment

Drying equipment is described in section 3.5.

B.2.3 Experimental design

Cooked chickpeas and soaked chickpeas were dehydrated by means of convective hot air drying. The oven was set to convective mode. Three temperature settings (160 °C, 180 °C, 200 °C) were investigated. After dehydration, samples were stored in sealed bags over a dessicator, for further analysis.

Cooked soybeans and soaked soybeans were dehydrated using combined microwave – hot air drying. The oven was set to combined mode. One temperature setting (160 °C) and three microwave power settings (210, 300, 560)

were investigated. After dehydration, samples were stored in sealed bags over a dessicator, for further analysis.

B.2.4 Dehydration procedure

A single layer of 40 g sample was spread over a glass petri dish, which was then placed in the centre of the oven cavity. Drying conditions were then set on the display panel. Dehydrated samples were stored in sealed plastic bags for further analysis.

B.2.5 Rehydration procedure

Rehydration procedure is described in section 3.8.

B.2.6 Texture evaluation

Average hardness of 25 rehydrated samples was calculated for each treatment. Texture evaluation equipment is described in section 3.3.

B.2.7 Colour measurement

The colour of the surface of five individual rehydrated samples for each treatment was measured. Colour measurement apparatus is described in section 3.9.

B.3 Results and discussion

B.3.1 Effect of cooking prior to drying on colour and texture of chickpeas subjected to hot air convective drying

Chickpeas were dehydrated to constant weight by convective hot air drying (Fig. B.1). The shape of drying curves for soaked chickpeas was similar to that for cooked samples, but soaked chickpeas reached the constant phase at a higher percentage of their original weight. This is because soaked chickpeas had lower original moisture content than cooked samples; in other words, cooked samples had more water to loose during drying.

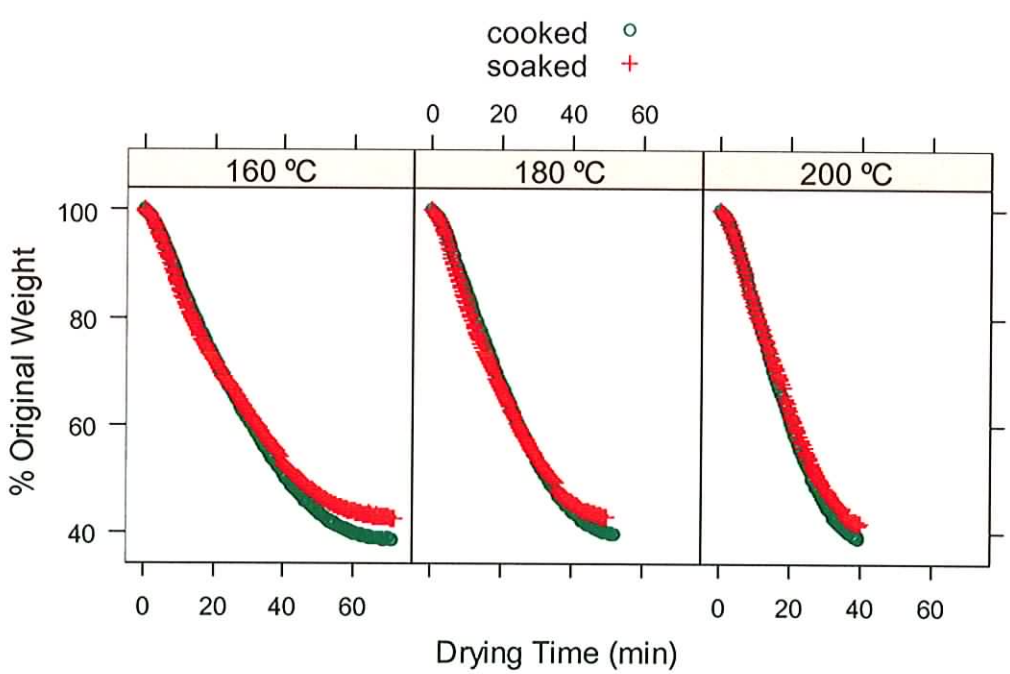


Fig. B.1. Drying curves for convective drying of soaked and cooked chickpeas.

Dehydrated chickpeas were then rehydrated in boiling water until they achieved constant weight (Fig. B.2). Soaked chickpeas gained less weight during rehydration than cooked chickpeas. This is analogous to observation that soaked samples lost less weight during the dehydration process.

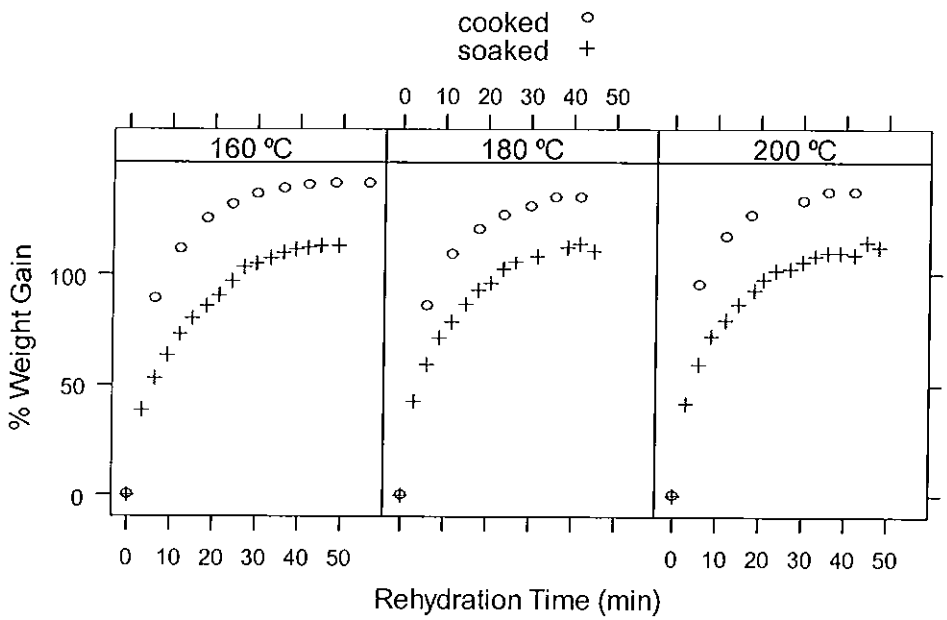


Fig. B.2. Rehydration curves for soaked and cooked chickpeas

CIELAB Lightness (L*) and yellowness (b*) colour values for soaked and cooked chickpeas upon rehydration are presented in Fig. B.3. It is clear that the cooking samples prior to dehydration produced a lighter (higher L*) and yellowier (higher b*) rehydrated chickpea, compared to soaked samples. Lighter yellow colour, rather than a darker product, is more desirable from a consumer's point of view.

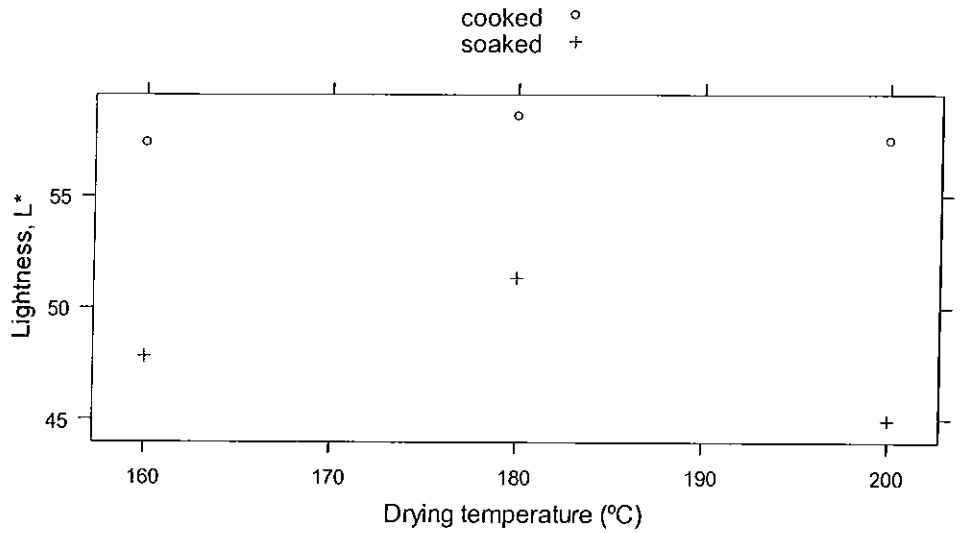


Fig. B.3 (a). Lightness values for soaked and cooked chickpeas on rehydration

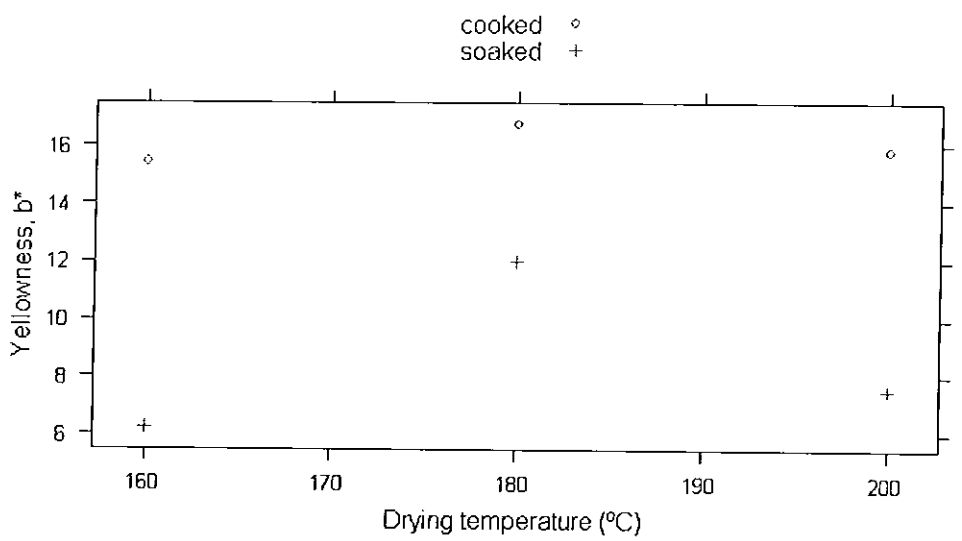


Fig. B.3 (b). Yellowness values for soaked and cooked chickpeas on rehydration

The average texture of rehydrated chickpeas, both soaked and cooked are displayed in Fig. B.4. It is clear from the graph that cooking chickpeas prior to drying results in a softer final product, when compared to normally cooked samples. The soaked samples resulted in a harder final product that would not be acceptable from a consumer point of view.

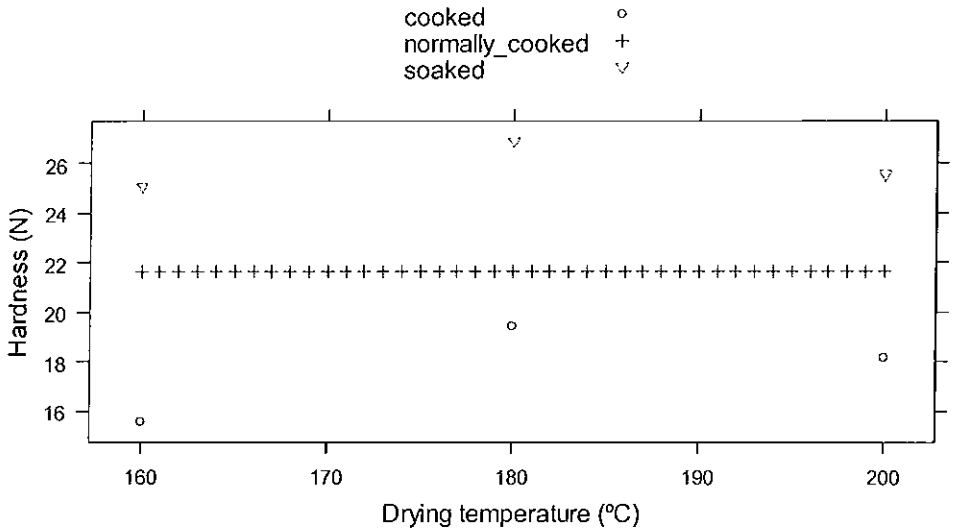


Fig. B.4. Texture of rehydrated soaked and cooked chickpeas.

B.3.2 Effect of cooking prior to drying on colour and texture of soybeans subjected to combined microwave-hot air convective drying

Soybeans were dehydrated to constant weight by convective hot air drying (Fig. B.5). The shape of drying curves was similar for cooked and soaked chickpeas, but soaked soybeans reached the constant phase at a higher weight. This is because soaked soybeans had lower original moisture content than cooked samples; that is, cooked samples had more water to loose during drying.

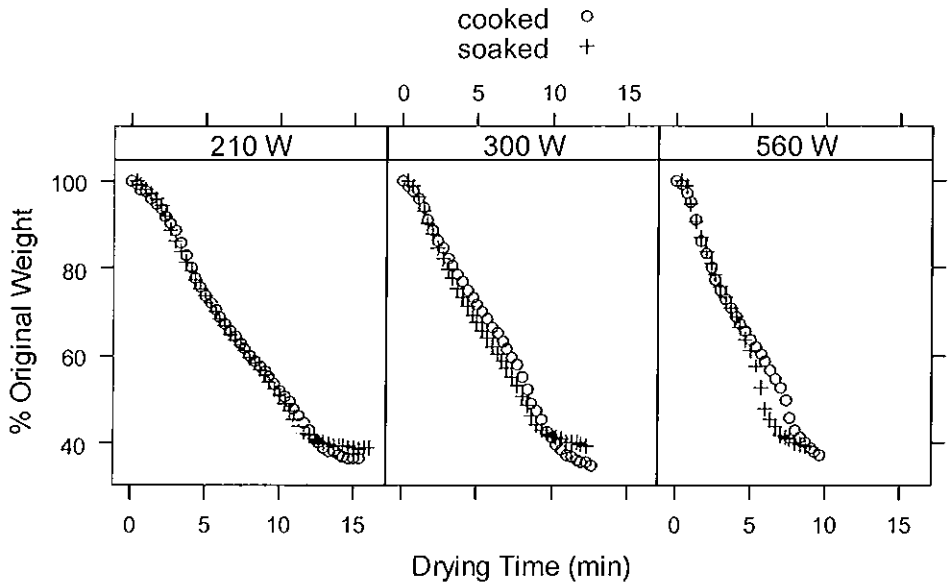


Fig. B.5. Drying curves for combined microwave-hot air drying of soaked and cooked soybeans

Dehydrated soybeans were then rehydrated in boiling water until they achieved constant weight (Fig. B.6). Soaked soybeans gained less weight during rehydration than cooked samples. This is analogous to observation that soaked samples lost less weight during the dehydration process.

Lightness (L*) and yellowness (b*) Hunterlab colour values for soaked and cooked chickpeas upon rehydration are presented in Fig. B.7. It is clear that the cooked samples produce a lighter and more yellow rehydrated soybean, which is more desirable from a consumer point of view.

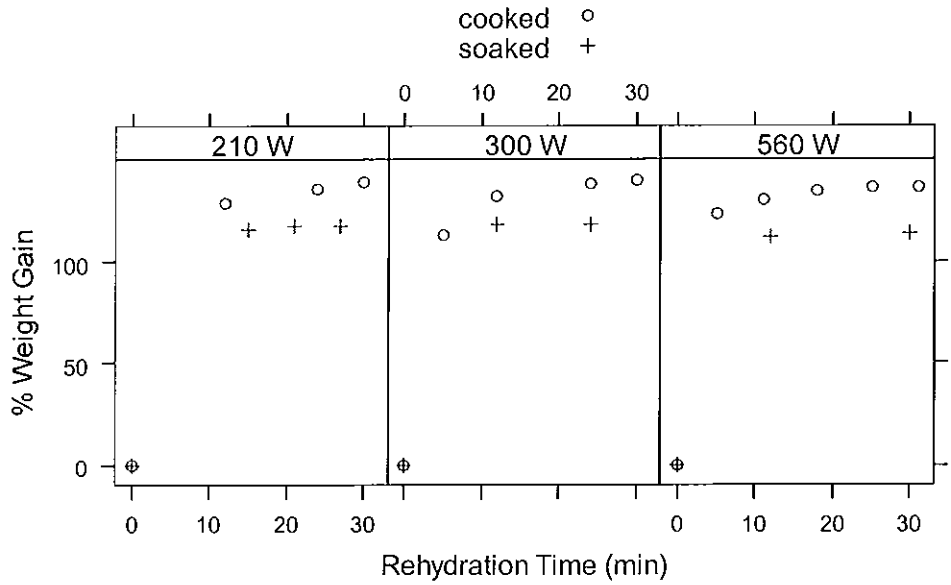


Fig. B.6. Rehydration curves for soaked & cooked chickpeas

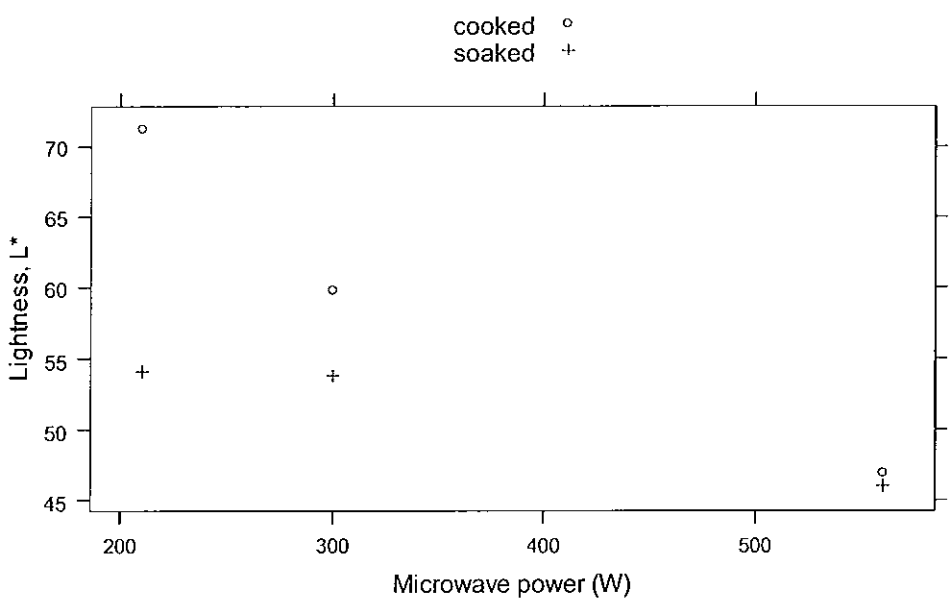


Fig. B.7 (a). Lightness values for soaked and cooked soybeans on rehydration

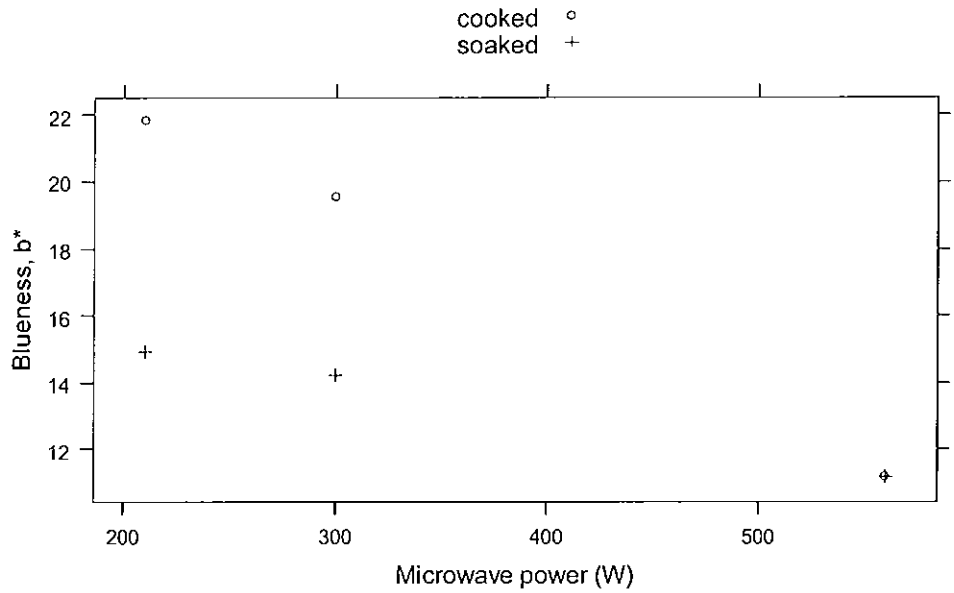


Fig. B.7 (b). Yellowness values for soaked and cooked soybeans on rehydration

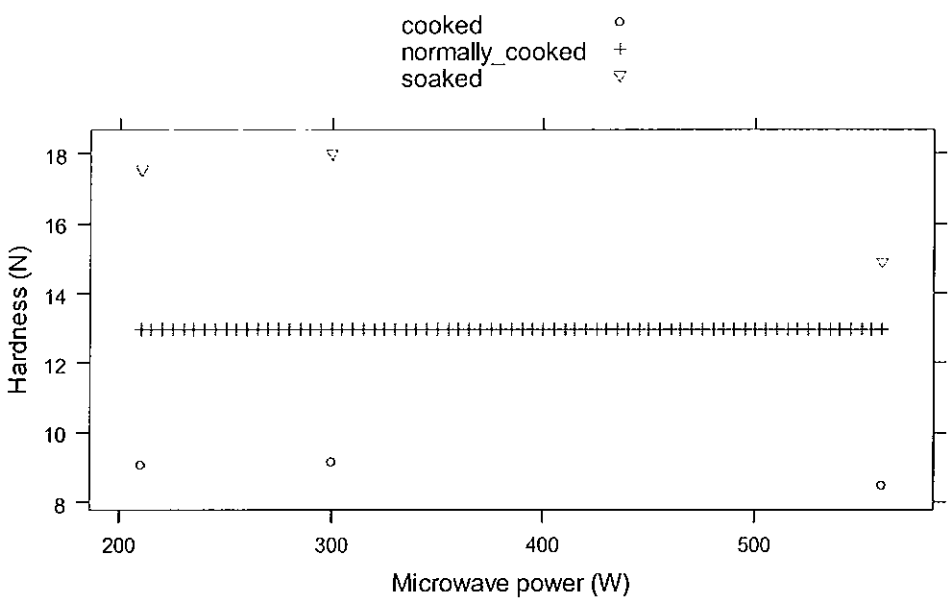


Fig. B.8. Texture of rehydrated soaked and cooked soybeans.

Average hardness of rehydrated soybeans, both soaked and cooked, is displayed in Fig. B.8. It is clear from the graph that cooking soybeans prior to drying results in a softer final product, when compared to normally cooked samples. The

soaked samples result in a harder final product that would not be acceptable from a consumer's point of view.

B.4 Conclusions

Considering the results described in the preceding sections, the necessity to cook chickpeas and soybeans prior to dehydration is clear. Without the cooking step, a poor quality final product, with a dull appearance and hard texture, is produced.

APPENDIX C

PRIMARY INVESTIGATION: PRODUCTION OF QUICK-COOK DEHYDRATED CHICKPEA PRODUCTS

Effects of microwave - hot air combination drying on dehydration and rehydration properties of pre-cooked chickpeas

Some of the results from this chapter have been presented at the EFFOST Food innovations for an increasing Europe Conference, Warsaw, Poland, and published as a peer-reviewed article in Trends in Food Science and Technology (see pages 289-292)

Summary

In this study, the production of quick-cook dehydrated chickpeas was investigated. Whole, pre-cooked chickpeas were dehydrated by continuous microwave - hot air application. Three microwave power levels (210 W, 300 W, 560 W) and three air temperature settings (23 °C, 160 °C, 250 °C) were employed. Moisture content was estimated by observation of sample weight loss during drying. Mathematical models were constructed to predict dehydration and rehydration kinetics as functions of processing conditions. Optimal drying conditions were estimated.

C.1 Introduction

This appendix comprises of a preliminary study into the production of quick-cook dehydrated chickpeas. The effects of fast dehydration, caused by combination of high levels of air temperature and microwave power, on product quality, were investigated. Quality was measured in terms of colour and texture of rehydrated samples. Dehydration and rehydration kinetics were also examined. Consequently, the primary objectives of the chapter were as follows:

1. Study the dehydration and rehydration properties of cooked chickpeas during combined microwave-hot air drying;
2. Investigate the effect of changing air temperature and microwave power on drying and rehydration properties;
3. Estimate optimal process conditions for production of quick cook, dehydrated chickpeas.

C.2 Materials and methods

C.2.1 Material

Raw material is described in section 3.1. Preparation of samples for dehydration is described in section 3.4. Note: In this study, pre-cooked chickpeas were packed in 50 g units and stored at 8 °C.

C.2.2 Drying equipment

Drying equipment is described in section 3.5.

C.2.3 Experimental design

Three microwave power (MW) settings (210 W, 300 W, 560 W) and three convection (T) settings (natural convection (ambient temperature = 23 °C), 160 °C (air velocity = 1 m/s), 250 °C (air velocity = 1 m/s)) were investigated. A fully randomised 3^2 design with three replications for each drying treatment was employed.

C.2.4 Moisture content determination

Moisture content determination is described in section 3.6

C.2.5 Dehydration procedure

A single layer of 50 g cooked chickpea sample was spread over a glass plate, which was placed on the rotating turntable in the centre of the oven

cavity. Drying conditions (i.e. microwave power, air temperature and drying time) were then set on the display panel of the oven. The sample was removed at specified time intervals during the drying process, and its weight recorded (weighing was completed in under 30 s to minimise temperature disturbance). After weighing, the sample was returned to the oven, and the drying procedure was repeated until the difference in consecutive readings was insignificant. Dehydrated samples were stored in sealed plastic bags for further analysis.

C.2.6 Calculation of Moisture ratio

Moisture ratio calculation is described in section 3.7.

C.2.7 Rehydration procedure

Rehydration procedure is described in section 3.8.

C.2.8 Texture evaluation

Average hardness of 25 rehydrated chickpeas was calculated for each drying treatment. Equipment for texture measurement is described in section 3.3.

C.2.9 Colour measurement

The colour of the surface of five individual rehydrated chickpeas was measured for each drying treatment. Colour measurement apparatus is described in section 3.9.

C.3 Results and discussion

C.3.1 Dehydration kinetics

Moisture Ratio (MR) was plotted as a function of microwave power (MW), air temperature (T) and time (t) (Fig. C.1(a)). For each set of drying conditions, MR decreased with time, approaching an asymptotic value of 0. Drying time ranged from just over 1 h (for MW = 210 W, T = 23 °C) to under 15 min (for MW = 560 W, T = 250 °C), depending on drying method; faster drying occurred as microwave power and air temperature were increased (Table C.1).

Given the asymptotic shape of the dehydration curves (Fig. C.1(a)), the following first order model, known as the Lewis model (see section 3.10.2.1), was chosen for primary modelling of the dehydration data (Eq. C.1).

$$MR = e^{-k_d t} \quad \text{...(C.1)}$$

k_d, the dehydration rate constant, is representative of the rate of dehydration. Non-linear regression of Eq. C.1 was performed for each individual experiment. The drying rate constant, k_d, showed a trend of increasing with both air temperature and microwave power (Table C.1). However, there was quite a large variation in k_d among repetitions of drying treatments. The necessity to open the microwave every minute to weigh the sample would have been a major source of this variation. This caused undesirable temperature fluctuations within the microwave cavity, disturbing the thermodynamic equilibrium.

After comparison of a number of different candidate models, by means of log-likelihood ratio tests, a linear model (see Eq. C.2) was found to best describe the dependence of k_d on MW and T ($r^2 > 0.95$).

$$k_d = a_d MW + b_d T \quad ...(C.2)$$

A general model (Eq. C.3) was therefore constructed to predict MR as a function of drying time, microwave power and air temperature.

$$MR = MR_0 e^{-(a_d MW + b_d T)t} \quad ...(C.3)$$

One–step nonlinear regression of Eq. C.3 was performed on the entire dataset of drying experiments. Predictive plots were generated from the model parameters (Fig. C.1(a)), and represent the experimental data adequately. Residual and quantile-quantile plots for the model fitting are shown in Fig. C.1(b)-(c). An intrinsic residual correlation is observed in the residual plot, which is inevitable due to the continuous weight monitoring; but it is believed that this effect did not affect parameter estimation or model fit significantly. Overall, the residuals seemed to be randomly distributed, with most lying between two standardised residuals. The quantile-quantile plot was close to linear. This indicated that the Eq. C.3 described the dehydration data well.

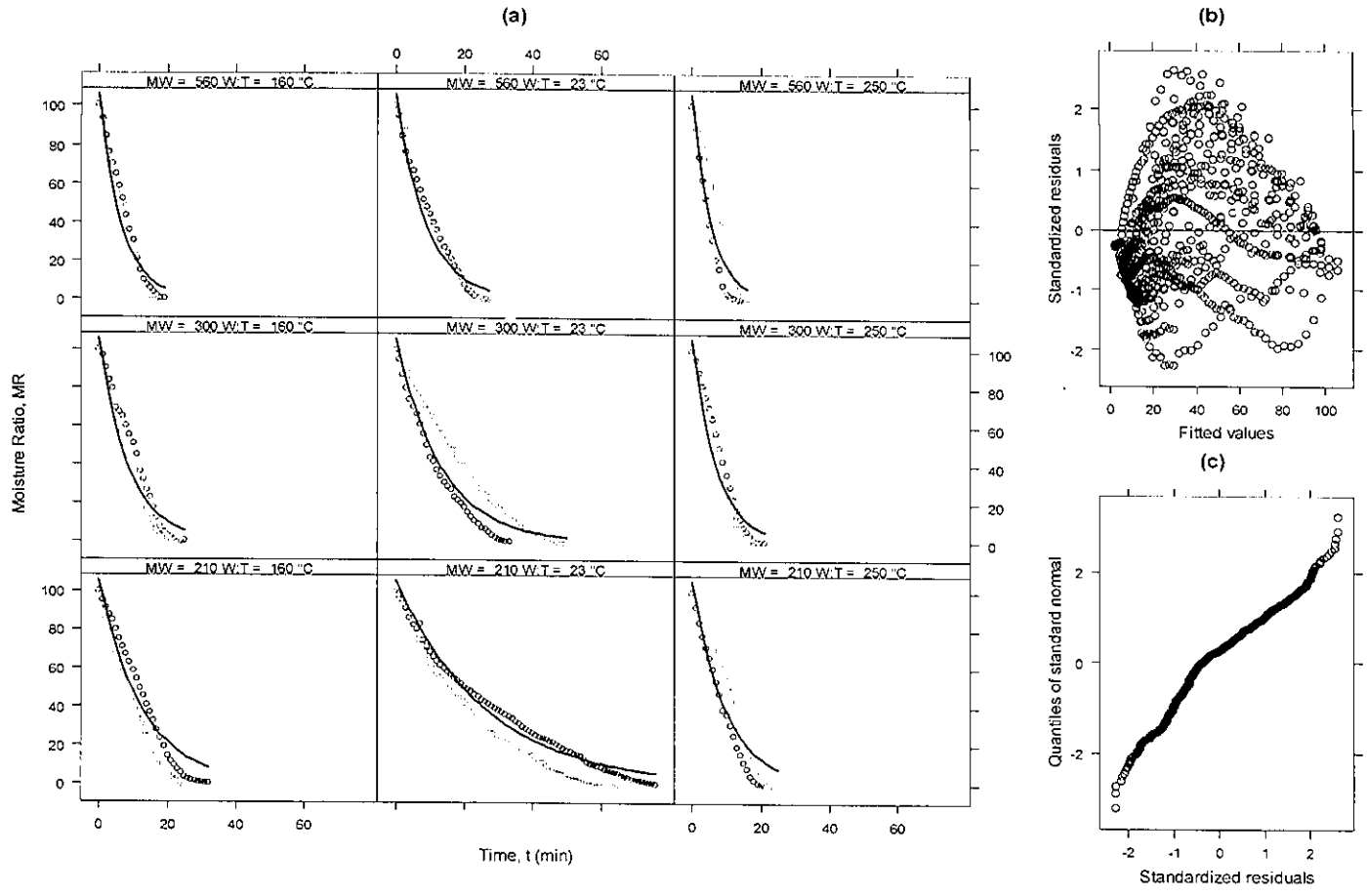


Fig. C.1. Moisture Ratio (MR) as a function of drying method and time; solid lines indicate predictive plots for nonlinear regression of Eq. C.3 on chickpea dehydration data **(a)**. Residual **(b)** and quantile-quantile **(c)** plot for generalised nonlinear regression of Eq. C.3 on chickpea dehydration data.

Table C.1. Dehydration time (t_d), dehydration rate constant (k_d), rehydration time (t_r), rehydration rate constant (k_r), CIELAB L* and CIELAB DE* values for chickpeas undergoing combined hot air-microwave drying.

MW (W)	T (°C)	t_d (min)	k_d (min^{-1})	t_r (min)	k_r (min^{-1})	L*	DE*
210	23	66 ± 7	0.04 ± 0.01	17 ± 4	0.27 ± 0.03	61.8 ± 3.3	6.5 ± 3.7
210	160	25 ± 5	0.11 ± 0.02	13 ± 2	0.33 ± 0.07	58.2 ± 2.2	5.2 ± 1.4
210	250	21 ± 1	0.11 ± 0.02	11 ± 4	0.31 ± 0.05	48.4 ± 0.5	16.4 ± 1.0
300	23	40 ± 7	0.07 ± 0.02	11 ± 2	0.31 ± 0.01	59.7 ± 3.7	5.5 ± 1.8
300	160	22 ± 2	0.12 ± 0.02	10 ± 1	0.32 ± 0.04	55.1 ± 1.7	8.3 ± 1.2
300	250	19 ± 2	0.13 ± 0.01	10 ± 1	0.33 ± 0.03	47.3 ± 4.7	19.0 ± 6.8
560	23	25 ± 1	0.10 ± 0.01	11 ± 1	0.30 ± 0.01	56.8 ± 3.0	6.0 ± 3.4
560	160	16 ± 2	0.15 ± 0.03	10 ± 1	0.36 ± 0.02	52.2 ± 3.2	11.5 ± 4.6
560	250	13 ± 2	0.20 ± 0.05	9 ± 2	0.40 ± 0.07	43.0 ± 0.6	24.5 ± 1.1

C.3.2 Rehydration kinetics

Rehydration time ranged from 9 min (for MW = 560 W, T = 250 °C) to 17 min (for MW = 210 W, T = 23 °C) (Table C.1). Weight gain on rehydration (WGR) was plotted as a function of drying parameters and time (Fig. C.2(a)), and increased to an asymptotic value for all drying conditions. The shape of the rehydration curves indicated a first order process. Therefore, an asymptotic model (Eq. C.4) with non-zero asymptote was chosen to describe the kinetics of rehydration. A non-linear regression of Eq. C.4 was initially performed on each individual experiment.

$$WGR = WGR_e - WGR_e * e^{-k_r t} \quad \text{...(C.4)}$$

Where WGR_e represents the asymptotic value of WGR, and k_r represents the rehydration rate constant.

To build a model to describe the effect of microwave power (MW), air temperature (T) and rehydration time on WGR, the regression parameters were investigated. WGR_e was fairly constant over the range of experimental conditions, and k_r showed an increasing trend with both MW and T (Table 1). After careful inspection of a number of different candidate models, which were compared using log-likelihood ratio tests, a linear model (Eq. C.5) was chosen to describe the effect of MW and T on k_r ($r^2 > 0.9$).

$$k_r = a_r MW + b_r T \quad \text{...(C.5)}$$

Combining Eq. C.4 and Eq. C.5 resulted in a non-linear model (Eq. C.6), which was then regressed on the entire data set. Predictive plots were generated from the regression coefficients, and are shown in Fig. C.2(a). Residual and quantile- quantile plots are displayed in Fig. C.2(b)-(c). The residuals seemed to be randomly distributed within two standardised residuals. The quantile-quantile plot was reasonably straight, indicating model suitability.

$$WGR = WGR_e - WGR_e * e^{-(a_1 MW + b_1 T)t} \quad \text{...(C.6)}$$

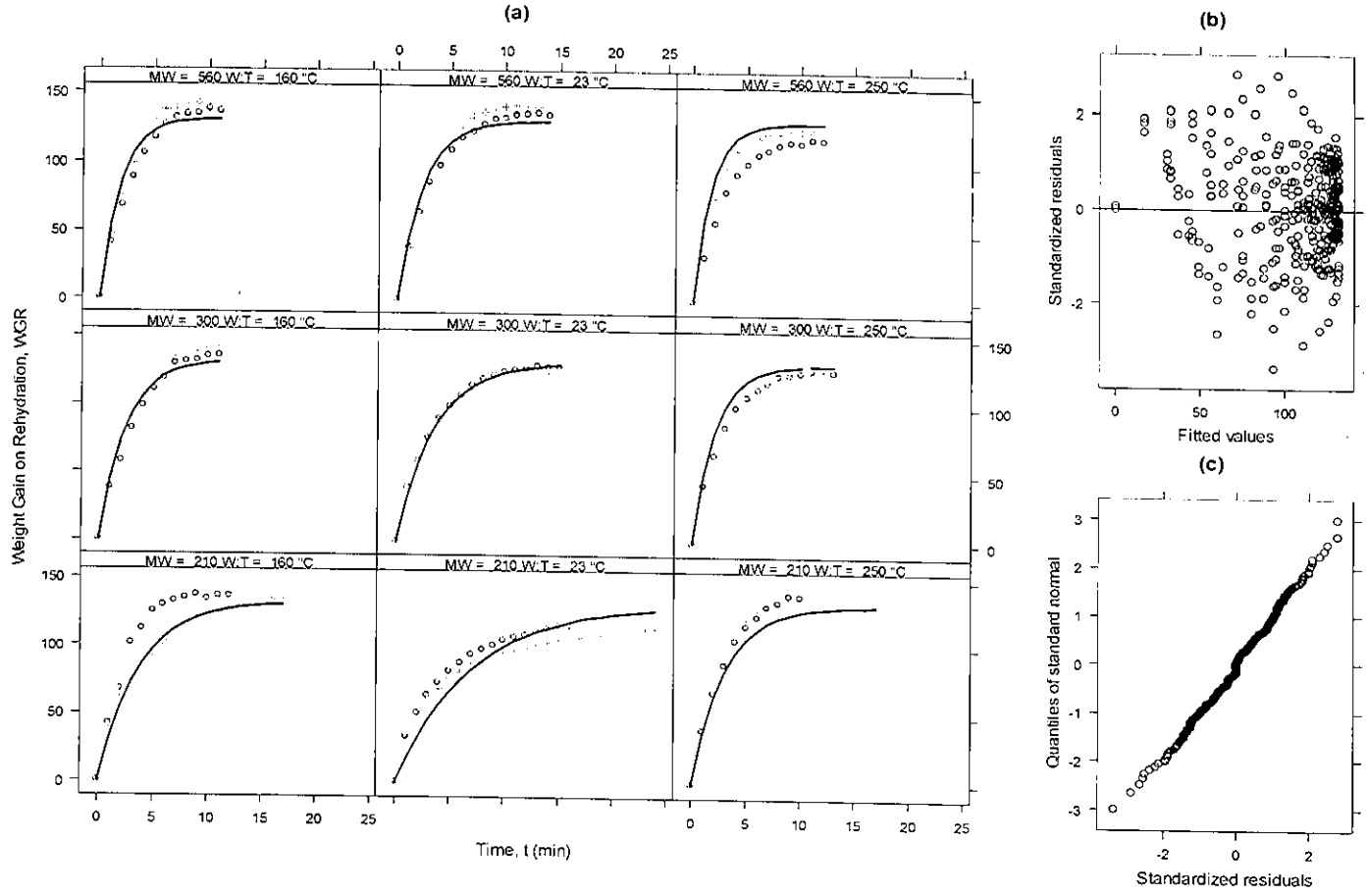


Fig.C. 2. Weight gain on rehydration (WGR) as a function of drying method and time, solid lines indicate predictive plots for nonlinear regression of Eq. C.6 on chickpea rehydration data **(a)**. Residual **(b)** and quantile-quantile **(c)** plot for generalised nonlinear regression of Eq. C.6 on chickpea rehydration data.

C.3.3 Texture of rehydrated samples

The effect of air temperature and microwave power on average hardness of rehydrated chickpeas is shown in Fig. C.3. Texture of freshly cooked chickpeas is also represented (Fig. C.3). Average hardness of rehydrated chickpeas was closest to that of cooked ones for samples dried at 160 °C, regardless of the microwave power level used. An increase in average hardness occurred for processing at convection temperature 250 °C and microwave powers 300 and 560 W. This may be due to case hardening of the product during the high temperature processing.

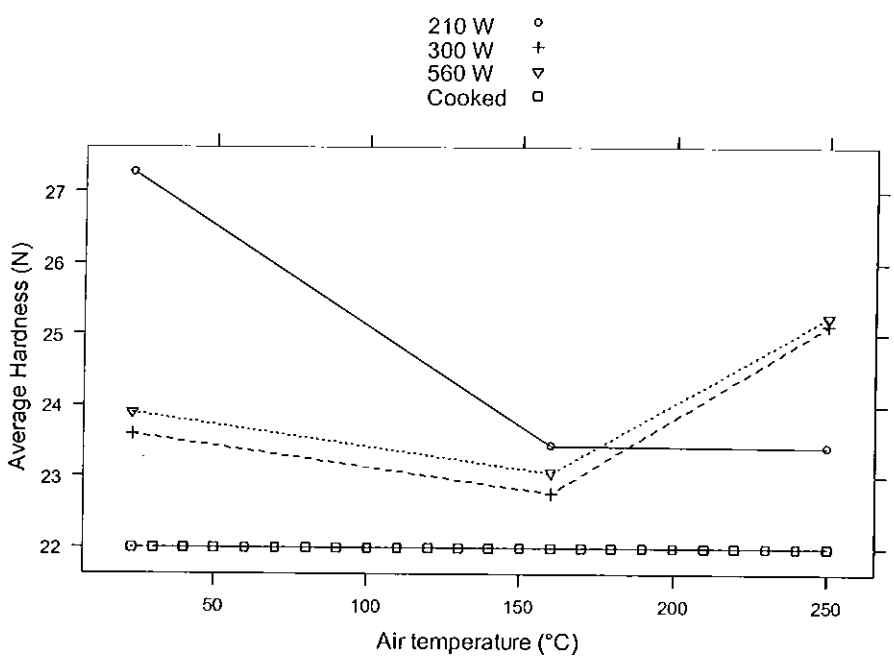


Fig. C 3. Average hardness of rehydrated chickpeas as a function of air temperature and microwave level.

C.3.4 Colour of rehydrated samples

Dehydration of cooked chickpeas ($L^*_0 = 62.8 \pm 1.4$, $a^*_0 = 8.8 \pm 1.4$, $b^*_0 = 23.8 \pm 3.3$) produced considerable colour change, regardless of drying method (Table C.1). Increasing air temperature from 23 °C to 160 °C, did not have a significant effect ($p > 0.05$) on either lightness (L*) or total colour change (DE*) of rehydrated chickpeas. However, when air temperature was increased from 160 °C to 250 °C, L* decreased significantly ($p < 0.05$), while DE* increased significantly ($p < 0.05$). Thus, although combination drying at 250 °C was the fastest method of dehydration, it resulted in significant darkening and colour change when compared to lower temperature drying. Analysis of variance of L* and DE* for combination drying at 160 °C showed that increasing the microwave power level resulted in significantly ($p < 0.05$) lower L* and higher DE*. Therefore, combination of air-drying at 160 °C with the lowest microwave level (210 W) would minimise both darkening and colour change.

C.3.4Conclusions

The study showed that fast dehydration of cooked chickpeas, by application of combined hot air-microwave drying, would yield quick cook, dehydrated products. It was also shown that combination of high temperatures with high levels of microwave power could adversely affect rehydrated product quality. Case hardening and significant colour change were associated with combination drying at 250 °C, while increasing microwave power resulted in significant darkening and colour change for combination drying at 160 °C. Optimum quality in terms of drying time, rehydration time, texture and colour was therefore achieved for combined drying with microwave power 210 W and air temperature 160 °C. The present study confirmed that cooked chickpeas would be suitable for drying at high temperatures and microwave power, demonstrating satisfactory rehydration properties.

List of publications

Peer-reviewed papers

1. Modelling the water absorption process in chickpeas *(Cicer arietinum., L.)* - the effect of blanching pretreatment on water intake and texture kinetics. Gowen, A., Abu-Ghannam, N., Frias, J., Oliveira, J. (2007). *Journal of Food Engineering*, 78: 810-819.

2. Influence of pre-blanching on the water absorption kinetics of soybeans. Gowen, A., Abu-Ghannam, N., Frias, J., Oliveira, J. (2007). *Journal of Food Engineering*, 78: 965-971.

3. Optimisation of dehydration and rehydration properties of cooked chickpeas *(Cicer arietinum* L.*)* undergoing microwave - hot air combination drying. Gowen, A., Abu-Ghannam, N., Frias, J., Oliveira, J. (2006). *Trends in Food Science and Technology*, 17: 177-183.

4. Comparative study of quality changes occurring upon dehydration and rehydration of cooked chickpeas *(Cicer Arietinum* L.*)* subjected to combined microwave-convective hot-air dehydration and convective hot-air dehydration. Gowen, A., Abu-Ghannam, N., Frias, J., Oliveira, J. (2006). *Journal of Food Science*, 71: E282 – E289.

5. Comparison of Dehydration and Rehydration of Cooked Legumes Undergoing Air-Drying, Microwave Drying and Combined Microwave-Hot Air Drying. Gowen, A., Abu-Ghannam, N., Frias, J., Oliveira, J. (2006). *Journal of Food Engineering*. In Review.

6. Characteristics of cooked chickpeas and soybeans during microwave, convective and combined microwave-convective drying. Gowen, A., Abu-Ghannam, N., Frias, J., Oliveira, J. (2006). *Journal of Food Processing and Preservation*. In Review.

Conference presentations

1. Comparison of Dehydration and Rehydration of Cooked Legumes Undergoing Air-Drying, Microwave Drying and Combined Microwave-Hot Air Drying. Gowen, A., Abu-Ghannam, N., Frias, J., Oliveira, J. (2006). Oral presentation at *CIGR Section VI International Symposium on the FUTURE OF FOOD ENGINEERING*, Warsaw, Poland.

2. Microwave-hot air combination drying of cooked chickpeas. Gowen, A., Abu-Ghannam, N., Frias, J., Oliveira, J. (2004). Oral presentation at *EFFOST Food innovations for an increasing Europe Conference*, Warsaw, Poland.

3. Modelling the effect of pre-blanching and soak temperature on the texture of soybeans and chickpeas. Gowen, A., Abu-Ghannam, N., Frias, J.,

Oliveira, J. (2004). Oral Presentation at *34th Annual Food Science and Technology Research Conference*, University College Cork, Cork, Ireland. Abstract published in The Irish Journal of Agriculture and Food Research.

4. Effect of boiling followed by microwave treatment on cooked soybean and chickpea texture. Gowen, A., Abu-Ghannam, N., Frias, J., Oliveira, J. (2004). Poster presented at *'Foodchain 2004' International Food Conference*, University College Dublin, Ireland.

5. Modelling the sorption kinetics of soybeans and chickpeas. Gowen, A., Abu-Ghannam, N., Frias, J., Oliveira, J. (2003). Oral presentation at *33rd Annual Food Science and Technology Research Conference*, University College Cork (UCC), Cork, Ireland. Abstract published in The Irish Journal of Agriculture and Food Research.

6. Modelling the sorption kinetics of soybeans. Gowen, A., Abu-Ghannam, N., Frias, J., Oliveira, J. (2003). Poster presentation at *1st Annual Postgraduate Research Conference*, Dublin Institute of Technology, Dublin, Ireland. Achieved 2nd place in poster competition.

7. The effect of blanching on the sorption kinetics of chickpeas. Gowen, A. and Abu-Ghannam, N. (2002). Poster presented at *32nd Annual Food Science and Technology Research Conference*, University College Cork, Cork, Ireland. Abstract published in The Irish Journal of Agriculture and Food Research.