DESIGN OF A NEW EQUIPMENT FOR SESAME SEED DEHULLING

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ABSTRACT

DESIGN OF A NEW EQUIPMENT FOR SESAME SEED DEHULLING

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In this study, new methods and processing equipments for sesame dehulling were investigated.

First, water absorption of sesame seed was studied at 20, 30, and 40°C. The data could be modeled using Peleg equation where it was found that the constant k_1 was inversely related to temperature but the effect of temperature on k_2 was negligible.

In the second phase of the work a lab scale continuous screw conveyor as dehuller and two equipments, (1) fluidized bed dryer and (2) hull separator to function as agitator, dryer and separator, for hull separation were designed. Fluidized bed unit was unsuccessful as it caused rapid drying of seeds before hulls can be removed.

Using designed dehuller and hull separator, seeds at 30.5, 50.4 and 70.7 % db moisture contents were processed at dehuller speeds of 420, 840, and 1150 rpm. It was found that the percentage of dehulled seeds was linearly dependent on moisture content, optimal speed of designed dehuller was 840 rpm, and results for the efficiency of dehulling the seeds were significantly the same at 420 and 1150 rpm. Repeated passes of seeds through dehuller not only increased the efficiency of dehulling but also the percentage of damaged seeds. A dehulling efficiency of about 92.5 % was attained after four passes.

The possibility of soaking seeds in an enzyme solution before dehulling was also investigated. By this means, after soaking in 0.2 % (v/v) Peelzyme-I solution for 15 min, a dehulling efficiency of 95 % was achieved.

Keywords: Sesame seed, dehuller, hull separator, fluidized bed dryer

ÖZ

SUSAM SOYMA ISLEMI IÇIN YENI BIR ARAÇ TASARIMI

Güngör, Ugras
Yüksek Lisans, Gida Mühendisligi Bölümü
Tez Yöneticisi: Prof. Dr. Ali Esin

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Bu çalismada susam soymak için yeni yöntemler ve isleme araci tasarimi arastirilmistir.

Çalismanin ilk asamasinda susamin su çekmesi 20, 30 ve 40°C sicakliklarinda incelenmis ve bulgularin Peleg denklemiyle açiklanabildigi görülmüstür. Iliskideki k_1 degismezinin sicaklikla ters orantili degismesine karsin sicakligin k_2' ye etkisi önemsiz olarak bulunmustur.

Çalismanin ikinci asamasinda sürekli bir helezon besleyici susam soymak için ve iki araç; (1) akiskan yatakli kurutucu, (2) karistirma, kurutma ve mekanik eleme etkili kabuk ayirici tasarlanmistir. Akiskan yatakli araç kabuklar soyulmadan kuruma yarattigindan istenen sonucu vermemistir.

Soyucu ve kabuk ayirici kullanilarak % 30.5, 50.4 ve 70.7 nem içerikli (kuru baz) susamlar 420, 840 ve 1150 dev/dak soyucu hizlarinda islenmistir. Tasarlanan soyucuda tohumlarin soyulma veriminin nem içerigine dogrusal olarak bagimli oldugu, en uygun soyucu hizinin 840 dev/dak ve soyulmus tohum yüzdelerinde 420 ve 1150 dev/dak'daki sonuçlari arasinda önemli bir fark bulunmadigi görülmüstür. Susamin soyucudan birkaç kez geçmesi ile yalnizca soyulmus tohum yüzdesinin degil, ayni zamanda zarar görmüs tohum yüzdesinin de arttigi bulunmustur. En fazla soyulmus tohum yüzdesi dört kez geçis sonunda % 92.5 olmustur.

Susamin soyma islemi öncesinde bir enzim çözeltisinde islatilmasi olasiligi bir seçenek olarak arastirilmis ve hacimsel olarak % 0.2'lik Peelzyme-I çözeltisinde 15 dakika islatmadan sonra tohumlarin % 95'inin soyulmasi gerçeklestirilmistir.

Anahtar kelimeler: Susam tohumu, soyucu, kabuk ayirici, akiskan yatakli kurutucu

To the missings of August 17, 1999

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TABLE OF CONTENTS

ABSTRACT.. iii
ÖZ v
DEDICATION vii
ACKNOWLEDGEMENTS viii
TABLE OF CONTENTS x
LIST OF TABLES xii
LIST OF FIGURES xv

CHAPTER

I. INTRODUCTION 1
  I. 1. Sesame (*Sesamum indicum L.*) 1
    I. 1. 1. Nutritive Value of Sesame Seeds... 3
    I. 1. 2. The Uses of Sesame Seeds.. 5
    I. 1. 3. Sesame Seed Processing 7
      I. 1. 3. 1. Soaking in Water.. 7
      I. 1. 3. 2. Dehulling... 9
      I. 1. 3. 3. Separation of Hulls 11
      I. 1. 3. 4. Centrifuging 12
      I. 1. 3. 5. Roasting 12
  I. 2. Water Absorption of Seeds 14
  I. 3. Objectives of the Study.. 17
II. MATERIALS AND METHODS 18
  II. 1. Sesame Seeds.. 18
  II. 2. Enzyme Preparations 18
      II. 2. 1. Peelzyme-I 18
      II. 2. 2. Buffer Solution.. 19
  II. 3. The Design of Dehuller 19

II. 3. 1. The Main Body of the Dehuller 19
II. 3. 2. Electrical Motor of the Dehuller 20
II. 3. 3. Measurement of Rotational Speed of Spiral Shaft 20
II. 4. The Design of Fluidized Bed Dryer 22
II. 4. 1. Measurement of Angle of Repose for Sesame Seeds 22
II. 5. The Hull Separator 24
II. 6. Experimental Procedure 26
II. 6. 1. Determination of Moisture Content of Seeds 26
II. 6. 2. Dehulling Efficiency 27
II. 6. 3. Determination of Water Absorption of Sesame Seeds 27
II. 6. 4. Effect of Moisture Content, Dehuller Speed and Number of Pass on Dehulling Efficiency 28
II. 6. 5. Use of Enzyme Solutions 29
II. 7. Data Analysis 29
III. RESULTS AND DISCUSSION 30
III. 1. Modeling Water Absorption of the Seeds 30
III. 2. Designed Equipment 35
III. 2. 1. Fluidized Bed Dryer 35
III. 2. 2. The Dehuller 35
III. 2. 3. The Hull Separator 37
III. 3. Effect of Moisture Content and Dehuller Speed on Dehulling Efficiency 39
III. 4. Effect of Number of Pass of Seeds through the Dehuller on Dehulling Efficiency 43
III. 5. Enzymatic Peeling of Sesame Seeds 46
IV. CONCLUSIONS AND RECOMMENDATIONS 48
REFERENCES 51

APPENDICES

A. ADDITIONAL TABLES RELATED TO SESAME SEEDS 57
B. PHOTOS OF DESIGNED EQUIPMENT 64
C. TABLES OF STATISTICAL TESTS 68
D. EXPERIMENTAL DATA 71

LIST OF TABLES

Table

1. Fatty acid composition of sesame oil 4

2. Composition of dehulled and unhulled sesame seeds 10

3. Values of the constants in Peleg equation... 33

4. Drying results in the hull separator for the seeds soaked at 30°C and after dehuller using 4.4 m/s velocity air with 0.017 kg water/kg bda humidity at 80°C 38

A.1. Sesame seed synonyms 57

A.2. World sesame production in 2002... 59

A.3. World sesame production in 2001... 60

A.4. Composition of sesame seeds.. 61

A.5. Amino acid composition of sesame seeds and FDA/WHO reference protein... 62

A.6. Sesame food uses.. 63

C.1. ANOVA table for the effect of temperature on the Peleg constant k_1 68

C.2. Results of Duncan's Multiple Range Test for the effect of temperature on the Peleg constant k_1 68

C.3. Summary of the $?^2$-test on experimental and predicted water absorbed 69

C.4. ANOVA table for observed and predicted equilibrium moisture contents of sesame seeds.. 69

C.5. ANOVA table for the effect of moisture content and dehuller speed on dehulling efficiency... 70

C.6. Results of Duncan's Multiple Range Test for the effect of moisture content and dehuller speed on dehulling efficiency................................... 70

D.1. Experimental data (Replication-1) of water absorption of seeds at 20°C 71
D.2. Experimental data (Replication-2) of water absorption of seeds at 20°C 72
D.3. Experimental data (Replication-3) of water absorption of seeds at 20°C 73
D.4. Experimental data (Average) of water absorption of seeds at 20°C 74
D.5. Experimental data (Replication-1) of water absorption of seeds at 30°C 75
D.6. Experimental data (Replication-2) of water absorption of seeds at 30°C 76
D.7. Experimental data (Replication-3) of water absorption of seeds at 30°C 77
D.8. Experimental data (Average) of water absorption of seeds at 30°C 78
D.9. Experimental data (Replication-1) of water absorption of seeds at 40°C 79
D.10. Experimental data (Replication-2) of water absorption of seeds at 40°C 80
D.11. Experimental data (Replication-3) of water absorption of seeds at 40°C 81
D.12. Experimental data (Average) of water absorption of seeds at 40°C 82
D.13. Data sets of the Peleg constants obtained by linear regression of data given in Tables D.1-D.12 83
D.14. Experimental data of sieve analysis for sesame hulls 83
D.15. Experimental data for the effect of moisture content and dehuller speed on dehulled seed percentage 84
D.16. Experimental data of dehulling efficiency for 30.5 %db moistened seeds 85
D.17. Experimental data of dehulling efficiency for 50.4 %db moistened seeds 86

D.18. Experimental data of dehulling efficiency for 70.7 %db moistened seeds 87

D.19. Experimental data of dehulling efficiency for 0.1 % Peelzyme-I solution soaked seeds 88

D.20. Experimental data of dehulling efficiency for 0.2 % Peelzyme-I solution soaked seeds 89

LIST OF FIGURES

Figure

1. Sesame plant (*Sesamum indicum L.*)............ 2
2. Sesame seeds............ 2
3. Sesame seed processing 8
4. Sesame peeler............ 11
5. Sesame centrifuge 12
6. Roaster with rotating boiler............ 13
7. Schematic drawing of sesame dehuller 21
8. Schematic drawing of fluidized bed dryer 23
9. Schematic drawing of hull separator............ 25
10. Water absorption characteristics of sesame seeds............ 31
11. Application of the Peleg equation to the experimental data............ 32
12. Dependence of Peleg k_1 on temperature 34
13. Particle size distribution curve for sesame seed hulls............ 39
14. Plot of moisture content vs. percent dehulled seed at 420 rpm............ 40
15. Plot of moisture content vs. percent dehulled seed at 840 rpm............ 41
16. Plot of moisture content vs. percent dehulled seed at 1150 rpm............ 41
17. Effect of dehuller speed on dehulled seed percentage 42
18. Effect of no. of pass on dehulling efficiency of seeds at 30.5 %db moisture content............ 43
19. Effect of no. of pass on dehulling efficiency of seeds at 50.4 %db moisture content............ 45

20. Effect of no. of pass on dehulling efficiency of seeds at 70.7 %db moisture content 45
21. Effect of no. of pass on dehulling efficiency of seeds soaked in 0.1 % (v/v) Peelzyme-I 47
22. Effect of no. of pass on dehulling efficiency of seeds soaked in 0.2 % (v/v) Peelzyme-I 47
B.1. Photo of designed dehuller 64
B.2. Photo of spiral shaft for designed dehuller 64
B.3. Photo of fluidized bed dryer 65
B.4. Photo of fluidized bed column 65
B.5. Photo of designed hull separator 66
B.6. Photo of fixed vessel and sieving equipment at the bottom side of hull separator 66
B.7. Photo of air distributor and agitator paddle of hull separator 67
B.8. Photo of hull separator with air source 67

CHAPTER I

INTRODUCTION

I. 1. Sesame (*Sesamum indicum* L.)

Sesamum indicum L. is an ancient oil crop which is cultivated mainly for its seeds all over the world. It is commonly known as sesame, benne, til, or sim sim (Table A.1). The cultivation of sesame is as old as rice and it started about 6000 years ago. The earliest records mentioning the use of sesame seed as a spice come from the Assyrian myth (Woltman, 2003; Anonymous, 2002a). A series of tablets in the British Museum claims that the gods drank sesame wine the night before they created the earth. Sesame was so valuable that the ancient Assyrians paid their loans in sesame or silver. Although the origin of the seed is not certain, some references claim that sesame seed was first brought from the Sundae Islands to India and then migrated to Egypt, China, Japan, and to the Mediterranean countries. In the late 17th century, African slaves brought sesame to America (Johnson and Peterson, 1974; Ashri, 1989). Nowadays, it is cultivated in many regions of the world (Table A.2-A.3).

Sesame (Figure 1) is an erect, tropical, and annual plant. It grows in tropical and sub-tropical areas, thus the plant is drought resistant. Depending on the variety and growing conditions, it may reach to the height from 50 to 250 cm. Some varieties are highly branched, whereas others are unbranched. The stem of

Figure 1: Sesame plant (Sesamum indicum L.)

Figure 2: Sesame seeds

the plant is covered with fine hair, and leaves are oblong or lanceolate, variable in shape and size. Sesame is rich in flowers, growing along its stem. The bell shaped white to pale-rose flowers begin to develop in the leaf axils 6 to 8 weeks after planting and this continues for several weeks. Multiple flowering is favored by opposite leaves.

The fruit of sesame plant is a capsule often containing 50-100 seeds. When the seeds are almost ripe, the pods open. Harvesting is done by hand; plants are cut and dried in the field. When shaken, the seeds fall out of the open pods (Johnson and Peterson, 1974; Ashri, 1989; Dudley et al., 2000; Anonymous, 2002b).

The seeds of sesame plant (Figure 2) are small and flattened. There is an outer fibrous cover, hull of the seed. This seed coat or outer epidermal cells contain calcium oxalate crystals with black brown or yellow brown colored and granular surface. The hull accounts for 15 to 29% of the whole seed (Robert, 1999). Sesame seed contains approximately 50% oil, 25% protein, 13% carbohydrate, 5% vitamins and minerals, 5% moisture (Table A.4). The plant is cultivated mainly for its seeds, thus understanding the nutritive value of sesame seeds is crucial.

I. 1. 1. Nutritive Value of Sesame Seeds

The oil in sesame is highly resistant to oxidative deterioration. This remarkable stability is due to the naturally occurring antioxidants and the extremely low content of easily oxidable linolenic acid (Rechtenbach and Nitz, 1999). Sesame oil is considered poly-unsaturated oil containing approximately 44% linoleic acid. Its mono-unsaturated fatty acid percentage is approximately 40% (Johnson and Peterson, 1974). Since sesame oil has a high level of unsaturated acids (~84%), it is assumed that it has a reducing effect on plasmacholesterol and on coronary heart disease (Woltman, 2003). Table 1 summarizes the fatty acid composition.

Table 1: Fatty acid composition of sesame oil (Johnson and Peterson, 1974)

Fatty Acids	%
Linoleic	44
Oleic	40
Linolenic	1
Palmitic	9
Stearic	5
Archidic	1

Sesame is rich in natural antioxidants or lignans, which are both oil and water-soluble. These antioxidative compounds preserve the stability of sesame seed and oil. A number of lipid-soluble antioxidants, have been isolated from sesame seeds, including sesaminol (Katsuzaki et al., 1994), sesamolinol (Osawa et al., 1985), pinoresinol (Katsuzaki et al. 1992) and vitamin E (ca. 97% gamma-tocopherol). Sesame oil has been found to contain considerable amounts (up to 1.5%) of the sesame lignans, sesamin and sesamolin (Beroza and Kinman, 1955). These compounds are being researched as potential industrial antioxidants and nutraceutical and pharmaceutical ingredients. The biological functions of sesame lignans are being investigated in both animal studies and human clinical trials (Dudley et al., 2000). Sesamin has been shown to decrease the serum level of LDL- cholesterol (low density lipoprotein), a risk factor for atherosclerosis in humans (Hirata et al.,1996). Additionally, sesamin in a mouse diet decreased the percentage of breast cancer (Anonymous, 2002a).

Sesame seed protein has become increasingly important with the new emphasis placed on nutrition (Johnson and Peterson, 1974). The unique quality of the sesame protein is traced to the presence of high amounts of methionine, cystine and tryptophan (Table A.5). Methionine is an essential amino acid required by human, and it is crucial for the maintenance and healthy function of liver. Cystine functions as an antioxidant and it can help slow down the aging process, deactivate free radicals, neutralize toxins. Cystine is necessary for the formation of the skin, which aids in the recovery from burns and surgical operations. Hair and skin are made up of 10-14% Cystine (Anonymous, 2003a). Tryptophan is also an essential amino acid, and it is necessary for the human body to have a healthy nervous system (Woltman, 2003). The limiting amino acid in sesame protein is lysine (Johnson and Peterson, 1974; Bahkali and Hussain, 1998). Evans and Bandemer (1967) reported the protein nutritive value of sesame as (15 to 42%) relative to casein as 100. However, supplementation of sesame seed proteins with 1.25% lysine significantly increased their protein nutritive value making them comparable to that of skimmed milk (Sastry et al., 1974).

I. 1. 2. The Uses of Sesame Seeds

Sesame is mainly consumed for its seeds with the exceptions that in the Far East (i.e. Chine, Korea) cooked leaves of sesame plant are sometimes eaten (Ashri, 1989) and chlorosesamone isolated from the roots of sesame plant is used as antifungal (Morris, 2002). Sesame seeds are used whole, or processed for oil, and meal for the consumption of human.

Whole seeds, often dehulled, enrich bakery products and candies; and seeds are used mainly on bread, bread sticks, cookies, crackers, biscuits, health snacks (such as sesame bars), in prepared breakfasts (as an additive to cereal mixes), and chips. The use of sesame as food is strongly influenced by cultural and traditional habits in different countries (Table A.6). In Greece, seeds are used in cakes; while in Africa, seeds are a main soup ingredient (Ashri, 1989; Morris, 2002).

In the Middle East, dehulled and roasted seeds are ground, and the final paste is a favored food, called Tahini. Another product of sesame seeds in the Middle East is Halva. It is made of tahini and sugar, and at random, one may add walnuts, peanuts or cocoa. Humus is another popular sesame product, and tahini, chickpeas and sweet additives are all its ingredients (Woltman, 2003).

Sesame seeds are widely used as a source of high quality edible oil. Due to the naturally occurring antioxidants, sesame oil is very stable and has a long shelf life (Johnson and Peterson, 1974; Ashri, 1989). Sesame oil is known to reduce cholesterol due to the high polyunsaturated fat content in the oil. Besides its utilization as salad and cooking oil, there are pharmaceutical applications of sesame oil such as the treatment of blurred vision, dizziness, and headaches. The Indians have used sesame oil as an antibacterial mouthwash, to relieve anxiety and insomnia (Annussek, 2001). In cosmetic industry it is used as skin softener, and in the manufacture of soap (Dark, 1998).

The cake or meal obtained after the oil extraction contains approximately 34 to 50 % protein, depending on the cultivar and extraction efficiency (Ashri, 1989). Where oil is extracted at the village level, the cake is often used as animal feed. However, in large mills the residual cake is considered too expensive for being used as animal feed; instead, it is processed as sesame flour. Sesame flour is an edible, creamy and light brown powder and it is usually mixed with other ingredients such as soybean flour and maize flour to obtain very nutritious food for human.

I. 1. 3. Sesame Seed Processing

Before the consumption of the sesame seeds, they are processed to remove the hulls and roasted to enhance flavor. The basic steps of the traditional method of sesame processing (Figure 3) include soaking in water, dehulling, separation of hulls, washing, centrifuging, and finally roasting.

I. 1. 3. 1. Soaking in Water

After an optional sifting process, seeds free from foreign particles such as soil or small stones are soaked in fresh water for six to ten hours depending on the sesame variety and temperature of the water. Soaking is prior to dehulling of the seeds, however it also aids in settling of the soil and stone particles which are mixed with seeds during harvesting. Thus, sifting the seeds before soaking is sometimes omitted by producers.

Usually wetting ponds are made of steel, and allow water straining system on the bottom. Seed to water ratio used in industry is approximately 1:1 or 1:2 (w/v) (Bulayci, 2003). After wetting the seeds for 6-10 hours, the water in the pond is strained. Usually sesame seed processors keep the wet seeds in the pond for a night (10-12 hours) and start dehulling in the following morning.

Soaking sesame seeds in water before dehulling is a time consuming method. Recent studies investigated new methods of preparing sesame seeds for further processing. Instead of water, mixtures of NaOH and Na_2CO_3 were used for soaking the seeds (Yehia et al., 2002). It was concluded that the optimized medium conditions for soaking the seeds was a mixture of 0.04% NaOH and 3% Na_2CO_3 at 35°C with a seed-to-solution ratio of 1:3 (w/v). The suitable soaking time was 40 minutes. The decreased soaking time before the hull removal by lye mixture appeared to be an advantage; however this technique had the disadvantages of

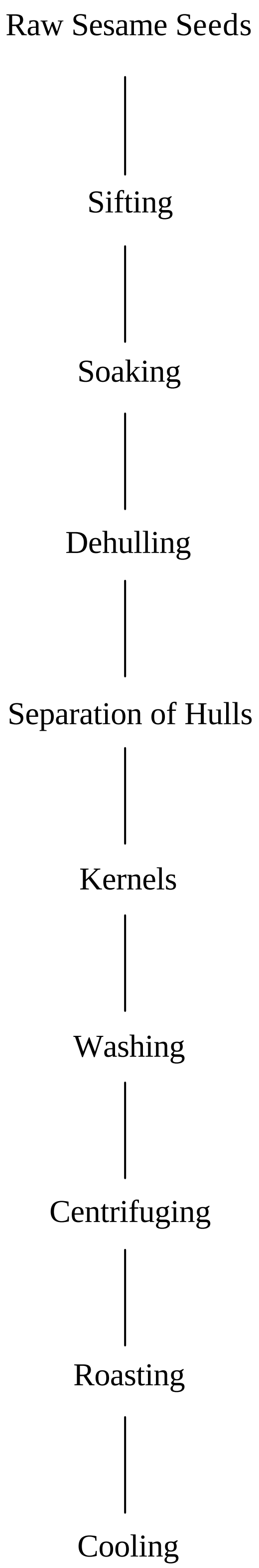

Figure 3: Sesame seed processing

(1) the corrosive effect of the lye mixtures on equipments and pipes, (2) the cost of the large quantities of water needed to wash off the lye residue on the seeds and (3) the problems in disposal of the washing water.

Enzymatic peeling has been suggested as a recent method for peeling of vegetables and fruits. There is limited amount of work in literature concerning enzymatic peeling, and almost all of these studies are about enzymatic peeling of citrus fruits (Soffer and Mannheim, 1996; Pretel et al., 1997; Toker and Bayindirli, 2003). Enzymatic peeling of these fruits relies on the fact that pectin, cellulose, and hemicellulose are the basic polysaccharides responsible for adherence of the peel on the fruit. Thus, peeling the fruit may be achieved by treating with appropriate glycohydrolases. Fibrous hull of sesame seed contains mainly insoluble (~78%) cellulose and hemicellulose, and the effect of soaking prior to dehulling in enzyme preparations containing cellulases and hemicellulases on dehulling of the seed is a question to be answered for the feasibility of enzymatic dehulling of sesame.

I. 1. 3. 2. Dehulling

As stated earlier, the outer fibrous cover of sesame seed accounts for 15 to 29% of the whole seed. Sesame seed hull is rich in fiber, carbohydrate, and calcium. As shown in Table 2, removal of the hull results in reduction of fiber by approximately 50%, increases the protein and oil contents of the seed (Johnson and Peterson, 1974), and total yield of oil extracted (Carr, 1989).

Table 2: Composition of dehulled and unhulled sesame seeds (Johnson and Peterson, 1974)

	Unhulled	Dehulled
Oil (%)	49	54
Protein (%)	20	25
Carbohydrates (%)	15.8	13.5
Fiber (%)	6	2.5
Moisture (%)	5	5
Ash (%)	5	5
Calcium (%)	1	0.5

Sesame seed hull contains approximately 35mg of oxalic acid per 100g of hull (Robert, 1999). Oxalic acid ($(COOH)_2.2H_2O$) may combine with calcium, iron, sodium, magnesium, or potassium to form less soluble salts known as oxalates; so, oxalic acid is known to interfere with mineral metabolism in the body. Oxalates, on the other hand, form tiny little insoluble crystals with sharp edges, which are irritating to tissue, especially to the digestive system (Anonymous, 2003b). They may also contribute to the formation of kidney stones. About 70% to 80% of all kidney stones are composed of calcium, usually combined with oxalate, or oxalic acid (Anonymous, 2003c). The bitter taste of the unhulled sesame seeds is also due to the presence of oxalic acid in hulls. When unhulled seeds are consumed, there is immediate sour or bitter taste in the mouth because of the corrosive action of oxalic acid. Because of all these reasons, dehulling, removal of the hull from the kernel, is one of the major processes prior to consumption of sesame seeds.

In the traditional method of sesame seed dehulling, the seeds in the wetting pond are taken to sesame peeler (Figure 4) by the aid of a screw conveyor

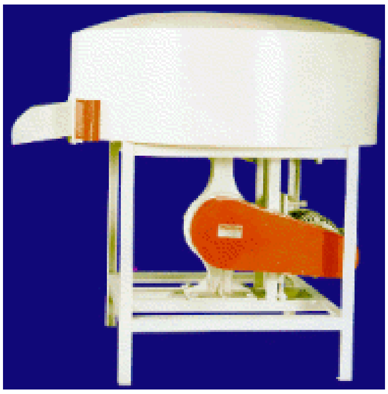

Figure 4: Sesame peeler (Gürmaksan, 2003)

Sesame peeler is simply a cylindrical vessel with a paddle agitator having two blades. The peelers available in market have capacities 100-200 kg seeds per 20-60 min (Gürmaksan, 2003; Gümüs, 2003). The paddle rotates at about 80 rpm. Sesame seeds rub against each other, the walls of the vessel and the paddle, while the paddle rotates and finally friction causes the hulls to be removed from the kernels.

I. 1. 3. 3. Separation of Hulls

Sesame peeler removes the hulls from the seeds; however kernels still need to be separated. Dehulled seeds and hulls are taken into a stainless steel pond which is filled with 20°Brix brine solution (Bulayci, 2003). Owing to the difference in the specific gravities of the hulls (<1.0) and the kernels (>1.0), they are separated in the solution. Kernels are collected by the workers, taken to the washing pond and washed with fresh water to remove the salt.

Separation of the hulls by using brine solution has some disadvantages such as the quantity of water required for preparing the brine solution and for washing the seeds, the quantity of salt needed, and the loss of hulls and small sesame seeds in the waste water. Yehia et al. (2002) reported that brine solution method may even lead to a seed loss of 19%.

I. 1. 3. 4. Centrifuging

Wet sesame seed kernels are taken into centrifugal separators where water on the surface of the kernels is removed. A typical sesame centrifuge works at 750-1000 rpm, and has a capacity of 100-150 kg/min (Figure 5).

Figure 5: Sesame centrifuge (Gümüs, 2003)

I. 1. 3. 5. Roasting

The roasting process is the key step for flavor development in the seed and also influences the quality of sesame oil. Roasting gives sesame a nut-like taste and smell. Shimoda et al. (1996) identified 166 volatile flavor compounds in roasted sesame oil. These volatile flavor compounds are primarily pyrazines, furans pyrroles, pyridines, and thiazoles. Shimoda et al. (1997) showed that increasing the roasting temperature increased the amount of flavor compounds. In literature there are studies on the effects of seed roasting temperature and time on the quality characteristics of sesame oil (Yoshida, 1994; Shimoda et al., 1997; Yoshida and Takagi, 1997). In these studies, it is concluded that as temperature increases, total volatile flavor compounds increases. Up to a roasting temperature of 180°C for 30 min, there were no significant differences ($p>0.05$) in the quality characteristics of oil such as acid value, peroxide value, carbonyl value, and anisidine value. Antioxidants remained with no significant differences at that temperature. At the roasting temperatures over 200°C for 30 min, burning and bitter tastes were detected. The optimized roasting conditions are 30 min at 160 or 180°C, 15 min at 200°C, and 5 min at 220°C for preparing good quality of sesame oil. Traditional producers roast sesame at 100-120°C for 2 hours when the sesame is to be used in bakery products. For tahini production the time of roasting is increased to 2.5 hours for improvement of flavor.

There are two types of roaster; steam-heated open roaster and roaster with rotating boiler (Figure 6).

Figure 6: Roaster with rotating boiler (Gürmaksan, 2003)

After the roasting process, seeds are cooled in vessels by air at ambient temperature or they are placed on trays and left there to cool down by natural convection.

I. 2. Water Absorption of Seeds

Processing of sesame seeds requires that the seeds be soaked in water prior to loosening of hulls. Thus, understanding the theory of water uptake into the seeds is practically important.

There has been extensive study to assess the penetration of water into food materials. However, most of these analyses were based on Fick's laws of diffusion (Hsu, 1983; Mazza and LeMaguer, 1980; Sayar et al. 2001). Quantitative analysis of water diffusion in seeds was first performed by Becker (1959, 1960); a simplified solution derived from Fick's diffusion equation for wheat kernels of arbitrary shape was utilized under the absorption condition. Hsu (1983) simplified the equation of continuity to describe the absorption of water by legumes. In his work, Hsu (1983) used the diffusion equation in spherical coordinates provided by Crank (1975). Sayar et al. (2001) analyzed the chickpea soaking by using the equation of continuity. A major difficulty in dealing with the equations based on Fick's diffusion equation is the complex mathematical solutions and estimation of the parameters on which variables depend. In some cases empirical approaches for modeling water absorption of food materials have been employed (Singh and Kulshrestha, 1987; Nussinovitch and Peleg, 1990) and empirical models were preferred because of their relative ease of use.

Peleg (1988) has proposed an empirical equation to model water absorption characteristics of food materials under isothermal conditions. The model is not derived from diffusion theories or any set of physical laws. A major feature of this equation is its simplicity compared to the other equations based on

Fick’s laws of diffusion. Because some food materials become biologically and/or physically unstable after long periods of exposure to moist environment or soaking, there are no data on their sorption behavior in long term experiments. Besides its simplicity, model of Peleg (1988) has the advantage of predicting successfully, or at least estimating the long range moisture gains of food materials by using short-time experimental data.

The two parameter, non-exponential empirical equation of Peleg (1988) assumes the form:

$$M(t) = M_o + t/(k_1+k_2t) \qquad (1)$$

where;

t : time

$M(t)$: moisture content at time $t>0$

M_o : initial moisture content at time $t=0$

k_1 : Peleg rate constant

k_2 : Peleg capacity constant

The units of k_1 and k_2 correspond to those of the moisture content and time units. For example, if the units of $M(t)$ and M_o are in % weight on dry basis, and the time is given in hours, then the unit of k_1 will be hour per %weight on dry basis and that of k_2 will be the reciprocal of % weight on dry basis.

From Eq. (1) when t ? 8, the equilibrium moisture content M_E is obtained as:

$$M_E = M_o + 1/k_2 \qquad (2)$$

The momentary sorption rate $dM(t)/dt$ is simply obtained by taking the derivative of $M(t)$ with respect to time, t in Eq. (1):

$$dM(t)/dt = k_1/(k_1 + k_2t)^2 \quad (3)$$

From Eq. (3), the initial rate, i.e., at t=0 is:

$$dM(t)/dt = 1/k_1 \quad (4)$$

A general feature of the mathematical relations in the form of Eq. (1) is that they can be transformed to a linear relationship in the form:

$$t/[M(t) - M_o] = k_1 + k_2t \quad (5)$$

Peleg’s equation is applicable to the curvilinear segment of the sorption curve. A plot of the sorption data in the form of $t/[M(t) - M_o]$ against time t gives a straight line with k_2, the gradient of the line, and k_1 as the ordinate-intercept. By such a plot, the characteristics of the Peleg constants may easily be studied. Studies in the literature showed that k_1 is inversely related to temperature (Sopade and Obekpa, 1990; Maharaj and Sankat, 2000; Turhan et al., 2002). On the other hand k_2 is a characterizing parameter for the food material to absorb moisture, and is not expected to vary with temperature (Peleg, 1988; Sopade and Obekpa, 1990). However, there are studies in the literature in which k_2 decreased with increasing temperature (Lopez et al., 1995; Turhan et al., 2002).

Although Peleg’s equation is not derived from any physical law or diffusion theories, its applications in various food materials has been demonstrated. The Peleg model was exploited to model water absorption of many starchy and oily kernels. Sopade and Obekpa (1990) applied the model for studying water absorption of soybean, cowpea and peanuts. Lopez et al. (1995) studied the water sorption behavior of hazelnut. Rice, chickpea, kidney beans and piegonpea grains are also among the food materials studied by using Peleg’s model (Singh and Kulshrestha, 1987; Peleg, 1988; Hung et al., 1993; Abu-ghannam and McKenna, 1997; Turhan et al., 2002).

I. 3. Objectives of the Study

The traditional method for sesame seed dehulling is time consuming, especially in the soaking step. The process needs a great deal of water in separation of hulls and washing seeds, and it is laborious. The method even may lead to appreciable seed losses.

The main aim of this work was to improve the sesame seed dehulling process by investigating new methods and processing equipments. The specific objectives were to model the water absorption of sesame seeds at 20, 30, and 40°C for an acceptable treatment time and temperature and to design a continuous sesame seed dehuller and equipment that would replace the brine solution technique in hull separation. To achieve the purpose, the effect of moisture content of seeds and rotational speed of dehuller on dehulling efficiency of sesame seeds by using the designed equipment was investigated. Further the possibility of soaking the seeds in an enzyme solution (Peelzyme-I) using different concentrations before dehulling was also tested as a preliminary study for enzymatic peeling of sesame seeds.

CHAPTER II

MATERIALS AND METHODS

II. 1. Sesame Seeds

Raw sesame seeds (*Sesamum indicum L*) used in this study were the local cultivars, harvested in the fields of Gaziantep. Before being used, they were kept in plastic bags which were closed tightly.

II. 2. Enzyme Preparations

II. 2. 1. Peelzyme-I

Peelzyme-I is the commercial name of the pectolytic enzyme preparation produced by Novo Nordisk A/S and complies with FAO recommended specifications for food grade enzymes. Peelzyme-I contains mainly hemicellulases, pectinases, and cellulases. It is used for various enzymatic peeling in citrus and canning industry and for the production for whole peeled fresh fruit. Optimum pH of Peelzym-I is in the range 2.0-6.0, and temperature range for usage is 10-50°C. Heat treatment at temperatures above 75°C for about 30-50 sec inactivates Peelzym-I (Novo Nordisk, 1998).

II. 2. 2. Buffer Solution

The buffer solution of sodium citrate/citric acid was used to stabilize the pH of solution, thus increase enzyme stability. 9.5 ml of 0.1M citric acid solution was mixed with 41.5 ml of 0.1 M sodium citrate solution, and diluted to a total of 100 ml distilled water to adjust pH as 6.0 (Lillie, 1948).

II. 3. The Design of Dehuller

II. 3. 1. The Main Body of the Dehuller

The dehuller designed was simply a screw conveyor rotating inside a pipe (Figure 7).

The pipe used was standard 2" pvc pipe (d_i=45 mm, L=600 mm). A standard T- of the same size and material was connected to the main pipe, and it served as the inlet for feed (Figure B.1). The inner surface of the pipe was covered with cotton woven wound plaster to increase friction and surface roughness.

The screw conveyor was constructed from a spiral plastic hose dressed tightly on a thick wooden stick (d_o=35 mm, L=770 mm) and fixed with screws (Figure B.2). Spiral plastic hose was 685 mm long with a screw pitch width 5 mm, and screw depth 3 mm, giving an outer diameter 43 mm. The rotation of the shaft was provided by an electrical motor through a belt and pulley system.

The pvc pipe used as the dehuller casing was fixed on a wooden base plate with two plastic C-clamps. The wooden shaft carrying the spiral hose inside this pipe was connected from both ends at the center to the rim towers placed up-right on the base. The location of the rims on the wooden towers was adjusted to be having the screw conveyor and the pipe coaxial (concentric) with 1 mm clearance.

II. 3. 2. Electrical Motor of the Dehuller

The electrical motor (220V/50Hz and 300W) used in the dehuller was fixed on the base with screws. The motor and the belting system were all covered with a removable wooden box for safety. The rotational speed of the motor was adjusted by using a Vi-Ko® dimmer that had a rotating potentiometer switch of 600W and 220V/50-60Hz.

II. 3. 3. Measurement of Rotational Speed of Spiral Shaft

The rotational speed of the spiral shaft was measured while the dehuller was being continuously fed with wet sesame seeds. The equipment used for rotational speed measurement was Digistrobe III®- Model 1965 (Ametek, Mansfield & Green Divison). Digistrobe III® worked on the principle of flashes per minute observed on the set point signed on the spiral shaft. Three points were marked on the Vi-Ko® dimmer, corresponding to the three rotational speeds of 1150, 840, and 420rpm.

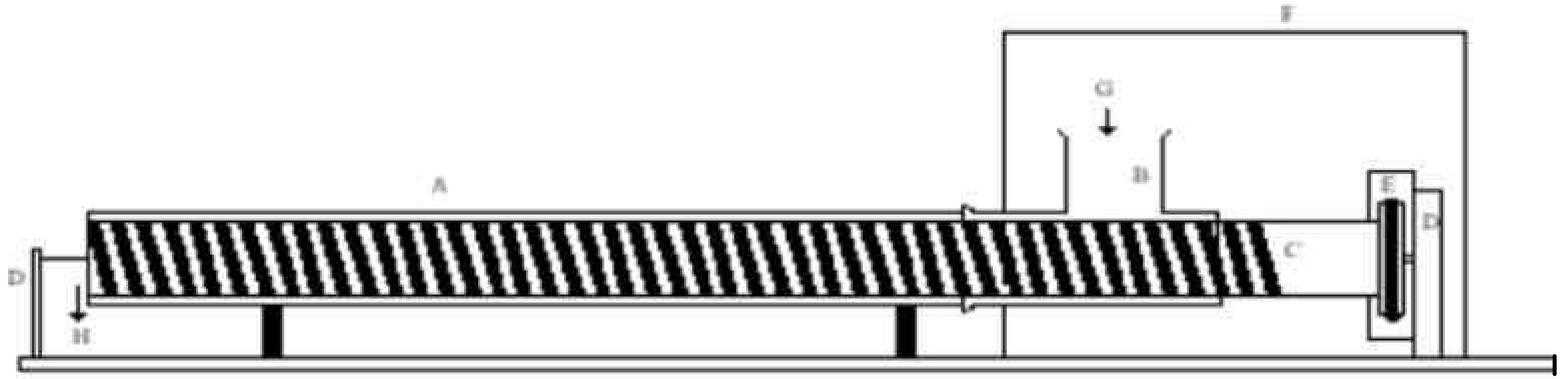

Figure 7: Schematic drawing of sesame dehuller; (A) Pvc pipe, (B) T-shaped pipe, (C) Rotating spiral shaft, (D) Rim towers (E) Belt connection, (F) Safety box for electrical motor, (G) Feed inlet, (H) Feed outlet

II. 4. The Design of Fluidized Bed Dryer

The cylindrical column used for the fluidized bed was designed for simultaneous drying and hull removal from aluminum with a height 180 mm and diameter 65 mm (Figures 8 and B.3). The inside surface of the bed was made of recessed aluminum mesh for increasing friction. A removable gauze filter for hull collection was placed on the top of the column. The base was a recessed aluminum mesh circular cone with 20 mm height. The angle between the surface and base was thus 31.6°, greater than the angle of repose for sesame seeds. Air distribution was through the slits on the bottom cylindrical walls of the column (Figure B.4). There were 20 slits with dimensions 5×20 mm. The air blower had 9.3 m/s capacity. Blowing air speed was measured by using Turbo-Meter^{TM} electronic wind speed indicator (Davis Ins.). The temperature could be adjusted in the range 50-220°C, and processing temperature was fixed at 80°C for sesame seeds. Wet bulb temperature of air fed was 35°C and using the psychrometric chart (under the assumption of 101.32 kPa air pressure) humidity of the air was found as 0.017 kg water vapor/kg bda.

II. 4. 1. Measurement of Angle of Repose for Sesame Seeds

A cylindrical box with 80 mm diameter and 150 mm height was filled with sesame seeds and placed on a smooth surface as the open side contacted with the surface. By removing the box gently, sesame seeds were allowed to accumulate on the surface. The height and base diameter of the sesame pile formed were measured using a ruler; the tangent of the angle of repose for sesame was calculated mathematically as the ratio of height to base radius.

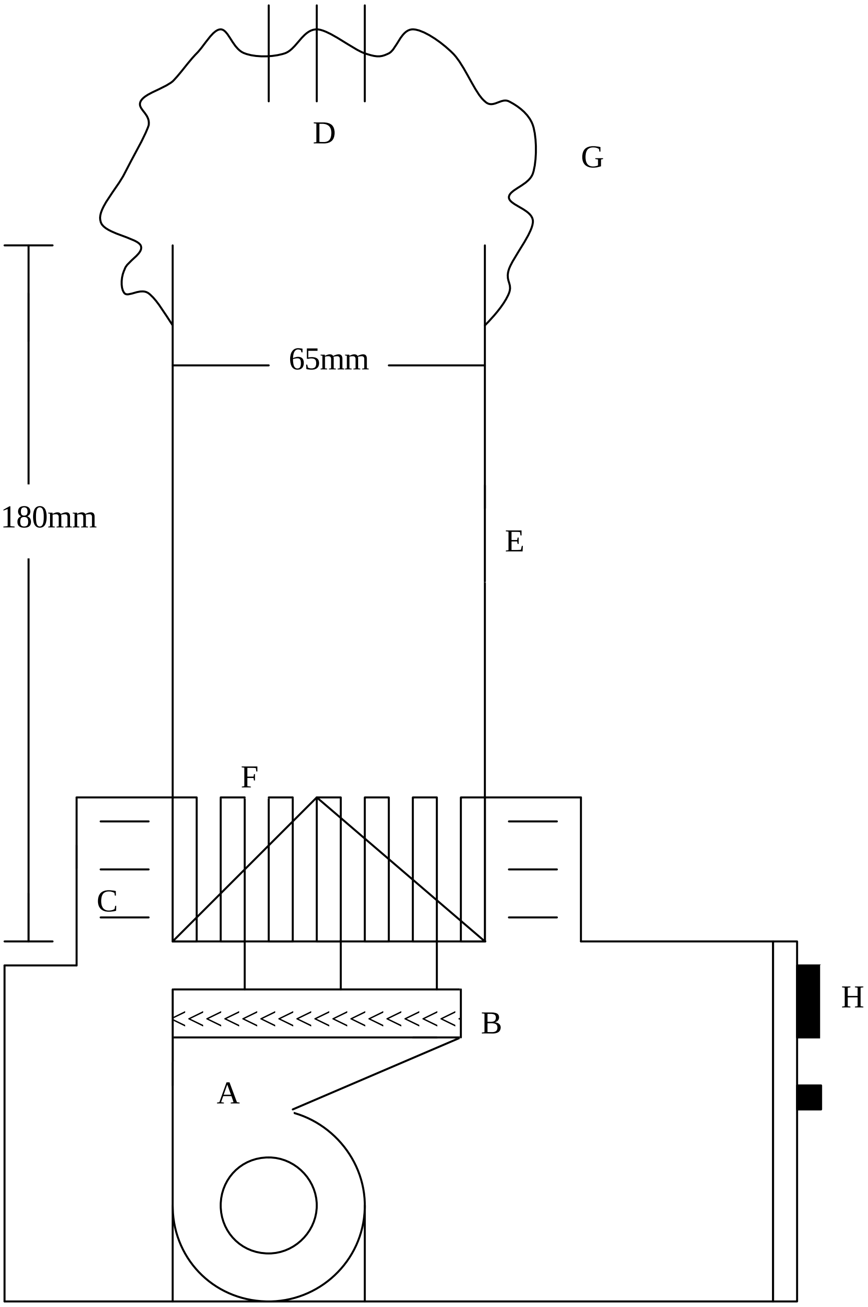

Figure 8: Schematic drawing of fluidized bed dryer: (A) Blower fan, (B) Electrical Heater, (C) Air Inlet, (D) Air Outlet, (E) Column, (F) Slits, (G) Gauze Filter, (H) Control Panel

II. 5. The Hull Separator

The lab scale hull separator (Figures 9 and B.5) designed for sesame seeds had the feature of combining three functions in one: agitation, drying, and mechanical sieving.

The equipment consisted of a fixed cylindrical aluminum vessel with its hemispherical bottom side acting as a mechanical sieving system (Figure B.6), and top covered with a lid having an air distributor and an agitator motor placed above (Figure B.7). The removable top lid also served as the feed inlet and product outlet.

The feed vessel of the hull separator was made of aluminum diameter 70 mm and height 40 mm. The vessel was tightly surrounded by a wooden plate 5 mm thick, and two wooden blocks were connected to that plate at one end and to the base at the other end. Thus, vessel was fixed to the base block.

A perforated circular aluminum plate with 1mm sieve size and 80 mm diameter was used as the support plate for the feed. The size of the holes was determined after carrying out a sieve analysis for the hulls of sesame seeds. On the bottom of the perforated plate, hull collecting box was placed. This box was constructed from aluminum sheets because of the ease of construction and heat stability feature. There was an exit on that box which let the hulls be collected when the process of separation ended. Together with the collecting box, sieving plate was connected to the bottom of the vessel by using Cook® heat resistant (up to 200°C) crystal clear films. This connection allowed the bottom sieve plate to move freely. The bottom side of the main body was attached to the electrical vibration system (Starex, 230V / 50Hz).

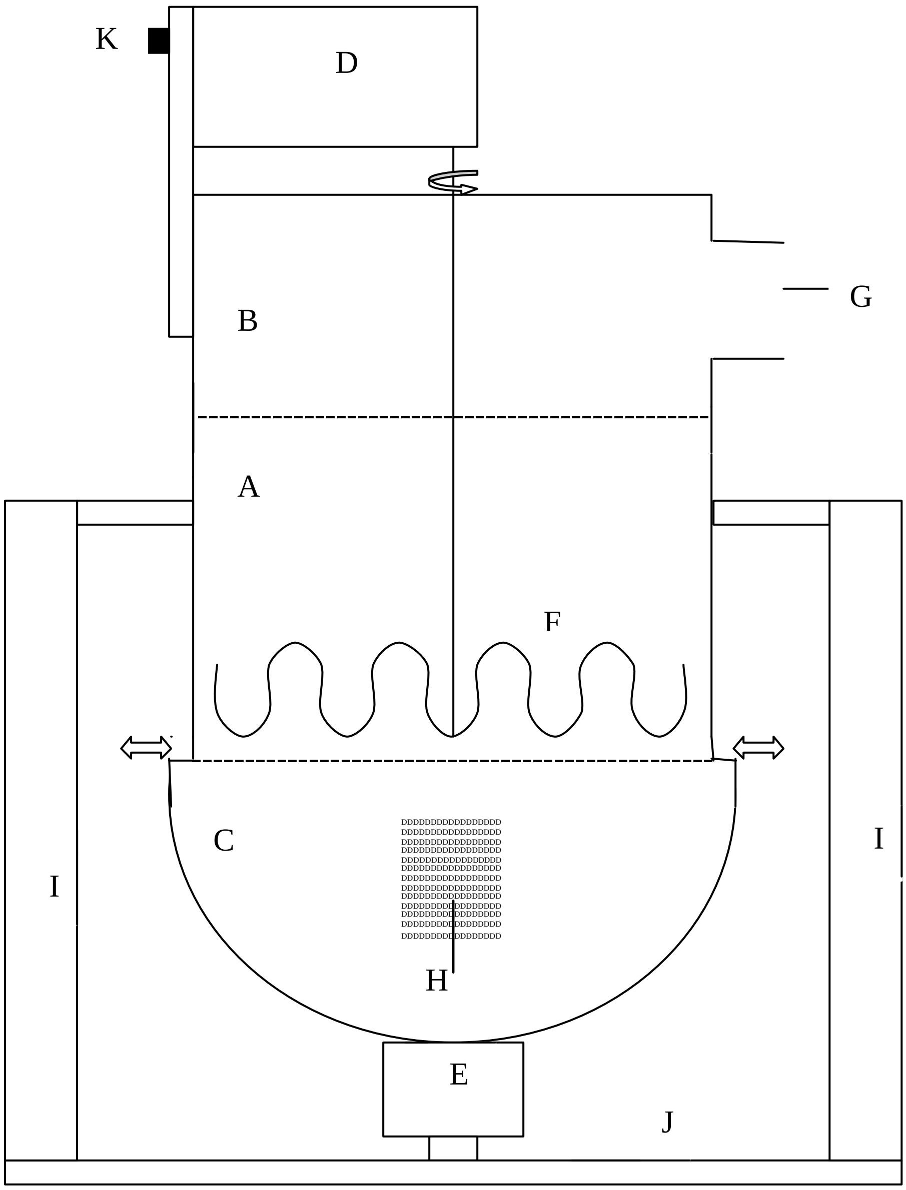

Figure 9: Schematic drawing of hull separator: (A) Feed vessel, (B) Top lid with air distributor, (C) Sieve with hull collecting box, (D) Electrical motor of agitator, (E) Electrical vibration system, (F) Sinusoidal wave-shaped blades, (G) Air in, (H) Air out, (I) Wooden blocks, (J) Base, (K) Control panel

The removable top lid of the feed vessel contained the drying and agitation systems. This top lid was a cylindrical vessel with closed upper surface and a perforated bottom. Its diameter was 70 mm and it had a length of 35 mm. There was an air inlet line on the cylindrical wall for hot air. This 40 mm long pipe had a diameter of 30 mm, and it was used to connect the main pipe from the air supply to the hull separator. The perforated bottom side served as the air distributor plate, and there were 25 nozzles / cm^2 which were less than 1mm in diameter. An agitator motor placed above the lid with its shaft (d=1 mm, L=90 mm) and paddle, prepared in the form of a sinusoidal wave made of iron wire (d=1 mm), going through the lid extended to the surface of the perforated support plate holding the seeds.

The rotational speed of the agitator paddle could be up to 810 rpm. The air fan used for drying the seeds had the capacity 9.3 m/s and its temperature could be adjusted in the range 50-220°C.

II. 6. Experimental Procedure

II. 6. 1. Determination of Moisture Content of Seeds

The initial moisture of the seeds was determined gravimetrically according to TS 1632 procedure (Anonymous, 1974). 6 grams of randomly chosen seeds were distributed into a petri dish, and kept inside the dessicator for 30 minutes. Weighed seeds were then put into the oven at 103°C for 3 hours. At the end of the 3 hour period, the lid of petri dish was closed; seeds were taken into the dessicator, and kept there until they were cooled (15-20 min). After being weighed, sesame seeds were placed into the oven for an additional hour. The procedure was repeated until the difference between the two successive weights were 0.005 g or less. All measurements were in triplicate. The results were expressed on dry basis as per 100 mass of dry seeds.

II. 6. 2. Dehulling Efficiency

5 grams of randomly chosen processed seeds (~1800 seeds) were placed on petri dishes, distributed as small groups and counted. The lamp and magnifying glass of a colony counter were used while counting the seeds for the ease of visualization. The number of the seeds was calculated in terms of dehulled, unhulled, and damaged seeds. Damaged seeds were the ones which were dehulled but cracked or changed in shape (op-pressed, flat, etc.).

II. 6. 3. Determination of Water Absorption of Sesame Seeds

15 grams of randomly chosen sesame seeds were soaked into distilled water in beakers. The ratio of seeds to water was 1:5 (w/v). The number of samples was 16, and samples were all kept in oven at constant temperature. At selected time intervals, one of the samples was taken, water inside the beaker was strained by using a kitchen sieve, and seeds were distributed onto a paper towel. After being wiped gently with clean paper towels, sesame seeds were weighed immediately. Water absorption of the seeds was calculated by using the difference between the initial (unsoaked) and final weights. Moisture contents at the selected intervals were calculated on dry basis.

The selected time intervals were 5, 10, 20, 40, 60, 100, 140, 200, 260, 320, 380, 440, 500, 560, 620, and 680 minutes. For each time interval, a new sample was removed quickly from the oven and used for water absorption determination.

The same procedure was used at the three temperatures 20, 30, and 40°C. Water used for soaking was also pre-heated to these temperatures before seeds were soaked.

All determinations were in triplicate, and the average of these was used for each time vs. moisture content data.

II. 6. 4. Effect of Moisture Content, Dehuller Speed and Number of Pass on Dehulling Efficiency

Sesame seeds soaked in distilled water with a seed to water ratio 1:5 (w/v) were kept in the oven at constant temperature 30°C. The soaking times selected were 17, 55, and 573 min to reach the moisture contents of 30.5, 50.4, and 70.7 % db, respectively. These times were determined using the results of section II.6.3 for the assigned moisture contents. Upon attaining the target moisture content, the seeds were immediately strained, a 6 g sample was taken for moisture determination, and the rest was fed to the dehuller.

The three rotational speeds for the dehuller were selected as 1150, 840, and 420 rpm. Sesame seeds were fed to the dehuller continuously, by keeping, the T-shaped pipe section always full, and the screw conveyor transporting the seeds continuously through the pipe at a constant rate. The capacities at the three different rotational speeds and residence time of the seeds inside the dehuller were also determined.

Sesame seeds were passed through the dehuller up to five times at 840 rpm. 20 grams of seeds were placed in fluidized bed and dried for 5 min at 80°C at an air speed of 4.4 m/s. The humidity of the air was 0.017 kg water vapor/kg bda. Hulls were collected using the gauze filter.

Besides fluidized bed, the designed hull separator was also used. 15 g of the dehuller product containing hulls, dehulled and unhulled sesame seeds was placed into the hull separator. The machine was operated for 5 min with all functions simultaneously. Ambient air with humidity 0.017 kg water vapor/kg bda and temperature 80°C used for drying was supplied to the chamber at the speed of 4.4 m/s.

II. 6. 5. Use of Enzyme Solutions

Sesame seeds were soaked into prepared Peelzyme-I solutions for 15 min at 30°C. Enzyme solutions used were 0.1% and 0.2% (v/v). Seed to enzyme solution ratio was 1:5 (w/v). After being soaked, seeds were rinsed with tap water flowing at a rate of 60 ml/sec for 30 seconds. Water was strained from the seeds, and seeds were fed to the dehuller rotating at 840 rpm. The number of pass of the seeds through the dehuller was four, and sesame seeds were processed in the hull separator after each pass. Operating conditions of the hull separator were the same as the ones used for the water soaked seeds.

II. 7. Data Analysis

The package computer program Microsoft® Excel 2002 was used for linear regression analysis of the absorption data. Chi-square test was performed to predict the suitability of the resulting equations in modeling the absorption phenomenon in sesame seeds. Mean data of dehulling efficiency for different moisture contents and dehuller speed was analyzed using two-way analysis of variance (ANOVA) without replication to determine if there existed significant differences. Duncan’s Multiple Range test was used to find which means were significantly different. Single factor ANOVA was performed to compare the observed and predicted equilibrium contents of sesame seeds.

CHAPTER III

RESULTS AND DISCUSSION

III. 1. Modeling Water Absorption of the Seeds

The experimentally obtained moisture absorption data for sesame seeds at 20, 30, and 40°C are given in Tables D.1-D.12 and the plots are shown in Figure 10. The curves indicate that at constant temperature seeds exhibit an initial high rate of moisture absorption which gradually decreased in the latter stages. Further, water uptake capacity of the seeds increases with an increase in temperature. This is a characteristic moisture absorption behavior described in the literature and is in agreement with the published studies (Kon, 1979; Sopade and Obekpa, 1990; Maharaj and Sankat, 2000).

When Eq.(5) was used to represent the experimental absorption data, Figure 11 was obtained with the $R^2>0.995$ in all of the cases. This indicates a good fit to the experimental data, and the Peleg equation can be successfully used for describing the water absorption characteristic of sesame seeds.

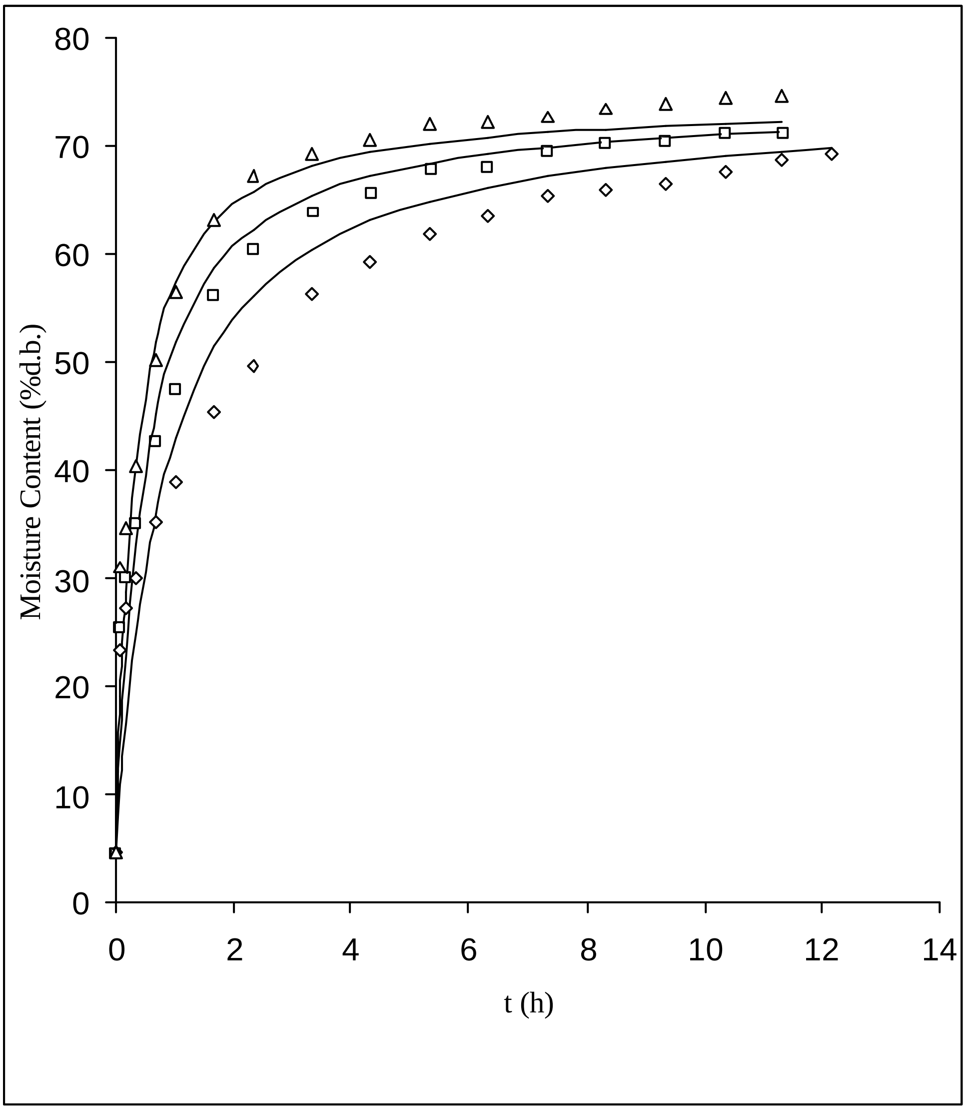

Figure 10: Water absorption characteristics of sesame seeds

(? : at 40°C, ?: at 30°C, ?: at 20°C, ?: predicted)

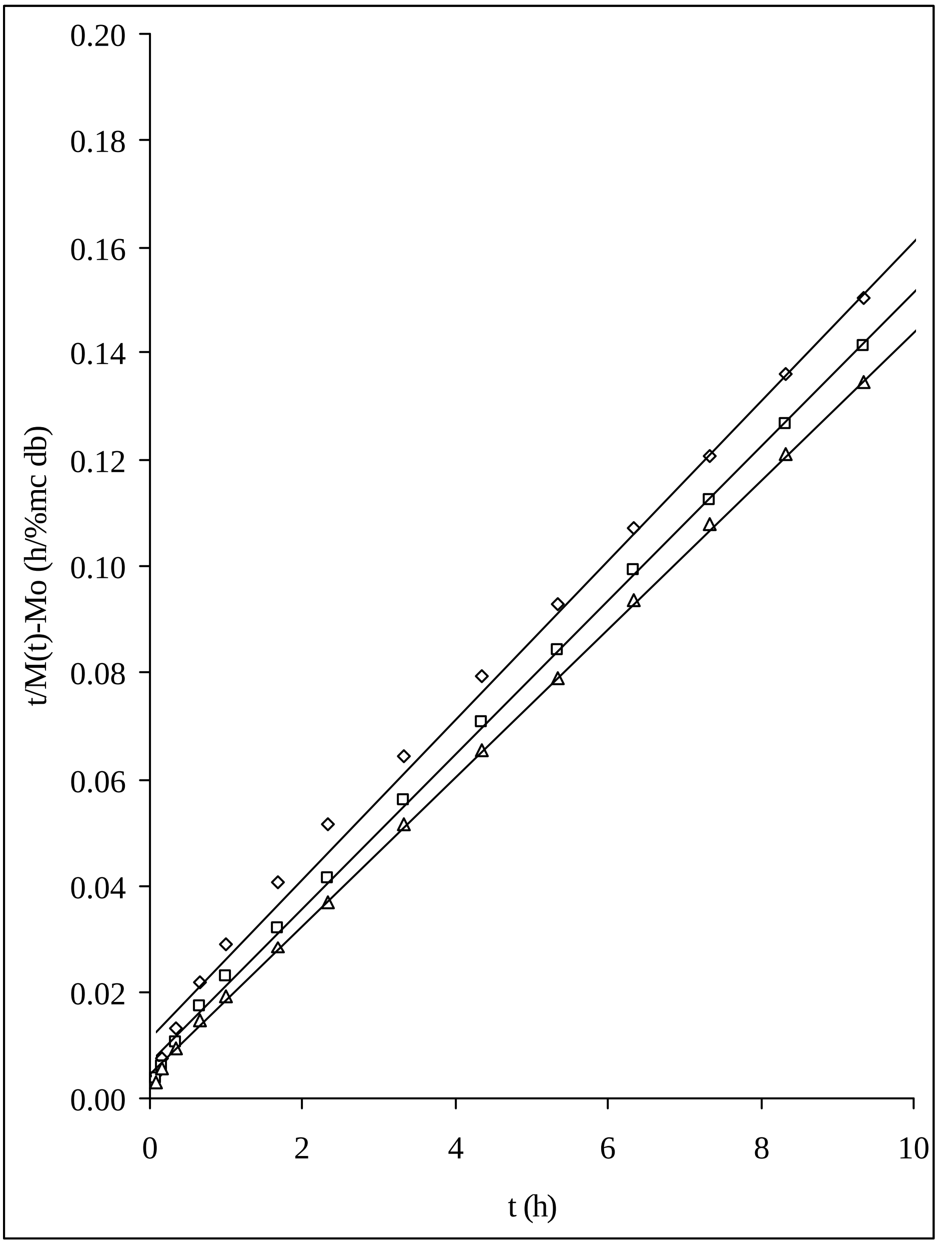

Figure 11: Application of the Peleg equation to the experimental data (?: at 20°C, ?: at 30°C, ? : at 40°C)

Table 3: Values of the constants in Peleg equation

Temperature (°C)	k_1(h/%mc db)	k_2 (%mc db)$^{-1}$	Mean k_2 ± SE	R^2
20	1.16×10^{-2}	1.48×10^{-2}	1.44×10^{-2}	0.9953
30	0.68×10^{-2}	1.45×10^{-2}	$\pm0.216\times10^{-3}$	0.9992
40	0.45×10^{-2}	1.39×10^{-2}		0.9997

Table 3 shows the values of the constants k_1 and k_2 in the Peleg equation at the three temperatures studied. Data sets for these constants are given in Table D.13. A linear regression analysis including ANOVA and Duncan’s Multiple Range tests (Table C.1 and C.2) was performed for the relationship between k_1 and temperature. It can be observed from Figure 12 that k_1 was inversely related to temperature, which is in agreement with the literature (Sopade and Obekpa, 1990; Maharaj and Sankat, 2000; Turhan et al., 2002). Peleg constant k_1 is related to mass transfer rate where its reciprocal indicates the initial hydration rate. As k_1 increases, initial water absorption rate decreases. This is also consistent with the plot in Figure 10 showing that at the initial times of the soaking period, more water is absorbed as the temperature was increased.

The constant k_2 is a characterizing parameter for the food material, and has been shown to define the equilibrium moisture content or saturation capacity by Peleg (1988) and is not expected to vary with temperature (Peleg, 1988; Sopade and Obekpa, 1990; Maharaj and Sankat, 2000). The values of k_2 at the three temperatures obtained from the linearized Peleg equation are not exactly the same, but are very close to each other. With regard to this fact, the mean value for k_2 at the three temperatures was calculated as 1.44×10^{-2} (%mc db)$^{-1}$ with a standard error of $\pm0.216\times10^{-3}$. Using this mean k_2 and the k_1 values obtained at the three temperatures, the suitability of the resulting linear equations in modeling the absorption phenomenon in sesame seeds was analyzed using ?^{2} –test.

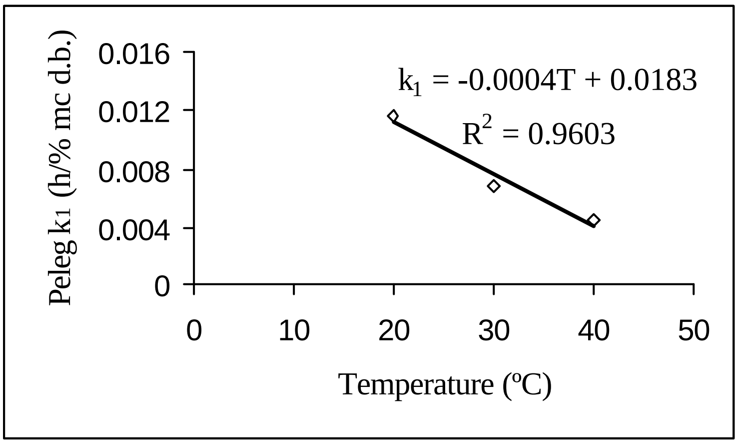

Figure 12: Dependence of Peleg k_1 on temperature

The observed values of moisture content were the experimental values and the predicted values obtained by using the linear equations were taken as the expected values. ?^{2} values for individual points for the whole soaking period were summed up. At 5 % significance level tabulated ?^{2} values were greater than the observed ?^{2} values indicating that these two were not significantly different (Table C.3). This suggests that using the mean k_2 values in linearized Peleg equation gives no significant difference between the predicted and observed values, thus effect of temperature on k_2 values found in this study was negligible.

The saturation moisture or the equilibrium moisture content of the seeds was calculated from Eq.(2) using the mean k_2 value as 74.0±1.05 % db. On the other hand, observed mean equilibrium moisture content as the mean of the three equilibrium moisture contents observed experimentally at 20, 30, and 40°C was 71.6±1.31 % db. Single factor ANOVA at 5% significance level (Table C.4) showed that the mean value of the calculated equilibrium moisture was significantly higher. Such a result is explained by Peleg (1988) as the sorption rate falls dramatically when equilibrium moisture content is reached and therefore the net weight gain can fall below the accuracy of the moisture determination method.

III. 2. Designed Equipment

III. 2 .1. Fluidized Bed Dryer

In this study the first equipment designed for sesame seed processing was a fluidized bed dryer. The dimensions of the bed were diameter 65 mm and height 180 mm. Air supply to the bed was through the slits placed at the bottom of the column wall just above the base. The base of the bed was designed as a circular cone of 20 mm high. The angle between the surface and the base was thus 31.6° which was greater than the angle of repose for sesame seeds (29.2°). The inner walls were made of recessed aluminum mesh. The design aimed to have a tangential air flow from the slits to give sesame seeds a circular motion on the rough surface area of the cone and seed to seed friction to dehull the seeds; as the seeds were dehulled, the kernels and the hulls could easily be separated by the elutriation of the hulls from the bed at an adjusted flow rate of air. Further, the fluidized bed would be used for drying of the kernels. However, the studies showed that a highly discouraging degree of hull removal can be attained with this design. Although fluidized bed dryers are known to provide perfect agitation (Williams, 1971), the internal friction of the seeds was not sufficient for the hull removal and also simultaneous drying of the seeds in the bed might have prevented the hull removal from kernels. It was later determined that for the hulls to be removable from the kernels, the moisture content of the seeds must be above a certain value.

III. 2. 2. The Dehuller

The second equipment designed was the sesame dehuller. It was simply a spiral shaft rotating inside a pvc pipe. Advantages of this equipment were that it was (1) a continuously operating dehuller, (2) easy to construct, (3) economical to maintain. The idea behind the design was that the forces due to the internal friction between the seeds while being pushed along the pipe with the screws together with the friction on the inner surface of the pvc pipe would remove the hulls from the kernels. For this purpose the inner surface of the pvc pipe was covered with cotton woven wound plaster to provide a rough surface for increased friction of the seeds.

Trials showed that the dehulling efficiency of the equipment was dependent on the dehuller speed. This was an expected result which can simply be explained by two counteracting phenomena. At the first place, by increasing the dehuller speed the forces due to higher energy input increases, but the residence time of the seeds in the dehuller decreases and off-sets the first effect. Results suggested that 840 rpm was the optimal dehuller speed within the three speeds studied. The residence time studies showed that at 420, 840 and 1150 rpm rotational speeds of the screw conveyor the residence times of the seeds in the pipe were 8.52 ± 0.021, 4.14 ± 0.064, and 3.14 ± 0.033 seconds with their standard errors respectively. To obtain a full capacity, the T section, feed inlet, was always kept full of seeds, thus screws on the rotating shaft were kept full. Feed rates with their standard errors were 22.3 ± 0.46 g/min at 1150 rpm, 15.1 ± 0.92 g/min at 840 rpm, and 10.2 ± 0.83 g/min at 420 rpm.

When the dehuller was used in combination with the fluidized bed dryer, the results were again unsatisfactory. The mixture of kernels, hulls, and unhulled seeds exiting the dehuller was taken to the fluidized bed dryer. Dryer was operated with an air flow rate of 4.4 m/s at 80°C for 5 min. Free hulls elutriated from the column were collected by the gauze filter. However, after the process seeds in the bed were examined and it was observed that there were free hulls kept as re-adhered to the kernels. Agitation of the seeds in the bed was not sufficient to remove these hulls. This necessitated the revision of the current designs or consideration of a new one.

III. 2. 3. The Hull Separator

This equipment was designed in such a way that it had the feature of three functions in one unit: agitation, drying, and mechanical sieving. The cylindrical vessel with the agitator was similar to that of the industrially used sesame peeler. However; because of the lab scale design it was quite small in dimensions compared to the industrial sesame peelers. Thus, the internal friction within the less sesame load during agitation was not effective enough for removing the hulls efficiently.

When the hull separator was used after dehulling the seeds in the dehuller, the agitator in the hull separator solved the problem of re-adhering of the free hulls onto the dehulled kernels. Thus, using the hull separator instead of the fluidized bed in the experiments seemed to be offering an advantage for obtaining satisfactory results. Accordingly, the screw conveyor dehuller was coupled with the hull separator to complete the process.

As the second function of the hull separator, by downward air supply, it was possible to manage the rubbing action between the seeds plus drying the kernels. The results in Table 4 for drying the dehulled seeds for 5 minutes at 80°C with 4.4 m/s velocity air containing 0.017 kg water/kg bda humidity were satisfactory (Humidity of the air was determined using the psychrometric chart for air-water vapor at 101.32 kPa under the assumption of 101.32 kPa air pressure.). These final moisture contents were below the maximum allowable moisture content (8.69 % db) required in TS 311 for sesame seeds (Anonymous, 1976).

Table 4: Drying results in the hull separator for the seeds soaked at 30°C and after dehuller using 4.4 m/s velocity air with 0.017 kg water/kg bda humidity at 80°C

soaking time at 30°C(min)	initial moisture content (%db)	final moisture content (%db)
17	31.1±0.11	6.32±0.234
55	36.7±0.32	7.96±0.247
573	60.2±0.85	8.65±0.115

Separation of hulls from the kernels was succeeded by simultaneous mechanical sieving during drying and agitation. A perforated plate with 1mm sieve opening was used as the support plate in the design. This sieve size was concluded after a sieve analysis for the previously separated hulls using fluidized bed dryer (Figure 13). Results shown in Table D.14 showed that 99.5 % of the hulls were smaller than 1mm particle size. A sieve analysis for the kernels indicated that 98.9 % of kernels were greater than 1mm. The particle size of the residual percentage was between 0.850 and 1mm. A more detailed sieve analysis for kernels was not performed because of the unavailability of various screen sizes between these two. However, for setting up a more efficient separation process design, detailed sieve analysis of the kernels can be recommended.

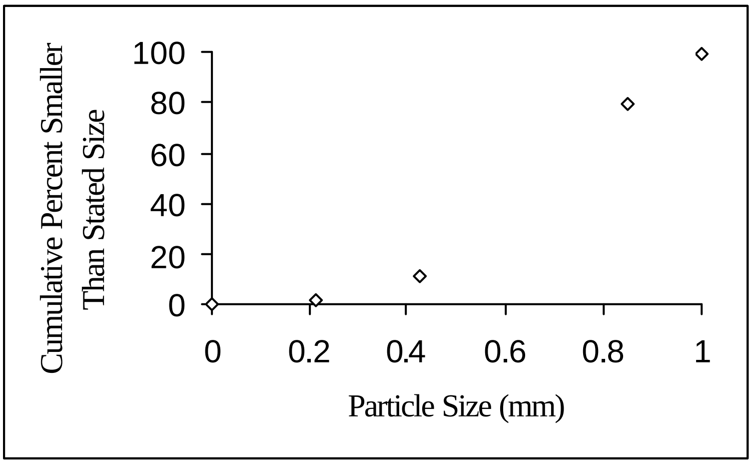

Figure 13: Particle size distribution curve for sesame seed hulls

III. 3. Effect of Moisture Content and Dehuller Speed on Dehulling Efficiency

In this work, three moisture contents, 30.5, 50.4, and 70.7 % db, were studied at three dehuller speeds of 420, 840, and 1150 rpm to investigate the effect of seed moisture content and dehuller speed on dehulling efficiency. The selected soaking temperature for the seeds was 30°C. Designed dehuller was used for dehulling the seeds and seeds were passed through the dehuller length only once. Designed hull separator was used to separate the hulls and kernels. Table D.15 shows the data obtained. All experiments were in triplicate, and mean values of the data were used in the data analysis. Two-way analysis of variance without replication was performed and no interaction between the moisture content of seeds and dehuller speed was assumed. Summary of the ANOVA table (Table C.5) shows that both the F values for dehuller speed and moisture content were higher than the critical F values, thus there was significant difference both among the dehuller speeds and the seed moisture contents at 5% significance level. Duncan's test was used to find out which means were different. The results in Table C.6

showed that at a constant dehuller speed, the means of dehulled seed percentages were significantly different at the three moisture contents. It can be observed from the plots of seed moisture content vs. dehulled seed percentage (Figures 14-16) that percentage of dehulled seeds was linearly dependent on the moisture content at a constant dehuller speed in the studied values of the parameters.

The results of Duncan’s test for the means of dehulled seed percentages at 420, 840, and 1150 rpm were not similar to those of the ones at the three moisture contents. Table C.6 shows that the means of the dehulled seed percentages at 420 and 1150 rpm were significantly the same. The dehulling efficiency at 840 rpm differed from these two at 5% significance level.

A plot of dehuller speed vs. dehulled seed percentage at the three moisture contents is given in Figure 17. It can easily be observed from the variation that 840 rpm is the optimal dehuller speed among three speeds at the three moisture contents.

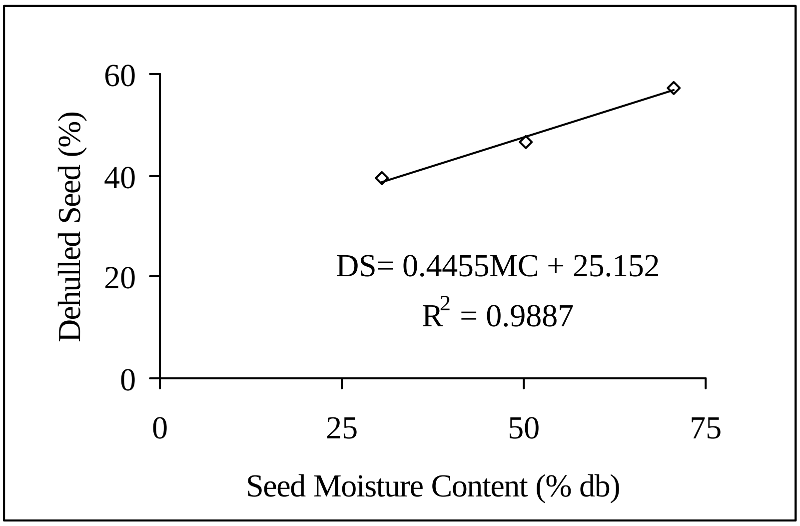

Figure 14: Plot of moisture content vs. percent dehulled seed at 420 rpm

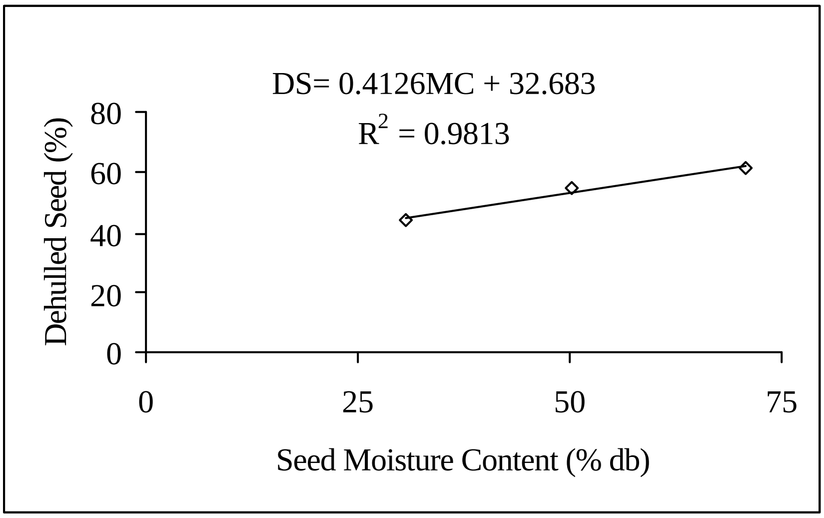

Figure 15: Plot of moisture content vs. percent dehulled seed at 840 rpm

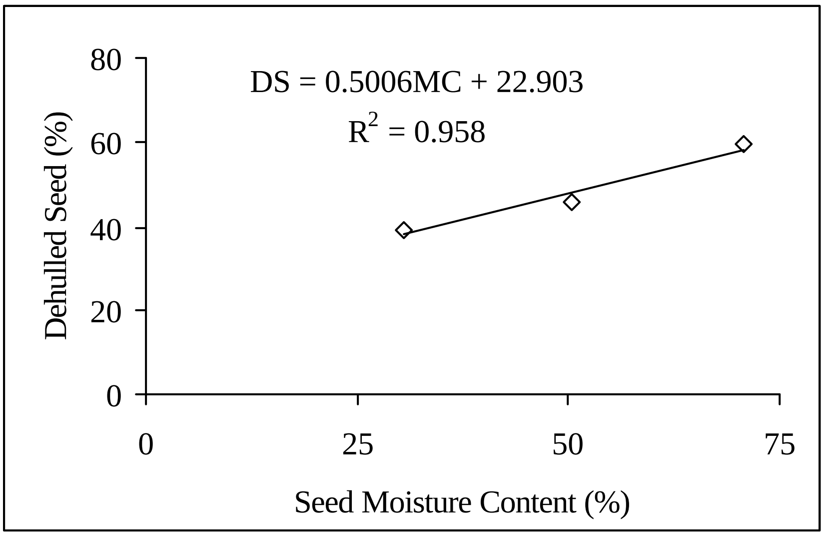

Figure 16: Plot of moisture content vs. percent dehulled seed at 1150 rpm

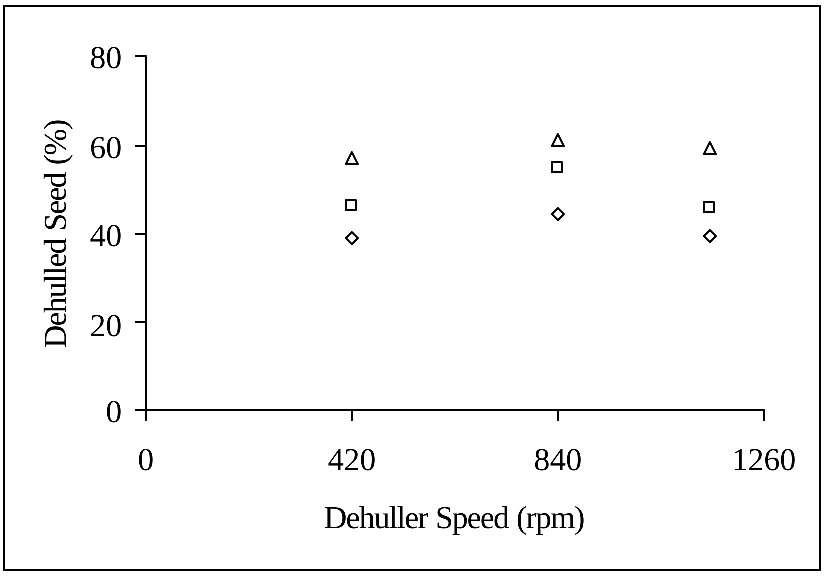

Figure 17: Effect of dehuller speed on dehulled seed percentage

(? : at 70.7 %db moisture content; ?: at 50.4 % db moisture content;

?: at 30.5 % db moisture content)

III. 4. Effect of Number of Pass of Seeds through the Dehuller on Dehulling Efficiency

Because the dehuller was a fixed length, as an additional study the effect of multiples of this length was investigated. For this purpose, the seeds were passed through the dehuller operating at the optimal dehuller speed of 840 rpm for several times to find the extent they could be dehulled. The experiments were conducted using the seeds at the three selected moisture contents of 30.5, 50.4, and 70.7 % db. The results are given in Tables D.16-D.18.

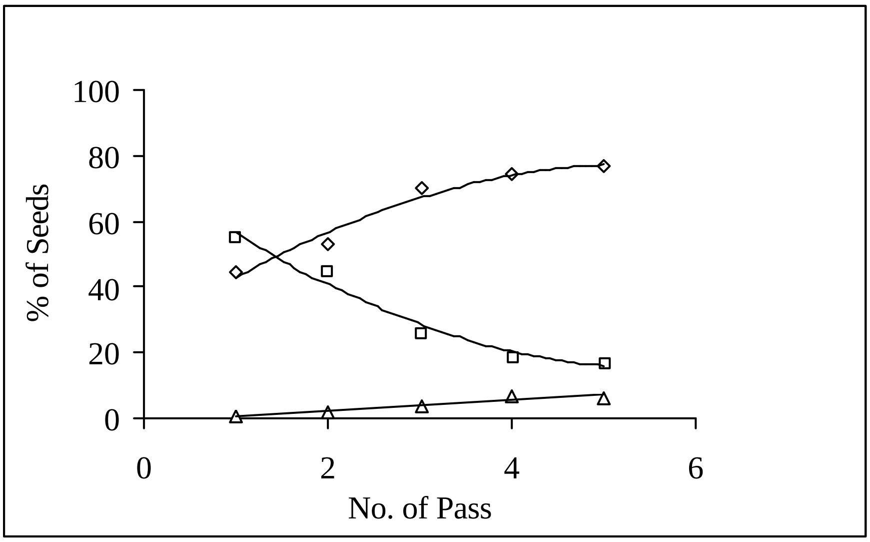

Figure 18: Effect of no. of pass on dehulling efficiency of seeds at 30.5 % db moisture content (?: % dehulled seeds, ?: % unhulled seeds, ? : % damaged seeds)

It can be observed from Figure 18 that as expected the percentage of dehulled and damaged seeds increased with repeated pass of the seeds through the dehuller. Percentage of the damaged seeds could be shown as pseudo-linearly dependent (R^2=0.90) on the number of pass, and increased up to 6.5 % at the 5th pass. Normally it can be inferred that their cumulative percentage should show an S-shaped trend to reach 100% as the number of passes is increased. The difference between the percentages of the acceptable whole seeds at the 1st and 2nd pass was 8.5 % whereas it was 2.5 % at the 4th and 5th pass. The data obtained for only the dehulled whole seeds could be represented by a second order polynomial with R^2=0.97. Theoretically, with the increasing number of pass, the percentage of the dehulled seeds, whole plus damaged, should asymptotically attain a value close to 100 %. However, with the repeated pass of the seeds through the dehuller the percentage of the damaged seeds increased in expense of the dehulled whole and the unhulled seeds. As an example, after the 6th pass the dehulled whole seed percentage decreased to 75.1 % from 76.8 %, of the 5th pass.

The results of the data analysis for the dehulled and damaged seed percentages of the seeds with 50.4 and 70.7 % db moisture contents were similar to those obtained for the seeds with 30.5 % db moisture content. Percentages of damaged seeds with the pseudo-linear dependence on the number of pass for both 50.4 and 70.7% db moistened seeds could be represented with R^2 values of 0.98 and 0.97, respectively (Figures 19-20). The dehulled whole seed percentages showed 2nd order polynomial behavior with R^2=0.99 while dehulling both of the feed seeds containing 50.4 and 70.7 % db initial moisture. The maximum possible dehulling achieved was 82.6 % with the seeds at 50.4 % db moisture content after five passes which was 92.5 % at the 4th pass for the 70.7 % db moisture containing feed.

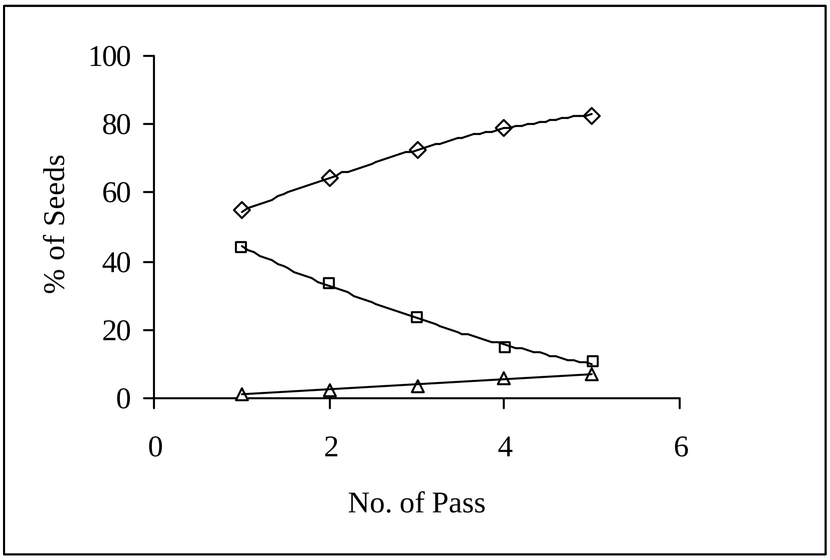

Figure 19: Effect of no. of pass on dehulling efficiency of seeds at 50.4 %db moisture content (?: % dehulled seeds, ?: % unhulled seeds, ? : % damaged seeds)

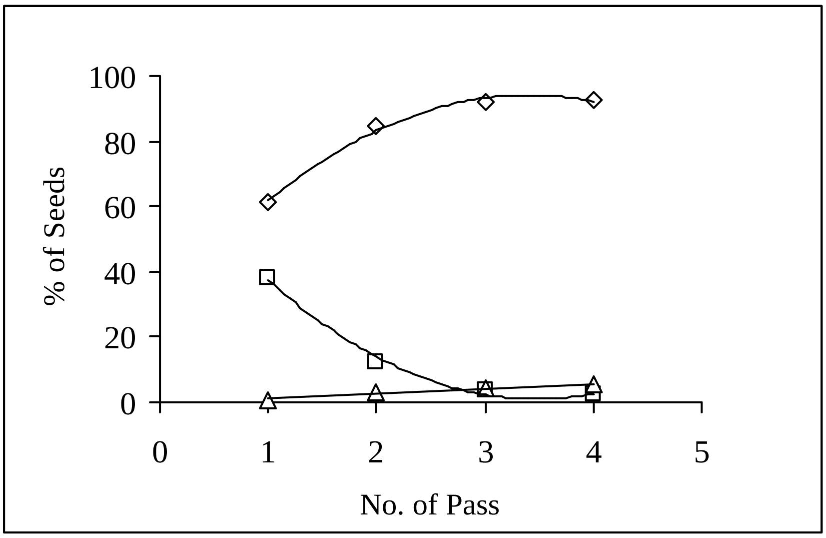

Figure 20: Effect of no. of pass on dehulling efficiency of seeds at 70.7 % db moisture content (?: % dehulled seeds, ?: % unhulled seeds, ? : % damaged seeds)

III. 5. Enzymatic Peeling of Sesame Seeds

Enzymatic peeling has been suggested as a more recent alternative for conventional peeling of fruits and vegetables. The process relies on the fact that pectin, cellulose and hemicellulose are the basic polysaccharides that maintain the adherence of the peel to fruit (Toker, 2000). Because about 78 % of total fiber of fibrous sesame hull is insoluble cellulose and hemicellulose, the possibility of soaking sesame seeds in different enzyme (Peelzyme-I) concentrations was investigated as an alternative method for traditional water soaking prior to dehulling. Two enzyme concentrations of 0.1 and 0.2 % (v/v) were used. Seeds were processed using the designed dehuller at 840 rpm and hull separator (for 5min, and at 80°C air temperature) after 15 minutes of soaking at 30°C.

The results are given in Tables D.19-D.20 and as a plot of number of pass vs. seed percentage in Figures 21 and 22. It was observed that similar to water soaked seeds, the percentages of dehulled seeds could be represented satisfactorily by a 2nd order polynomial of number of pass for both 0.1 and 0.2 % (v/v) enzyme treatments with R^2 values of 0.99 and 0.98, respectively. The percentage of damaged seeds increased linearly with the number of pass through the dehuller for which linear approximations yield R^2 values of 0.94 and 0.91 for 0.1 and 0.2 % (v/v) enzyme concentrations, respectively. The maximum dehulled whole seed percentages were 84.9 % for 0.1% (v/v) enzyme soaked seeds, and 95.0 % for 0.2 % (v/v) enzyme soaked seeds after the 4th pass through the dehuller.

However, when sesame seeds were soaked in water for about 10 hours a dehulling efficiency for the whole kernels 92.5 % was achieved after the 4th pass, compared to 95 % efficiency of soaking for 15 min in 0.2 % (v/v) Peelzyme-I solution. This result, when compared on the basis of time consumption undoubtedly indicates superiority of using a suitable solution. On the other hand, the disadvantage of water and time consumption for washing seeds must be considered.

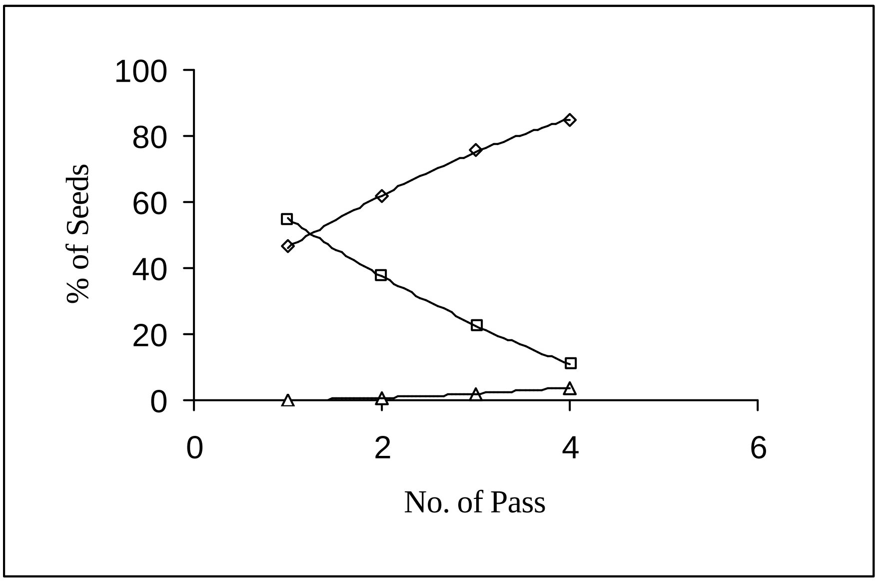

Figure 21: Effect of no. of pass on dehulling efficiency of seeds soaked in 0.1 % (v/v) Peelzyme-I (?: % dehulled seeds, ?: % unhulled seeds, ? : % damaged seeds)

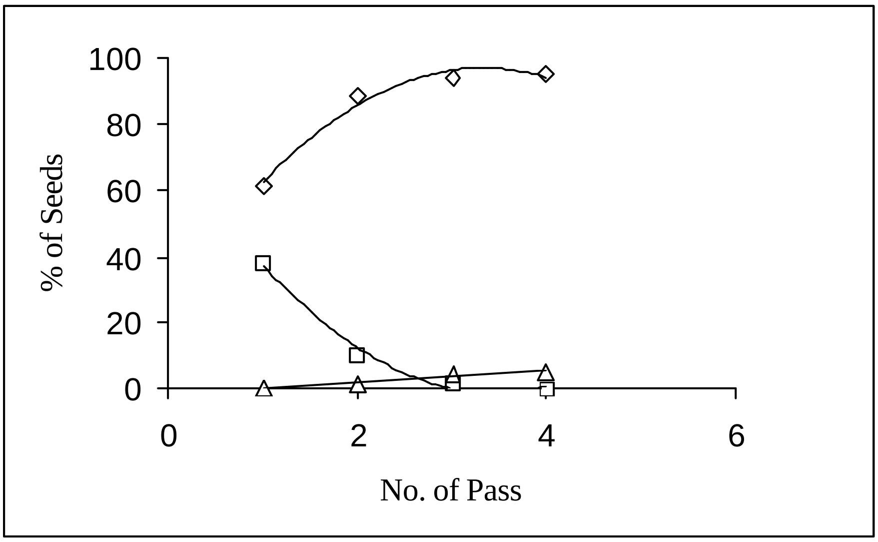

Figure 22: Effect of no. of pass on dehulling efficiency of seeds soaked in 0.2 % (v/v) Peelzyme-I (?: % dehulled seeds, ?: % unhulled seeds, ? : % damaged seeds)

CHAPTER IV

CONCLUSIONS AND RECOMMENDATIONS

In this study the possibility of improving the traditional sesame seed dehulling process by new methods and processing equipments was investigated.

Because soaking of the seeds is the necessary initial step of the dehulling process, first water absorption kinetics of sesame seeds were determined. The results indicate that water absorption rate of the seeds at 20, 30, and 40°C can satisfactorily be represented with the Peleg equation. In accordance with the literature the temperature dependency of the rate constant k_1 of the equation shows an inverse variation whereas the capacity constant k_2 appears to be quite insensitive.

Studies showed that for the seeds to be dehulled efficiently and with the least damage they should be above a critical minimum surface moisture content and sufficient frictional force should be acting on their surface, mostly of the seed to seed rubbing type. With regard to these facts of the dehullers designed and tested:

i. The fluidized bed design is not suitable as before the seeds can be dehulled the surface moisture content of seeds falls below the critical minimum and also seed to seed friction is inadequate because of continuous air flow between seeds.

ii. The variable speed screw conveyor type dehuller necessitates a hull separator unit as the product from the dehuller contains the removed hulls adhered to the dehulled kernels as well as the determination of size-rotational speed-dehulling efficiency relations.

Instead of the traditional hull-kernel separation of the dehulled mixture by the brine solution technique, two new designs were tested:

i. Performance of the fluidized bed unit is inadequate because despite the fact that it offers the advantage of drying the wet dehulled kernels at the same time rapid surface drying severely reduces the separation efficiency.

ii. Agitated bed dryer and separator system with downward flow of air through the bed and the sieving distributor is a successful design to be integrated with the screw conveyor dehuller for which the optimum design and the operational parameters must be determined.

Dehulling the seeds by soaking in an enzyme solution seems to be highly reducing the soaking time from several hours to about 15 minutes, but necessities a thorough washing and drying operations afterwards.

In the light of the conclusions above as a continuation of this work, the followings can be recommended to be studied:

i. Improvement of the dehuller design parameters as screw depth, pitch, and rotational speed and their effect on dehulling efficiency for scale-up.

ii. The possibility of a continuous hull kernel separator design.

iii. The effects of enzyme concentration, type, soaking time and temperature on the dehulling efficiency and on the quality attributes of product.

REFERENCES

1. Abu-Ghannam N., McKenna B. 1997. Hydration kinetics of kidney beans (*Phaseolus vulgaris* L.). J. Food Sci. 62:520-523.

2. Anonymous. 1974. Determination of moisture and volatile matter. Oleaginous seeds. TSE:TS 1632.

3. Anonymous. 1976. Sesame Seed. TSE: TS 311

4. Anonymous. 2002a. Sesame seed and tahini production. Dimirtis Perrotis College of Agricultural Studies. The American Farm School URL:http://www.afs.edu.gr/agroweb/agroweb2002/html/sesame.htm

5. Anonymous. 2002b. Susam Tarimi (*Sesamum indicum L.*). GAP Official webpage. URL: http://www.gap.gov.tr/Turkish/Tarim/Tarlayt/susam.html

6. Anonymous. 2003a. Cystine. Austin Nutritional Research. URL:http://www.anrvitamins.com/glossary

7. Anonymous. 2003b. ARS Phytochemical Database. URL: http://www.ars-grin.gov/duke/highchem.html

8. Anonymous. 2003c. Kidney stones. My HealthandAge. Health and Age. URL: http://www. healthandage.com/html/well_connected/pdf/doc81.pdf

9. Anonymous. 2003d. Sesame. Major Food and Agricultural Commodities and Producers. FAO Database.
URL: http:// www.fao.org/es/ess/top/Topproducers_EN.htm

10. Anonymous. 2003e. Fibre Content of Selected foods. Diet &IBD.
URL: http://www.julies-story.org/index.html

11. Annussek, G. 2001. Sesame oil. In: Gale encyclopedia of alternative medicine. Gale Group and Looksmart.

12. Ashri A. 1989. Sesame. pp.375-387. In: Röbbelen G., Downey R.K., Ashri A. (eds.), Oil Crops of the World-their Breeding & Utilization. Mc Graw-Hill Publishing Company.

13. Bahkali A. H., Hussain M. A. 1998. Protein and oil composition of sesame seeds grown in the Gizan area of Saudi Arabia. Int. J. Food Sci. 49:6.

14. Becker H.A. 1959. A study of diffusion in solids of arbitrary shape, with application to the drying of wheat kernel. J. Appl. Polymer Sci. 1(2):212.

15. Becker H.A. 1960. On the absorption of liquid water by the wheat kernel. Cereal Chem. 37:309.

16. Beroza M., Kinman., M. L. 1955. Sesamin, sesamolin, and sesamol content of the oil of sesame seed as affected by strain, location grown, ageing, and frost damage. J. Am. Oil Chem. Soc. 32:348-350.

17. Bulayci Brothers Industry Trade Co. Ltd., 2003
http://www.bulayhan.com

18. Carr R. 1989. Processing of Oilseed Crops. pp.226-259. In: Röbbelen G., Downey R.K., Ashri A. (eds.), Oil Crops of the World-their Breeding & Utilization. Mc Graw-Hill Publishing Company.

19. Crank J. 1975. "The Mathematics of Diffusion", 2nd ed. Oxford University Press, Ely House, London.

20. Dark, Graham.1998. On-line medical dictionary.
URL: http://www.graylab.ac.uk/cgi-bin/omd?sesame+oil.

21. Dudley T.S., Grichar W.J., Amanda A.M. 2000. Crop profile for sesame in United States. Texas Agricultural Experiment Station, College Station and Yoakum
URL: http:// cipm.ncsu.edu/cropprofiles/docs/ussesame.html

22. Evans R. J., Bandemer S. L. 1967. Nutritive value of some oilseed proteins. Cereal Chem. 44:417-426.

23. Fukuda Y., Nagata T., Osawa T., Namiki M. 1986. Contribution of lignan analogues to antioxidative activity of refined unroasted sesame seed oil. J. Am. Oil Chem. Soc. 63:1027-1031.

24. Gümüs Food Machinery Manufacturing. 2003. Sesame processing unit.
URL: http://www.gumusmak.com/susamtr.htm

25. Gürmaksan. 2003. Tahin, helva, lokum gida makinalari.
URL: http://www.telerehber.com/gurmaksan/urun4.htm

26. Hirata F., Fujita K., Ishikura Y., Hosoda K., Ishikawa T., Nakamura H. 1996. Atherosclerosis.122:135-136.

27. Hsu, K.H. 1983. A diffusion model with a concentration dependent diffusion coefficient for describing water movement in legumes during soaking. J. Food Sci. 48:618-622, 643.

28. Hung T.V., Liu L.H., Black R.G., Trewhella M.A. 1993. Water absorption in chickpea (C. Arietinum) and field pea (P. Sativum) cultivars using Peleg model. J. Food Sci. 58:848-852.

29. Johnson A.H., Peterson M. S. 1974. “Encyclopedia of Food Technology”, pp. 793-795.The Avi Publishing company, Inc. Westport Connecticut.

30. Katsuzaki H., Kawasumi M., Kawakishi S., Osawa T. 1992. Structure of novel antioxidative lignan glucosides isolated from sesame seed. Biosci. Biotech. Biochem. 56:2087-2088.

31. Katsuzaki H., Kawakishi S., Osawa T. 1994. Sesaminol glucosides in sesame seeds. Phytochemistry. 35:773-776.

32. Katzer G. 1999. Gernot Katzer's Spice Dictionary. Sesame Synonyms URL:http://www. ang.kfunigraz.ac.at/~katzer/engl/Sesa_ind.html

33. Kon, S. 1979. Effect of soaking temperature on cooking and nutritional quality of beans. J. Food Sci. 44: 1329.

34. Lillie R.D. 1948. "Histopathologic Technique", Blakiston, Philadelphia and Toronto.

35. Lopez A., Pique M.T., Clop M., Tasias J., Romero A., Boatella J., Garcia J. 1995. The hygroscopic behavior of the hazelnut. J. Food Engineering. 25:197-208.

36. Maharaj V., Sankat C.K. 2000. The hydration characteristics and quality of dehydrated dasheen leaves. Canadian Agricultural Engineering. 42:81-85.

37. Mazza G. and LeMaguer M. 1980. Dehydration of onions: Some theoretical and practical considerations. J. Food. Technology. 15:181-194.

38. Morris J.B. 2002. Food, industrial, nutraceutical, and pharmaceutical uses of sesame genetic resources. pp. 153–156. In: J. Janick and A. Whipkey (eds.), Trends in new crops and new uses. ASHS Press, Alexandria, VA. URL: http://www.hort.purdue.edu/newcrop/ncnu02/v5-toc.html

39. Novo Nordisk. 1998. Product Sheet

40. Nussinovitch A., Peleg, M. 1990. An empirical model for describing weight changes in swelling and shrinking gels. Food Hydrocolloids. 4:69-76.

41. Osawa T., Nagata M., Namiki M., Fukuda Y. 1985. Sesamolinol, a novel antioxidant isolated from sesame seeds. Agric. Biol. Chem. 49:3351-3352.

42. Peleg M. 1988. An empirical model for the description of moisture sorption curves. J. Food Sci. 53:1216-1219.

43. Pretel M.T., Lozano P., Riquelme F., Romojaro F. 1997. Pectic enzymes in fresh fruit processing: Optimization of enzymatic peeling of oranges. Process Biochemistry. 32:43-49.

44. Rechtenbach K., Nitz S. 1999. Extraction of gamma-tochopherol and lignan compounds of Sesamum indicum L. With accelerated solvent extraction (ASE). Scientific Publications. No:3. Technische Universitat München, Germany.
URL:http://www.rechtenbach.de

45. Robert A.S. 1999. Considerations in using common Asian protein meals. American Soybean Association Technical Bulletin Vol AN21. Singapore. URL: http://www.asasea.com

46. Sastry M.C., Subramanian N., Parpia H.A.B. 1974. Effects of dehulling and heat processing on nutritive value of sesame proteins. J. Am. Oil Chem. Soc. 51:115-118.

47. Sayar S., Turhan M., Günasekaran S. 2001. Analysis of chickpea soaking by simultaneous water transfer and water-starch reaction. J. Food Engineering. 50:91-98.

48. Shimoda M., Nakada Y., Nakashima M., Osajima Y. 1997. Quantitative comparison of volatile flavor compounds in deep-roasted and light-roasted sesame seed oil. J. Agric. Food Chem. 45:3193-3196.

49. Shimoda M., Shiratsuchi H., Nakada Y.Wu Y., Osajima Y. 1996. Identification and sensory characterization of volatile flavor compounds in sesame seed oil. J. Agric. Food Chem. 44:3909-3912.

50. Singh B.P.N., Kulshrestha S.P. 1987. Kinetics of water sorption by soybean and pigeonpea grains. J. Food Sci. 52:1538-1541, 1544.

51. Soffer T., Mannheim C.H. 1996. Optimization of enzymatic peeling of oranges and pomelo. Lebensmittel-Wissenschaft und Technologie. 27:245-248.

52. Sopade P.A., Obekpa J.A. 1990. Modeling water absorption in soybean, cowpea and peanuts at three temperatures using Peleg’s equation. J. Food Sci. 55:1084-1087.

53. Toker I. 2000. Enzymatic peeling of stone fruits. M.Sc. thesis. Department of Food Engineering, METU, Ankara.

54. Toker I., Bayindirli A., 2003. Enzymatic peeling of apricots, nectarines and peaches. Lebensmittel-Wissenschaft und Technologie. 36:215-221.

55. Turhan M., Sayar S., Günasekaran S. 2002. Application of Peleg model to study water absorption in chickpea during soaking. J. Food Engineering. 53:153-159.

56. Williams A.G. 1972. “Industrial Drying”, 1st Ed. CRC Press, Cleveland, Ohio.

57. Woltman O. 2003. Sesame seed. International Dipasa Group
URL: http://www.dipasa.nl

58. Yehia G.M., Hussein O.A., Yaldes I.A., 2002. Wet decortication of sesame seeds by new methods. Unupress.
URL: http://www.unu.edu/unupress/food/8F121e/8F121E09

59. Yoshida H. 1994. Composition and quality characteristics of sesame seed (Sesamum indicum) oil roasted at different temperatures in an electric oven. J. Sci. Food Agric. 65:331-336.

60. Yoshida H., Takagi S. 1997. Effects of seed roasting temperature and time on the quality characteristics of sesame (Sesamum indicum L.) oil. J. Sci. Food Agric. 75:19-26.

APPENDIX A

ADDITIONAL TABLES RELATED TO SESAME SEEDS

Table A.1: Sesame seed synonyms (Katzer, 1999)

Arabic	Sasim, Zelzlane
Bengali	7LO
Chinese	Zi ma zi, Moa, Mua Chi
Dutch	Sesamzaad
English	Semsem, Gingelly
Estonian	Harilik seesam
Finnish	Seesami
French	Sésame, Teel, Till
German	Sesam, Vanglo
Greek	Sousámi
Hindi	7LO* LQJOL
Hungarian	Szézámfû, Szézámmag
Italian	Sesamo

Table A.1.(cont.)

Japanese	Goma, Koba
Portuguese	Gergelim
Romanian	Susan
Sanskrit	7LOD
Turkish	Susam, Küncü

Table A.2: World sesame production in 2002 (FAO Database, 2003)

Rank	**Country**	**Production (Metric Tones)**	
	World	2,820,701	
1	China	790,000	*
2	India	580,000	*
3	Sudan	274,000	
4	Myanmar	225,000	*
5	Uganda	106,000	
6	Pakistan	69,600	F
7	Bangladesh	49,000	F
8	Chad	43,390	F
9	Mexico	40,000	F
10	Central African Republic	39,400	
11	United Rep. of Tanzania	39,000	F
12	Thailand	39,000	F
13	Nigeria	38,200	
14	Paraguay	35,930	
15	Egypt	34,849	F
16	Guatemala	32,386	
17	Republic of Korea	31,043	F
18	Iran	27,000	F
19	Venezuela	27,000	F
20	Somalia	25,000	F
	Turkey	24,000	

F: FAO estimate

*: Unofficial figure

Table A.3: World sesame production in 2001 (FAO Database, 2003)

Rank	Country	Production (Metric Tones)
	World	3,209,887
1	China	804,111
2	India	730,200
3	Myanmar	426,384
4	Sudan	262,000
5	Uganda	102,000
6	Nigera	74,000 *
7	Pakistan	69,600
8	Bangladesh	49,000 *
9	Chad	43,390
10	Mexico	42,879
11	United Rep. of Tanzania	39,000 *
12	Thailand	39,000
13	Egypt	34,849
14	Central African Republic	32,400
15	Guatemala	31,751
16	Burkina Faso	31,230
17	Republic of Korea	31,043
18	Iran	27,000 *
19	Venezuela	26,910
20	Somalia	25,000 F
	Turkey	23,000

F: FAO estimate

*: Unofficial figure

Table A.4: Composition of sesame seeds

(Johnson and Peterson, 1974; Anonymous, 2003e)

Nutrient	**Units**	**Value per 100g**
Proximates		
Total lipid	g	49.0
Protein	g	20.0
Carbohydrates	g	15.8
Fiber (soluble)	g	1.2
(insoluble)	g	4.7
Water	g	4.8
Ash	g	4.6
Energy	kcal	588.0
Minerals		
Calcium, Ca	mg	1310.0
Iron, Fe	mg	7.8
Magnesium, Mg	mg	347.0
Phosphorus, P	mg	776.0
Potassium, K	mg	407.0
Sodium, Na	mg	40.0
Zinc, Zn	mg	10.3
Vitamins		
Niacin	mg	4.7
Thiamin	mg	0.7
Pantothenic acid	mg	0.7
Vitamin B-6	mg	0.2
Vitamin A	IU	66.0

Table A.5: Amino acid composition of sesame seeds and FDA/WHO reference protein (Bahkali and Hussain, 1998)

Amino Acid (g/16g N)	Tested Trait	FAO/WHO (minimum)
Aspartic acid	—	—
Threonine*	3.7	4.0
Serine	—	—
Glutamic Acid	—	—
Glysine	—	—
Alanine	—	—
Valine*	4.6	5.0
Methionine*+Cystine	4.8	3.5
Isoleucine*	4.0	4.7
Leucine*	8.0	7.0
Phenylalanine+Tyrosine*	9.6	6.0
Histidine*	2.7	—
Tryptophan*	1.3	1.0
Lysine*	2.7	5.5
Arginine*	12.0	—

* : Essential amino acids

Table A.6: Sesame food uses (Morris, 2002)

Food	**Country**
Sesame cakes, wine, and brandy	Biblical Babylon
Bread stick, cracker	Worldwide
Salad and cooking oil	Worldwide
Roasted seed	India, Worldwide
Substitute for olive oil	Europe
On bread	Sicily, Worldwide
Cakes	Greece
Soup, spice, seed oil	Africa
Salad and fish oil	Japan
Confectionery	China, Worldwide
Sesame seed buns, chips	United States

APPENDIX B

PHOTOS OF DESIGNED EQUIPMENT

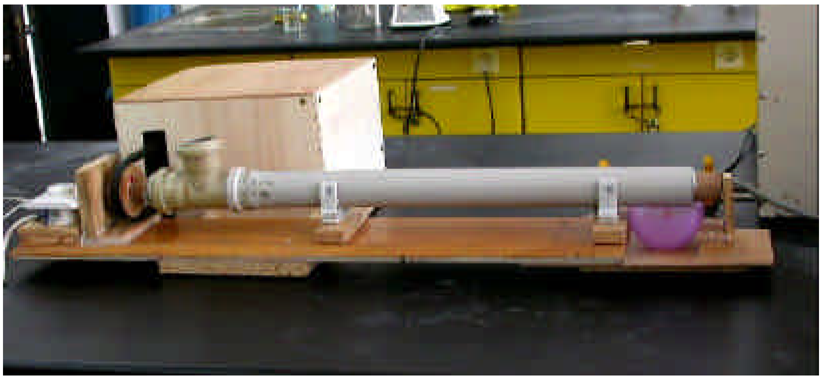

Figure B.1: Photo of designed dehuller

Figure B.2: Photo of spiral shaft for designed dehuller

Figure B.3: Photo of fluidized bed dryer

Figure B.4: Photo of fluidized bed column

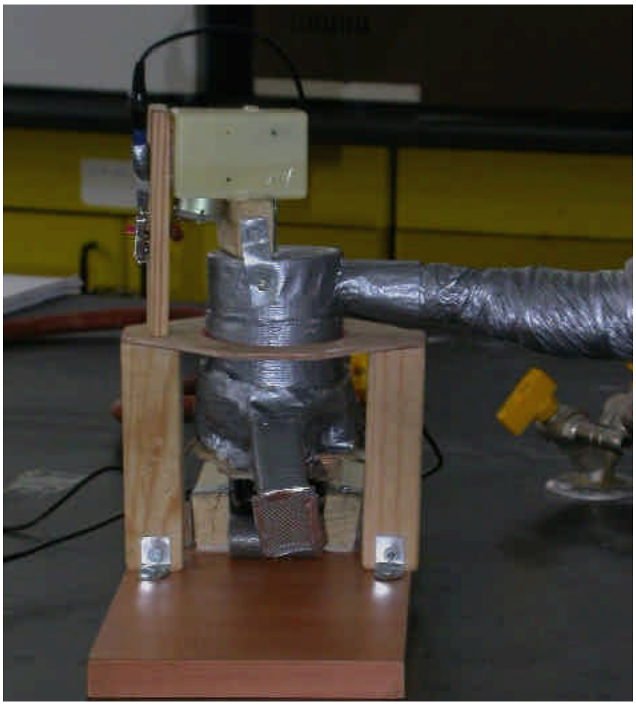

Figure B.5: Photo of designed hull separator

Figure B.6: Photo of fixed vessel and sieving equipment at the bottom side of hull separator

Figure B.7: Photo of air distributor and agitator paddle of hull separator

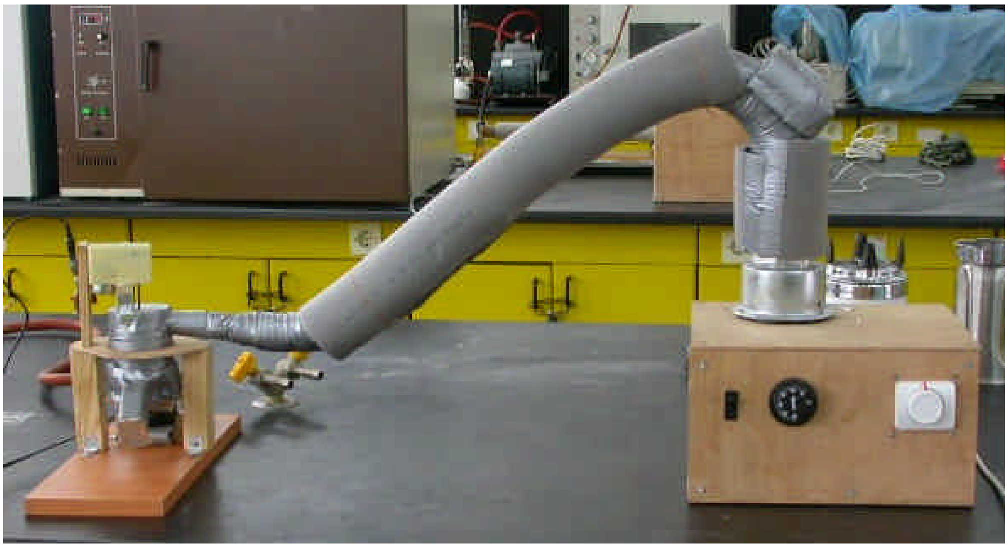

Figure B.8: Photo of hull separator with air source

APPENDIX C

TABLES OF STATISTICAL TESTS

Table C.1: ANOVA table for the effect of temperature on the Peleg constant k_1

ANOVA: Single Factor a=0.05

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
k_1 groups	$7.88*10^{-5}$	2	$3.94*10^{-5}$	499.606	$2.13*10^{-7}$	5.143
Error	$4.73*10^{-7}$	6	$7.89*10^{-8}$			
Total	$7.93*10^{-5}$	8				

Table C.2: Results of Duncan's Multiple Range Test for the effect of temperature on the Peleg constant k_1

	Temperature		
	20°C	30°C	40°C
mean k_1 (h/%mc db)	0.0116^a	0.0066^b	0.0045^c

a-c: means with different letters are significantly different (a=0.05)

Table C.3: Summary of the $?^2$-test on experimental and predicted water absorbed

	Soaking temperature (°C)		
	20	30	40
$?^2_{obs}{}^{*}$	24.55	10.85	9.23
critical values:	df=17	df=16	df=16
Sig. level	5%	5%	5%
$?^2{}_{table}{}^{**}$	27.59	26.30	26.30

*: $?^2_{obs}$=S $(M_{obs}-M_{exp})^2 / M_{exp}$

**: tabulated $?^2$ values

Table C.4: ANOVA table for observed and predicted equilibrium moisture contents of sesame seeds

ANOVA: Single Factor a=0.05

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between groups	8.88167	1	8.882	1.387	0.3041	7.70865
Error	25.6067	4	6.402			
Total	34.4883	5				

Table C.5: ANOVA table for the effect of moisture content and dehuller speed on dehulling efficiency

ANOVA: Two-Factor Without Replication a=0.05

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Dehuller Speed	63.1467	2	31.5733	8.973946	0.03322	6.94428
Moisture Content	499.74	2	249.87	71.01942	0.00075	6.94428
Error	14.0733	4	3.51833			
Total	576.96	8				

Table C.6: Results of Duncan's Multiple Range Test for the effect of moisture content and dehuller speed on dehulling efficiency

	moisture content (% d.b.)		
dehuller speed (rpm)	30.5	50.4	70.7
420	39.3^a	46.5^c	57.2^e
840	44.6^b	54.8^d	61.2^f
1150	39.4^a	45.7^c	59.5^e

a-f: Means with the same letter are significantly the same at 5% level.

APPENDIX D

EXPERIMENTAL DATA

Table D.1: Experimental data (Replication-1) of water absorption of seeds at 20°C

t (min)	**t** (h)	**W** (g)	**M(t)** (%db)	**t/M(t)-Mo** (h/%mc db)
0	0	15	4.529617	_
5	0.08333	17.83	24.25087	0.004226
10	0.16667	18.29	27.45645	0.007270
20	0.33333	18.7	30.31359	0.012928
40	0.66667	19.44	35.47038	0.021547
60	1	20.04	39.65157	0.028472
100	1.66667	20.77	44.73868	0.041450
140	2.33333	21.52	49.96516	0.051355
200	3.33333	22.52	56.93380	0.063608
260	4.33333	23	60.27875	0.077729
320	5.33333	23.31	62.43902	0.092098
380	6.33333	23.5	63.76307	0.106922
440	7.33333	23.78	65.71429	0.119856
500	8.33333	23.83	66.06272	0.135428
560	9.33333	23.93	66.75958	0.149981
620	10.3333	24.02	67.38676	0.164394
680	11.3333	24.15	68.29268	0.177741

Table D.2: Experimental data (Replication-2) of water absorption of seeds at 20°C

t (min)	**t** (h)	**W** (g)	**M(t)** (%db)	**t/M(t)-Mo** (h/%mc db)
0	0	15	4.529617	_
5	0.08333	17.59	22.57840	0.004617
10	0.16667	18.13	26.34146	0.007641
20	0.33333	18.56	29.33798	0.013436
40	0.66667	19.39	35.12195	0.021792
60	1	19.9	38.67596	0.029286
100	1.66667	20.93	45.85366	0.040332
140	2.33333	21.48	49.68641	0.051672
200	3.33333	22.45	56.44599	0.064206
260	4.33333	22.72	58.32753	0.080548
320	5.33333	23.2	61.67247	0.093333
380	6.33333	23.49	63.69338	0.107048
440	7.33333	23.74	65.43554	0.120404
500	8.33333	23.73	65.36585	0.136980
560	9.33333	23.88	66.41115	0.150826
620	10.3333	24.04	67.52613	0.164030
680	11.3333	24.17	68.43206	0.177354
730	12.1667	24.3	69.33798	0.187733

Table D.3: Experimental data (Replication-3) of water absorption of seeds at 20°C

t (min)	**t** (h)	**W** (g)	**M(t)** (%db)	**t/M(t)-Mo** (h/%mc db)
0	0	15	4.529617	_
5	0.08333	17.65	22.99652	0.004513
10	0.16667	18.37	28.01394	0.007097
20	0.33333	18.65	29.96516	0.013105
40	0.66667	19.36	34.91289	0.021942
60	1	19.82	38.11847	0.029772
100	1.66667	20.85	45.29617	0.040883
140	2.33333	21.4	49.12892	0.052318
200	3.33333	22.35	55.74913	0.065079
260	4.33333	22.83	59.09408	0.079417
320	5.33333	23.17	61.46341	0.093676
380	6.33333	23.42	63.20557	0.107937
440	7.33333	23.67	64.94774	0.121376
500	8.33333	23.84	66.13240	0.135275
560	9.33333	23.87	66.34146	0.150996
620	10.3333	24.06	67.66551	0.163668
680	11.3333	24.24	68.91986	0.176010
730	12.1667	24.27	69.12892	0.188341

Table D.4: Experimental data (Average) of water absorption of seeds at 20°C

t (min)	**t** (h)	**W(ave)** (g)	**SE** of W(ave)	**M(t)** (%db)	**t/M(t)-Mo** (h/%mc db)
0	0	15	0.000	4.529617	_
5	0.08333	17.69	0.072	23.27526	0.006068
10	0.16667	18.26	0.071	27.27062	0.007329
20	0.33333	18.64	0.041	29.87224	0.013153
40	0.66667	19.40	0.023	35.16841	0.021759
60	1	19.92	0.064	38.81533	0.029167
100	1.66667	20.85	0.046	45.29617	0.040883
140	2.33333	21.47	0.035	49.5935	0.051778
200	3.33333	22.44	0.049	56.37631	0.064292
260	4.33333	22.85	0.081	59.23345	0.079214
320	5.33333	23.23	0.043	61.8583	0.093031
380	6.33333	23.47	0.025	63.55401	0.1073
440	7.33333	23.73	0.032	65.36585	0.120542
500	8.33333	23.80	0.035	65.85366	0.13589
560	9.33333	23.89	0.019	66.50407	0.1506
620	10.3333	24.04	0.012	67.52613	0.16403
680	11.3333	24.19	0.027	68.5482	0.177032
730	12.1667	24.27	0.015	69.15215	0.188273

Table D.5: Experimental data (Replication-1) of water absorption of seeds at 30°C

t (min)	**t** (h)	**W** (g)	**M(t)** (%db)	**t/M(t)-Mo** (h/%mc db)
0	0	15	4.529617	_
5	0.08333	17.9	24.73868	0.004124
10	0.16667	18.76	30.73171	0.006361
20	0.33333	19.42	35.33101	0.010822
40	0.66667	20.58	43.41463	0.017145
60	1	21.21	47.80488	0.023108
100	1.66667	22.38	55.95819	0.032407
140	2.33333	22.96	60.00000	0.042064
200	3.33333	23.45	63.41463	0.056607
260	4.33333	23.78	65.71429	0.070824
320	5.33333	24.37	69.82578	0.081679
380	6.33333	24.23	68.85017	0.098465
440	7.33333	24.29	69.26829	0.113276
500	8.33333	24.41	70.10453	0.127081
560	9.33333	24.44	70.31359	0.141879
620	10.3333	24.57	71.21951	0.154946
680	11.3333	24.58	71.28920	0.169763

Table D.6: Experimental data (Replication-2) of water absorption of seeds at 30°C

t (min)	**t** (h)	**W** (g)	**M(t)** (%db)	**t/M(t)-Mo** (h/%mc db)
0	0	15	4.529617	_
5	0.08333	18.09	26.06272	0.003870
10	0.16667	18.65	29.96516	0.006553
20	0.33333	19.42	35.33101	0.010822
40	0.66667	20.42	42.29965	0.017651
60	1	21.1	47.03833	0.023525
100	1.66667	22.44	56.37631	0.032146
140	2.33333	23.08	60.83624	0.041440
200	3.33333	23.6	64.45993	0.055620
260	4.33333	23.81	65.92334	0.070583
320	5.33333	24.02	67.38676	0.084848
380	6.33333	24.11	68.01394	0.099762
440	7.33333	24.36	69.75610	0.112429
500	8.33333	24.45	70.38328	0.126543
560	9.33333	24.47	70.52265	0.141429
620	10.3333	24.31	69.40767	0.159273
680	11.3333	24.53	70.94077	0.170654

Table D.7: Experimental data (Replication-3) of water absorption of seeds at 30°C

t (min)	**t** (h)	**W** (g)	**M(t)** (%db)	**t/M(t)-Mo** (h/%mc db)
0	0	15	4.529617	_
5	0.08333	18.06	25.85366	0.003908
10	0.16667	18.61	29.68641	0.006625
20	0.33333	19.3	34.49477	0.011124
40	0.66667	20.41	42.22997	0.017683
60	1	21.18	47.59582	0.023220
100	1.66667	22.41	56.16725	0.032276
140	2.33333	23.02	60.41812	0.041750
200	3.33333	23.48	63.62369	0.056407
260	4.33333	23.76	65.57491	0.070986
320	5.33333	23.88	66.41115	0.086186
380	6.33333	23.98	67.10801	0.101206
440	7.33333	24.3	69.33798	0.113154
500	8.33333	24.42	70.17422	0.126946
560	9.33333	24.46	70.45296	0.141579
620	10.3333	24.55	71.08014	0.155271
680	11.3333	24.56	71.14983	0.170119

Table D.8: Experimental data (Average) of water absorption of seeds at 30°C

t (min)	**t** (h)	**W(ave)** (g)	**SE** of W(ave)	**M(t)** (%db)	**t/M(t)-Mo** (h/%mc db)
0	0	15.00	0.000	4.529617	_
5	0.08333	18.02	0.059	25.55168	0.003964
10	0.16667	18.67	0.045	30.12776	0.006511
20	0.33333	19.38	0.040	35.05226	0.010921
40	0.66667	20.47	0.055	42.64808	0.017489
60	1	21.16	0.033	47.47967	0.023283
100	1.66667	22.41	0.017	56.16725	0.032276
140	2.33333	23.02	0.035	60.41812	0.041750
200	3.33333	23.51	0.046	63.83275	0.056208
260	4.33333	23.78	0.015	65.73751	0.070797
320	5.33333	24.09	0.146	67.87456	0.084195
380	6.33333	24.11	0.072	67.99071	0.099799
440	7.33333	24.32	0.022	69.45412	0.112952
500	8.33333	24.43	0.012	70.22067	0.126856
560	9.33333	24.46	0.009	70.42973	0.141628
620	10.3333	24.48	0.084	70.56911	0.156472
680	11.3333	24.56	0.015	71.12660	0.170178

Table D.9: Experimental data (Replication-1) of water absorption of seeds at 40°C

t (min)	**t** (h)	**W** (g)	**M(t)** (%db)	**t/M(t)-Mo** (h/%mc db)
0	0	15	4.529617	_
5	0.08333	18.99	32.33449	0.002997
10	0.16667	19.46	35.60976	0.005362
20	0.33333	20.29	41.39373	0.009042
40	0.66667	21.5	49.82578	0.014718
60	1	22.51	56.86411	0.019108
100	1.66667	23.45	63.41463	0.028304
140	2.33333	24.04	67.52613	0.037039
200	3.33333	24.24	68.91986	0.051768
260	4.33333	24.49	70.66202	0.065525
320	5.33333	24.63	71.63763	0.079474
380	6.33333	24.61	71.49826	0.094572
440	7.33333	24.78	72.68293	0.107601
500	8.33333	24.92	73.65854	0.120548
560	9.33333	24.97	74.00697	0.134336
620	10.3333	25.03	74.42509	0.147840
680	11.3333	25.06	74.63415	0.161663

Table D.10: Experimental data (Replication-2) of water absorption of seeds at 40°C

t (min)	**T** (h)	**W** (g)	**M(t)** (%db)	**t/M(t)-Mo** (h/%mc db)
0	0	15	4.529617	_
5	0.08333	18.74	30.59233	0.003197
10	0.16667	19.18	33.65854	0.005722
20	0.33333	20.15	40.41812	0.009288
40	0.66667	21.54	50.10453	0.014628
60	1	22.37	55.88850	0.019471
100	1.66667	23.41	63.13589	0.028438
140	2.33333	23.97	67.03833	0.037328
200	3.33333	24.22	68.78049	0.051880
260	4.33333	24.42	70.17422	0.066012
320	5.33333	24.69	72.05575	0.078982
380	6.33333	24.73	72.33449	0.093405
440	7.33333	24.76	72.54355	0.107821
500	8.33333	24.85	73.17073	0.121404
560	9.33333	24.73	72.33449	0.137650
620	10.3333	25.05	74.56446	0.147546
680	11.3333	25.04	74.49477	0.161985

Table D.11: Experimental data (Replication-3) of water absorption of seeds at 40°C

t (min)	**t** (h)	**W** (g)	**M(t)** (%db)	**t/M(t)-Mo** (h/%mc db)
0	0	15	4.529617	_
5	0.08333	18.71	30.38328	0.003223
10	0.16667	19.33	34.70383	0.005523
20	0.33333	20.15	40.41812	0.009288
40	0.66667	21.58	50.38328	0.014539
60	1	22.5	56.79443	0.019133
100	1.66667	23.38	62.92683	0.028540
140	2.33333	23.96	66.96864	0.037370
200	3.33333	24.38	69.89547	0.050995
260	4.33333	24.52	70.87108	0.065319
320	5.33333	24.71	72.19512	0.078819
380	6.33333	24.76	72.54355	0.093118
440	7.33333	24.77	72.61324	0.107711
500	8.33333	24.9	73.51916	0.120791
560	9.33333	24.98	74.07666	0.134202
620	10.3333	25.08	74.77352	0.147106
680	11.3333	25.09	74.84321	0.161183

Table D.12: Experimental data (Average) of water absorption of seeds at 40°C

t (min)	**t** (h)	**W(ave)** (g)	**SE** of W(ave)	**M(t)** (%db)	**t/M(t)-Mo** (h/%mc db)
0	0	15.00	0.000	4.529617	_
5	0.08333	18.81	0.089	31.10337	0.003136
10	0.16667	19.32	0.081	34.65738	0.005532
20	0.33333	20.20	0.047	40.74332	0.009205
40	0.66667	21.54	0.023	50.10453	0.014628
60	1	22.46	0.045	56.51568	0.019236
100	1.66667	23.41	0.020	63.15912	0.028427
140	2.33333	23.99	0.025	67.17770	0.037245
200	3.33333	24.28	0.050	69.19861	0.051545
260	4.33333	24.48	0.030	70.56911	0.065617
320	5.33333	24.68	0.024	71.96283	0.079091
380	6.33333	24.70	0.046	72.12544	0.093694
440	7.33333	24.77	0.006	72.61324	0.107711
500	8.33333	24.89	0.021	73.44948	0.120913
560	9.33333	24.89	0.082	73.47271	0.135377
620	10.3333	25.05	0.015	74.58769	0.147497
680	11.3333	25.06	0.015	74.65738	0.161610

Table D.13: Data sets of the Peleg constants obtained by linear regression of data given in Tables D.1-D.12

Temperature	**Replicate**	$\mathbf{k_1}$ (h/%mc db)	$\mathbf{k_2}$ (%mc db)$^{-1}$
20°C	I	0.0111	0.0149
	II	0.0117	0.0148
	III	0.0119	0.0148
30°C	I	0.0066	0.0145
	II	0.0064	0.0146
	III	0.0069	0.0145
40°C	I	0.0045	0.014
	II	0.0045	0.014
	III	0.0045	0.0139

Table D.14: Experimental data of sieve analysis for sesame hulls

Size (mm)	**Cumulative% smaller than stated size**
0	0
0.212	1.314
0.425	10.657
0.85	79.416
1	99.451

Table D.15: Experimental data for the effect of moisture content and dehuller speed on dehulled seed percentage

DEHULLER SPEED	**Replication**	**MOISTURE CONTENT**		
		30.5% (d.b.)	**50.4% (d.b.)**	**70.7% (d.b.)**
420rpm	**I**	41.454	50.015	60.739
	II	39.234	43.339	57.218
	III	37.320	46.068	53.569
	Ave	39.336	46.474	57.175
	SE	0.975	1.582	1.690
		39.3±0.98	**46.5±1.58**	**57.2±1.69**
840rpm	**I**	46.225	56.065	60.000
	II	44.666	53.820	63.978
	III	42.771	54.517	59.756
	Ave	44.554	54.801	61.225
	SE	0.815	0.542	1.101
		44.6±0.82	**54.8±0.54**	**61.2±1.10**
1150rpm	**I**	43.666	46.064	57.892
	II	34.542	42.337	61.148
	III	39.919	48.818	59.576
	Ave	39.376	45.740	59.539
	SE	2.160	1.530	0.768
		39.4±2.16	**45.7±1.53**	**59.5±0.77**

Table D.16: Experimental data of dehulling efficiency for 30.5 % db moistened seeds

No. of pass	Replicate	% dehulled	% unhulled	% damaged
1	**I**	46.225	53.158	0.617
	II	44.666	55.059	0.275
	III	42.771	56.813	0.416
	Ave	44.554	55.010	0.436
	SD	1.412	1.493	0.140
	SE	0.815	0.862	0.081
		44.6±0.82	**55.0±0.86**	**0.44±0.081**
2	**I**	51.752	46.900	1.348
	II	51.744	46.512	1.744
	III	55.894	41.825	2.281
	Ave	53.130	45.079	1.791
	SD	1.954	2.306	0.382
	SE	1.128	1.331	0.221
		53.1±1.13	**45.1±1.33**	**1.79±0.221**
3	**I**	71.538	23.847	4.615
	II	68.384	28.103	3.513
	III	70.288	26.517	3.195
	Ave	70.070	26.156	3.774
	SD	1.297	1.756	0.608
	SE	0.749	1.014	0.351
		70.1±0.75	**26.2±1.01**	**3.8±0.35**
4	**I**	72.539	20.725	6.736
	II	73.034	19.805	7.161
	III	77.340	15.763	6.897
	Ave	74.304	18.764	9.910
	SD	2.156	2.155	0.175
	SE	1.245	1.244	0.101
		74.3±1.25	**18.8±1.24**	**6.93±0.101**
5	**I**	73.256	19.847	6.897
	II	79.310	15.518	5.172
	III	77.966	15.678	6.356
	Ave	76.844	17.014	6.142
	SD	2.596	2.004	0.720
	SE	1.499	1.157	0.416
		76.8±1.50	**17.0±1.16**	**6.14±0.416**

Table D.17: Experimental data of dehulling efficiency for 50.4 % db moistened seeds

No. of pass	Replicate	% dehulled	% unhulled	% damaged
1	**I**	56.065	42.997	0.938
	II	53.820	45.060	1.120
	III	54.517	43.608	1.875
	ave	54.801	43.888	1.311
	SD	0.938	0.865	0.406
	SE	0.542	0.499	0.234
		54.8±0.54	**43.9±0.50**	**1.31±0.234**
2	**I**	64.444	32.222	3.334
	II	65.815	31.310	2.875
	III	62.456	36.140	1.404
	ave	64.238	33.224	2.538
	SD	1.379	2.095	0.823
	SE	0.796	1.210	0.475
		64.2±0.80	**33.2±1.21**	**2.5±0.48**
3	**I**	75.661	19.048	5.291
	II	70.037	26.592	3.337
	III	72.222	25.185	2.593
	ave	72.640	23.608	3.740
	SD	2.315	3.275	1.138
	SE	1.337	1.891	0.657
		72.6±1.34	**23.6±1.89**	**3.7±0.66**
4	**I**	76.344	18.280	5.376
	II	80.098	13.514	6.388
	III	81.081	12.500	6.419
	ave	79.174	14.765	6.061
	SD	2.041	2.520	0.485
	SE	1.178	1.455	0.280
		79.2±1.18	**14.8±1.46**	**6.06±0.280**
5	**I**	83.014	10.672	6.314
	II	81.260	11.228	7.512
	III	83.617	9.165	7.218
	ave	82.630	10.355	7.015
	SD	0.999	0.872	0.510
	SE	0.577	0.503	0.294
		82.6±0.58	**10.4±0.50**	**7.02±0.294**

Table D.18: Experimental data of dehulling efficiency for 70.7 % db moistened seeds

No. of pass	**Replicate**	**% dehulled**	**% unhulled**	**% damaged**
1	**I**	60.000	38.378	1.622
	II	63.918	35.567	0.515
	III	59.756	39.627	0.617
	ave	61.225	37.857	0.918
	SD	1.907	1.698	0.500
	SE	1.101	0.980	0.289
		61.2±1.10	**37.9±0.98**	**0.92±0.289**
2	**I**	82.805	13.575	3.620
	II	86.047	11.047	2.906
	III	85.075	12.935	1.990
	ave	84.642	12.519	2.839
	SD	1.358	1.073	0.667
	SE	0.784	0.619	0.385
		84.6±0.78	**12.5±0.62**	**2.84±0.385**
3	**I**	89.958	6.276	3.766
	II	92.169	2.409	5.422
	III	93.574	2.410	4.016
	ave	91.900	3.698	4.401
	SD	1.488	1.823	0.729
	SE	0.859	1.053	0.421
		91.9±0.86	**3.7±1.05**	**4.4±0.42**
4	**I**	92.708	2.084	5.208
	II	91.469	3.318	5.213
	III	93.378	1.289	5.333
	ave	92.518	2.230	5.251
	SD	0.791	0.835	0.058
	SE	0.457	0.482	0.033
		92.5±0.46	**2.2±0.48**	**5.25±0.033**

Table D.19: Experimental data of dehulling efficiency for 0.1 % Peelzyme-I solution soaked seeds

No. of pass	**Replicate**	**% dehulled**	**% unhulled**	**% damaged**
1	**I**	43.353	56.535	0.112
	II	51.754	51.846	0.092
	III	44.014	55.878	0.108
	ave	46.374	54.753	0.104
	SD	3.814	2.073	0.009
	SE	2.202	1.197	0.0052
		46.4±2.20	**54.8±1.20**	**0.104±0.0052**
2	**I**	63.032	36.525	0.443
	II	58.824	40.138	1.038
	III	63.170	36.049	0.781
	ave	61.675	37.572	0.754
	SD	2.017	1.826	0.244
	SE	1.165	1.054	0.141
		61.7±1.17	**37.6±1.05**	**0.75±0.141**
3	**I**	76.116	20.424	3.459
	II	73.623	25.115	1.262
	III	76.680	22.134	1.186
	ave	75.473	22.558	1.969
	SD	1.328	1.938	1.054
	SE	0.767	1.119	0.609
		75.5±0.77	**22.6±1.12**	**2.0±0.61**
4	**I**	84.833	12.211	2.956
	II	87.273	8.181	4.546
	III	82.661	13.307	4.032
	ave	84.922	11.233	3.845
	SD	1.884	2.204	0.663
	SE	1.088	1.273	0.383
		84.9±1.09	**11.2±1.27**	**3.9±0.38**

Table D.20: Experimental data of dehulling efficiency for 0.2 % Peelzyme-I solution soaked seeds

No. of pass	**Replicate**	**% dehulled**	**% unhulled**	**% damaged**
1	**I**	61.415	38.414	0.171
	II	61.395	38.453	0.152
	III	62.312	37.520	0.168
	Ave	61.707	38.129	0.164
	SD	0.428	0.431	0.008
	SE	0.247	0.249	0.005
		61.71±0.247	**38.13±0.249**	**0.164±0.0048**
2	**I**	87.760	11.971	0.269
	II	88.613	10.104	1.283
	III	88.816	9.210	1.974
	Ave	88.396	10.428	1.175
	SD	0.458	1.150	0.700
	SE	0.264	0.664	0.404
		88.40±0.264	**10.4±0.66**	**1.2±0.40**
3	**I**	93.787	1.641	4.572
	II	94.643	1.786	3.571
	III	93.007	1.748	5.245
	Ave	93.812	1.725	4.463
	SD	0.668	0.061	0.688
	SE	0.386	0.035	0.397
		93.8±0.39	**1.73±0.035**	**4.5±0.40**
4	**I**	95.071	0.133	4.796
	II	94.948	0.155	4.897
	III	95.011	0.162	4.827
	Ave	95.010	0.150	4.840
	SD	0.0500	0.0124	0.0424
	SE	0.0290	0.0071	0.0244
		95.010±0.0290	**0.150±0.0071**	**4.840±0.0244**