PROCESSING OF HIGH QUALITY MANGO CHIPS

A Thesis

by

YOLANDA NUNEZ GALLEGOS

Submitted to the Office of Graduate Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

May 2009

Major Subject: Biological and Agricultural Engineering

PROCESSING OF HIGH QUALITY MANGO CHIPS

A Thesis

by

YOLANDA NUNEZ GALLEGOS

Submitted to the Office of Graduate Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

Approved by:

Chair of Committee,	Rosana Moreira
Committee Members,	Elena Castell-Perez
	Luis Cisneros-Zevallos
Head of Department,	Gerald Riskowski

May 2009

Major Subject: Biological and Agricultural Engineering

ABSTRACT

Processing of High Quality Mango Chips.

(May 2009)

Yolanda Nunez Gallegos, B.S., Universidad Autonoma de Yucatan (UADY)

Chair of Advisory Committee: Dr. Rosana Moreira

Potato chips are very popular in the United States. Recently, an enormous interest in developing snacks from fruits and vegetables with high quality has been assessed. Mango, due to its characteristic flavor and nutritional value, is excellent for snack production. Osmotic dehydration (OD) as a pre-treatment and vacuum frying (1.33 kPa) processes were proposed to obtain high quality mango chips.

Mango 'Tommy Atkins' slices were pre-treated with different OD concentrations (40, 50, and 65w/v), times (45, 60, and 70 min), and temperatures (22, 40, and 57^{o}C). Physical and chemical properties (a_w, pH, ^{o}Brix, sugar gain, water loss, and shrinkage) after OD were studied. The pre-treated slices were vacuum fried (1.33 kPa) at 120, 130, and 138^{o}C and product quality attributes (PQA) (oil content, texture, porosity, color, microstructure, and carotenoid content) were determined. Microstructure of the chips was analyzed using an environmental scanning electron microscope. Effect of frying temperatures at optimum OD (65 w/v at 40^{o}C) times was tested. The consumer tests showed that samples were all acceptable. The best mango chips process was the one with 65 w/v concentration for 60 min (pre-treatment) and vacuum frying at 120^{o}C.

Kinetic studies on oil content, texture, porosity, color, and carotenoid retention were performed. Oil absorption was modeled by a fractional conversion kinetic model. Absorption rate constant increased with frying temperature. Diameter changes in the chips, although not significant ($P>0.05$), followed an initial expansion to later decrease. Thickness of the slices increased (puffed) (around 60%) with time for all frying temperatures. Texture changes were for two frying periods: (1) water removal and crust formation and (2) slices became tougher and crispier and the end of frying. Porosity in the samples increased with frying, and a fractional conversion best described this phenomenon. Color $*a$ (redness) increased with frying time and temperature and was modeled using a logistic model. Color $*b$ (yellowness) increased up to 30 s of frying and then decreased. Carotenoids degradation followed a first order model, with a significant ($P<0.05$) decrease with frying temperature. Mango chips fried under atmospheric fryer had less carotenoid retention (25%) than with a vacuum fryer.

DEDICATION

To my parents, Yolanda and Victor

Thank you for all your affection, support and strength.

Without you would not be possible to be the person I am.

I am really grateful to have you, and

I will keep trying every day to be a better daughter for you.

I love you and admire you.

ACKNOWLEDGEMENTS

I would like to thank Dr. Moreira, Dr. Castell, and Dr. Cisneros for being members of my committee, especially Dr. Moreira, my major advisor and my friend, for all her advice and strength that made me a better professional and a stronger person. Also, thank you to Dr. Castell, who advised me in difficult moments in my life and gave me calm when I needed. Paulo Da Silva and Carmen Gomes, thank you for all your help and patience at the lab. Thanks to all my friends in the department: Lisa, Georgia, Carla, Akilesh, Isin, Ezekiel, and Kim.

Thanks to the Biological and Agricultural Engineering Department (Texas A&M University) for providing equipments and office space to achieve my work.

I would like to thank my brothers Pablo and Victor for all their advice and for being there for me. To my boyfriend Fernando, thank you for your love and for always guiding me and helping me in difficult moments. My very special thanks to Ana Cardenas for being a sister to me and an excellent friend and for making me laugh in difficult moments.

TABLE OF CONTENTS

Page

ABSTRACT iii

DEDICATION v

ACKNOWLEDGEMENTS vi

TABLE OF CONTENTS vii

LIST OF FIGURES xi

LIST OF TABLES xvii

CHAPTER

I INTRODUCTION 1

II LITERATURE REVIEW 4

2.1 Osmotic dehydration 4
2.1.1. Background 4
2.1.2. Fruit: syrup ratio 7
2.2 Vacuum frying 8
2.3 Product quality properties 9
2.3.1. Water activity 9
2.3.2. pH 11
2.3.3. Degree of shrinkage and expansion 12
2.3.4. Bulk and true density 13
2.3.5. Oil content 15
2.3.6. Color 17
2.3.7. Texture 19
2.3.8. Carotenoid 21

CHAPTER Page

III MATERIALS AND METHODS 23

3.1 Selection and preparation 23
3.1.1. Mango chemical composition 23
3.1.1.1. Mango variety 24
3.1.2. Raw mango selection 26
3.1.3. Raw mango preparation 27
3.1.4. Osmotic solution preparation 27
3.1.5. Fruit: syrup ratio 27
3.2 Raw mango physicochemical properties 28
3.2.1. Moisture content 28
3.2.2. Water activity 28
3.2.3. pH 28
3.2.4. Degree brix 29
3.2.5. Color 29
3.3 Osmotic dehydration 29
3.3.1. Coding 32
3.3.2. Sugar uptake and water loss 32
3.3.3. Degree of shrinkage 33
3.4 Vacuum frying 34
3.4.1. De-oiling process 35
3.5 Product quality attributes 36
3.5.1. Moisture content 36
3.5.2. Shrinkage and expansion 36
3.5.3. Bulk density 37
3.5.4. True density 37
3.5.5. Porosity 38
3.5.6. Oil content 38
3.5.7. Color 39
3.5.8. Texture 39
3.5.9. Total carotenoids content 39
3.6 Sensory analysis 41
3.7 Mango microstructure 42
3.8 Statistical analysis 42

IV EFFECT OF OPERATING CONDITIONS ON MANGO SLICES DURING OSMOTIC DEHYDRATION AND VACUUM FRYING . 43

4.1 Preliminary data for osmotic dehydration 43
4.1.1. Effect of temperature during osmotic dehydration on oil content in mango chips 43

CHAPTER Page

4.1.2. Effect of fruit/syrup ratio on the water loss and sugar gain in mango chips 47
4.2 Effect of osmotic dehydration on mango chemical properties 49
4.2.1. Moisture content 49
4.2.2. Water activity 54
4.2.3. pH 54
4.2.4. Degree Brix 54
4.3 Effect of osmotic dehydration on the water loss and and sugar gain 57
4.3.1. Water loss 57
4.3.2. Sugar uptake 61
4.3.3. Dehydration efficiency index 64
4.4 Effect of osmotic dehydration and vacuum frying on mango chips product quality attributes (PQA) 66
4.4.1. Shrinkage 66
4.4.1.1. Shrinkage during osmotic dehydration 66
4.4.1.2. Shrinkage during vacuum frying 76
4.4.2. Texture 71
4.4.3. Oil content 75
4.4.4. Color 78
4.5 Pre-treatment selection 85
4.6 Effect of de-oiling process on the oil content in mango chips 91
4.7 Effect of frying temperature on the mango chips product quality attributes (PQA) 92
4.7.1. Moisture and oil content 92
4.7.2. Shrinkage 97
4.7.3. Texture 100
4.7.4. Color 104
4.7.5. Sensory evaluation 108
4.7.6. Effect of osmotic dehydration and vacuum frying in mango microstructure 111

V KINETIC STUDIES OF PRE-TREATED VACUUM FRIED MANGO CHIPS 117

5.1 Effect of vacuum frying temperature and frying time on moisture content in pre-treated mango chips 117
5.2 Effect of oil temperature and frying time on the oil content of pre-treated mango chips 122

CHAPTER Page

5.3 Effect of oil temperature and frying time on the diameter and thickness changes of pre-treated mango chips 127
5.3.1. Diameter changes 127
5.3.2. Thickness changes 131
5.4 Effect of oil temperature and frying time on the texture of pre-treated mango chips 133
5.5 Effect of oil temperature and frying time on the porosity of pre-treated mango chips 140
5.6 Effect of oil temperature and frying time on the color of pre-treated mango chips 145
5.7 Effect of oil temperature and frying time on the carotenoids (beta-carotene) degradation in mango chips 151

VI CONCLUSIONS 156

VII RECOMMENDATIONS FOR FURTHER STUDY 161

REFERENCES 162

APPENDIX A 174

APPENDIX B 175

VITA 181

LIST OF FIGURES

Page

Figure 3-1 Tommy Atkins mango size……..…..……. 25

Figure 3-2 Tommy Atkins mango boxes 26

Figure 3-3 Osmotic dehydration of mango slices..... 30

Figure 3-4 Flow chart for pre-treatment and vacuum frying of mango slices 31

Figure 3-5 Vacuum frying system set up 35

Figure 3-6 Standard curve for beta-carotenes (µg beta-carotenes/ml) 41

Figure 4-1 Oil content [w.b.] in mango chips pre-treated at different OD temperatures with solution concentration of 40, 50, and 65 w/v for 60 min (mango:syrup ratio = 1:4) and fried at 120^{o}C for 2 min without de-oiling 46

Figure 4-2 Sugar uptake and water loss for mango to syrup ratios of 1:4 and 1:10 in mango pre-treated with 65w/v OD concentration at 22^{o}C. 48

Figure 4-3 Moisture content (MC) of mango slices pre-treated (mango: syrup ratio = 1:4) with different osmotic solution concentrations and temperatures for 45 min then vacuum fried at 120^{o}C for 2 min. 51

Figure 4-4 Moisture content (MC) of mango slices pre-treated (mango: syrup ratio = 1:4) with different osmotic solution concentrations and temperatures for 60 min then vacuum fried at 120^{o}C for 2 min 52

Figure 4-5 Moisture content (MC) of mango slices pre-treated (mango:syrup ratio = 1:4) with different osmotic solution concentrations and temperatures for 70 min then vacuum fried at 120^{o}C for 2 min 53

Page

Figure 4-6 Water loss(W_L) in mango slices at different OD times, concentrations, and temperatures (mango: syrup = 1:4) 58

Figure 4-7 Sugar uptake (S_U) in mango slices at different OD times, concentrations, and temperatures (mango: syrup ratio = 1:4)..... 63

Figure 4-8 Water loss/sugar uptake (W_L/S_U) in mango slices at different OD times, concentrations and temperatures (mango: syrup ratio = 1:4)..... 65

Figure 4-9 Diameter degree of shrinkage [%] for mango slices after OD at different times, temperatures, and OS concentrations (mango: syrup ratio = 1:4)..... 68

Figure 4-10 Degree of shrinkage in diameter [%] for mango slices after OD at different times, temperatures, and OS concentrations (mango: syrup ratio = 1:4)..... 70

Figure 4-11 Maximum force (Peak) to compress 5 mango chips pre-treated with OD (mang: syrup ratio = 1:4) at different times, temperatures, and OS concentrations and vacuum fried at 120^{o}C for 2 min (P = 1.33 kPa, and de-oiled at 225 for 25 s)… 73

Figure 4-12 Work done (N*mm) to compress 5 mango chips pre-treated with OD (mango: syrup ratio = 1:4) at different times, temperatures, and OS concentrations and vacuum fried at 120^{o}C for 2 min (P = 1.33 kPa, and de-oiled at 225 for 25 s)… 74

Figure 4-13 Oil content [w.b.] in mango chips pre-treated with OD (mango: syrup ratio = 1:4) at different times, temperatures, and OS concentrations and vacuum frying at 120^{o}C for 2 min (P = 1.33 kPa, de-oiled at 225 rpm for 25 s)…..... 77

Figure 4-14 Color *L in mango chips pre-treated with OD (mango: syrup ratio = 1:4) at different times, temperatures, and OS concentrations and vacuum frying at 120^{o}C for 2 min (P = 1.33 kPa, de-oiled at 225 rpm for 25 s) 80

Figure 4-15 Color *a in mango chips pre-treated with OD (mango: syrup ratio = 1:4) at different times, temperatures, and OS concentrations, and vacuum frying at 120^{o}C for 2 min (P = 1.33 kPa, de-oiled at 225 rpm for 25 s) 83

Page

Figure 4-16 Color *b in mango chips pre-treated with OD (mango: syrup ratio = 1:4) at different times, temperatures, and OS concentrations and vacuum frying at 120°C for 2 min (P = 1.33 kPa, de-oiled at 225 rpm for 25 s) 84

Figure 4-17 *Dehydration efficiency index* (DEI = W_L/S_U) in mango slices at different OD (mango: syrup ratio = 1:4) times, concentrations, and temperatures..... 86

Figure 4-18 Comparison of pre-treatments for 50w/v and 65w/v OS concentration during 45 min at 22 and 40°C. Mango chips were vacuum (P = 1.33 kPa) fried at 120°C for 2 min (de-oiled at 225 rpm for 25 s) 88

Figure 4-19 Comparison of pre-treatments for 50w/v OS concentration during 60 and 70 min at 22 and 40°C. Mango chips were vacuum (P = 1.33 kPa) fried at 120°C for 2 min (de-oiled at 225 rpm for 25 s). 89

Figure 4-20 Comparison of pre-treatments for 65w/v OS concentration during 60 and 70 min at 22 and 40°C. Mango chips were vacuum (P = 1.33 kPa) fried at 120°C for 2 min (de-oiled at 225 rpm for 25 s). 90

Figure 4-21 Moisture content after vacuum (P = 1.33 kPa, de-oiled at 225 rpm for 25 s) frying at different frying temperatures and OD (mango: syrup ratio = 1:4) times (65 w/v at 40°C)…..... 95

Figure 4-22 Oil content after vacuum (P = 1.33 kPa, de-oiled at 225 rpm for 25 s) frying at different frying temperatures and OD (mango: syrup ratio = 1:4) times (65 w/v at 40°C)…..... 96

Figure 4-23 Degree of shrinkage in mango chips after vacuum frying (P = 1.33 kPa, de-oiled at 225 rpm for 25 s) at different frying temperatures and OD (mango: syrup ratio = 1:4) times (65 w/v at 40°C)… 99

Figure 4-24 Maximum force (Peak) to compress the mango chips after vacuum frying (P = 1.33 kPa, de-oiled at 225 rpm for 25 s) at different frying temperatures and OD (mango: syrup ratio = 1:4) times (65 w/v and 40°C) 102

Page

Figure 4-25 Work done to compress the mango chips after vacuum frying (P = 1.33 kPa, de-oiled at 225 rpm for 25 s) at different frying temperatures and OD (mango: syrup ratio = 1:4) times (65 w/v and 40^{o}C) 103

Figure 4-26 Color *a in mango chips after vacuum (P = 1.33 kPa, de-oiled at 225 rpm for 25 s) frying at different frying temperatures and OD (mango: syrup ratio = 1:4) times (65 w/v and 40^{o}C) 106

Figure 4-27 Color *b in mango chips after vacuum (P = 1.33 kPa, de-oiled at 225 rpm for 25 s) frying at different frying temperatures and OD (mango: syrup ratio = 1:4) times (65 w/v and 40^{o}C) 107

Figure 4-28 Comparison of mango chips pre-treated (mango: syrup ratio = 1:4) for 60 min and vacuum fried (P = 1.33 kPa, de-oiled at 225 rpm for 25 s) at 120, 130, and 138^{o}C 110

Figure 4-29 Environmental scanning electron photomicrographs of the cross section (I) and surface (II) of raw (A) and pre-treated (40 w/v OD concentration at 40^{o}C for 60 min) (B) mango slices. Slices were viewed at 15 kV 113

Figure 4-30 Environmental scanning electron photomicrographs of the cross section (I) and surface (II) of mango slices pre-treated (65 w/v OD concentration at 40^{o}C for 60 min) (C) and vacuum fried at 120^{o}C (1.33 kPa, de-oiled at 225 rpm for 25 s) (E). Slices were viewed at 15 kV 114

Figure 4-31 Environmental scanning electron photomicrographs of the cross section (I) and surface (II) of mango slices vacuum fried at 138^{o}C (1.33 kPa, de-oiled at 225 rpm for 25 s) (F) and traditionally fried at 165^{o}C for 2 min (G) . Slices were viewed at 15 kV 115

Figure 4-32 Mango chips pre-treated (65 w/v, 40^{o}C for 60 min) and fried under vacuum (P = 1.33 kPa, de-oiled at 225 rpm for 25 s) at (a) 120^{o}C and (b) 138^{o}C and (c) atmospheric frying (165^{o}C)…..... 116

Page

Figure 5-1 Drying rate on mango chips pre-treated with OD (65 w/v and 40^{o}C) for 60 min and fried under vacuum (P = 1.33 kPa, de-oiled at 225 rpm for 25 s) at different frying temperatures [120^{o} C, MC(t) = 2.715*exp(-0.07351*t) + 0.05482, R^2 = 0.98; 130^{o} C, MC(t)=2.801*exp(-0.0916*t) + 0.08195, R^2 = 0.98; 138^{o} C, MC(t)=2.796*exp(-0.09716*t) + 0.0596, R^2 = 0.98] 118

Figure 5-2 Effect of frying temperature on the diffusion coefficient (D_e) of mango slices pre-treated with OD (65w/v and 40^{o}C) for 60 min and fried under vacuum (P = 1.33 kPa) and de-oiled for 25 s at 225 rpm 121

Figure 5-3 Oil content (OC) of mango chips pre-treated with OD (65 w/v and 40^{o}C) for 60 min and fried under vacuum (P = 1.33 kPa, de-oiled at 225 rpm or 25 s) and de-oiled at 225 for 25 s at different frying temperatures. [120^{o} C, OC(t) =-0.3337*exp(-0.02017t) + 0.3048, R^2=0.93; 130^{o} C, OC(t)= -0.3343*exp(-0.02663t) + 0.3058, R^2 = 0.94; 138^{o} C, OC(t)= -0.02591 + 0.006592t – 1.239*10^{-5}t^2 – 3.54*10^{-7}t^3, R^2 = 0.96. 123

Figure 5-4 Oil absorption on mango chips pre-treated with OD (65 w/v and 40^{o}C) for 60 min and fried under vacuum (P = 1.33 kPa, de-oiled at 225 for 25 s) at different frying temperatures [120^{o} C, OR(t) = 1.293*exp(-0.02268*t), R^2= 0.93; 130^{o} C, OR(t) = 1.283*exp(-0.02631*t), R^2= 0.94; 138^{o} C, OR(t) = 2.042*exp(-0.03163*t), R^2= 0.95] 126

Figure 5-5 Diameter changes (DC) on mango chips pre-treated with OD (65 w/v and 40^{o}C) for 60 min and fried under vacuum (P = 1.33 kPa, de-oiled at 225 for 25 s) at different frying temperatures [120^{o}C, DC = 4.37* exp (0.001582*t), R^2 = 0.94; 130^{o}C, DC = 4.559 + 8.932x10^{-3}*t – 1.19x10^{-3}*t^2 + 2.646x10^{-5}*t^3, R^2 = 0.99; 138^{o}C, DC = 4.557 + 3.953x10^{-3}*t – 5.952x10^{-6}*t^2 + 1.736x10^{-6}*t^3, R^2 = 0.981] 129

Figure 5-6 Diameter changes (DC) on mango chips pre-treated with OD (65 w/v and 40^{o}C) for 60 min and fried under vacuum (P = 1.33 kPa, de-oiled at 225 rpm for 25 s) at different frying temperatures [120^{o} C, DC = 4.776*exp(-0.0005372*t), R^2 = 0.94; 130^{o} C, DC = 4.799*exp(-0.0006067*t), R^2 = 0.97; 138^{o}C, DC = 4.54*exp(-0.0001257*t), R^2 = 0.91] 130

Page

Figure 5-7 Thickness changes (TC) on mango chips pre-treated with OD (65 w/v and 40^{o}C) for 60 min and fried under vacuum (P = 1.33 kPa, de-oiled at 225 rpm for 25 s) at different frying temperatures [120^{o} C, TC = 0.2873 + 0.02534*t – 8.03x10^{-5}*t^{2} , R^2 = 0.97; 130^{o} C, TC = 0.8128 + 0.009172*t + 5.48x10^{-6}*t^{2}, R^2 =1; 138^{o}C, TC = 0.5334 + 0.02562*t – 0.00014*t^{2}, R^2 = 0.95] 132

Figure 5-8 Maximum force (peak (P)) to compress mango chips pre-treated with OD (65 w/v and 40^{o}C) for 60 min and fried under vacuum (P = 1.33 kPa, de-oiled at 225 rpm for 25 s) at different frying temperatures [120^{o} C, P= 48.99*exp(-0.1172*t), R^2 = 0.99; 130^{o} C, P = 43.49*exp(-0.0742*t), R^2 = 0.98; 138^{o}C, P = 43.9*exp(-0.103*t), R^2 = 0.98]. 136

Figure 5-9 Work required to compress mango chips pre-treated with OD (65 w/v and 40^{o}C) for 60 min and fried under vacuum (P = 1.33 kPa, de-oiled at 225 rpm for 25 s) at different frying temperatures [120^{o} C, W = 42.95*exp (-0.09124*t), R^2 = 0.96; 130^{o} C, W = 38.47*exp (-0.08331*t), R^2 = 0.99; 138^{o}C, W = 36.26*Exp (-0.1102*t), R^2 = 0.98]. 137

Figure 5-10 Maximum force (peak (P)) required to compress mango chips pre-treated with OD (65 w/v and 40^{o}C) for 60 min and fried under vacuum (P = 1.33 kPa, de-oiled at 225 rpm for 25 s) at different frying temperatures [120^{o} C, P = -27.1*exp(-0.0405*t) + 5.85, R^2 = 0.91; 130^{o} C, P = -16.97*exp(-0.0405*t) + 6.27, R^2 = 0.94; 138^{o}C, P = -23.32*exp(-0.0405*t) + 7.85, R^2 = 0.90] 138

Figure 5-11 Work required to compress mango chips pre-treated with OD (65 w/v and 40^{o}C) for 60 min and fried under vacuum (P = 1.33 kPa, de-oiled at 225 rpm for 25 s) at different frying temperatures [120^{o} C, W = -170*exp(-0.04*t) + 28.65, R^2 = 0.90; 130^{o} C, W = -93.93* exp(-0.04*t) + 29.09, R^2 = 0.96; 138^{o}C, W = -132.6*exp(-0.04*t) + 38, R^2 = 0.95]..... 139

Figure 5-12 Porosity (Por) change in mango chips pre-treated with OD (65 w/v and 40^{o}C) for 60 min and fried under vacuum (P = 1.33 kPa, de-oiled at 225 rpm for 25 s) at different frying temperatures [120^{o} C, Por = -0.8849*exp(-0.024*t) + 0.6087, R^2= 0.95; 130^{o} C, Por = -0.9098* exp(-0.02797*t) + 0.523, R^2= 0.91; 138^{o}C, Por= -0.6486* exp(-0.03904*t) + 0.503, R^2= 0.95]..... 143

Page

Figure 5-13 Porous ratio changes (PR) in mango chips pre-treated with OD (65 w/v and 40^{o}C) for 60 min and fried under vacuum (P = 1.33 kPa, de-oiled at 225 rpm for 25 s) at different frying temperatures [120^{o} C, PR = 1.475*exp(-0.02527*t), R^2 = 0.95; 130^{o} C, PR = 1.483*exp(-0.02899*t), R^2 = 0.92; 138^{o}C, PR = 1.663*exp(-0.03995*t), R^2 = 0.95]..... 144

Figure 5-14 Color *a in mango chips pre-treated with OD (65 w/v and 40^{o}C) for 60 min and fried under vacuum (P = 1.33 kPa, de-oiled at 225 rpm for 25 s) at different frying temperatures [120^{o} C, *a = 4 + 10.21/(1 + 0.7036*exp(-0.006469*t)), R^2 = 0.80; 130^{o} C, *a = 3 + 10.11/(1 + 0.4573*exp(-0.016*t)), R^2 = 0.84; 138^{o}C, *a = 4 + 12.52/(1 + 0.8618*exp(-0.0111*t)), R^2 = 0.88]..... 147

Figure 5-15 Color *b in mango chips (de-oiled fro 25 s at 225 rpm) pre-treated with OD (65 w/v and 40^{o}C) for 60 min and fried under vacuum (P = 1.33 kPa, de-oiled at 225 rpm for 25 s) at different frying temperatures. For 0< t < 20 s = [120^{o} C, *b = -7.339*exp(-0.053*t) + 69.79, R^2 = 0.88; 130^{o} C, *b = -5.832*exp(-1.112*t) + 66.94, R^2 = 1; 138^{o}C, *b = -6.172*exp(-0.8047*t) + 72.27, R^2 = 0.99]. For 30 < t < 140 s = [120^{o} C, *b = 13.16*exp(-0.006187*t) + 57, R^2 = 0.97; 130^{o} C, *b = 17.55*exp(-0.003421*t) + 51, R^2 = 0.83], and for 30 < t < 105 s , 138^{o}C [*b = 28.61*exp(-0.01055*t) + 50, R^2 = 0.92]..... 150

Figure 5-16 Beta-carotenes (C) in mango chips pre-treated with OD (65 w/v and 40^{o}C) for 60 min and fried under vacuum (P = 1.33 kPa, de-oiled at 225 rpm for 25 s) at different frying temperatures. [120^{o} C, C = 46.37*exp(-0.004367*t) + 6.651, R^2 = 0.94; 130^{o} C, C = 19.1* exp(-0.02117*t) + 30.72, R^2 = 0.94; 138^{o}C, C = 22.31*exp(-0.0449*t) + 28.92, R^2 = 0.99]..... 154

Figure 5-17 Effect of frying temperature on the rate constant k for carotenoid degradation in mango chips pre-treated (OD concentration 65 w/v at 40^{o}C for 60 min) and fried under vacuum (P = 1.33 kPa, de-oiled at 225 rpm for 25 s)..... 155

LIST OF TABLES

Page

Table 2-1 Water activity ranges of some fruits……. 10

Table 3-1 Raw mango (*Mangifera Indica L.*) nutritional composition in 100 g of edible portion…..……..…… 23

Table 3-2 Mango varieties and their physical characteristics mostly consumed in U.S……..…… 24

Table 4-1 Effect of osmotic dehydration temperatures and solution concentration on the final oil content of mango chips fried at 120^{o}C for 2 min without de oiling……..……. 45

Table 4-2 Sugar uptake, water loss, ^{o}Brix, and moisture content (MC) in mango slices after osmotic dehydration (65 w/v at 22^{o} C) for different fruit to syrup ratios (1:4 and 1:10)……..… 47

Table 4-3 Moisture content after OD [w.b.] and after 2 minutes vacuum frying [w.b.] at 120^{o}C for mango slices pre-treated at different OD times, temperatures, and concentration…… 50

Table 4-4 Brix, a_w, and pH values before (B) and after (A) osmotic dehydration (OD) (Mango:syrup ratio = 1:4) for 45 min, for each concentration and temperature in the process……. 55

Table 4-5 Brix, a_w, and pH values before (B) and after (A) osmotic dehydration (OD) (Mango:syrup ratio = 1:4) for 60 min, for each concentration and temperature in the process…….. 56

Table 4-6 Brix, a_w, and pH values before (B) and after (A) osmotic dehydration (OD) (Mango:syrup ratio = 1:4) for 70 min, for each concentration and temperature in the process……. 56

Table 4-7 Water loss (W_L), sugar uptake (S_U) and water loss to sugar uptake ratio (W_L/ S_U) at different times, concentrations, and temperatures for the OD process (mango:syrup ratio = 4:1)……..……..……..…….. 59

Page

Table 4-8 Effect of time, solution concentration, and temperature during OD (mango: syrup ratio = 4:1) on mango diameter degree of shrinkage after vacuum frying at 120°C for 2 min (de-oiled at 225 rpm for 25 s)…..…….. 67

Table 4-9 Effect of time, solution concentration, and temperature during OD (mango:syrup ratio = 4:1) on mango chips texture (peak and work) after vacuum fried (de-oiled at 225 rpm for 25 s) at 120° C for 2 min…… 72

Table 4-10 Effects of OD (mango:syrup ratio = 4:1) time, temperature and solution concentration on the oil content (OC) in mango chips vacuum fried at 120° C for 2 min and de-oiled for 25 s at 225 rpm…… 76

Table 4-11 Effect of OD (mango:syrup ratio = 1:4) time, temperature and solution concentration on the parameter *L, *b, and *a in mango slices vacuum fried (P = 1.33kPa, de-oiled at 225 rpm for 25 s) at 120° C for 2 min.……..……..……... 79

Table 4-12 De-oiling process at different speeds (rpm) and time (s) for mango chips pre-treated with OD (mango:syrup ratio = 1:4) solution (65w/v at 40° C) during 60 min, and vacuum fried (P = 1.33 kPa) at 120°C for 2min…….…...…... 92

Table 4-13 Effect of OD (mango:syrup ratio = 4:1) pre-treatment times (65 w/v at 40°C) Moisture (MC) and vacuum frying (1.33 kPa, de-oiled at 225 rpm for 25 s) temperatures on moisture content and oil content in mango chips……..…..… 93

Table 4-14 Effect of vacuum frying (1.33 kPa, de-oiled at 225 rpm for 25 s) (VF) temperature on the shrinkage (diameter) of mango slices subjected to different OD (mango:syrup ratio = 4:1) times (65w/v at 40°C)…..…... 98

Table 4-15 Effect of vacuum frying (P =1.33kPa, de-oiled at 225 for 25 s) temperature on texture (force peak (N) and work (N*mm)) of the mango chips subjected to different OD (mango:syrup ratio = 1:4) times (65 w/v and 40°C)……..……..……... 101

Page

Table 4-16 Color *a and *b for mango chips pre-treated at different OD (mango:syrup ratio = 1:4) times (65 w/v and 40°C) and different vacuum frying (P = 1.33 kPa, de-oiled at 225 rpm for 25 s) temperatures 105

Table 4-17 Sensory analysis results for mango chips pre-treated (mango:syrup ratio = 1:4) during 45, 60, and 70 min and vacuum fried (P = 1.33 kPa, de-oiled at 225 rpm for 25 s) at three different temperatures..... 109

Table 5-1 Diffusion coefficients for mango chips pre-treated with OD (65 w/v and 40°C) for 60 min and fried under vacuum (1.33 kPa) at different temperatures..... 120

Table 5-2 Oil absorption rate constant (k) values (Eqn. 5-5) for mango chips pre-treated with OD (65 w/v and 40°C) for 60 min and fried under vacuum (P = 1.33 kPa, de-oiled at 225 for 25 s) at different temperatures..... 124

Table 5-3 Texture kinetic coefficients (P_o, W_o, and k) values for the first period ($0< t <40$ s) for mango chips pre-treated with OD (65 w/v and 40°C) for 60 min and fried under vacuum (P = 1.33 kPa, de-oiled at 225 for 25 s) at different temperatures..... 134

Table 5-4 Texture kinetic coefficients (P_o, W_o, P_e, W_e, and k) values for the second period ($40< t <140$ s) for mango chips pre-treated with OD (65 w/v and 40°C) for 60 min and fried under vacuum (P = 1.33 kPa, de-oiled at 225 for 25 s) at different temperatures..... 135

Table 5-5 Porous formation rate constant (k) values (Eqn. 5-6) for mango chips pre-treated with OD (65 w/v and 40°C) for 60 min and fried under vacuum (P = 1.33 kPa, de-oiled at 225 rpm for 25 s) at different temperatures..... 142

Table 5-6 Color *a coefficients (A_o, A, and k) values (Eqn. 5-11) for mango chips pre-treated with OD (65 w/v and 40°C, mango:syrup ratio = 1:4) for 60 min and fried under vacuum (P = 1.33 kPa, de-oiled at 225 rpm for 25 s) at different temperatures..... 146

Page

Table 5-7 Color *b coefficients (B_o, B_e, and k) values for the first period (0< t <20 s) for mango chips pre-treated with OD (65 w/v and 40^{o}C, mango:syrup ratio = 1:4) for 60 min and fried under vacuum (P = 1.33 kPa, de-oiled at 225 rpm for 25 s) at different temperatures…..……..…. 149

Table 5-8 Color *b coefficients (B_o, B_e, and k) values for the second period (30< t <140 s) for mango chips pre-treated with OD (65 w/v and 40^{o}C, mango:syrup ratio = 1:4) for 60 min and fried under vacuum (P = 1.33 kPa, de-oiled at 225 rpm for 25 s) at different temperatures……..... 149

Table 5-9 Carotenoid degradation coefficients (C_o, C_e, and k) values for the second for mango chips pre-treated with OD (65 w/v and 40^{o}C, mango:syrup ratio = 1:4) for 60 min and fried under vacuum (P = 1.33 kPa, de-oiled at 225 rpm for 25 s) at different temperatures..……..... 153

CHAPTER I

INTRODUCTION

Potato chips are very popular in the United States. They represent 33% of the total sales of snacks in the US Market (Garayo & Moreira, 2002). Recently, tremendous interest in the development of snacks from fruits like pineapple (Reynes *et al*, 1997) and apple (Shyu & Hwang, 2001) has grown due to their high level of phytochemicals and minerals contents. Another very popular fruit for snack production is mango (*Mangifera indica*. L), a worldwide accepted tropical fruit due to its bright color, characteristic taste, and nutritional value. Mango imports to the United States and Europe have grown steadily in response to increased demand and affordable prices. In the US alone, this fruit experienced a 40% increase in importation between 1996 and 2004 (Saúco, 2004).

To achieve good quality potato chip, in terms of good texture and sensory characteristics, it is essential to reduce its final oil content. High oil content is a major factor affecting consumer acceptance of deep-fat fried products (Bunger *et al*, 2003). Numerous studies have revealed that excessive consumption of fat is a key dietary contributor to coronary heart disease and perhaps cancer of the breast, colon, and prostate (Browner *et al*, 1991). To minimize oil absorption in snack foods, several pretreatments are used to partially dehydrate the raw material before frying.

Osmotic dehydration, for instance, has been used to reduce the initial moisture content, conserve, and retain the initial quality of processed fruits and vegetables (Heng *et al*, 1990; Torregiani & Bertolo, 2001a). During osmotic processing, water flows from

---

This thesis follows the style and format of the *Journal of Food Engineering*.

the product into the concentrated osmotic solution, while small amounts of the osmotic solute is transferred from the solution into the product (Dermesonlouoglou *et al*, 2007).

Vacuum frying technology is a process of deep-fat frying under reduced pressure [<60 Torrs ~ 8 kPa]. During vacuum frying, the boiling point of water in the food is decreased, thus minimizing the degradation of product quality attributes (Garayo & Moreira, 2002). Since the food is heated at lower temperature and oxygen content, the natural color and flavor of the fruits and vegetables can be better preserved than in the conventional deep-fat frying processes (Hidaka *et al*, 1991; Kato & Sato, 1991).

In addition to produce high quality fruit chips, a pre-treatment is needed to provide enough texture (firm structure) in the fruit slices before they can be ready for frying. Atmospheric frying, alone, cannot be used to fry fruits (Da Silva & Moreira, 2008) because the product's texture and color completely deteriorate, resulting in the collapse of the product's structure and over cooked appearance (dark color). Because of the high sugar content of the product after osmotic dehydration, vacuum frying is the only technology acceptable to produce high quality deep-fat fried fruit chips.

The general objective of this study was to develop an optimum process for reduced oil content and high product quality characteristics (shrinkage and expansion, texture, color, and beta-carotene) of "Tommy Atkins" mango chips using osmotic dehydration as pre-treatment and vacuum frying processing.

The main objective was accomplished by carrying out the following specific objectives:

- To evaluate the best osmotic dehydration pre-treatment of mango chips at different temperatures, times, and solute concentrations; and
- To determine the kinetic changes in for oil absorption, moisture loss, shrinkage and expansion, porosity, texture, and beta-carotene (total carotenoids) changes at different frying temperatures during the vacuum frying process.

CHAPTER II

LITERATURE REVIEW

Deep-fat frying of foods is usually performed at high temperatures (about 180^{o}C) and atmospheric pressure. It is one of the most common unit operations worldwide that uses hot oil to give a characteristic flavor and texture to the food. The frying technology involves different sectors of the food industry, including supplier of oils and ingredients, fast-food restaurants, food processors, and manufacturers of frying equipment (Moreira *et al*., 1999). During the past 10 years, the American Heart Association and the World Health Organization have encouraged the reduction of consumptions of fats in foods to less than 30% of calories for the general population (USDA, 1990; USDA & USDHHS, 1990). Therefore, pre-treatments to reduce oil content and retain product quality together with vacuum frying technology can be used to address this concern.

2.1 Osmotic dehydration

2.1.1. Background

There is a high demand for high-quality processed fruits with preserved natural flavor, color, and texture (Torreggiani & Bertolo, 2001a,b). Osmotic dehydration (OD) is a technique used to remove water from fruits and vegetables by placing the solid food, whole or in pieces, in sugar or salt aqueous solutions of high osmotic pressure. During this process, water flows out of the food into the solution and the solute from the solution is transferred into the product due to the water and solute activity gradients across the cell's membrane. These coexisting flows can modify the chemical properties,

the sensory properties, and physical properties of the food, such as water content, water activity, flavor, and texture (Torreggiani, 1993). Usually, osmotic dehydration is not used for more than a 50% weight reduction because of the decrease in the dehydration rate with time. Water loss for fruits and vegetables mainly occurs during the first two hours and the maximum sugar uptake in thirty minutes (Conway *et al.*, 1983). A partial OD step is generally combined with other more aggressive drying technologies, including freezing, drying, and deep-fat frying to provide better final product quality characteristics (Torreggiani & Bertolo, 2001a; Lombard *et al.* 2008; Behsnilian & Speiss, 2006).

The rate of water loss in the product during OD increases with the temperature and the concentration in the osmotic solution (Lombard *et al*, 2008; Conway *et al*, 1983; Heng *et al*, 1990; and Behsnilian & Spiess, 2006). However, high temperature has a detrimental effect on tissue structure (Lazarides, 2001) and may cause enzymatic browning and flavor deterioration at temperatures above 45^{o}C; at higher temperatures, for example 60°C, the product's tissue is modified favoring impregnation phenomena and thus solid uptake (Farkas & Lazar, 1969; Heng *et al.*, 1990; Torreggiani, 1993). The best processing temperature depends on the fruit (Torreggiani, 1993).

The interest in osmotic treatments arises primarily from the need for quality improvement and from economic factors. Quality improvement is related not only to the water removal with minimal thermal stress but also to the impregnated solutes and the modification of the product's structure (Torreggiani & Bertolo, 2001b). Solutes, such as sucrose, glucose, fructose, corn syrup, and sodium chloride are often used for osmotic

dehydration (Azuara & Beristain, 2002). Low molar mass saccharides (glucose, fructose, and sucrose) facilitate the sugar uptake because of the high diffusion velocity of penetration of the molecules.

Lazarides, Katsanidis, & Nicholaidis (1995) studied the mass transfer kinetics during OD in apples aimed at minimal sugar uptake. Corn syrup solids of 18-32 DE (dextrose equivalents) offered a superior osmotic medium compared with corn syrup above 38 DE. They observed that the solid uptake rate of sugar penetration in the fruit was inversely related to the size of the sugar molecule. Shyu & Hwang (2001) studied the effects of processing conditions on the quality of vacuum fried apple chips. They found that by pre-treating apples with 30% fructose before frying resulted in a more uniform porosity was observed on the chips' surface.

The effect of OD on mass fluxes (water loss and sugar uptake) was investigated in mango (Giraldo *et al*, 2003) and pineapple (Lombard *et al*, 2008) using sucrose solution. Most of the water loss in the fruit was due by increasing sugar concentration (35-70^{o}Brix) and temperature (20-45^{o}C) in the solution.

Osmotic dehydration was applied as a pre-treatment of "Tommy Atkins" mangoes using commercial sucrose (Torezan *et al*, 2004) and maltodextrin (Da Silva & Moreira, 2008) for atmospheric and vacuum frying respectively. Da Silva & Moreira (2008) results showed that vacuum fried chips (blue and sweet potatoes, green beans, and "Tommy Atkins" mangoes) were highly accepted by a consumer sensory panel compared to the atmospheric fried chips.

2.1.2. Fruit: syrup ratio

Numerous studies have used different ratios for fruits and vegetables in the OD syrup solution. Torregianni (1993) recommended a ratio of 1 g of fruit or vegetable to 3-5 g of syrup (sugar or sugar+NaCl) for OD (small time period, 15 to 240 min) as a pre-treatment for further drying. Behsnilian & Spiess (2006) used a ratio of 1:20 w/w during OD (up to 20 hours) for apples, potatoes and carrots at 25 and 45^{o}C recommending immersion times no more than 4 h due to the slowing water loss pace.

Saputra (2001) used a pineapple to syrup (glucose and fructose at 50, 60 and 70% concentration) ratio of 1:10 w/v at different temperatures (30, 50 and 70^{o} C) during the OD process. Da Silva & Moreira (2008) used the same ratio of fruit and vegetable (blue and sweet potato, green beans, and mango) to syrup (maltodextrin) at 22^{o} C for OD as a pre-treatment for further vacuum frying process. Saputra (2001) and Da Silva & Moreira (2008) used the 1:10 syrup ratio, to avoid significant changes in sugar concentration in the solution during OD.

Madamba & Lopez (2002) optimized the process of OD in mango using sugar as the osmotic agent (40, 50 and 60% w/w) at 20, 30, and 40^{o} C. They used a mango: sugar ratio of 1:5 w/w finding the effect of time and thickness to be the most affecting OD variables.

Torezan, Campos-Favareto, Pallet, & Castle de Menezes (2004) combined OD with deep-fat frying for mango chips using a mango: sugar ratio of 1:4. Their results showed low oil content (22-17 % wet basis) and an acceptable sensory test for the chips.

2.2 Vacuum frying

In vacuum frying operations, food is heated under reduced pressure and minimal exposure to oxygen in a closed system thus lowering the boiling points of both the frying oil and the moisture in food. Vacuum frying has some advantages that include: (1) reduction of the oil content in the fried product, (2) preservation of natural color and flavors and (3) reduction of adverse effects on oil quality (Garayo & Moreira, 2002). Granda, Moreira, & Tichy (2004) also found that vacuum frying can diminish acrylamide (a carcinogen compound found in rats) formation in potato chips.

During the vacuum frying process, oil uptake is attributed to the surface region of the fried product and restricted to a depth of a few cells (Keller *et al*, 1986). Pre-frying treatments have shown to be effective in reducing the oil absorption by lowering the moisture content of the food prior to frying.

Garayo & Moreira (2002) studied the effects of vacuum frying on potato chips. They obtained lower oil content and better product quality attributes (color and texture) in potato chips compared with traditional fryer. Granda (2005) found a decreased by 94% decrease in acrylamide content in potato chips when using vacuum frying compared with the atmospheric fryer.

Vacuum frying has also been applied to process fruits. Several studies in product quality characteristics of carrot (Fan *et al*, 2005), apples (Shyu & Hwang, 2001), pineapples (Perez-Tinoco *et al*, 2008), blue and sweet potatoes, green beans, and mangoes (Da Silva & Moreira, 2008) have shown high quality (oil content, enhanced color, nutrients retention, and good texture) using vacuum frying.

2.3 Product quality properties

2.3.1 Water activity

Water activity (a_w) is an important factor that affects the stability of osmotic dehydrated products. It can be expressed as the ratio of the water vapor (W_{vp}) in any kind of food to the water vapor pressure (W_v) of pure water at specified temperature:

$$a_w = W_{vp} / W_v \qquad [2\text{-}1]$$

The water activity in fruits ranges between 0.89 and 0.92 (Moreno-Tinjaca, 2005). Controlling water activity in fruits (Table 2-1) helps to maintain proper structure, texture, stability, density and rehydration properties given that high values of water activity tend to increase non-enzymatic and enzymatic reactions, lipid oxidation, vitamins degradation and protein denaturation (Maltini *et al*, 2003).

Table 2-1 Water activity ranges of some fruits.

Fruits	Water Activity
Apples	0.988-0.975
Bananas	0.971-0.964
Cherries	0.986-0.959
Grapefruit	0.985-0.980
Lemons	0.989-0.982
Melons	0.991-0.970
Mangoes	0.986-0.978
Peaches	0.989-0.979
Pineapple	0.988-0.985
Strawberries	0.997-0.986

Source: Chirife & Fontan. (1982)

During OD, the migration of water from the product to the solution provokes a change in product's water activity depending completely on concentration and temperature in the OD solution (Gabriel, 2007) as well as on its structure. As a result, reducing a_w by using sugary solutions can slow down some unwanted chemical reactions.

Mujica-Paz, Valdez-Fragosa, Lopez-Malo, Palou, & Welti-Chanes (2003) observed at different syrup concentrations a reduction in the initial water activity in mango (0.2%), melon (0.2%), and apple (0.5%) by using impregnation and OD. Water activity in fruits and vegetables is generally measured using a hygrometer that measures relative humidity of the air in contact with food at given moisture content.

2.3.2. pH

The inactivation of the enzyme polyphenol oxidase is an important factor when fruits are processed using heat in terms of preserving their original color (Wang *et al*., 2007). Lower pH values decrease the enzymatic reactions taking place in a food product (Granda, 2005). Non-enzymatic browning is mainly an effect in fruit and vegetable processing, thus reducing pH also aids to diminish dark color in the product.

Fruits and vegetables favors non-enzymatic reactions, one of the major causes in quality and color changes during produce processing (Falade *et al.* 2004). The addition of citric acid helps to reduce enzymatic and non-ezymatic reactions by lowering the pH in the food process.

Jung, Choi, & Ju (2006) used citric acid to reduce the formation of acrylamide content in fried and baked corn chips and French fries. They found that by using 0.2% citric acid treatments induced 82.2% and 72.8% inhibition of acrylimide formation in fried and baked corn tortillas. French frieds acrylamide formation was reduced in 73.1-79% using 1-2% of citric acid.

Da Silva & Moreira (2008) used 0.15% citric acid in the 50w/w maltodextrin solution in sweet potatoes, green beans and "Tommy Atkins" mangoes to reduce pH and decrease discoloration.

When using citric acid in one of the sequences during their experiment, Tovar, Garcia & Mata (2001) observed no significant change in pH at 24^{o}C and 13^{o}C in mango treated with and without OD solutions, after being stored several days.

2.3.3. Degree of shrinkage and expansion

Shrinkage is usually expressed by the ratio between the volume of the sample before and after drying (Yan *et al*. 2007). It can affect the physical properties of materials such as density and porosity (Taiwo *et al*¸ 2007) as well as product appearance. Expansion is also considered a result of frying food stuffs. The effect of OD and vacuum frying in mango slices involve changes in the volume.

Numerous studies have been reported in relation to changes in shrinkage during OD of various fruits and vegetables; that is the case of pumpkins (Mayor *et al*, 2005), apples (Mavroudis *et al*, 1998), and mangoes (Giraldo *et al,* 2003).

Mayor, Moreira, Chenlo, & Sereno (2005) studied the shrinkage kinetics of pumpkin by OD with different sodium chloride solution concentrations and temperatures. Their results showed a simple Fick's second order diffusion model describing volume changes in the fruit.

Mavroudis, Gekas, & Sjoholm (1998) confirmed that the degree of shrinkage was strongly related to the amount of water loss during the OD process with 50 w/w sucrose solution. Giraldo, Talens, Fito, & Chiralt (2003) studied the influence of sucrose solution concentration on the kinetics during OD of mango (Kent variety) finding that fruit volume is highly (around 50% of the water can be removed) affected when concentration of the solution increases.

Taiwo & Baik (2007) found that sweet potato chips during frying experienced both shrinkage and expansion in radial direction and in thickness respectively. Baik and

Mittal (2005) found that frying at higher temperatures resulted in greater shrinkage at the same frying period.

Changes in diameter and thickness (shrinkage and expansion) before and after frying in tortilla chips (Kawas & Moreira, 2001) were measured using a steel caliper. They concluded that the greatest degree of shrinkage (9% in diameter) occurred during the first five seconds of frying in tortilla chips. No expansion changes were found for freeze-dried and steamed-baked tortilla chips, only for the control chips (tortillas prepared from nixtamalized dry mass flour) were experienced an increased in thickness expansion of 10% after the 30 s of frying.

2.3.4. Bulk and true density

Bulk density is the mass per unit bulk volume (kg/m^3), including air. Due to material irregularities, bulk density in food can be difficult to calculate by its own geometrical characteristics (Kawas-Escoto, 2000). Bulk density of irregular shaped samples can be determined using different techniques. It can be obtained by volumetric displacement of glass beads (Marousis & Saravacos, 1990), liquid displacement techniques with toluene (Costa *et al*, 2001) or by water-ethanol mixture displacement technique (Da Silva, Moreira, & Gomes, 2008).

Kawas-Escoto (2000) determined bulk density in tortilla chips using the volumetric displacement with toluene. She found the bulk density decreased from 880 to 580 kg/m^3 after 60 s of frying.

Caixeta, Moreira, & Castell-Perez (2002) studied the effects of superheated steam at different temperatures (115, 130 and 145^oC) and two levels of heat transfer

coefficient (100 and 160 W/m^2 ^oC) on the product quality attributes of impingement-dried potato chips. They showed the important effect of temperature and convective heat transfer coefficient in the bulk density of potato chips. Bulk volume was decreased about 70-80% as the drying proceeded. Bulk density was determined by the method of volume displacement with toluene used by Costa *et al* (2001). To measure bulk density an apparatus was filled with toluene and closed hermetically with a lid. The sample was weighed and the volume in the apparatus was recorded with and without the sample.

Solid or true density is the weight of the material per unit of solid volume (kg/m^3) (Kawas-Escoto, 2000). True density does not account for the air volume of all open and closed pores in the food material. It is usually measured with a pycnometer which uses gas displacement where the gas is capable of covering all the open pores up to the diameter of the gas (usually helium) molecule; the residue solid sample is considered the solid or true density.

Numerous studies agreed that there is a slightly increased change in solid density for tortilla chips during traditional frying (Kawas-Escoto, 2000). Potato chips subjected to superheated steam experience an increase in solid density (1500-1600 Kg/m^3) when water is evaporated during a drying process (Caixeta *et al*, 2002). Da Silva, Moreira, & Gomes (2008) found a not significant decrease in the solid density of vacuum-fried potato chips during the process.

2.3.5. Oil content

Oil content is one of the most important product quality attributes for fried foods. Ways to reduce oil absorption by keeping color and texture is a challenge in frying processing.

Gamble & Rice (1987) by visual observation found that oil uptake was due to the mechanism of fast water evaporation creating pores in the food resulting in areas were oil could take place in the chip. Moreira, Sun, & Chen (1997) observed that oil uptake is essentially a surface-related phenomenon resulting from the competition between drainage and suction into the porous crust once the fried potato is removed from the oil and begins to cool down. Based on the previous mechanisms many oil reduction techniques have been proposed and developed.

Several pre-treatments have been used to reduce oil content in chips. Krokiba, Oreopoulous, Maroulis, & Marinos-Kouris (2001a,b) used osmotic dehydration as a pre-treatment in French fries using different OD solutions prepared with sugar, NaCl, and maltodextrin 21 and 12 DE, to reduce oil content around 60%, 35%, 20% and 15% respectively. Tran, Chen, & Southern (2007) reduced about 30% in oil content in traditional fried potato crisps using OD as a pre-treatment and sugar as the OD solution.

Da Silva & Moreira (2008) observed that by using OD pre-treatment (maltodextrin) combined with vacuum frying technology it is possible to fry sweet potatoes and green beans with less oil (24% and 16%, respectively) and better quality than with traditional frying. Additionally, Shyu & Hwang (2001) used OD pre-treatment and vacuum frying to produce apple chips with less oil content. They found that the

amount of oil in the chips was strongly related to the OD solutions concentration (70% fructose) and frying temperature (100^{o}C) to produce chips with 16.91% oil.

Oil content has been determined in fried foods by using several methods, which can be classified as extraction, hydraulic press, refractometric method, and NIR spectroscopy (Moreira *et al*, 1999). The most recent methods used are the extraction methods. These methods consist of extracting the oil from the food material by using light petroleum or diethyl ether. There are two types of apparatus that achieve this process: the Bolton or Bailey Walker and the Soxhlet. The Soxhlet method provides a faster way of determining fat in foods (Granda, 2005; Moreira *et al*, 1999); which gives intermittent extraction by soaking the sample into the condensed solvent (generally petroleum ether) and finally evaporating the solvent to obtain clean oil from the sample. After the extraction the ether is recollected by the Soxhlet system.

The Soxhlet method has been used to determine oil content in potato chips (Edward *et al*, 1979; Garayo & Moreira, 2002; Granda, 2005; Bouchon & Pyle, 2004; Tran *et al* 2007), French fries (Krokiba *et al*, 2001a,b), tortilla chips (Kawas-Escoto, 2000), etc.

The Soxhlet method has been used in sweet and blue potatoes, green beans and mango chips (Da Silva & Moreira, 2008), apple chips (Shyu & Hwang, 2001), and carrot chips (Fan *et al*, 2005).

2.3.6. Color

Thermal treatments in fruit and vegetables sometimes carry negatives effects including non-enzymatic browning and nutrient loss. Non-enzymatic browning reactions mainly cause loss of color. Discoloration and browning due to thermal treatments are the result of several reactions. These include Maillard reactions caused by reducing sugars and amino acids, caramellization and ascorbic acid browning processes (Ibarz *et al*, 1999). A proper application of combined processes can be effective in decreasing color loss.

Frying temperature and thickness in fruits and vegetables can also affect the color of the chips. Using vacuum frying, which uses lower temperatures, can help to decrease this effect. Granda (2005) observed a relationship between *a** parameter (green-red) with the amount of acrylamide present in potato chips (White Rose var.). The author obtained lower values of *a** using vacuum frying than the traditional frying method (-2.718 and 0.309, respectively). Garayo & Moreira (2002) studied the influence of different pressures used during vacuum frying comparing with the traditional frying. In their work, **L* (lightness) was higher at a vacuum pressure of 3.115 kPa at 140^{o}C frying temperature than the atmospheric fryer. Parameter **a,* which is related to the Maillard reactions, was significantly higher during traditional frying than vacuum frying.

Fan, Zhang, & Mujumdar (2005) observed the effects of vacuum degree (95 kPa to 60 kPa) and temperature (60 to 100^{o}C) in carrots using vacuum frying. **L* decreased in all vacuum cases where temperature increased; **a* and **b* varied randomly due to the

interactions between chromoplast degradation and concentrated action during heating and drying.

Perez-Tinoco, Perez, Salgado-Cervantes, Reynes, & Vaillant (2008) studied the effect of vacuum frying on color (**L*, lightness; **H*, hue angle; and **C*, chroma) in pineapples. They showed that the color attributes (**L*, **H*, and *C) in pineapple tended to decrease with temperature and time.

Osmotic dehydration, in contrast, may act as a pre-treatment to reduce water content and preserve mango color and other sensory properties (Giraldo *et al*, 2003). Recently, Da Silva & Moreira (2008) used OD pre-treatment before frying green beans and mangoes to provide the product with better color and texture. They proved with blue potatoes, green beans and mangoes that by using vacuum frying than conventional frying, a significant difference in color (**L*, **a*, and **b*) can be obtained than using a conventional fryer. The Hue[^{o}] and Chroma value for traditional frying were (37, 13), (58, 41), (61, 10), and (72, 32) for blue and sweet potatoes, green beans and mangoes, respectively. In the case of vacuum frying Hue[^{o}] and Chroma were (31, 12), (62, 46), (84, 18), and (86, 44) for blue and sweet potatoes, green beans and mangoes, respectively.

Several methods can be used to determine color in chips. Chips have mainly been measured using a spectrocolorimeter, or by subjectives method as the Snack Food Association Potato Chip Color chart (chips are rated on a scale of 1-5, 1 being the lightest color). Video Image Analysis has also been used to measure color (Granda, 2005).

2.3.7. Texture

The most important quality attribute in chips to consumers is their texture (Granda, 2005). The distinctive texture of a chip depends on several factors, including type of raw material, thickness of the slices, pre-treatment technique, and frying temperature (Lisinska, 1989).

Texture of food products can be determined by two different ways: Instrumental analysis and sensory evaluation. Texture determination by instrumental examination is more accurate, simpler and less time consuming (Kayacier & Singh, 2003). The Instron and the Texture Analyzer (Texture Technologies Corp., New York) are usually used for force deformation studies (Kawas-Escoto, 2000).

There are two attributes measured to determine texture in chips, hardness and crispiness. Hardness is defined as the force at maximum compression during the first bite (also called fracturability), on the other hand; crispiness is the force with which a sample cracks, fractures or crumbles (also called brittleness) (Steffe, 1996; Kayacier & Sigh, 2003).

Several instrumental set ups have been developed and utilized for the determination of texture in chips due to their high variations. This high variation can be attributed to not uniform shape of the sample, and air bubbles in chips which can be considered weak points (Kayacier & Singh, 2003).

Kawas-Escoto (2000) studied the changes in tortilla chips during frying. The author measured fracturability (hardness) of the chips comparing baked tortilla (force peak of 1.26 N) with the fried tortilla (13.87 N). The author observed that fracturability

increased with frying time until a point where the parameter dropped substantially as they became crispier. A Texture analyzer compression test to find changes in tortilla chips was used. The sample was placed on a hollow cylinder and a cylindrical probe was used to break it. Garayo (2001) and Granda (2005) used the same approach for potato chips used by Kawas-Escoto (2000). Granda (2005) compared the texture parameters of potato chips vacuum and traditionally fried.

Kasahara, Osorio, Moyano, Pizarra & Beltran (2002) studied the texture of French fried potatoes pre-treated with soaking solutions (20 % sugar/2% salt for 15 min and 3% just salt for 50 min). A significant better texture difference was found for the pre-treated samples. Maximum force (peak), rigidity (slope of the curve) and work (area under the curve) were obtained using a multiple puncture attachment with the Texture Analyzer. They found that pre-treating the samples with 3% salt increased the work (hardness) to break the samples during frying time at 180^{o}C.

Shyu & Hwang (2001) used the Texture Analyzer for breaking force determination of vacuum fried apple chips after pre-treatments. Da Silva & Moreira (2008) worked in the texture of blue and sweet potato, green bean and mango chips osmotic dehydrated in a maltodextrin solution. They used the Texture Analyzer with a steel blade probe to fracture the sample, and the force required to break the chips was measured. They found no significant different on the force required to break the products ($P<0.05$) when frying under vacuum and atmospheric pressure.

2.3.8. Carotenoids

Carotenoids, which impart yellow, orange, and/or red colors to many fruits, have antioxidant health properties; more than 600 varieties have been found in plants (Perkins, 2007). Carotenoids are an excellent micronutrient found in cancer-preventive foods, thus their determination in fruits and vegetables has become especially important (Cano & Ancos, 1994).

Several fruits and vegetables contain large amounts of ß-carotenes. Mango has approximately 60% of the mango. Beta-carotenes are the principal provitamin and the main pigment in mangoes (Wilberg *et* al, 1995; Moreno-Tijaca, 2005; Perkins, 2007). Normally, mango has around 765 IU/100 g of vitamin A and 445 mcg/100g of ß-carotenes (USDA/ARS, 2007).

Mercadante & Rodriguez-Amaya (1998) agreed that carotenoid content present in mango (Keitt and Tommy Atkins varieties) increases when it ripens. They also observed a disappearance of violaxanthin, becoming beta-carotene the major carotenoid in mango juice processing.

Ahmed, Shivhare & Sandhu (2002) observed that high temperature, oxidation, light, enzymatic, non-ezymatic, etc, are main factors for carotenoids degradation in papaya by following a first order reaction.

On the other hand, osmotic dehydration, on the contrary, could reduce carotenoids losses in comparison with other dehydration processes because part of the osmotic solution remains on the surface layer of the mango preventing oxygen for penetrating and oxidizing the specific carotenoid (Shi & Maguer, 2001). OD can be also

used to improve phytochemical characteristics for further processing (Torreggiani & Bertolo, 2001b).

The principal carotenoid present in mango is beta-carotene (mainly vitamin A precursor), for that reason, its determination can be related by the total carotenoids obtained in the mango sample.

Moreno-Tinjaca (2005) and Da Silva & Moreira (2008) determined total carotenoids content by using a UV-1601 spectrophotometer (Shi-madzu Corp., MD) at 453 and 450 nm respectively following the methodology cited by Rodriguez-Amaya (1989) with little modifications.

Da Silva & Moreira (2008) compared total carotenoids content in mango (Tommy Atkins) chips pre-treated with OD solution. They observed a smaller loss in total carotenoids by using vacuum frying than the traditional one.

CHAPTER III

MATERIALS AND METHODS

3.1 Selection and preparation

3.1.1. Mango chemical composition

Mango (*Mangifera indica L.)* is a tropical fruit rich in vitamin C and provitamin A carotenoids, mineral salts, and carbohydrates (Moreno-Tinjaca, 2005). Table 3-1 shows the chemical composition of raw mango.

Table 3-1. Raw mango (*Mangifera Indica L.)* nutritional composition in 100 g of edible portion.

Nutrients	Units	Amount in 100 g
Water	g	81.71-82.42
Energy	kcal	57.65-65.00
Protein	g	0.51-0.70
Total Lipid	g	0.20-0.27
Ash	g	0.50
Carbohydrates	g	14.10-17.00
Dietary Fiber	g	1.80-2.60
Calcium, Ca	mg	10.00-12.00
Magnesium, Mg	mg	9.00-13.00
Phosphorus, P	mg	11.00-16.00
Potassium, K	mg	156.00-180.00
Vitamin C, total ascorbic acid	mg	27.70-37.00
Folates	µg_DFE	14.00
Vitamin A, IU	IU	765.00
Total Sugars	g	13.80-14.80
Fructose	g	3.00
Glucose	g	0.70
Sucrose	g	10.10
Alpha-carotenes	µg	16.00-27.00
Beta-carotenes	µg	445.00-696.00

Adapted from: Moreno-Tinjaca (2005); USDA/ARS (2007)

3.1.1.1. Mango variety

The Mango is one of the finest and most popular tropical fruits and has been cultivated in India since 2000 BC or earlier. The Portuguese introduced the Mango to a wider audience in the 16th century taking the fruit to Africa from Southern India. It reached Brazil and the West Indies in the 18th century and Mexico and Florida in the 19th Century. India remains the world's largest producer. There are over 400 varieties of Mango throughout the world (Singh, 1960). The U.S. (the world's largest importer of mangoes) imports mainly from countries south of the border, like, Mexico, and South America. The varieties generally imported to the U.S. are Haden, Tommy Atkins, Keitt, Kent, Manila, and Ataulfo (Table 3-2).

Table 3-2. Mango varieties mostly consumed in the U.S. and their physical characteristics mostly consumed in U.S.

Mango Variety	**Place of Origen**	**Season**	**Flavor**	**Shape**	**Color**	**Texture**
Haden	Mexico, Ecuador, Peru	Oct-Dec March-May	Luscious	Medium to large and oval to round	Green to yellow with red highlights	Firm
Tommy Atkins	Mexico, Ecuador, Brazil, Peru, Florida	Year-round	Mildly sweet	Medium to large and oval to oblong	Golden to greenish skin with crimson blush	Firm, fairly fibrous texture
Keitt	Mexico	Jun-Aug	Rich and Fruity	Large oval	Green with slight dark red blush	Very smooth
Kent	Mexico, Ecuador, Peru	Jan-March May-Aug	Vibrant	Large oval	Greenish skin with dark red blush and small yellow dots	Juicy and tender
Manila or Ataulfo	Mexico	Feb-Aug	Sweet	Small flattened oval	Yellow	Buttery

Source: National Mango Board, 2007

The variety used in this study was “Tommy Atkins”. This mango variety was considered the most advantageous due to its physical properties (texture, flavor, color, shape, and season availability). Tommy Atkins (Table 3-2) is produced year-round. The fruit is medium to large in size, weighing 16 to 25 oz (450 to 700 g). It is oval to oblong in shape with a broadly rounded tip and an average smaller diameter of 10 cm. Its larger diameter is less than 15 cm (10-12 cm) (Fig 3-1). The fruit surface is smooth, and the skin is thick and resistant to mechanical injury. Ground color is orange-yellow and the blush is bright to dark red. The flesh is medium to dark yellow in color. Flavor is mildly sweet. The texture of the flesh is quite firm because of the presence of fine-textured fibers excellent for processing (Campbell, 1973).

Fig 3-1 Tommy Atkins mango size.

3.1.2. Raw mango selection

Half green, "Tommy Atkins", mangoes were purchased from a local retail store at College Station, Texas (Fig. 3-2). A non-destructive compression test of firmness was carried out randomly using Texture Analyzer -TA-XT2- (Texture Technologies Corp., Scarsdale, NY) compression test. A circular flat plate probe (7.5 cm diameter) and a flat base were used to compress the mango at a test speed of 0.5 mm/s through a distance of 7 mm. This test was enough to detect firmness without affecting the integrity of the mango. Those mangoes that fall in the range of 25-30 N were selected for process. This range provides texture required for good slicing and handling.

Fig. 3-2. Tommy Atkins mango boxes.

3.1.3. Raw mango preparation

The mangoes were washed thoroughly and then sliced using a Mandolin slicer (Matfer model 2000, France), and the thickness (1.48-1.70 mm) was measured using a thickness gage (Mitutoyo Thickness Gage, Japan). Mango slices were cut and rounded using a metal cylindrical cutter (5.08 cm diameter). Then, the samples were placed in aluminum foil to avoid any moisture loss before further treatments.

3.1.4. Osmotic solution preparation

Maltodextrin (Cargill Dry MD 01913, Cargill, Mineapolis, MN) was weighed and mixed with distilled water in a proportion of 40, 50, and 65 w/v during five hrs at room temperature to dissolve it completely. About 0.15% of citric acid was added into the solution to decrease browning of the sample. The OD solution and mango slices were utilized in a proportion of 4:1 and 1:10 to see the effect of mango:syrup ratio on the dehydration rate.

3.1.5. Fruit: syrup ratio

To set the right proportion of mango and maltodextrin solution for the OD process, a preliminary study was carried out. The initial concentration of the OD solution was 50 w/v at 22± 0.5^{o} C. Two ratios were tested, 1:4 and 1:10 fruit: syrup solution ratio. The effects on water loss and sugar gain for both cases were analyzed in detail (see section 3.3.2). Water activity and ^{o}Brix were measured before and after the OD process using a Rotronic Hydrometer (Rotronic Instrument Corp., Huntington, NY) respectively, and the pH measured with a digital pH meter (Corning model 350 pH/ion analyzer, Corning, Inc) at 22± 0.5^{o}C. Moisture content was measured (method 930.04 AOAC,

1990) before and after OD process using a vacuum oven (Squared Lab Line Instrument, Melrose Park, IL.), at 70^{o} C and ≤ 13.3 kPa to a constant weight. All the parameters were measured in triplicate for each treatment.

3.2. Raw mango physicochemical properties

3.2.1. Moisture content

Raw mangoes used for OD were cut in small pieces to measure moisture content. Moisture content (method 930.04 AOAC, 1990) was determined in triplicate. Moisture content in wet basis was calculated as follows:

$$MC(w.b.) = \frac{(M_{wet} - M_{dry})}{M_{wet}} \quad [3\text{-}1]$$

where M_{wet} = weight of the wet sample [Kg] and M_{dry} = weight of the dry sample [Kg].

3.2.2. Water activity

The water activity of the raw mango was determined using a Rotronic Hydrometer (Rotronic Instrument Corp., Huntington, NY) at room temperature. Around 5 g of sample was placed in an air-tight chamber connected to a panel display where the corresponding water activity and temperature were measured. Readings were made in triplicate.

3.2.3. pH

The pH measurement of mango flesh was determined using a digital pH meter (Corning model 350 pH/ion analyzer, Corning, Inc). The pH meter was previously calibrated with standard solutions, pH 4, 7 and 10. A glass electrode was immersed in the mango juice (10 ml), using a squeezer to avoid any solid in the sample. The experiment was carried out at room temperature and three replications were recorded.

3.2.4. Degree brix

The juice utilized to measure pH was also used to calculate ^{o} Brix, which was evaluated using a refractometer (ABBE ATAGO model 3T, Bellevue). Few drops were placed in the refractometer lens. The soluble solid content (Brix) can be determined by correlating the refraction angles and refractive index value established by the refractometer. The measurements were recorded in triplicate at room temperature.

3.2.5. Color

A Labscan XE colorimeter (Hunter Lab. Inc., Reston, VA, USA) with the universal v.3.73 software was used to evaluate the color of raw mangoes using the CIELAB system. A mixture of small pieces of mango was used and placed in a special glass container. The measuring aperture diameter of the colorimeter was 36 mm and it was calibrated using standard white and black tiles. Five readings from the plate were obtained. The parameter used to determine the color of the raw mango were *L** (lightness-darkness), *a** (redness-greenness), and *b** (yellowness-blueness).

3.3 Osmotic dehydration (OD)

The OD pre-treatment was performed at two room temperatures (22 and 40^{o}C). The OD process was performed at lower temperatures than 45^{o}C because of the development of enzymatic browning and flavor deterioration. At higher temperatures (60°C), the product's tissue is modified favoring impregnation phenomena and thus solid uptake (Farkas & Lazar, 1969; Heng *et al.*, 1990; Torreggiani, 1993).

Three different concentrations were used: 40, 50, and 65 w/v. The solution and around 500 g of mango slices were placed in a stainless steel bowl container and it was

heated using a heating/stirring plate (Laboratory Stirrer/Hot plate, Corning, Corp., model PC-220, USA). The container was hand stirred approximately every 5 min during 30 seconds to homogenize the solution around the slices. The temperature was controlled by introducing a mercury thermocouple at the center of the system. After OD treatment, the mango slices were drained from the solution and placed in a coarse type filter paper (both sides) for removal of the residual sugar solution left on their surfaces. Fig. 3-3 shows the OD of mango slices.

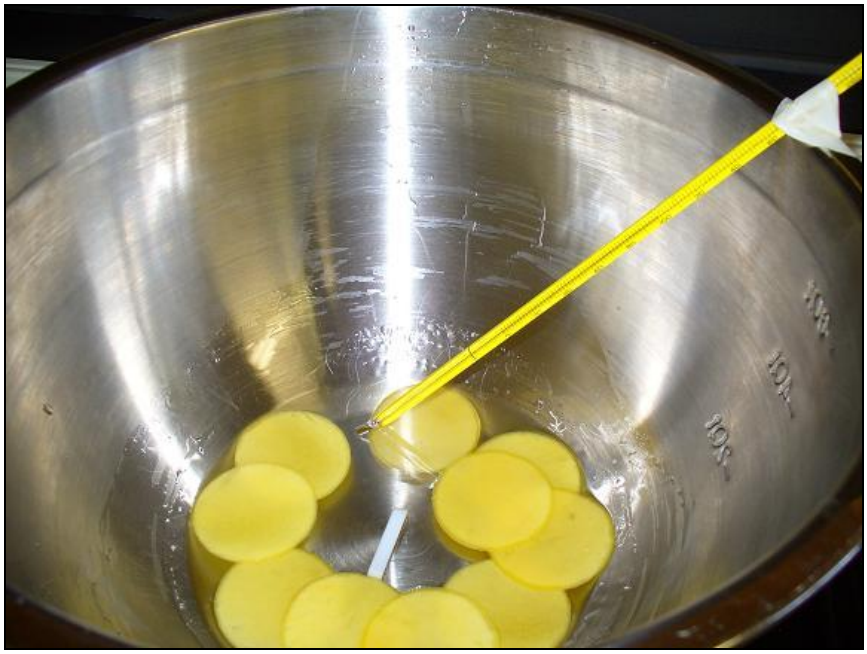


Fig. 3-3. Osmotic dehydration of mango slices.

Osmotic dehydration and frying were conducted following the steps described in Fig. 3-4.

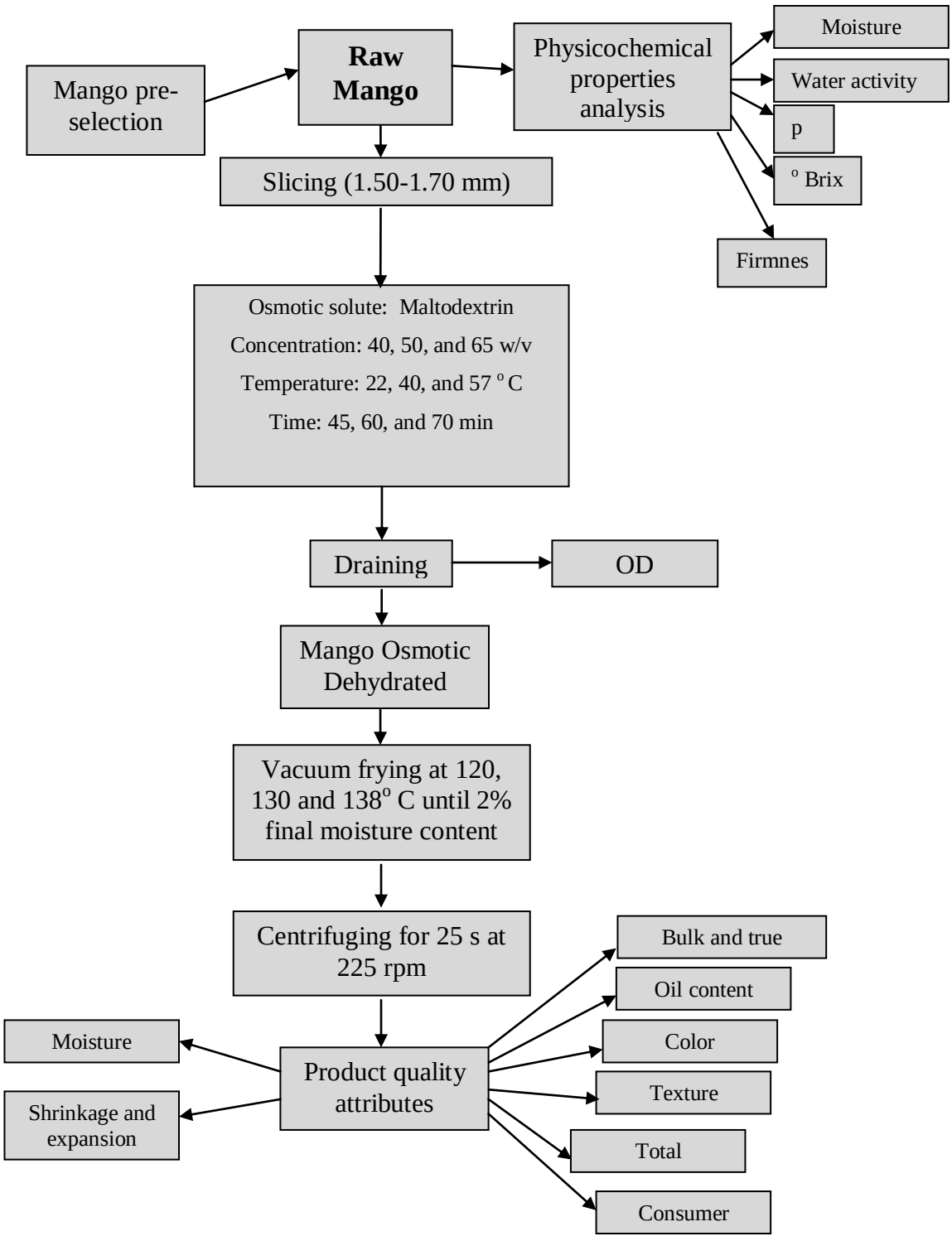


Fig. 3-4. Flow chart for pre-treatment and vacuum frying of mango slices.

3.3.1. Coding

Coding of 8 slices was carried out to obtain the water loss and solid uptake before and after OD. They were marked with a fine point sharpie. The slices were marked with points corresponding with the designated code. Based on the coding, weight of the slices, moisture content, water activity, pH, and ^{o} Brix were recorded following the same methodology described in sections *3.2.2* to *3.2.4* before and after OD.

3.3.2. Sugar uptake and water loss

During OD, two major countercurrent flows take place simultaneously: (1) water coming out of the solute (mango slices) and (2) sugar (maltodextrin) coming into the sample. Although the main goal of this pre-treatment was to increase water loss, a certain level of sugar uptake was needed since it prevents loss of volatile flavor components during vacuum frying (Lazarides, 2001; Da Silva & Moreira, 2008).

Sugar uptake and water loss were calculated based on moisture content, ^{o} Brix, and weight of the eight slices before and after OD, using the following equations.

(a) Material Balance:

$$w_o + s_o = w_t + s_o + s'_u \qquad [3\text{-}2]$$

where w_o and w_t are the initial and final water content [Kg of water/Kg of product] of the slices, respectively; and s_o and s'_u the initial sugar content and the sugar uptake [Kg of sugar/Kg of product] by the osmotic dehydration process, respectively.

(b) Sugar uptake (S_U) [Kg]:

$$S_U = M_t(1 - w_t) - M_o(1 - w_o) \quad [3\text{-}3]$$

where M_o and M_t are the initial and final slice weight [Kg], respectively; and w_o and w_t are initial and final water content [Kg of water/Kg of product], respectively.

(c) Water loss (W_L) [Kg]:

$$W_L = M_o - M_t + S_U \quad [3\text{-}4]$$

(d) Final sugar content in the slices (B_t):

$$B_t = \frac{\left[\frac{B_o}{100}(M_o) + S_U\right]}{M_t} \quad [3\text{-}5]$$

where B_o and B_t are the initial and final ^{o}Brix [Kg of sugar/100Kg of product], respectively.

3.3.3. Degree of shrinkage

The effect of OD on the temperature and time during osmotic dehydration on the diameter of the slices was analyzed. The diameter was measured using a plastic caliper (MG Tool Company, New York, NY). Four slices and four readings per slice were recorded for each treatment, and the degree of shrinkage (D_i) [%] calculated as (Kawas-Escoto, 2000):

$$D_i = (d_o - d_t)/d_o * 100 \quad [3\text{-}6]$$

where d_o and d_i are the initial and final diameter in m, respectively.

3.4. Vacuum frying

The vacuum frying system used in this study was the one assembled by Garayo (2001) with several modifications. This fryer system (Fig. 3-5) is located in the Food Engineering Laboratory of the Biological and Agricultural Engineering Department at Texas A&M University, College Station, Texas. The fryer consists of a cast aluminum vacuum vessel with a capacity of 6 L and with a resistance heater with a maximum temperature generated at 140^{o}C. Inside the pan there is a basket and also a centrifuging system (de-oiling system) with a maximum rotational speed of 750 rpm (G-force = 72.01 g). Vacuum is achieved in the vessel by a dual seal vacuum pump (model 1402 Welch Scientific Co., Skokie, IL) with a vacuum capacity of 10 Torrs (1.33 kPa). Between the vessel and the pump a condenser is needed to condense the water vapor coming from the mango chips to avoid water going to the pump. The condenser (concentric cylinder) has a removable three-quart center well designed for dry-ice/alcohol slurry. A 50-50 mix of dry-ice and 95% ethanol was used. Fresh canola oil was used in all frying experiments.

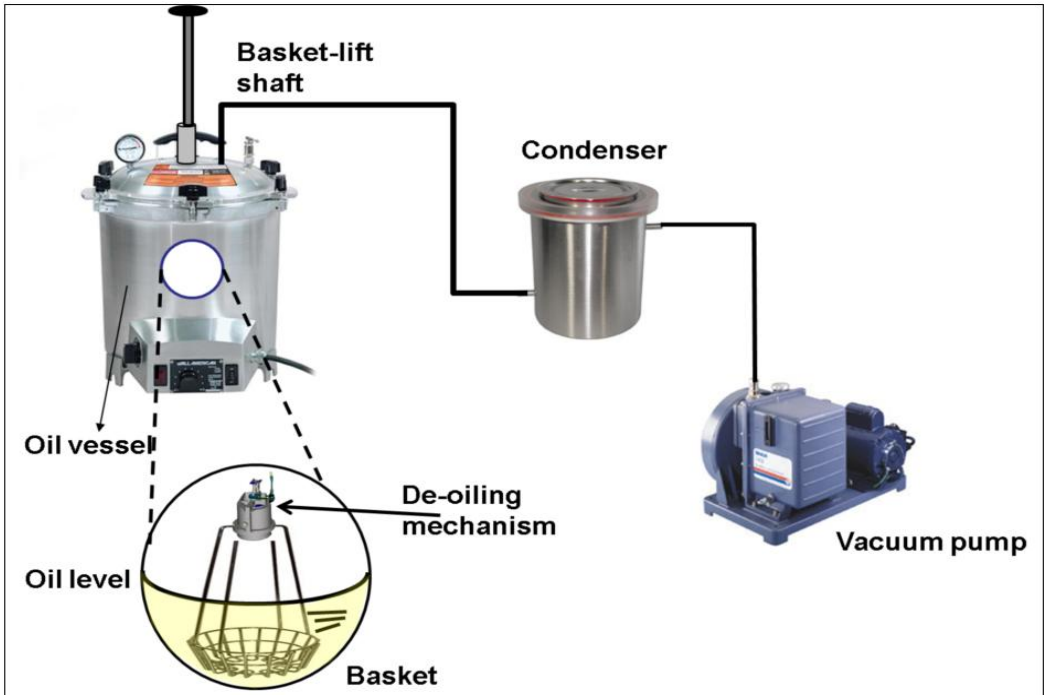


Fig. 3-5. Vacuum frying system set-up.

The frying process consists of placing the mango slices into the basket, closing the lid and connecting the vacuum hose to the vessel. When the pressure in the vessel reaches 10 Torrs (1.33 kPa), the basket is loaded into the oil. Once the chips are fried, the basket is raised up and the centrifuging system is applied for 25 sec at a speed of 225 rpm. Then, around 6 mango chips are cooled down at ambient temperature and then placed in plastic bags for further examination.

3.4.1. De-oiling process

Once the mango slices were osmotically dehydrated (65 w/v concentration solution at 40^{o} C) and vacuum fried (120^{o}C), they were subjected to a de-oiling process. The de-oling process was carried out at four different speeds [G-force] (1.63, 6.48,

14.63, and 25.92 g) and different times (15, 25, 35, and 45 s) combinations. Oil content for all cases was determined using Soxhlet System HT extraction unit (Pertorp, Inc., Silver Spring, MD), the same method used by Da Silva and Moreira (2008), with petroleum ether (AACC, 1986) as the solvent. Each test was conducted in triplicate.

3.5. Product quality attributes

3.5.1. Moisture content

Moisture content of the final product (method 930.04 AOAC, 1990) was carried out using equation (3-1). Around 3 g of mango chips were ground using a coffee blender (model CB65 Applica Consumer Products Inc., Miami Lake, Fl) and placed in a vacuum oven (Squared Lab Line Instrument, Melrose Park, IL.) at 70^{o}C during 7 hrs. The test was performed in triplicate.

3.5.2. Shrinkage and expansion

Frying temperature and time have a detrimental effect on the volume of the chip. The chips experience a series of changes that finally give their shape and form. The diameter of the fried chips was measured by using the same caliper used in section *3.3.3.* Degree of shrinkage was obtained using equation (3-6). Around 16 readings were taken for four slices.

Chips expansion was measure using a caliper (MG Tool Company, New York, NY). Around 12 readings were made for 3 slices for each treatment. The degree of expansion was calculated using the following equation (E_i) [%]:

$$E_i = ((e_t - e_o)/e_o) * 100 \qquad [3\text{-}7]$$

where e_o and e_t are the initial and final thickness [mm], respectively.

3.5.3. Bulk density

The bulk volume was measured using the liquid displacement technique with water-10% ethanol (Da Silva, Moreira, & Gomes, 2008). The apparatus was filled with a mixture of water with 10% of ethanol and hermetically closed with a lid. The initial volume was recorded turning the device up side down and a second lecture of the volume displaced by the sample was recorded. Around 0.01 Kg of mango chips were used and the test was performed in triplicate. Bulk density (kg/m^3) was determined using the following equation (D_B):

$$D_B\ [kg/m^3] = W_c/V_b \qquad [3\text{-}8]$$

where W_c and V_b are the weight of the chips [Kg] and bulk volume[m^3], respectively.

3.5.4. True density

The volume of the chips was determined using a compressed helium gas multi-pycnometer (Quantachrome & Trade, NY). The sample was ground using a coffee blender (model CB65 Applica Consumer Products Inc., Miami Lake, Fl). The solid volume was determined by two pressure readings given by the pycnometer. By knowing the volume of the reference and the cell, the solid volume (V_p) was calculated by:

$$V_p = V_c - V_r(P_1/P_2 - 1) \qquad [3\text{-}9]$$

where V_c and V_r are the volume cell and reference, respectively; and P_1 (around 17 psi) and P_2 are initial and final pressure [Pa] given by the pycnometer, respectively. The true

or solid density (kg/m^3) was calculated by the weight of the sample divided by its solid volume. The test was carried out in triplicate.

3.5.5. Porosity

Porosity of the mango chips was determined using bulk density and true density by (Eq 3-10).

$$\varepsilon = 1 - \rho_b/\rho_s \quad [3\text{-}10]$$

where ε is porosity of the mango chips, ρ_b is bulk density [kg/m^3] and, ρ_s is solid density [kg/m^3], respectively.

3.5.6. Oil content

Oil content was determined using the Soxtec System HT extraction unit (Pertorp, Inc., Silver Spring, MD) with petroleum ether (AACC, 1986) as the solvent. Mango chips were ground using a coffee blender, and around 3 g of the sample was placed on cellulose thimbles (model 2800256, Whatman, England) and covered with cottom. Before starting the extraction, aluminum cups were dried for 15 min at 105^{o}C and cooled down in a dessicator for 25 min. The cups weight was recorded and once the thimbles were in the unit, 50 ml of the solvent were placed on each cup. The samples were soaked in the cups during 40 min and then by turning the air and evaporation position in the equipment the petroleum ether was evaporated and recollected. The cups with the oil were put in the oven again at 105^{o}C during 15 min to ensure no ether was present. Next, the cups were left to cool down in a dessicator for 25 min and weighed. The test was performed in triplicate for each treatment. Oil content (OC) was calculated by:

$$OC[\%] = [(C_2 - C_1)/M_i] * 100 \quad [3\text{-}11]$$

where C_2 and C_1 are the intial and the final cup weight [Kg], respectively; and M_i was the sample weight [Kg].

3.5.7. Color

The same procedure used to measure the color in raw mango was used to measure color in the fried chips. A Labscan XE colorimeter (Hunter Lab, Inc., Reston, VA, USA) was used utilizing the CIELAB system. Parameters *a, *b, and *L were recorded to determine the color. The chips were ground using a coffee blender to obtain a homogenous sample from all the chips tested and to decrease error during reading. About five readings were made at room temperature.

3.5.8. Texture

A compression test had to be developed to measure texture of chips accurately. A circular cylindrical probe (7.5 cm diameter) and a support with a flat base of 14x12.7 cm were mounted in a TA-XT2 Texture Analyzer (Texture Technologies Corp., Scarsdale, NY). A compression test with 45% strain was applied to 5 stacked mango chips. The test speed compression was set at 0.6 mm/s. Peak (maximum force) and work values (area under the curve) were determined from a force (N) vs. distance (mm) plot. Around 12 replications were conducted for each treatment.

3.5.9. Total carotenoids content

Total carotenoids content was determined using a UV-1601 Spectrophotometer (Shimadzu Corp., MD) at a 450 nm following the methodology used by Da Silva & Moreira (2008) with slightly modification. Before doing the extraction, the mango chips were cut in small pieces and covered with aluminum to avoid minimal loss of

carotenoids. In fifty milliliters of acetone, a 1 g of sample was added, and grinded for 1 min using a homogenizer (Ultra-Turrax T-25, IKA-WERKE, Germany). The samples were allowed to rest in the solvent in a dark place at 22^{o} C for 35 hr. Then, the solution was filtered using a Whatman® filter paper # 4 and the extracted solution placed in decantation balloons with 50 mL of pretroleum ether. The residue was washed 4-5 times with 100 ml of distilled water. Finally, a small amount of sodium sulfite was added to bind any remaining water.

The carotene extract was recovered from the previous extraction using a Rota-vapor-R110 (Brinkman Instruments, Westbury, NY) at 32^{o} C during 7 min to evaporate solvents (petroleum ether and acetone) residues. Then, the concentrated sample was diluted with hexane to make possible the spectrophotometric determination at 22^{o} C. The test was performed in triplicate. Total carotenoids content was determined using a standard curve where beta-carotene was used as the standard.

The concentration of beta-carotenes was determined with a previous standard curve developed at a concentration between 1 to 4 µg/ml (Fig. 3-6) in which *x* and *y* correspond to concentration and absorbance, respectively,

$$Y = -0.023 + 0.21X, \qquad R^2 = 0.99 \qquad [3\text{-}12]$$

The concentration of carotenoid (carotenes) was calculated as:

$$X\left[\frac{\mu g}{g}\right] = \left(\frac{Y + 0.023}{0.21}\right)\left[\frac{\mu g}{ml}\right] * \frac{10ml}{W_{sample}[g]} \qquad [3\text{-}13]$$

where W_{sample} = sample weight in grams [Kg of solids].

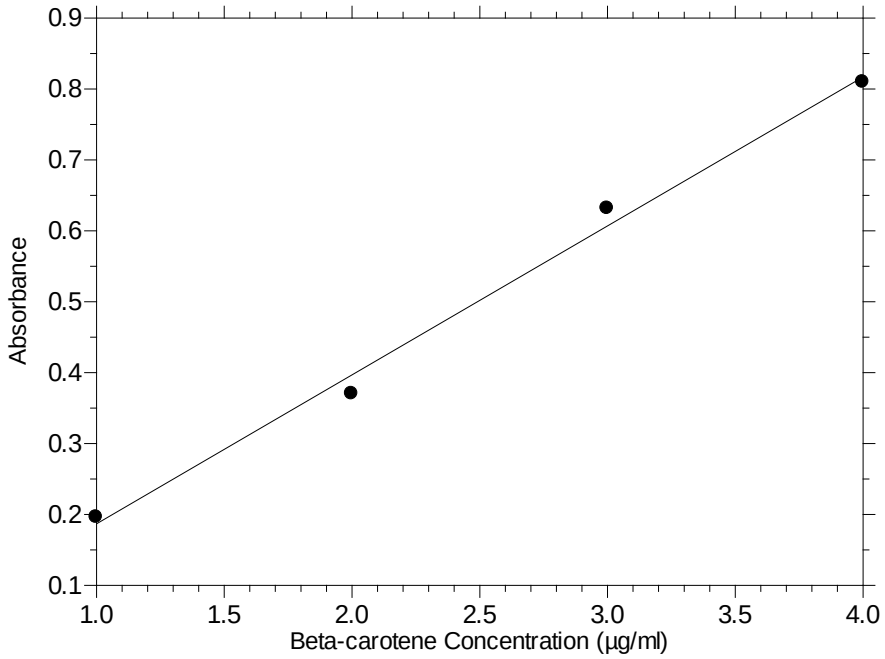


Fig. 3-6 Standard curve for beta-carotene (µg beta-carotenes/ml).

3.6. Sensory analysis

Sensory evaluation of mango chips was performed with a 30-member consumer panel (faculty, students, and staff) at Texas A&M University. The quality attributes tested were: color, odor, texture, flavor, and overall quality. Three frying temperatures (120, 130, and 138^{o} C) and different OD times (45, 60, and 70 min) at 40^{o} C were evaluated.

The samples were placed in capped-glass-labeled containers and presented to each panelist at once. The containers were coded with a random three digits number to identify the temperature and OD treatment.

The same nine-point hedonic scale used by Carr, Meilgaard & Civille (1999) was used, with a score of 1 to 9 where 1 was the most disliked and 9 the most liked attribute. Scores higher or equal to 5 were considered acceptable.

3.7. Mango microstructure

Microstructure of mango slices pre-treated with OD concentration of 40 and 65 w/v were compared with the raw samples using the environmental scanning electron microscope (Model XL30 ESEM-FEG). Also, microstructure of mango chips fried under vacuum at 120 and 138^{o}C and atmospheric pressure at 165^{o}C was compared. The ESEM microscope permits the imaging (under vacuum and using an electron beam) of a wet system (sample) with no prior specimen preparation. The surface and cross sectional areas were obtained.

3.8. Statistical analysis

Experiments were conducted in triplicate for each treatment. Raw and fried mango properties as well as differences among treatments were detected with the program SPSS software (version 15.0 for Windows, 2006) using one-way analysis of variance (ANOVA) using Duncan's multiple range tests. Statistical significance was expressed at the $P<0.05$ level.

CHAPTER IV

EFFECT OF OPERATING CONDITIONS ON THE PROPERTIES OF MANGO SLICES DURING OSMOTIC DEHYDRATION AND VACUUM FRYING

4.1 Preliminary data for osmotic dehydration

4.1.1 Effect of temperature during osmotic dehydration on oil content of mango chips

The effect of the osmotic dehydration (OD) temperature in mango chips vacuum fried to a final moisture content around 2% was evaluated based on the final oil content. Mango slices were fried at 120^{o}C for 2 min. Table 4-1 shows the oil content [w.b.] for different OD temperatures (22, 40, and 57^{o}C) at different OD concentrations (40, 50, and 65 w/v) for 60 min.

There was a high oil content value (around 59% w.b.) when the mango slices were pre-treated at a temperature of 57^{o}C and solution concentration of 40 w/v. No significant changes (P>0.05) were observed when the samples were pre-treated with an OD concentration of 40 w/v at 22^{o}C and 40^{o}C. However, a slightly decrease in oil content in the samples treated at 40^{o}C was observed compared with other temperatures for OD concentrations of 50 and 65 w/v. These differences in oil content with OD concentrations can be attributed to water loss and product quality preservation (microstructure) due to high OD concentrations. Also, high OD temperatures contribute to water loss, although very high temperatures can damage the mango tissue which could result in high oil content mango chip. Therefore, based on the preliminary results it was

concluded that OD at 57^{o}C damaged the mango tissue thus affecting its quality. It was decided then to consider only OD temperatures of 22^{o}C and 40^{o}C for the next experiments in this study (Fig. 4-1).

During OD, the higher the osmotic solution concentration, the higher the water loss (Torregiani, 1993; Madamba & Lopez, 2002; Sablani & Rahman, 2003; Giraldo *et al*, 2003; Tran *et al*, 2007; Lombard *et al*, 2008). Water removed during OD is extremely related to the OD temperature (Mavroudis *et al*, 2001; Madamba & Lopez, 2002; Sablani & Rahman, 2003; Lombard *et al*, 2008).

Madamba & Lopez (2002) used the response surface methodology (RSM) approach to obtain the optimum conditions for mango slices during OD. They found that the optimum parameters for OD were a temperature of 35^{o}C and an osmotic solution (OS) concentration of 65 w/v during 6 hours. Osmotic dehydration carried at low process temperatures (up to 50^{o}C) does not affect the semi-permeable characteristics of cell membranes. Moderate temperatures also favor color and flavor retention in products with superior organoleptic and nutritional values characteristics (Lazarides, 2001). Torezan, Favareto, Pallet, & Menezes (2004) fried mango slices, "Tommy Atknis" variety, pre-treated with an osmotic solution (65^{o} Brix sucrose) during 80 and 120 min at 45^{o}C. They obtained low values of oil content (around 12% w.b.) for mango slices fried at 40^{o}C for 120 min in a traditional (atmospheric) fryer.

Table 4-1. Effect of osmotic dehydration temperatures and solution concentrations on the final oil content of mango chips vacuum fried at 120°C for 2 min without de-oiling.

OD concentration[w/v]	Temperature[°C]	Oil content[w.b.]
40	22	0.48 ± 0.00^{a}
40	40	0.47 ± 0.01^{a}
40	57	0.59 ± 0.01^{b}
50	22	0.47 ± 0.01^{d}
50	40	0.46 ± 0.01^{d}
50	57	0.55 ± 0.01^{f}
65	22	0.45 ± 0.01^{w}
65	40	0.43 ± 0.01^{w}
65	57	0.55 ± 0.01^{y}

[a-w] Means within a column with different letters are significantly different ($P<0.05$), frying oil temperature = 120°C and frying time = 2 min. Mango:syrup ratio = 1:4.

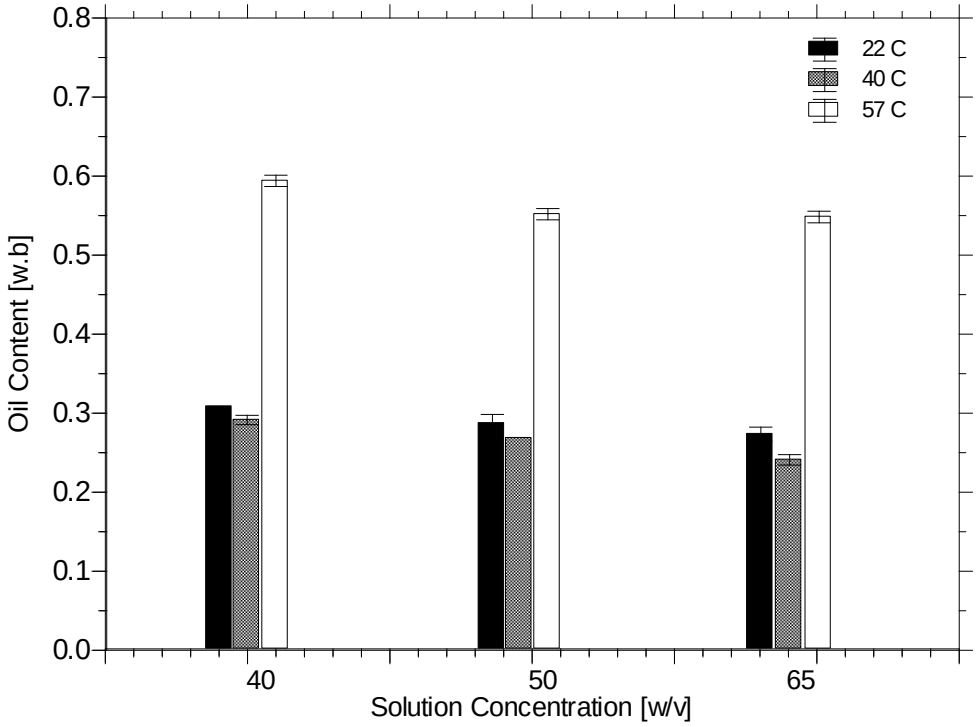


Fig. 4-1 Oil content [w.b.] in mango chips pre-treated at different OD temperatures with solution concentration of 40, 50, and 65 w/v for 60 min (mango:syrup ratio = 1:4) and fried at 120^{o}C for 2 min without de-oiling.

4.1.2 Effect of fruit/syrup ratio on the water loss and sugar gain in mango chips

The sugar uptake for mango slices treated with two different fruit:syrup ratios (1:4 and 1:10) were 0.13 ± 0.01 and 0.14 ± 0.01, respectively (Table 4-2). The water loss in slices was 0.47 ± 0.04 and 0.41 ± 0.05, respectively. There was no significant difference (P>0.05) for sugar uptake and water loss for both treatments (Table 4-2 and Fig. 4-2). The same results were obtained for ^{o}Brix.

Torregiani (1993) found that a good product:syrup ratio was around 1:3-5 for OD during 15-240 min for further drying. Saputra (2001) used a ratio of 1:10 w/v for long OD time periods (3-7 hours) in pineapple slices to avoid significant changes in the OD concentration. Madamba & Lopez (2002) used a ratio of 1:5 w/w for OD in mango slices during 3-7 hours without considering the changes in the OD concentration with time.

Based on the results shown in Table 4-2 and Fig. 4-2 for sugar uptake and water loss, it was decided to use an OD ratio (fruit to syrup) of 1:4 for further studies.

Table 4-2 Sugar uptake, water loss, ^{o}Brix, and moisture content (MC) in mango slices after osmotic dehydration (65 w/v at 22^{o} C) for different fruit to syrup ratios (1:4 and 1:10).

Ratio (mango:solution)	**Sugar uptake [g]**	**Water loss [g]**	**^{o} Brix [g/g]**	**MC [w.b.]**
1:4	0.13 ± 0.01^{a}	0.47 ± 0.04^{a}	0.22 ± 0.00^{a}	0.78 ± 1.28^{a}
1:10	0.14 ± 0.01^{b}	0.41 ± 0.05^{b}	0.22 ± 0.00^{a}	0.77 ± 0.17^{a}

$^{a-b}$ Means within a column with different letters are significantly different (P<0.05)

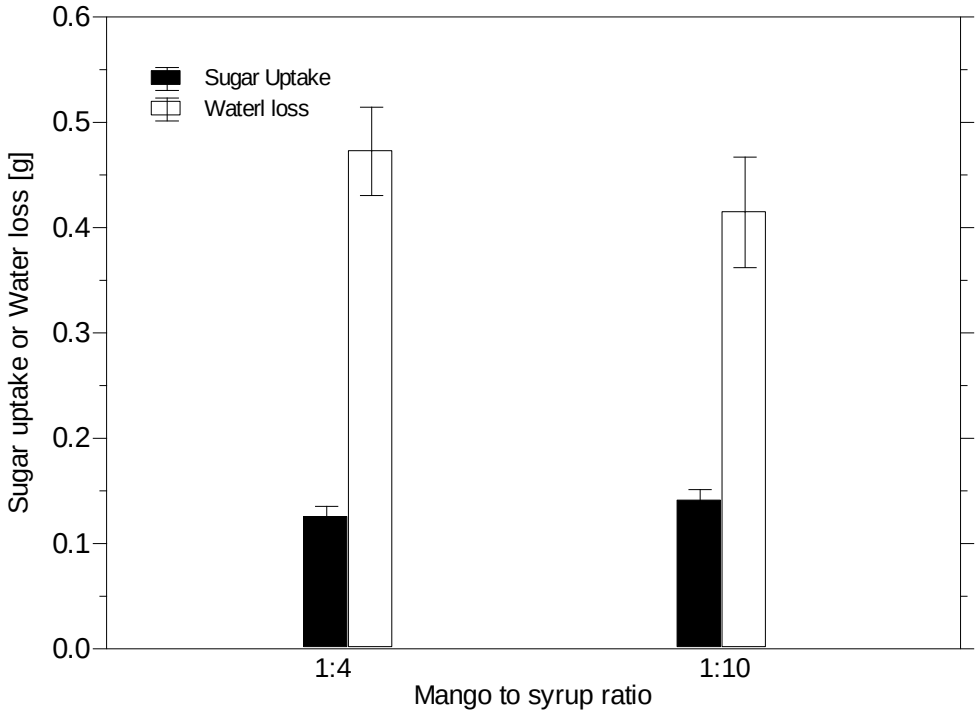


Fig. 4-2 Sugar uptake and water loss for mango to syrup ratios of 1:4 and 1:10 in mango pre-treated with 65w/v OD concentration at 22^{o}C.

4.2 Effect of osmotic dehydration on mango chemical properties

4.2.1 Moisture content

Figs. 4-3 to 4-5 and Table 4-3 show the effect of concentration, time and temperature during OD and vacuum frying (at 120^{o}C for 2 min) on the moisture content of the mango chips. The moisture content of raw mango "Tommy Atkins" ranged between 84 and 87% (w.b). Mango slices pre-treated with maltodextrin solution had significantly ($P<0.05$) lower moisture content after OD (Table 4-3). The lowest moisture content obtained in mango slices was 69% (w.b.) when using 65 w/v concentration and 70 min OD. After vacuum frying, the chips moisture content was 1% after this pre-treatment. These results agree with those obtained by Giraldo *et al* (2003) and Lombard *et al* (2008). The moisture content decreased when the OD concentration, time, and temperature for OD increased (Figs. 4-3 to 4-5).

Giraldo, Talens, Fito, & Chiralt (2003) observed a decrease in the moisture content of mangoes (Kent var.) when the OD sucrose concentration (35, 45, 55, and 65 % w/w) and time increased from 35 to 65% w/w and for 15 to 300 min, respectively. Lombard, Oliveira, Fito & Andres (2008) found that at higher temperature (30, 40 and 50^{o} C) during OD with sucrose (45, 55, 65% w/w) pineapple chips had the higher water loss.

In this study, the most important OD parameter was concentration (Table 4-3). The OD experiments were carried out for 45, 60, and 70 min and it is possible that was never reached with the sugar solution. The OD concentration contributed to high values of removed water as the concentration increased due to high hydrodynamics forces. At

higher concentration, more sugar (maltodextrin) migrated into the sample, thus increasing water loss. As expected, higher temperatures accelerate the OD process, therefore increasing the amount of water removed.

Table 4-3 Moisture content after OD [w.b.] and after 2 minutes vacuum frying [w.b.] at 120^{o}C for mango slices pre-treated at different OD times, temperatures, and concentrations.

OD Time[min]	**Temperature[^{o}C]**	**Concentration[w/v]**	**MC^{1} [w.b.]**	**MC^{2} [w.b.]**
45	22	40	0.84±0.00^{a}	0.13±0.01^{a}
45	22	50	0.81±0.00^{b}	0.07±0.00^{b}
45	22	65	0.79±0.00^{c}	0.05±0.00^{c}
60	22	40	0.82±0.00^{d}	0.11±0.01^{a,f}
60	22	50	0.80±0.00^{e}	0.04±0.00^{d}
60	22	65	0.77±0.01^{f}	0.03±0.00^{e}
70	22	40	0.80±0.00^{e}	0.10±0.00^{f}
70	22	50	0.77±0.00^{f}	0.02±0.00^{e}
70	22	65	0.75±0.00^{g}	0.02±0.00^{g}
45	40	40	0.80±0.00^{e}	0.12±0.00^{a}
45	40	50	0.80±0.00^{e}	0.05±0.01^{c}
45	40	65	0.74±0.01^{h}	0.02±0.00^{e}
60	40	40	0.80±0.00^{e}	0.10±0.00^{f}
60	40	50	0.78±0.00^{c}	0.02±0.00^{g}
60	40	65	0.73±0.00^{k}	0.02±0.00^{h}
70	40	40	0.78±0.00^{c}	0.08±0.00^{k}
70	40	50	0.73±0.00^{k,h}	0.02±0.00^{h}
70	40	65	0.69±0.00^{m}	0.01±0.00^{m}

$^{a-m}$ Means in a column with different letters are significantly different (P<0.05).
^{1} After osmotic dehydration (OD), ^{2} after vacuum frying (VF)
Mango:syrup ratio = 4:1

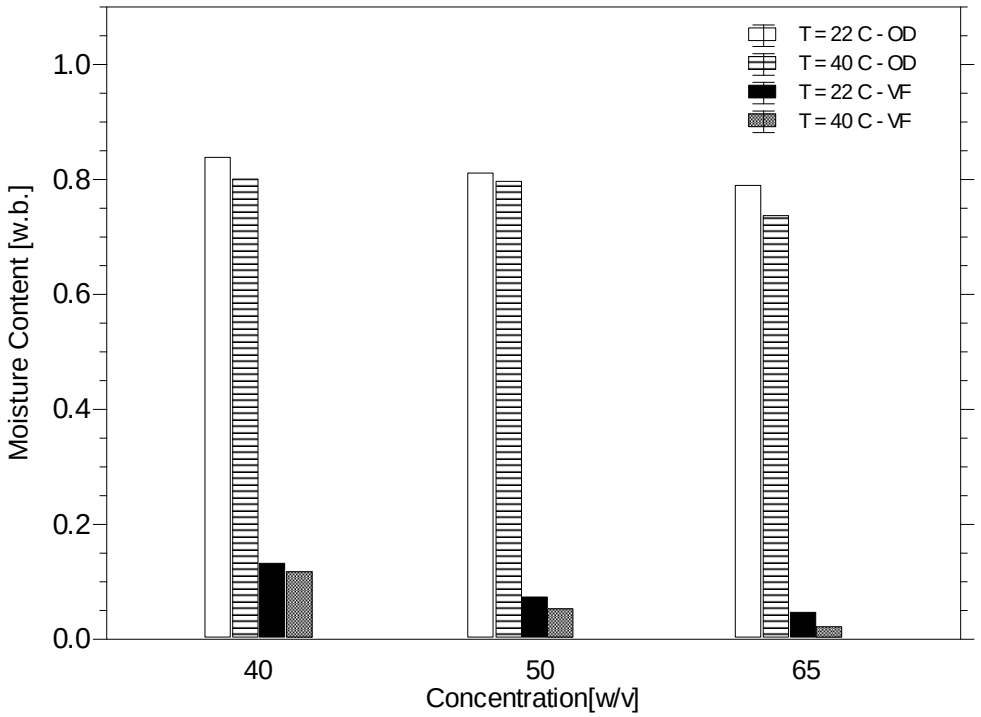


Fig. 4-3 Moisture content (MC) of mango slices pre-treated (mango:syrup ratio = 1:4) with different osmotic solution concentrations and temperatures for 45 min then vacuum fried at 120^{o}C for 2 min.

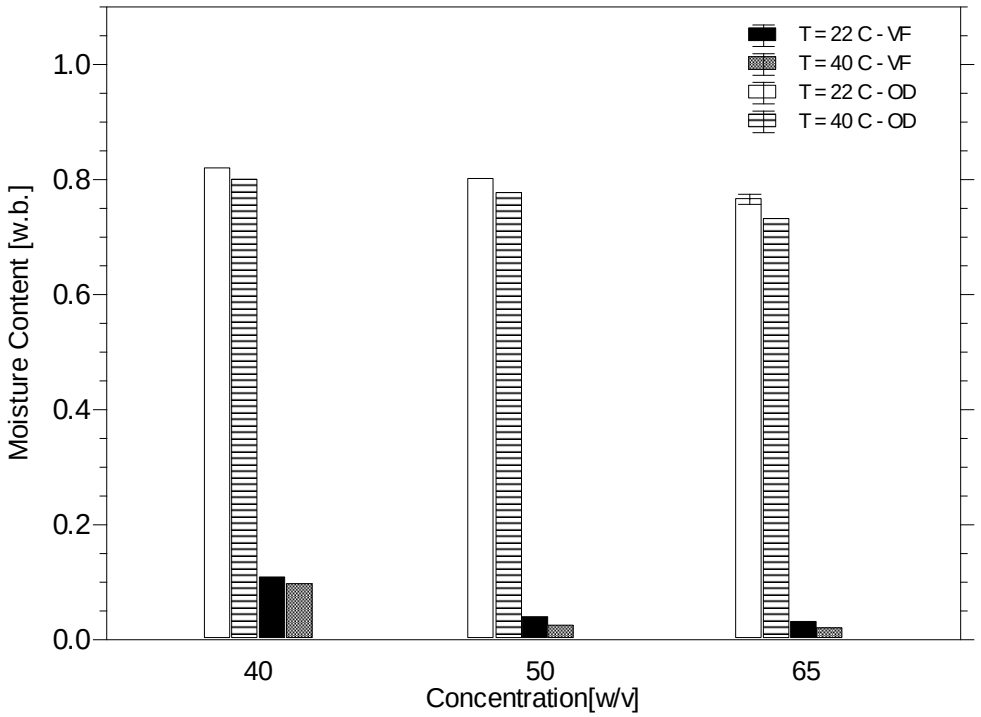


Fig. 4-4 Moisture content (MC) of mango slices pre-treated (mango:syrup ratio = 1:4) with different osmotic solution concentrations and temperatures for 60 min then vacuum fried at 120^{o}C for 2 min.

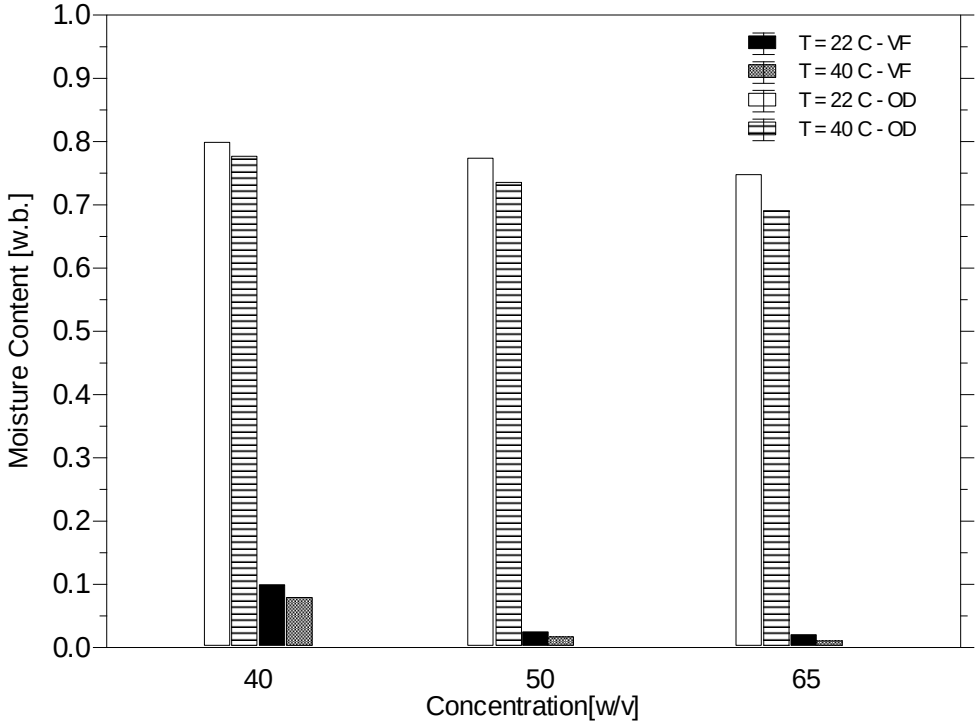


Fig. 4-5 Moisture content (MC) of mango slices pre-treated (mango:syrup ratio = 1:4) with different osmotic solution concentrations and temperatures for 70 min then vacuum fried at 120^{o}C for 2 min.

4.2.2 Water activity

It is well know that water activity (a_w) can be decreased by removing water or by adding solutes to the fruit. Tables 4-4 to 4-6 show the effect of concentration and temperature for different times on the water activity of the mango slices. No significant (P>0.05) changes in a_w (0.98) of the samples treated at different concentrations and temperatures were observed (Table 4-4).

Similar results were observed for Mujica-Paz, Valdez-Fragoso, Lopez-Malo, Palou, & Welti-Chanes (2003) who studied the changes in water activity (a_w) for mango, melon, and apple concluding that this property decreases when the concentration of the osmotic solution increases. They found that the lowest water activity of mango was 0.985 when the OD concentration was 60^o Brix at 25^o C.

4.2.3 pH

The pH of raw mango was around 3.4 to 4.1. There was no clear effect of OD on the pH value of mango slices (Tables 4-4 to 4-6). In most of the cases the pH decreased due to the 0.15% citric acid added into the solution before OD. The pH value decreased down to around 4-5% in some cases.

The use of citric acid was mainly to control the pH of mango slices to obtain better product's color during vacuum frying (Da Silva & Moreira, 2008).

4.2.4 Degree brix

The ^{o}Brix of raw mangoes used in this experiment was around 12 to 15 ^{o}Brix. As was expected, a significant increase (P<0.05) in ^{o}Brix (Tables 4-4 to 4-6) was observed

for each OD concentration, time, and temperature during OD. This increase is attributed to the sugar gain and water loss during the OD process.

When water is flowing out of the mango slices during the osmotic process, the concentration of sugar in the sample goes up, creating even higher value of ^{o} Brix. The higher the osmotic solution concentration, the higher the ^{o}Brix. In Tables 4-4 to 4-6 the highest ^{o}Brix in the mango slices was for 65w/v at 40^{o} C.

Table 4-4 Brix, a_w, and pH values before (B) and after (A) osmotic dehydration (OD) (Mango:syrup ratio = 1:4) for 45 min, for each concentration and temperature in the process.

OD Temperature [^{o}C]	**OD Concentration [w/v]**	**a_w**	**pH**	**^{o}Brix [gsugar/gsolution]**
22	40(B)	0.98±0.00^{a}	3.98±0.04^{a}	12.95±0.05^{a}
22	40(A)	0.98±0.00^{a}	3.77±0.02^{b}	15.86±0.80^{b}
22	50(B)	0.97±0.00^{b}	4.05±0.01^{c}	12.92±0.28^{a}
22	50(A)	0.97±0.00^{b}	3.90±0.01^{d}	18.00±0.86^{c}
22	65(B)	0.98±0.00^{a}	3.98±0.04^{a}	13.03±0.13^{a}
22	65(A)	0.98±0.00^{a}	3.77±0.01^{b}	21.43±0.37^{d}
40	40(B)	0.98±0.00^{a}	4.03±0.01^{e}	14.00±0.17^{e}
40	40(A)	0.98±0.00^{a}	3.99±0.02^{a}	18.86±0.80^{c}
40	50(B)	0.98±0.00^{a}	3.41±0.02^{f}	11.57±0.36^{g}
40	50(A)	0.98±0.00^{a}	3.43±0.02^{f}	18.25±0.05^{c}
40	65(B)	0.98±0.00^{a}	3.52±0.02^{g}	12.1±0.17^{h}
40	65(A)	0.98±0.00^{b}	3.51±0.02^{g}	20.56±0.50^{k}

$^{a-k}$ Means within a column for each parameter (a_w, pH and ^{o} Brix) with different letters are significantly different ($P<0.05$)

Table 4-5 Brix, a_w, and pH values before (B) and after (A) osmotic dehydration (OD) (Mango:syrup ratio = 1:4) for 60 min, for each concentration and temperature in the process.

OD Temperature [^{o}C]	**OD Concentration [w/v]**	a_w	**pH**	**^{o}Brix [gsugar/gsolution]**
22	40(B)	0.98±0.00^a	3.76±0.01^b	13.67±0.28^a
22	40(A)	0.98±0.00^a	3.56±0.02^c	17.25±0.00^b
22	50(B)	0.98±0.00^a	3.77±0.00^b	13.97±0.06^d
22	50(A)	0.98±0.00^a	3.57±0.04^c	18.86±0.00^e
22	65(B)	0.98±0.00^a	4.09±0.03^d	13.96±0.06^d
22	65(A)	0.98±0.00^b	4.00±0.02^e	22.35±0.00^f
40	40(B)	0.98±0.00^a	4.09±0.03^d	13.66±0.28^a
40	40(A)	0.98±0.00^a	4.06±0.03^e	19.19±0.00^g
40	50(B)	0.98±0.00^a	4.07±0.03^e	13.50±0.50^a
40	50(A)	0.98±0.00^b	3.98±0.03^e	20.78±0.00^h
40	65(B)	0.98±0.00^a	4.07±0.03^e	13.97±0.06^a
40	65(A)	0.97±0.00^c	4.00±0.05^e	25.66±0.00^j

$^{a-j}$ Means within a column for each parameter (a_w, pH and ^{o} Brix) with different letters are significantly different ($P<0.05$)

Table 4-6 Brix, a_w, and pH values before (B) and after (A) osmotic dehydration (OD) (Mango:syrup ratio = 1:4) for 70 min, for each concentration and temperature in the process.

OD Temperature [^{o}C]	**OD Concentration [w/v]**	a_w	**pH**	**^{o}Brix [gsugar/gsolution]**
22	40(B)	0.98±0.01^a	3.98±0.01^a	13.33±0.63^a
22	40(A)	0.98±0.00^a	3.95±0.02^a	19.09±0.00^b
22	50(B)	0.98±0.00^a	4.05±0.02^b	14.16±0.38^{a,d}
22	50(A)	0.97±0.00^a	3.99±0.02^a	21.55±0.00^c
22	65(B)	0.98±0.00^a	4.09±0.03^b	14.40±0.36^d
22	65(A)	0.97±0.00^b	4.00±0.02^a	24.67±0.00^e
40	40(B)	0.98±0.00^a	4.09±0.03^b	14.40±0.36^d
40	40(A)	0.97±0.00^b	4.06±0.03^b	21.78±0.00^f
40	50(B)	0.98±0.00^a	4.07±0.03^b	14.42±0.29^d
40	50(A)	0.97±0.00^b	3.98±0.03^a	25.41±0.00^g
40	65(B)	0.98±0.00^a	4.07±0.03^b	14.42±0.29^d
40	65(A)	0.96±0.00^c	4.00±0.05^b	30.19±0.00^j

$^{a-j}$ Means within a column for each parameter (a_w, pH and ^{o} Brix) with different letters are significantly different ($P<0.05$)

4.3 Effect of osmotic dehydration on the water loss and sugar gain

4.3.1 Water loss

Water loss (Table 4-7 and Fig. 4-6) in mango slices after OD was calculated using Equation 3-4 for each pre-treatment. Water loss in mango is an effect of concentration, time, and temperature during OD. Water removal is a characteristic of prime importance in this study; it indicates the effectiveness of the process.

Lazarides, Katsanidis, & Nickolaidis (1995) found that in apple slices the maximum water loss (64%) occurred at the highest concentration (65 w/w) and temperature (50^{o}C) after 3 h of OD. Also, Lombard, Oliveira, Fito, & Andres (2008) concluded in their kinetic study with pineapple pre-treated with an OD solution (45-65^{o}Brix at 30 to 50^{o}C for 20 to 240 min), that water loss is mainly affected by temperature. They selected a parameter (high/low water loss and high/low solids gain) for quality evaluation.

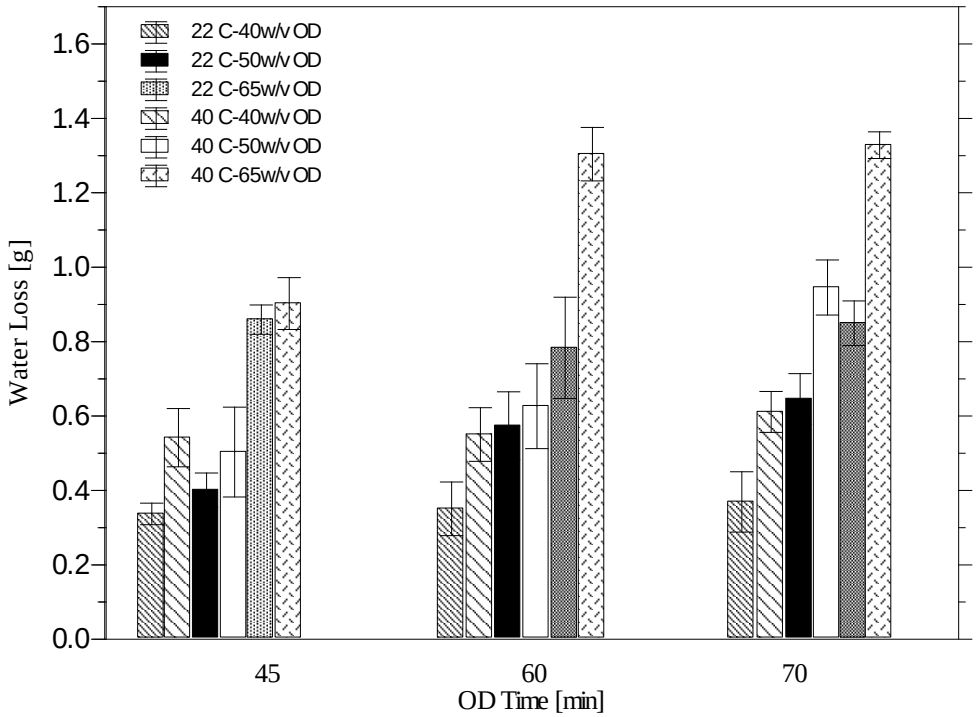


Fig. 4-6 Water loss (W_L) in mango slices at different OD times, concentrations, and temperatures (Mango:syrup ratio = 1:4).

Table 4-7 Water loss (W_L), sugar uptake (S_U) and water loss to sugar uptake ratio (W_L/S_U) at different times, concentrations, and temperatures for the OD process (mango:syrup ratio = 4:1).

OD Temperature [^oC]	OD Time [min]	OD Concentration [w/v]	W_L [g water/g product]	S_U [g sugar/g product]	W_L/S_U [g/g]
22	45	40	$_{a}0.34\pm0.03^{a}$	$_{a}0.09\pm0.01^{a}$	$_{a}4.10\pm1.05^{a}$
22	45	50	$_{c}0.40\pm0.05^{a,d}$	$_{b}0.09\pm0.00^{a}$	$_{c}4.37\pm0.86^{a}$
22	45	65	$_{e}0.85\pm0.04^{b}$	$_{c}0.18\pm0.02^{b}$	$_{d}4.98\pm0.80^{a}$
40	45	40	$_{g}0.54\pm0.08^{c,d}$	$_{e}0.12\pm0.01^{c}$	$_{f}4.74\pm1.44^{a}$
40	45	50	$_{h}0.50\pm0.12^{d}$	$_{f}0.14\pm0.00^{c}$	$_{g}3.60\pm0.93^{a}$
40	45	65	$_{k}0.90\pm0.07^{b}$	$_{h}0.18\pm0.02^{b}$	$_{j}5.13\pm0.94^{a}$
22	60	40	$_{a}0.35\pm0.07^{e}$	$_{a}0.09\pm0.02^{d}$	$_{a}3.94\pm1.45^{b}$
22	60	50	$_{d}0.57\pm0.09^{f}$	$_{b}0.11\pm0.02^{d}$	$_{c}5.25\pm1.23^{b,c}$
22	60	65	$_{f}0.78\pm0.14^{g}$	$_{c,d}0.20\pm0.01^{e,f}$	$_{e}4.11\pm0.92^{b}$
40	60	40	$_{g}0.55\pm0.07^{f}$	$_{e}0.14\pm0.02^{f}$	$_{f}3.92\pm0.86^{b}$
40	60	50	$_{h}0.63\pm0.11^{f}$	$_{f,g}0.17\pm0.03^{f}$	$_{g}3.75\pm0.62^{b}$
40	60	65	$_{l}1.30\pm0.07^{e}$	$_{h}0.20\pm0.02^{e}$	$_{k}6.38\pm0.75^{c}$
22	70	40	$_{b}0.37\pm0.08^{h}$	$_{a}0.15\pm0.01^{g}$	$_{b}2.52\pm0.73^{d}$
22	70	50	$_{d}0.65\pm0.07^{j}$	$_{b}0.15\pm0.02^{g}$	$_{c}4.41\pm1.12^{d,e,f,g}$
22	70	65	$_{e}0.85\pm0.06^{k}$	$_{d}0.23\pm0.02^{h}$	$_{d}3.63\pm0.62^{d,e,f}$
40	70	40	$_{g}0.61\pm0.06^{j}$	$_{e}0.15\pm0.02^{g}$	$_{f}4.15\pm0.88^{f}$
40	70	50	$_{i}0.95\pm0.07^{k}$	$_{g}0.18\pm0.02^{j}$	$_{h}5.45\pm1.00^{g}$
40	70	65	$_{m}1.33\pm0.04^{l}$	$_{h}0.21\pm0.01^{h}$	$_{k}6.31\pm0.30^{h}$

[a-k] Means within a column with different superscript letters are significantly different ($P<0.05$)
[a-m] Means within a column with different subscript letters are significantly different ($P<0.05$)

Water loss will not only affect the final composition of the product but also the sensorial quality and stability of the product (Lombard *et al*, 2008). In this study, the highest water loss (about 35% w.b.) corresponded to the highest osmotic solution (OS) concentration (65w/v) and OD time (70 min) at 40^{o}C. The lowest water removed (about 10% w.b.) corresponded to the lowest OS concentration (40w/v), temperature (22^{o}C), and time (45min) during OD. These results agree with the results found by Lazarides *et al* (1995), Lombard *et al* (2008), and Giraldo *et al* (2003). The OS concentration is a

very important parameter for water loss during OD because it determines the diffusion of water from the mango to the OS due to an hydrodynamic mechanism. The higher the concentration the greater the hydrodynamic force to remove water. Lazarides, Katsanidis, & Nickolaidis (1995) obtained most of the water loss (25%) removed during the first hour while it took 3 hours to remove 40% of the water in the apples. They found also an increase in water loss when increasing the solutes in the osmotic solution.

Temperature is also an important factor for water removal; higher temperature softens the mango tissue and the water removal process is faster. An increase of the temperature results in a decrease of the viscosity of the OS. This improves the surface contact between material and solution and results in an enhanced dewatering effect. Fig. 4-6 shows the increasing trend of water loss as the OD concentration, temperature, and time increase.

One of the objectives of this study was to minimize oil absorption during frying, which is linked to the initial moisture content of the sample before frying. Therefore, pre-treatments (65 w/v, 60, or 70 min, and 40^{o}C) resulting in high water loss were preferred for further frying.

4.3.2 Sugar uptake

The sugar uptake in mango slices at different concentration, time, and temperatures during OD are shown in Table 4-7 and Fig 4-7. Sugar gain during the OD is affected mostly by OD concentration and time, and sample thickness (Madamba & Lopez, 2002). Fig. 4-7 shows the increasing tendency for sugar uptake when the OS concentration increases, as well as for time. When using the highest concentration (65w/v) no significant ($P>0.05$) sugar gain value (about 5% w.b. for 45 min and 60 min, and 6% for 70 min) was observed for each OD time at 22 and 40^{o}C.

Hydrodynamic mechanisms (HDM) are responsible for the gain of external solution in the sample pores (Chiralt & Talens, 2005) in this case attributed to OD with maltodextrin. The mechanism of maltodextirn uptake mechanism can be explained at the moment before the sample membranes get loose, and the external solutes diffuse freely to all parts of the tissue. During OD, a sugar uptake effect is considered to cause the changes in mango slices sugar content.

It seems that the osmotic solute is a major effect for sugar uptake, as well as OD time. Lombard, Oliveira, Fito & Andres (2008) found an increase in the sugar content in pineapple pre-treated with sucrose solution due to an increase of the OD time of the OS (20 to 240 min). However, Giraldo, Talens, Fito & Chiralt (2003) obtained a slightly increase in the sugar gain rate constant (0.00037 s^{-5}) when the osmotic solution concentration was lower (35^{o}Brix).

They found that the overall mass loss rate of the samples increased when the OS concentration increased from 35^{o} Brix to 55^{o} Brix remaining constant after 55^{o} Brix.

Sugar penetration is inversely related to the size of the sugar molecule (Lazarides *et al*, 1995) in the OS. Lazarides, Katsanidis, & Nickolaidis (1995) found that corn syrup solids of large molecular size (<38 DE) gave negative solid gain values in apples during OD. In this study the maltodextrin used was 24 DE because of the minimal amount of sugar needed to improve mango chips quality characteristics.

OD temperature had an insignificant ($P>0.05$) effect on sugar uptake when using OD concentration of 65w/v. For 45 min and 60 min OD, the temperature caused a significant effect ($P<0.05$) for 40 and 50w/v OD concentrations. For 70 min OD no differences in sugar gain were observed for each OD concentration for both temperatures (22 and 40^{o}C). This last treatment was more effective for water loss (Fig. 4-7).

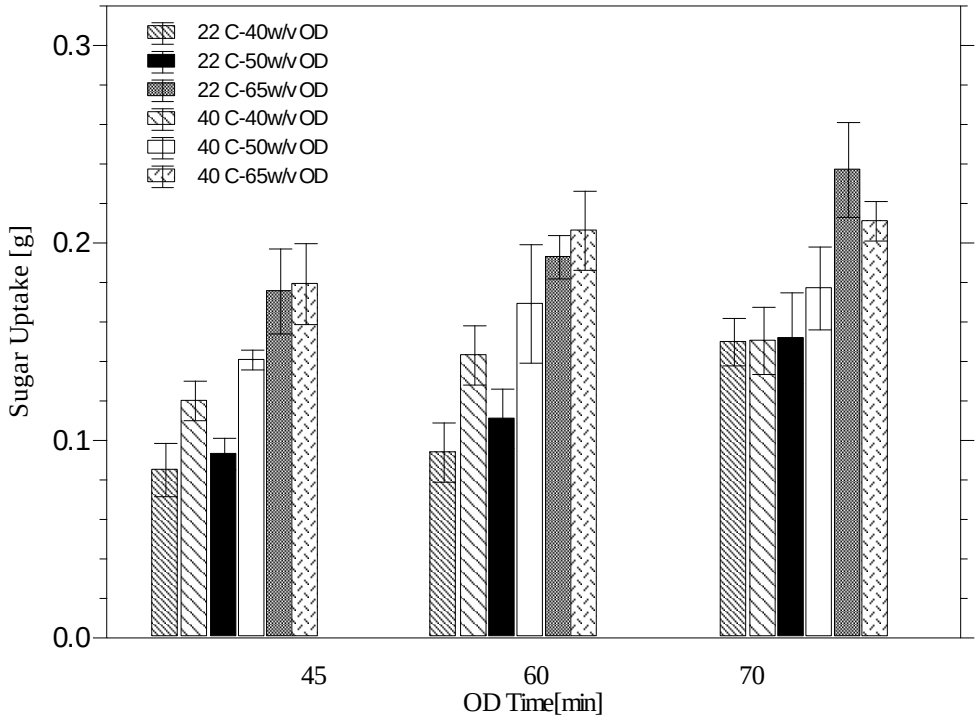


Fig. 4-7 Sugar uptake (S_U) in mango slices at different OD times, concentrations, and temperatures (mango:syrup ratio = 1:4).

4.3.3 Dehydration efficiency index

Dehydration efficiency index (DEI), which is the ratio of water loss/sugar uptake (W_L/S_U), helped to obtain the best pre-treatment for further vacuum frying. The best pre-treatment is the one with a highest value of DEI, with some sugar uptake to give the desired product properties. Table 4-7 shows that for 45 min, there was not significant effect (P>0.05) of OS concentration (40, 50, and 65w/v) and temperature (22 and 40^{o}C) on DEI (about 4.5 g of water loss/g of sugar uptake) during OD. Osmotic dehydration for 60 min showed similar effects for DEI (about 4.2 g of water loss/g of sugar uptake) as for 45 min for 40 and 50w/v OS concentrations at 22 and 40^{o}C. However, the highest DEI (about 6.4 g of water loss/g of sugar uptake, the highest DEI) was obtained at 65 w/v at 40^{o}C for OD of 60 min. In the case of 70 min OD, more differences among OS concentrations and OD temperatures were observed (Fig. 4-8). At this OD time, mango tissue starts to get loose due to intense hydrodynamic mechanism and the rate migration of sugar from the OS into the sample increases.

Solution concentration, OD temperature, and process duration have an impact on DEI. Regular and high OD concentrations result in an increased in water loss and sugar uptake rates favoring higher DEI values (Lazarides, 2001). Madamba & Lopez (2002) concluded that the variable mostly affecting water loss and sugar gain in mango slices during OD with sucrose was time. Saputra (2001) found that the highest mass transfer rate in pineapple, when using sucrose as the osmotic agent, was at the highest concentration (70%) and time (9 hours) at 50^{o}C.

An increase in OD temperature increases water loss rate giving higher value of DEI (Lazarides *et al*, 1995). However, since one of the targets of this work was to get high quality mango chips, the use of high temperatures (above 45^{o}C) can cause damage in the mango tissue resulting in flavor deterioration and enzymatic browning (Farkas *et al*, 1969; Heng *et al.*, 1990; Torreggiani, 1993).

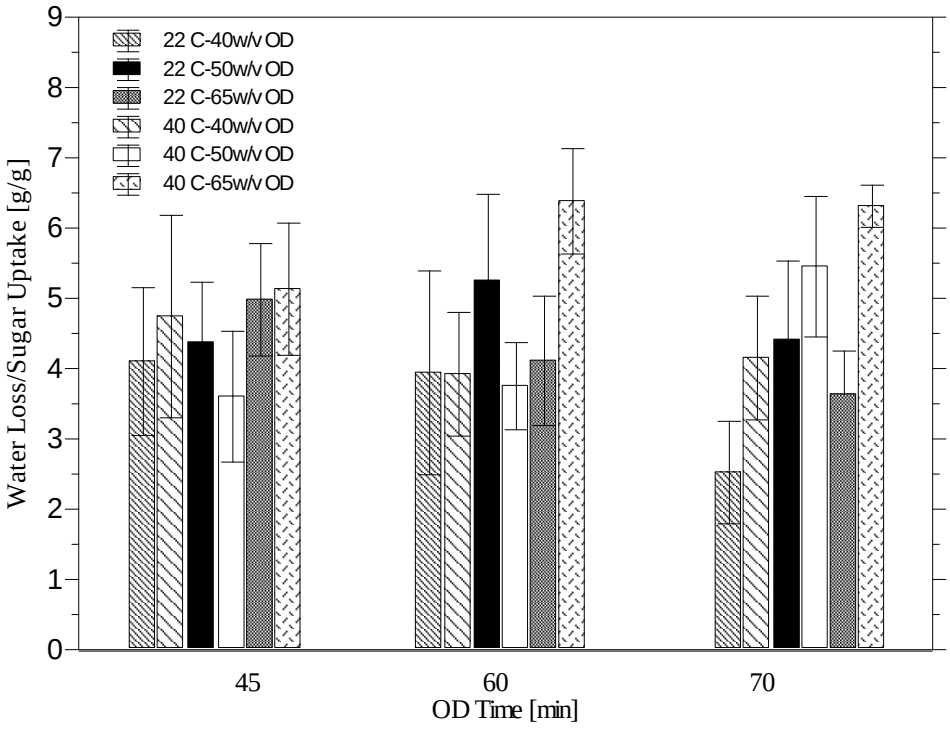


Fig. 4-8 Water loss/sugar uptake (W_L/S_U) in mango slices at different OD times, concentrations, and temperatures (mango:syrup ratio = 1:4).

4.4 Effect of osmotic dehydration and vacuum frying on mango chips product quality attributes (PQA)

4.4.1 Shrinkage

4.4.1.1. Shrinkage during osmotic dehydration

Table 4-8 shows the effects of OD at different times (45, 60, and 70 min), temperatures (22 and 40^{o}C) and concentrations (40, 50, and 65w/v). The greatest change in diameter size after OD (10.19±0.94%) occurred during 70 min and 65w/v at 40^{o}C. These changes in diameter during OD are extremely related to the OD concentration, temperature, and time. Plant tissue shrinks during the osmotic treatment as a result of the water removal from the symplasma (protoplasts) (Behsnilian & Spiess, 2006). There is a relationship between the water removed during OD and the degree of shrinkage in potato, reported by Lazarides and Mavoroudis (1996). In apple slices this effect has also been observed by Mavoroudis *et al* (1998) when increasing the temperature from 5 to 40^{o}C and OD time.

Table 4-8 Effect of time, solution concentration, and temperature during OD (mango: syrup ratio = 1:4) on mango diameter degree of shrinkage after vacuum frying at 120°C for 2 min (P = 1.33 kPa, de-oiled at 225 rpm for 25s).

Time[min]	Temperature[°C]	Concentration [w/v]	% Shrinkage after OD	% Shrinkage after VF
45	22	40	1.72 ± 0.28^{a}	2.52 ± 0.39^{a}
45	22	50	2.07 ± 0.28^{a}	4.97 ± 0.97^{b}
45	22	65	3.80 ± 0.45^{b}	8.85 ± 2.00^{c}
45	40	40	1.82 ± 0.57^{a}	2.68 ± 0.65^{a}
45	40	50	3.20 ± 0.42^{b}	5.43 ± 0.85^{b}
45	40	65	7.96 ± 1.05^{c}	12.02 ± 1.31^{c}
60	22	40	1.93 ± 0.22^{f}	4.95 ± 0.93^{e}
60	22	50	$2.25\pm0.58^{f,h}$	5.49 ± 0.81^{e}
60	22	65	4.05 ± 0.65^{g}	9.14 ± 0.30^{f}
60	40	40	2.63 ± 0.32^{h}	5.29 ± 0.85^{e}
60	40	50	$3.57\pm0.87^{g,h}$	6.66 ± 1.03^{e}
60	40	65	9.74 ± 0.46^{k}	14.52 ± 2.32^{g}
70	22	40	2.14 ± 0.41^{l}	3.05 ± 0.75^{k}
70	22	50	4.28 ± 0.92^{m}	$8.10\pm1.01^{m,p}$
70	22	65	4.55 ± 0.85^{m}	10.58 ± 2.30^{m}
70	40	40	2.34 ± 0.62^{l}	3.26 ± 0.12^{k}
70	40	50	5.01 ± 0.74^{m}	11.07 ± 1.3^{p}
70	40	65	10.19 ± 0.94^{n}	15.00 ± 1.5^{q}

[a-n] Means in a column with different letters are significantly different (P<0.05)
[a-q] Means in a column with different letters are significantly different (P<0.05)
VF = Vacuum frying, OD = Osmotic dehydration.

Another important factor for water removal is the OD concentration (Girald *et al*, 2003). The higher the OD concentration the greater the water removed as well as the sugar uptake. This sugar uptake can also cause more solids and less water available in the sample. Fig. 4-6 and 4-9 shows the relationship between the water loss and degree of shrinkage in the radial direction during OD of mango slices. Sample tissue shrinks provoking changes in the radial direction due to water loss. Mango slices shrinkage is mainly produced by HDMs (hydrodynamic mechanisms) which depend basically on OD

times, temperatures, and concentrations. High values of the degree of shrinkage is not preferred by the consumer; however, when the slices were subjected to vacuum frying a radial expansion was observed (Fig. 4-10) for all chips resulting in an expected round shape.

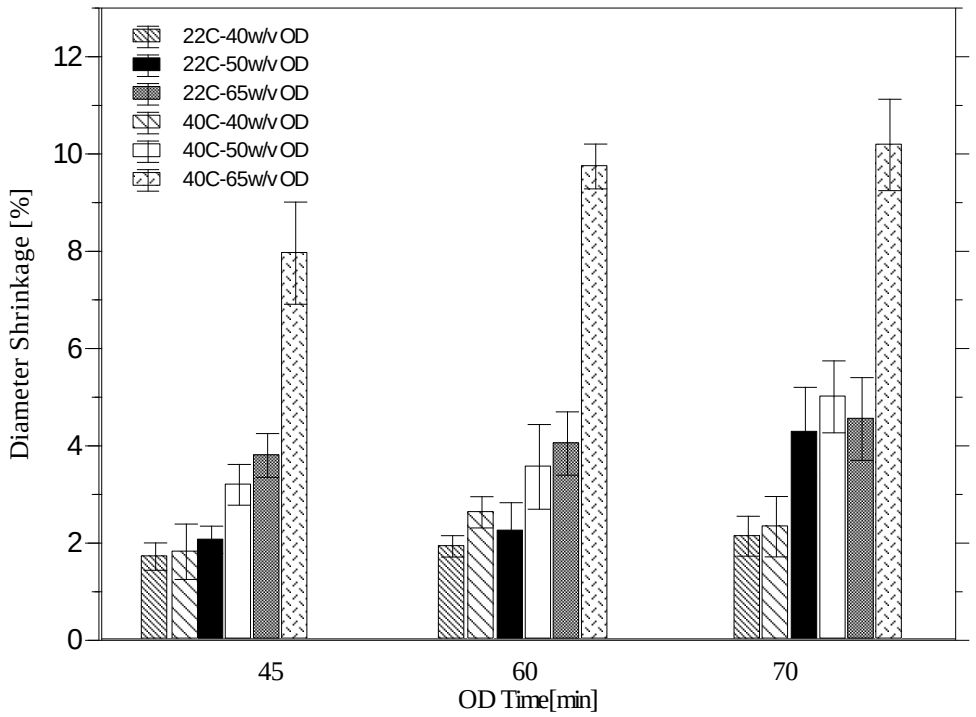


Fig. 4-9. Degree of shrinkage in diameter [%] for mango slices after OD at different times, temperatures, and OS concentrations (mango:syrup ratio = 1:4).

4.4.1.2. Shrinkage during vacuum frying

Fig. 4-10 shows the degree of shrinkage on vacuum-fried pre-treated mango chips. The highest degree of shrinkage was 15.00±1.5 ($P<0.05$) when vacuum frying at 120^{o}C for 2 min. These results were found when the samples were pre-treated at the highest OS concentration (65 w/v) and time (70 min) at 40^{o}C. The degree of shrinkage in mango chips depends on OD time, temperature, and concentration, since removing water from the sample reduces its volume. The degree of shrinkage is related to the water loss and oil uptake (Moreira *et al*, 1999; Caixeta *et al*, 2001; Tran *et al*; 2007). In Table 4-8 and Fig. 4-9 the effect of high concentration (65 w/v) at 40^{o}C in the OD solution resulted in higher degree of shrinkage in mango slices; however, this effect was less significant after vacuum frying (Fig. 4-10).

Taiwo, Baik & Farinu (2007) observed that by using OD the in sweet potato sample shrunk less than when using blanching or air-drying pre-treatments after traditional frying (atmospheric pressure). Kawas-Escoto (2000) obtained about 9% degree of shrinkage in tortilla chips with no pre-treatment after traditional frying process (T = 170^{o}C for 0.5-5 min).

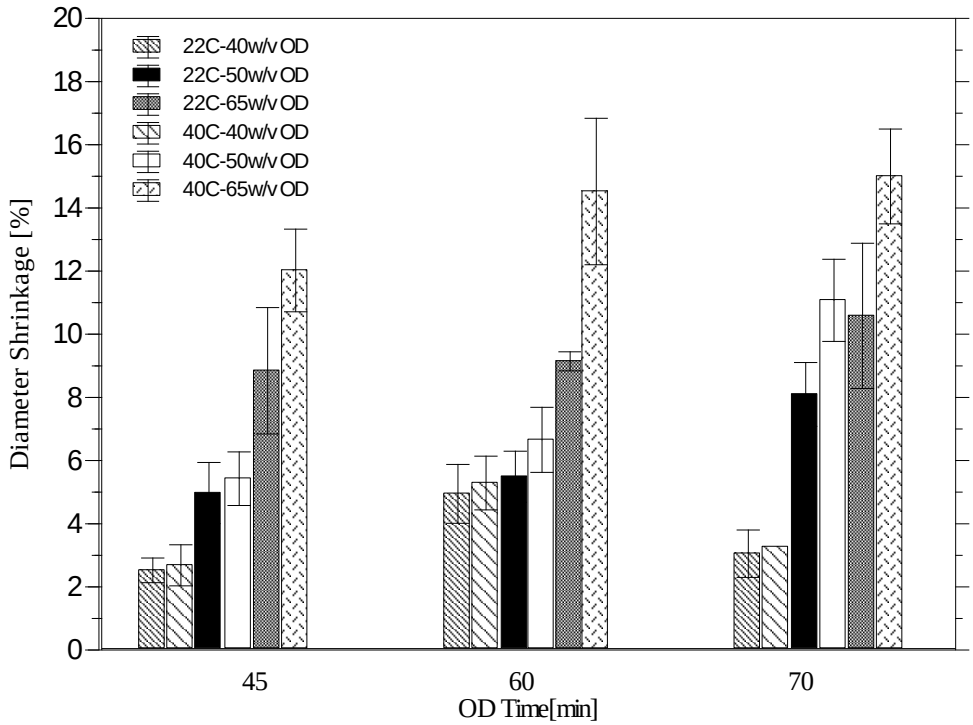


Fig. 4-10. Degree of shrinkage in diameter [%] for vacuum fried mango chips at 120^{o}C for 2 min (P = 1.33 kPa, de-oiled at 225 rpm for 25 s). Effect of OD at different times, temperatures, and OS concentrations (mango:syrup ratio = 1:4).

4.4.2 Texture

The effect of OS concentration, time, and temperature on the mango chips texture after vacuum frying at 120^{o}C for 2 min is shown in Fig. 4-11 and 4-12. Table 4-9 shows the results to compress mango chips pre-treated using different OD parameters (concentration, time, and temperature). The maximum force (peak) (7.61±1.10 N), when compressing 5 slices, was found when using the pre-treatment with 65w/v OS concentration, 70 min, and 40^{o}C. However, this value was not significantly different (P>0.05) from those pre-treatment obtained for 65w/v (22^{o}C) and 50w/v (40^{o}C). Low values of the maximum force (around 5 N) and work (around 28 N*mm) were considered an indicator of 'sogginess' on the mango chips (Table 4-10). In both cases, the texture (peak force and work) increases when OS concentration, OD time, and temperature increase.

Table 4-9 Effect of time, solution concentration, and temperature during OD (mango:syrup ratio = 1:4) on mango chips texture (peak and work) after vacuum fried at 120^{o} C for 2 min (P= 1.33 kPa, and de-oiled at 225 rpm for 25 s).

Time [min]	Temperature [^{o}C]	Concentration [w/v]	Force Peak [N]	Work [N*mm]
45	22	40	1.87±0.64^{a}	3.37±0.78^{a}
45	22	50	5.33±0.81^{b}	22.44±3.12^{b}
45	22	65	4.76±1.37^{b}	11.75±2.33^{c}
45	40	40	4.70±1.17^{b}	7.52±1.62^{d}
45	40	50	5.84±0.71^{b}	24.62±3.46^{b}
45	40	65	4.83±1.40^{b}	19.28±4.61^{e}
60	22	40	5.02±0.99^{c}	20.65±2.87^{f,g}
60	22	50	5.84±0.88^{c}	23.08±2.06^{f}
60	22	65	6.16±0.80^{c}	22.66±2.46^{f,g}
60	40	40	6.62±1.25^{c}	21.12±2.03^{g}
60	40	50	5.98±1.04^{c}	30.09±4.69^{g,h}
60	40	65	6.38±1.36^{c}	29.95±4.85^{h}
70	22	40	5.67±1.25^{d}	26.23±3.03^{k}
70	22	50	6.03±1.14^{d,f}	27.35±3.00^{l}
70	22	65	6.90±1.21^{d,f}	33.87±3.22^{m}
70	40	40	6.70±1.02^{d,f}	32.36±3.40^{l,m}
70	40	50	6.20±0.79^{f}	33.17±4.82^{m}
70	40	65	7.61±1.10^{f}	37.76±4.71^{m}

$^{a-f}$ Means within a column with different letters are significantly different (P<0.05)
$^{a-m}$ Means within a column with different letters are significantly different (P<0.05)

The variation was high in the texture data due to several reasons, including the shape of the samples (some samples were a little bent and not uniform), the degree of puffiness, how much they expanded; and possibly small cracks that may increase the error measurement. The increasing values of maximum force (peak) and work (Table 4-9) are the consequences of water loss as an effect of OS concentration, OD temperature, and OD time on mango chips. Baik & Taiwo (2007) used OD as one of their pre-treatments to fry sweet potato, they found that OD increases product hardness. In this study, maltodextrin (sugar) uptake increases hardness in texture since it built up a tighter

structure in the mango chips. The effect of sugar uptake in the microstructure of mango chips is explained in section 4.7.5.

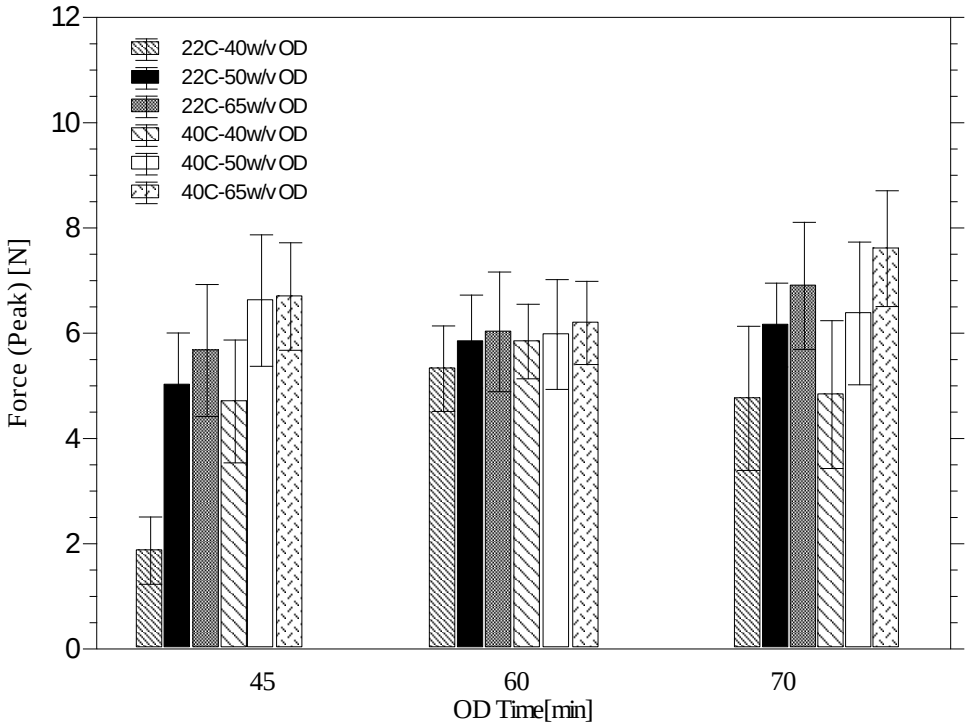


Fig. 4-11. Maximum force (Peak) to compress 5 mango chips pre-treated with OD (mang:syrup ratio = 1:4) at different times, temperatures, and OS concentrations and vacuum fried at 120^{o}C for 2 min (P = 1.33 kPa, and de-oiled at 225 for 25 s).

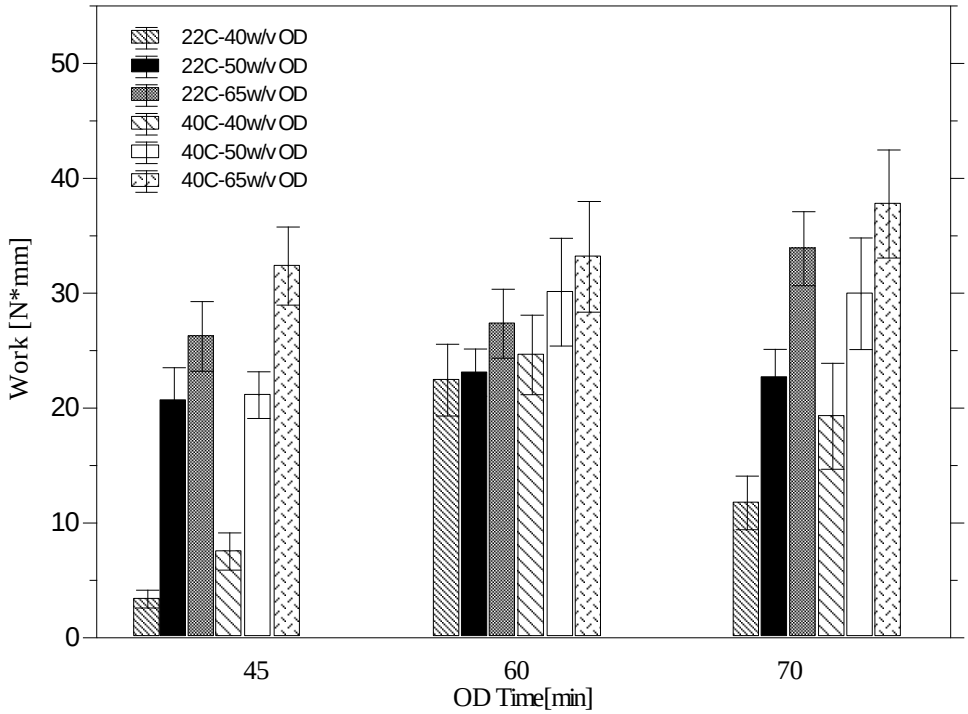


Fig. 4-12. Work done (N*mm) to compress 5 mango chips pre-treated with OD (mang:syrup ratio = 1:4) at different times, temperatures, and OS concentrations and vacuum fried at 120^{o}C for 2 min (P = 1.33 kPa, and de-oiled at 225 for 25 s).

4.4.3. Oil content

Osmotic dehydration pre-treatment affects the total oil content in mango chips (Fig. 4-13). The de-oling system (discussed in section 4.6) removes part of the oil (from 75.4% d.b. to 45% d.b.) at the surface thus decreasing the final oil content in mango chips. The highest oil content (31.85±0.33% w.b.) was obtained at the lowest OS concentration (45w/v), time (45 min), and temperature (22^{o}C). This can be attributed to the moisture content, and the lack of solids uptake, which protect the sample from heating damage. In contrast, the lowest oil content (21.90±0.65 % w.b.) was found with 65w/v, 70 min at 40^{o}C (Table 4-10). Additionally, the fried samples were de-oiled (centrifuging for 25 s at 225 rpm) before removing them from the fryer.

Previous studies show that low initial moisture content results in low oil content (Moreira & Barrufet, 1998; Kawas, 2000; Shyu & Hwang, 2001; Garayo & Moreira, 2002; Torezan *et al*, 2004; Granda, 2005; Fan, 2005; Tran *et al*, 2007). Dehydration of mango slices prior to frying produces more compactness in the fried product due to less water being evaporated during the frying process.

As reported by Da Silva & Moreira (2008), the product structure and composition have an important effect on the oil content of mango slices ("Tommy Atkins" variety). The combination of OD pre-treatment and vacuum frying reduces this effect in fruits due to sugar uptake during OD and lower frying temperatures achieved under vacuum.

Table 4-10 Effects of OD (mango:syrup ratio = 1:4) time, temperature and solution concentration on the oil content (OC) in mango chips vacuum fried (P = 1.33 kPa) at 120^{o} C for 2 min and de-oiled for 25 s at 225 rpm.

Time[min]	Temperature[^{o}C]	Concentration[w/v]	Oil Content [w.b.]
45	22	40	$_{A}31.85\pm0.33^{a}$
45	22	50	$_{C}29.43\pm0.57^{b}$
45	22	65	$_{D}27.66\pm0.41^{b,c}$
45	40	40	$_{F}30.03\pm1.24^{b,d}$
45	40	50	$_{H}28.16\pm1.14^{b,c,d}$
45	40	65	$_{L}25.83\pm0.65^{c}$
60	22	40	$_{A}30.85\pm0.36^{e}$
60	22	50	$_{C}28.72\pm1.13^{f,g}$
60	22	65	$_{D}27.36\pm0.88^{g}$
60	40	40	$_{F}29.15\pm0.58^{e,g}$
60	40	50	$_{H}26.85\pm0.15^{g}$
60	40	65	$_{M}24.11\pm0.66^{h}$
70	22	40	$_{B}28.43\pm0.61^{l,m}$
70	22	50	$_{C}27.93\pm0.19^{m}$
70	22	65	$_{E}24.10\pm0.65^{n}$
70	40	40	$_{G}26.59\pm0.5^{m}$
70	40	50	$_{K}22.94\pm0.66^{n,p}$
70	40	65	$_{N}21.90\pm0.65^{p}$

[a-p] Means within a column with different superscript letters are significantly different (P<0.05) for each OD time (45, 60, and 70 min).

[A-N] Means within a column with different subscript letters are significantly different (P<0.05) for each OD concentration (40, 50, 65 w/v).

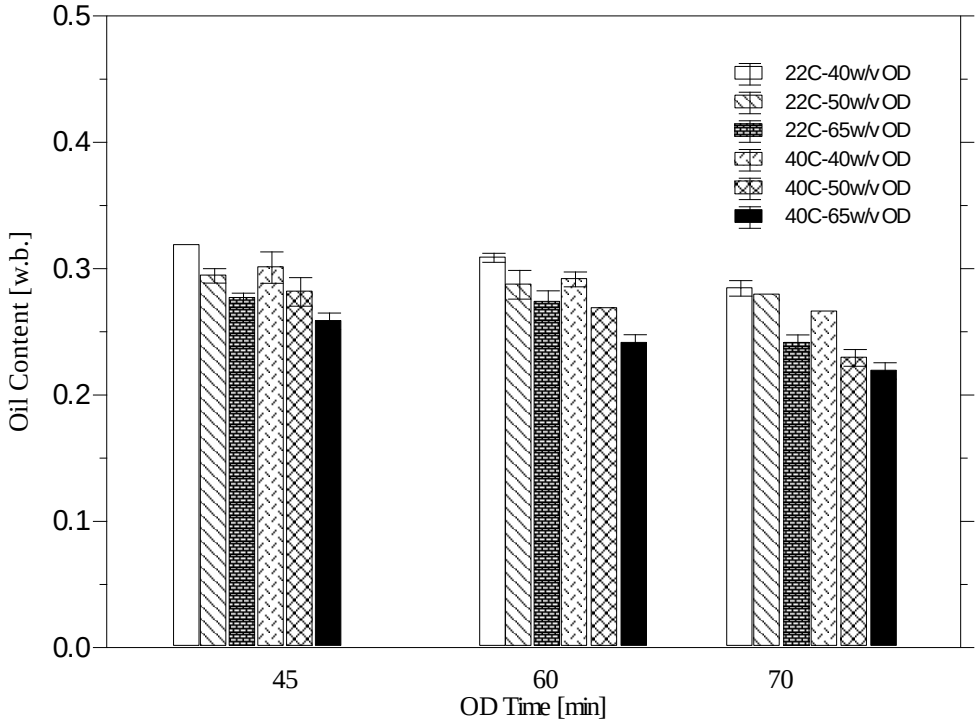


Fig. 4-13. Oil content [w.b.] in mango chips pre-treated with OD (mango:syrup ratio = 1:4) at different times, temperatures, and OS concentrations and vacuum frying at 120^{o}C for 2 min (P = 1.33 kPa, de-oiled at 225 rpm for 25 s).

4.4.4 Color

The differences in color parameters (*L, *a, and *b) from raw to fried mango chips are shown in Figs. 4-14 to 4-16. Table 4-11 gives the values for these parameters as a function of OS concentration, OD time, and temperatures.

Although no real explanation can be given, seems that the changes in color *L increased when OS concentration, OD time, and temperature increase. However, this color reflectance reading effect may occur due to the sugar uptake (maltodextrin) in the mango chips due to OS concentration, which yields a brighter color thus causing error in the color measurement.

Hunter color values *L for 70 min OD and high OS concentrations (50 and 65w/v) were high meaning that the mango chips were too bright (maltodextrin effect); this can confuse consumers by thinking the brightness is due to oil content in the chips.

Table 4-11 Effect of OD (mango:syrup ratio = 1:4) time, temperature and solution concentration on the parameter **L*, **b*, and **a* in mango slices vacuum fried (P = 1.33kPa, de-oiled at 225 rpm for 25 s) at 120^{o} C for 2 min.

Time [min]	**Temperature [^{o}C]**	**OD Concentration [w/v]**	***L**	***a**	***b**
0	22	N/T	$56.94\pm3.36^{a,b,c}$	$7.89\pm1.09^{a,b}$	$59.85\pm3.89^{a,c,d,e}$
45	22	40	54.54 ± 0.31^{a}	7.54 ± 0.51^{a}	59.52 ± 0.14^{a}
45	22	50	56.80 ± 0.47^{b}	7.43 ± 0.58^{a}	67.09 ± 0.18^{b}
45	22	65	62.31 ± 0.27^{c}	8.25 ± 0.13^{b}	60.19 ± 1.14^{c}
45	40	40	47.63 ± 0.16^{d}	9.13 ± 0.16^{c}	64.51 ± 1.11^{d}
45	40	50	65.03 ± 0.30^{e}	9.02 ± 0.60^{c}	57.10 ± 0.33^{e}
45	40	65	66.40 ± 0.12^{f}	11.19 ± 0.47^{d}	63.30 ± 0.42^{d}
0	22	N/T	57.98 ± 0.21^{j}	7.89 ± 0.35^{h}	$60.96\pm1.25^{g,k}$
60	22	40	61.11 ± 1.10^{g}	10.26 ± 0.16^{e}	$63.46\pm0.71^{g,h}$
60	22	50	61.11 ± 1.10^{g}	10.26 ± 0.16^{e}	64.59 ± 0.45^{h}
60	22	65	64.95 ± 0.35^{h}	11.24 ± 0.12^{f}	63.22 ± 0.35^{h}
60	40	40	59.51 ± 0.37^{j}	10.94 ± 0.13^{g}	$62.93\pm0.63^{h,k}$
60	40	50	61.99 ± 4.01^{g}	10.91 ± 0.26^{g}	54.04 ± 0.36^{j}
60	40	65	64.74 ± 0.30^{h}	$11.36\pm0.31^{f,g}$	62.11 ± 0.17^{k}
0	22	N/T	58.81 ± 0.32^{k}	$10.36\pm1.60^{k,l}$	$61.85\pm4.10^{m,n}$
70	22	40	57.85 ± 1.01^{k}	9.28 ± 0.31^{k}	60.60 ± 0.35^{m}
70	22	50	69.36 ± 0.29^{l}	8.36 ± 0.37^{l}	57.89 ± 0.43^{n}
70	22	65	$67.86\pm1.08^{l,m}$	13.37 ± 0.10^{m}	67.66 ± 0.33^{p}
70	40	40	58.85 ± 0.69^{k}	$13.48\pm0.27^{m,n}$	66.49 ± 0.26^{q}
70	40	50	67.80 ± 0.32^{m}	13.6 ± 0.10^{n}	$67.10\pm0.50^{p,q}$
70	40	65	66.69 ± 0.09^{n}	$13.14\pm0.47^{m,n}$	67.71 ± 0.58^{p}

$^{a-p}$ Means within a column with different superscript letters are significantly different ($P<0.05$). N/T = no treatment

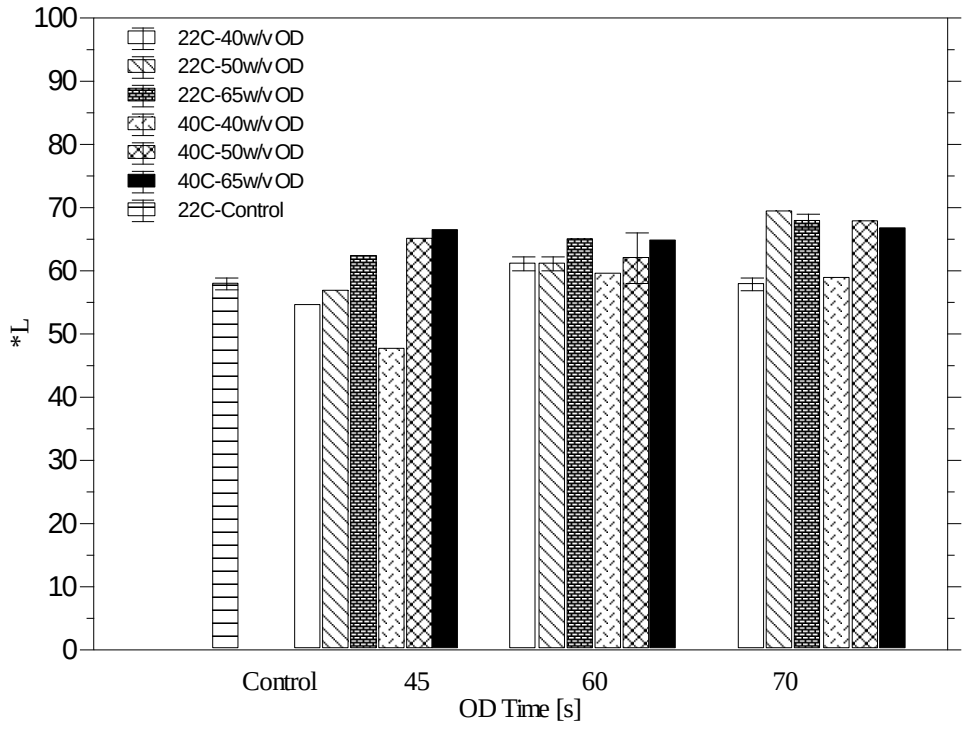


Fig. 4-14. Color *L in mango chips pre-treated with OD (mango:syrup ratio = 1:4) at different times, temperatures, and OS concentrations and vacuum frying at 120^{o}C for 2 min (P = 1.33 kPa, de-oiled at 225 rpm for 25 s).

Color parameters *a and *b are related to non-enzymatic browning reactions and carotenoids content, respectively. More reasonable data were obtained for the parameters *a and *b. Hunter color *a (redness) increases in many dehydration processes for fruits and vegetables representing Maillard reactions during heating (Shi *et al*, 1999; Shyu & Hwang, 2001; Baik & Mittal, 2005; Taiwo *et al*, 2007; Da Silva & Moreira, 2008). In all the cases for OD times, the maximum value for color *a (11.19±0.47, 11.36±0.31, and 13.14±0.47 for 4, 60, and 70 min, respectively) was obtained at 65w/v OS concentration at 40^{o}C (pre-treatment with the maximum water loss) after vacuum frying for 2 min. However, at 60 and 70 min for 65 w/v no significant (P>0.05) change was observed with other OD concentrations when pre-treated at 40^{o}C. The more dehydrated the mango slices the higher value of *a (Fig. 4-15). Also, at higher values of sugar uptake, increased by higher OD concentration, the Maillard reactions can intensify.

In mango slices, the *b color (yellowness) increased with OS concentration and time, and slightly decreased with OD temperature (Fig. 4-16). The maximum value for color *b (64.51±1.11, 63.22±0.35, and 67.66±0.33 for 45, 60, and 70 min) was obtained when using 65w/v OS concentration at 22^{o}C. However, OD at 40^{o}C did not show a significant difference (P>0.05) when pre-treating with 65 w/v concentration at 22^{o}C for 70 min. Color *b can be related to the amount of beta-carotenes present in the mango (yellow color) as reported by Fan (2005) in carrots.

However, beta-carotenes degrade with temperature. The increase in *b when the OS concentration and OD time increases can be attributed to a higher carotenoids concentration due to less water available in the fried sample.

Shyu & Hwang (2001) observed that in apple chips pre-treated with a fructose solution that the values of *a and *b increased after vacuum frying for 30 min at 110^{o}C. Also, Da Silva & Moreira (2008) found also an increase in color *b for green bean, mango, and sweet potato chips pre-treated with maltodextrin as the osmotic agent (50w/v OS concentration) and fried under vacuum (P = 1.33kPa) at 120^{o}C for 360 s.

In this study, *a was high for high OS concentrations and OD times at 40^{o}C, however, this value is mostly attributed to the moisture content since the different pre-treated samples were fried at the same temperature and time (120^{o}C for 2 min). In addition, the *b color was high (around 65) when pre-treating the product with high OS concentrations during 60 and 70 min. Mango has a characteristic yellow color (from 58 to 63), so high values of *b are preferred.

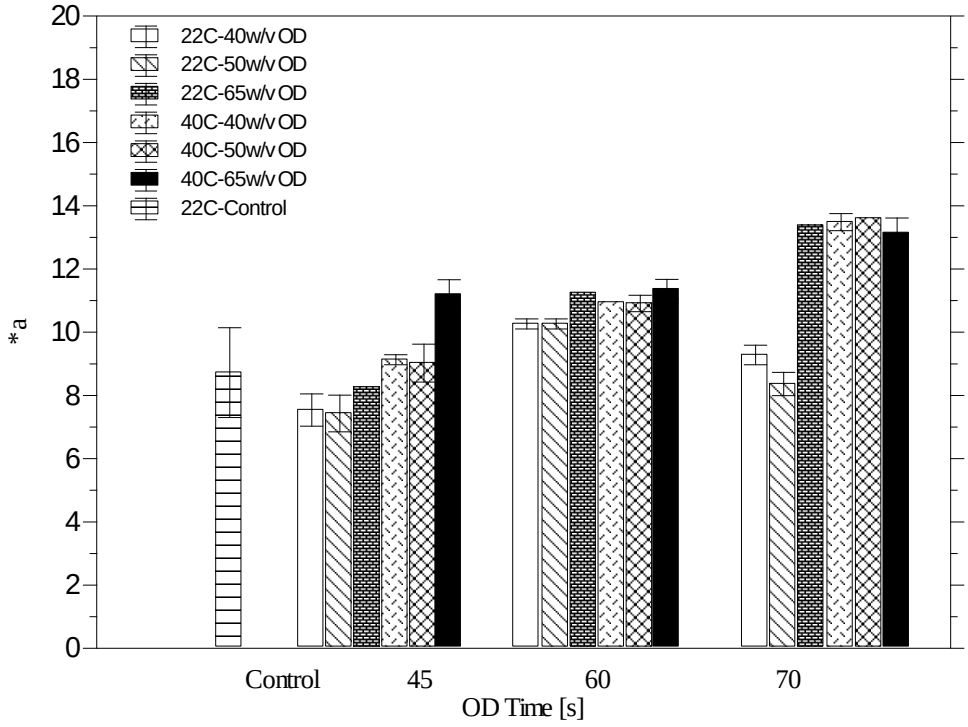


Fig. 4-15. Color **a* in mango chips pre-treated with OD (mango:syrup ratio = 1:4) at different times, temperatures, and OS concentrations, and vacuum frying at 120^{o}C for 2 min (P = 1.33 kPa, de-oiled at 225 rpm for 25 s).

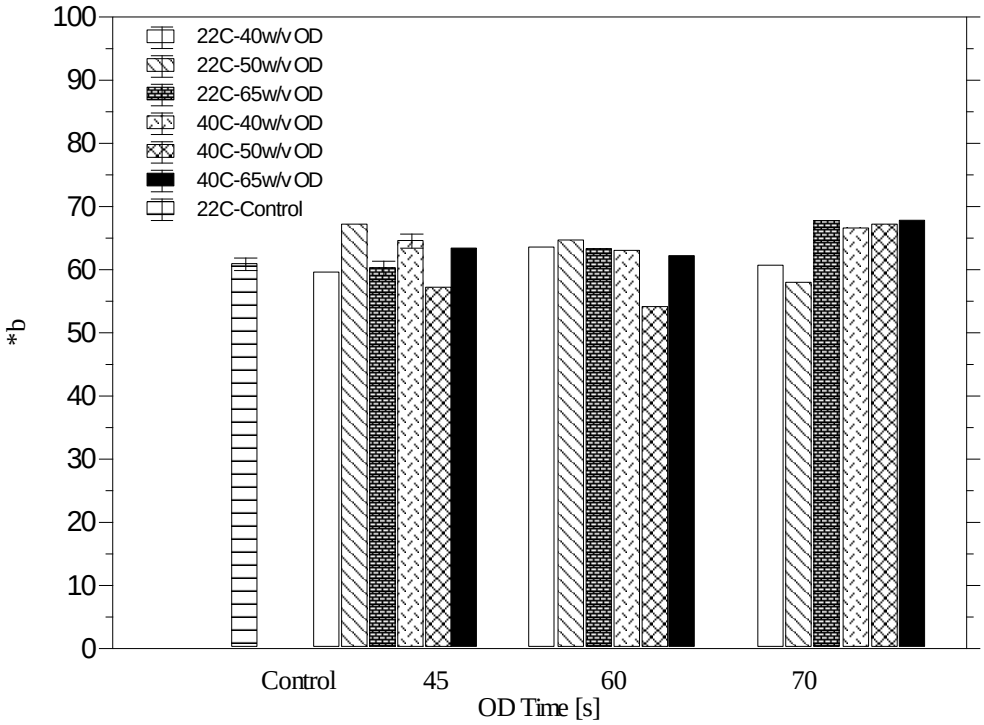


Fig. 4-16. Color **b* in mango chips pre-treated with OD (mango:syrup ratio = 1:4) at different times, temperatures, and OS concentrations and vacuum frying at 120°C for 2 min (P = 1.33 kPa, de-oiled at 225 rpm for 25 s).

4.5 Pre-treatment selection

The best pre-treatment for mango slices prior to vacuum frying was based on the mango chips product quality attributes (PQA). In this study, texture, oil content, color, and *dehydration efficiency index* (DEI) were the parameters mostly considered for the pre-treatment selection for mango chips. Mango chips texture was obtained when they reached a final moisture content less than 2% w.b. Table 4-9 shows that in any case, 40w/v concentration showed the required texture for 2min frying at 120^{o}C. Also, OD for 45 min did not showed the required texture (crispy) results for any concentrations (40, 50, 65 w/v).

Shrinkage was more significant in slices pre-treated with high OS concentration and temperature. However, shrinkage was related to the moisture removed which was one of the objectives of this study because it reduces the final oil content in the chips. The oil content was related to the pre-treatment dehydration level (amount of water removed). The more dehydrated the samples the less the oil content present in the mango chips (Table 4-10). Final moisture content after OD was a consequence of OS concentration, time, and temperatures as discussed previously in section 4.3. One of the objectives of this study was to reduce the final oil content in mango chips, therefore, high OD concentrations (50 and 65w/v) at 40^{o}C for 70 min were considered the best pre-treatment.

The higher the *dehydration efficiency index* (DEI= W_L/S_U) (Fig. 4-17) *i.e*; high values of water loss and low sugar gain, the higher the quality of mango chips. High DEI

was achieved with high OS concentrations (50 and 65w/v), times (60 and 70 min), and temperature of 40^{o}C.

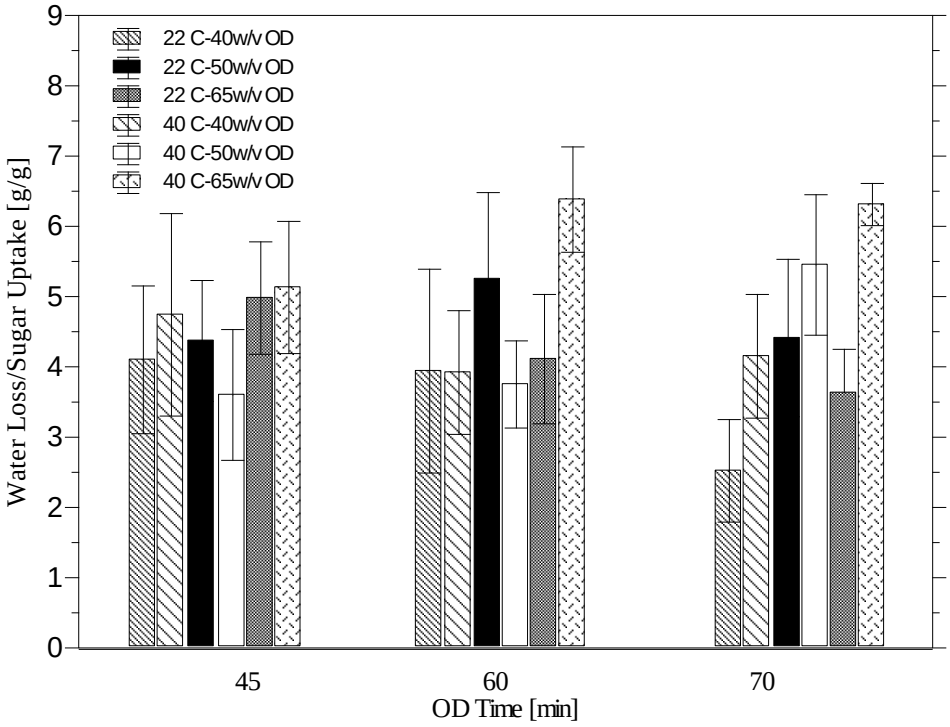


Fig. 4-17. *Dehydration efficiency index* (DEI = W_L/S_U) in mango slices at different OD (mango:syrup ratio = 1:4) times, concentrations, and temperatures.

The greatest value for DEI (6.38±0.75) was found for 65w/v OS concentration, 60 min at 40^{o}C. This pre-treatment also has a considerable sugar uptake needed for good texture in the mango chips (Fig. 4-7). Therefore, the best pre-treatment based on DEI was 65w/v OS concentration during 60 min at 40^{o}C.

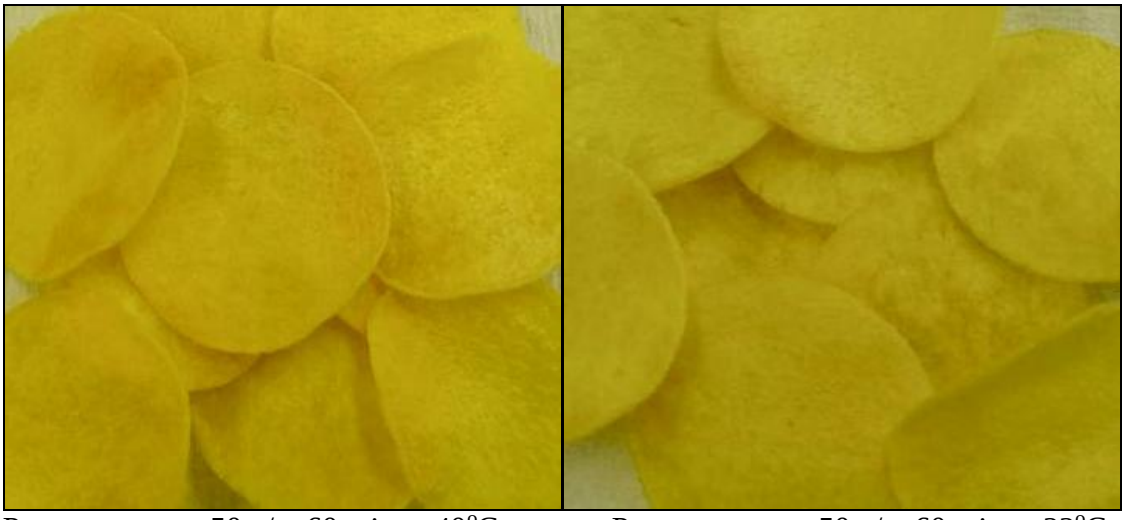
Figs. 4-18 to 4-20 show the mango chips for OD concentrations (50 and 65w/v), OD times (45, 60, and 70 min), and OD temperatures (22 and 40^{o}C). Their appearance is very similar, though samples treated for 45 min OD they were soggy (Fig. 4-18). Mango chips treated with the best pre-treatment had more intense color and were curlier than Fig. 4-18 and 4-19 because more water was removed.

The OD concentration and temperature combination selected, to follow further experimentation, was the one with 65w/v at 40^{o}C. These parameters had the highest score based on P.Q.A (texture, oil content, and color) required for good quality mango chips fried at 120^{o}C for 2 min (P = 1.33 kPa, de-oiled at 225 rpm for 25 s).

Pre-treatment: 50w/v, 45 min at 40°C Pre-treatment: 50w/v, 45 min at 22°C

Pre-treatment: 65w/v, 45 min at 40°C Pre-treatment: 65w/v, 45 min at 22°C

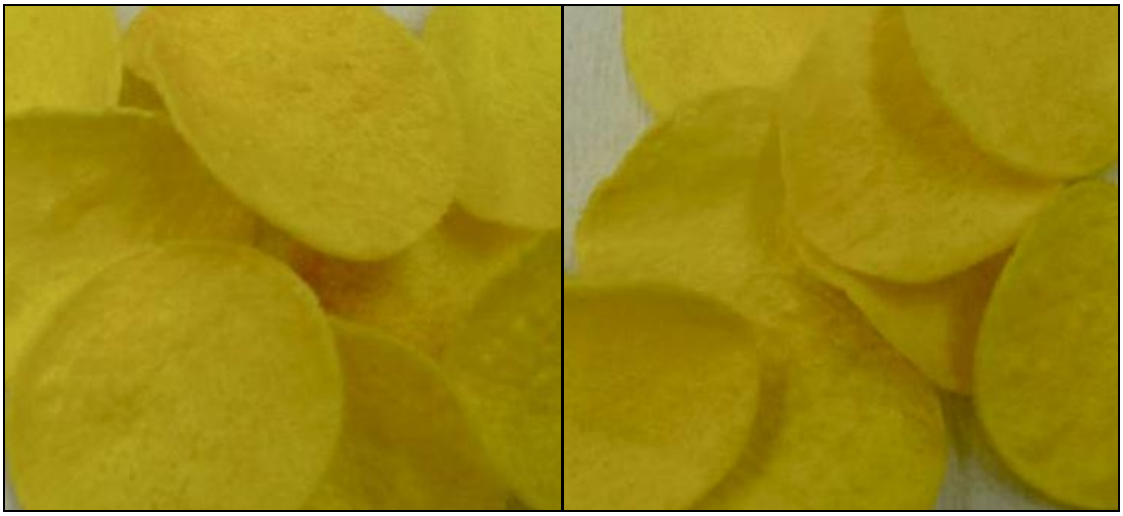
Fig. 4-18. Comparison of pre-treatments for 50w/v and 65w/v OS concentration during 45 min at 22 and 40°C. Mango chips were vacuum (P = 1.33 kPa) fried at 120°C for 2 min (de-oiled at 225 rpm for 25 s).



Pre-treatment: 50w/v, 60 min at 40°C Pre-treatment: 50w/v, 60 min at 22°C

Pre-treatment: 50w/v, 70 min at 40°C Pre-treatment: 50w/v, 70 min at 22°C

Fig. 4-19. Comparison of pre-treatments for 50w/v OS concentration during 60 and 70 min at 22 and 40°C. Mango chips were vacuum (P = 1.33 kPa) fried at 120°C for 2 min (de-oiled at 225 rpm for 25 s).



Pre-treatment: 65w/v, 60 min at 40°C Pre-treatment: 65w/v, 60 min at 22°C

Pre-treatment: 65w/v, 70 min at 40°C Pre-treatment: 65w/v, 70 min at 22°C

Fig. 4-20. Comparison of pre-treatments for 65w/v OS concentration during 60 and 70 min at 22 and 40°C. Mango chips were vacuum (P = 1.33 kPa) fried at 120°C for 2 min (de-oiled at 225 rpm for 25 s).

4.6 Effect of de-oiling process on the oil content of mango chips

The de-oiling process was carried out to eliminate most of the superficial oil in the mango chips. Superficial oil removal before pressurizing the vacuum frying system is very important. The oil can migrate into the sample easily and fast when a sudden increase in pressure (from 1.33 to 101.03 kPa) occurs.

The values for oil content (OC) in mango chips at different speeds and times are shown in Table 4-12. The maximum centrifuging speed in the de-oiling system (Chapter III, Fig. 3-3) available is 750 rpm (G-force = 72.01 g). When de-oiling for 25 s the maximum OC value found was 0.25 ± 0.00 w.b. at a speed of 113 rpm (G-force = 1.63 g). The lowest value was 0.18 ± 0.00 w.b. at a speed of 450 rpm (G-force = 25.95 g) for 25 s. When changing the time at a fixed speed (338 rpm: G-force = 14.63 g), significant differences ($P<0.05$) were found in all the cases. The minimum OC value reached at 338 rpm was 0.22 ± 0.00 w.b. for 45 s. The sample control was significant different ($P<0.05$) for all de-oiling test (Table 4-12). In this study, the effect of speed had more impact than time when centrifuging to remove the superficial oil in the mango chips.

Da Silva, Moreira, & Gomes (2008) found that potato chips centrifuged for 40 s at 750 rpm (G-force = 72.01 g) had a lower oil content (around 10% w.b.) when fried in vacuum frying at 120^{o}C for 360 s. Most of the oil absorbed in the product was at the surface, the non-centrifuged samples absorbed around 42% w.b. oil during the process. In the present study, the mango slices were fried by placing a mesh over the sample to avoid them to float or leave the basket during the centrifuging process. This may result in higher oil content than the one reported by Da Silva *et al* (2008). The oil at the surface

was not efficiently removed because of the position of the chips being parallel to the x-axis due to the presence of the mesh, resulting in less centrifugal force. The best quality mango chips were those centrifuged at 225 rpm for 25 s. They were not so oily (0.23 w.b. compared to 0.43 w.b. for samples) at the surface, but contain enough oil to provide god mouth-feel sensation when eaten.

Table 4-12 De-oiling process at different speeds (rpm) and time (s) for mango chips pre-treated with OD (mango:syrup ratio = 1:4) solution (65w/v at 40^{o} C) during 60 min, and vacuum fried (P = 1.33 kPa) at 120^{o}C for 2min.

De-oiling time [s]	**Speed (G-force) [g]**	**Oil Content [w.b.]**
0	0	$_{q}0.43\pm0.01^{a}$
25	1.63	0.25 ± 0.00^{b}
25	6.48	0.23 ± 0.00^{c}
25	14.63	0.22 ± 0.00^{d}
25	25.92	0.18 ± 0.00^{e}
15	14.63	$_{w}0.26 \pm 0.00$
25	14.63	$_{x}0.24 \pm 0.00$
35	14.63	$_{y}0.22 \pm 0.00$
45	14.63	$_{z}0.22 \pm 0.00$

[a-e] Means within a column with different superscript letters are significantly different (P<0.05)
[q-z] Means within a column with different subscript letters are significantly different (P<0.05)

4.7 Effect of frying temperature on mango chips product quality attributes

4.7.1 Moisture and oil content

Mango chips pre-treated at different OD times were fried under vacuum at three different temperatures (120, 130, and 138^{o}C) to a final moisture content (MC) around 2% [w.b.] (Table 4-13 and Figs. 4-21 and 4-22). The OS concentration and OD temperature used was the previously selected in section **4.5** (65w/v at 40^{o}C). The frying

times were established based on the final moisture content (around 2% w.b.) for further experiments.

Table 4-13 Effect of OD (mango:syrup ratio = 1:4) pre-treatment (65 w/v at 40^{o}C) times Moisture (MC) and vacuum (P = 1.33kPa, de-oiled at 225 rpm for 25 s) frying temperatures on moisture content and oil content in mango chips.

OD times [min]	Frying times[s]	Frying temperatures [^{o}C]	Moisture content [w.b.]	Oil content [w.b.]
45	150	120	$0.02\pm0.00_{a}$	$_{A}0.26\pm0.01^{a}$
45	130	130	$0.02\pm0.00_{a}$	$_{D}0.26\pm0.00^{a}$
45	98	138	$0.02\pm0.00_{a}$	$_{W}0.30\pm0.00^{b}$
60	128	120	$0.02\pm0.00_{a}$	$_{B}0.24\pm0.01^{d}$
60	120	130	$0.02\pm0.00_{a}$	$_{F}0.25\pm0.00^{d}$
60	75	138	$0.02\pm0.00_{a}$	$_{X}0.27\pm0.00^{e}$
70	109	120	$0.02\pm0.00_{a}$	$_{C}0.22\pm0.01^{q}$
70	115	130	$0.02\pm0.00_{a}$	$_{G}0.23\pm0.00^{q}$
70	60	138	$0.02\pm0.00_{a}$	$_{X}0.28\pm0.00^{p}$

$^{a-p}$ Means within a column with different superscript letters are significantly different (P<0.05)
$^{A-X}$ Means within a column for oil content to compare OD times with different subscript letters are significantly different (P<0.05)

Frying temperatures and OD times have a significant (P<0.05) effect on the oil content in mango chips (Table 4-13). Part of the superficial oil was removed by using the de-oiling system at 225 rpm for 25 s. The lowest oil content in the chips was 0.22±0.01 w.b. with 70 min OD and vacuum frying (P = 1.33 kPa) at 120^{o}C, and the highest 0.30±0.00 w.b. with 45min OD and a vacuum frying temperature of 138^{o}C (Fig. 4-22). The difference in oil content for both treatments was around 15% d.b. This significant difference (P<0.05) can be attributed to the tissue damaged caused by frying at high temperatures. In addition, longer OD times (60 or 70 min) helps to decrease the

oil absorbed in mango chips resulting in a more compact structure and higher sugar uptake in the mango slices. This effect may modify the product structure by making the samples more concentrated thus increasing the mango slices specific gravity and leaving less space for oil uptake. Tran, Chen, & Sothern (2007) found a decrease in the final oil uptake (around 30% less oil compared with the no pre-treated samples) in potato chips fried under traditional frying at 180^{o}C when pre-drying and dipping them in a sugar solution.

Shyu & Hwang (2001) attributed the increase of oil content in vacuum (P = 98.66 kPa) fried apple chips to frying temperature. They fried the apple chips for 30 min at three different temperatures (90, 100, and 110^{o}C) resulting in a higher oil content at higher frying temperatures (0.38, 0.39, and 0.394 w.b. at 90, 100, and 110^{o}C, respectively). Also, Fan (2005) concluded that vacuum (60, 80, and 95 kPa) frying temperature (60, 80, and 100^{o}C) and pre-treatment conditions affect the final oil content in carrot chips. Oil content increased (around 38% d.b. and 40.5 % d.b. at 80^{o}C and 100^{o}C, respectively) with vacuum frying temperatures higher than 60^{o}C.

Table 4-13 shows lower values oil content in the mango chips compared with those reported by Da Silva & Moreira (2008) for the same mango variety with an approximate oil content of 0.33 w.b. when pre-treating with a maltodexrin solution (50w/w) at 22^{o}C for 1 h and vacuum fried at 120^{o}C for 360 s. The significant difference in final oil content in mango chips in this study 0.24 w.b. with the values reported by Da Silva & Moreira (2008) was attributed to the type of pre-treatment used and the application of the de-oiling system. When using a pre-treatment with higher OS

concentration (65 w/v) and higher temperature (40^{o}C) more water is removed from the sample resulting in less oil content in the product. The de-oiling process helps to remove the oil at the surface of the product.

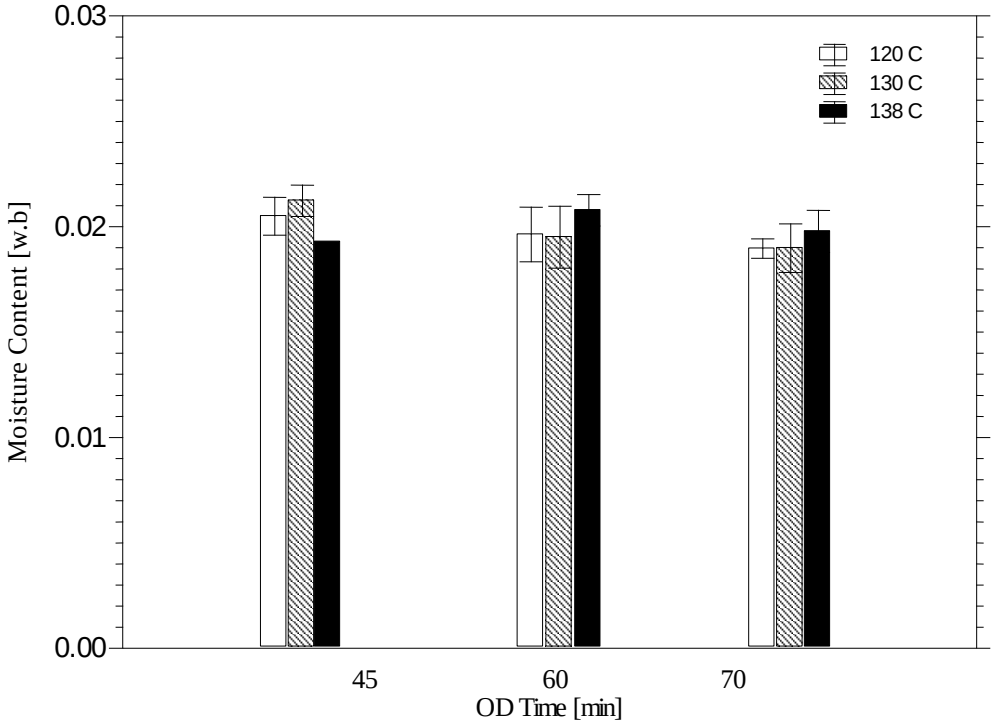


Fig. 4-21. Moisture content after vacuum (P = 1.33 kPa, de-oiled at 225 rpm for 25 s) frying at different frying temperatures and OD (mango:syrup ratio = 1:4) times (65 w/v at 40^{o}C).

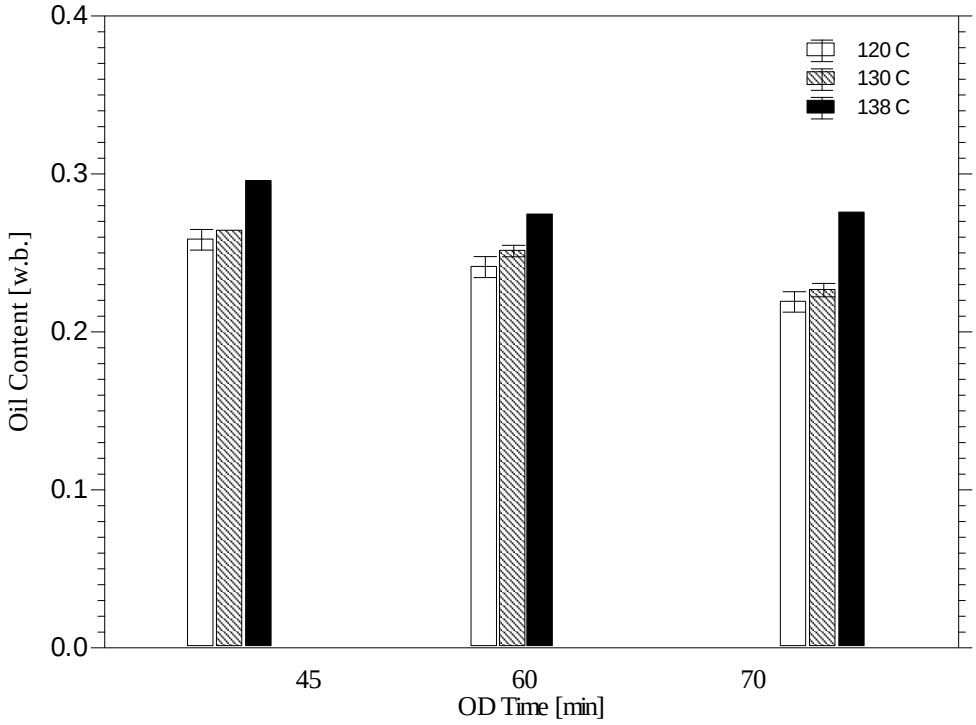


Fig. 4-22. Oil content after vacuum (P = 1.33 kPa, de-oiled at 225 rpm for 25 s) frying at different frying temperatures and OD (mango:syrup ratio = 1:4) times (65 w/v at 40^{o}C).

4.7.2 Shrinkage

The degree of shrinkage (in diameter) in mango chips is affected by frying temperature (Table 4-14). The greatest change in diameter was found at frying temperature of 138^{o}C; the degree of shrinkage was 16.93±0.04 % after 70 min OD. At 120^{o}C the changes in diameter were significantly lower ($P<0.05$) than for frying temperature of 130 and 138^{o}C. The minimum degree of shrinkage observed (12.02±0.04 %) was after 45 min OD and a frying temperature of 120^{o}C. The difference with the lowest and highest degree of shrinkage was around 41% (Table 4-14).

Fig. 4-23 shows that at the lowest OD time (45min) and frying temperature of 120^{o}C mango chips did not shrink as much compared with the other cases. However, after 45min of OD the least degree of shrinkage was obtained after OD resulting in less diameter shrinkage at the end of frying. After 60 min of OD at 130^{o}C, the samples had significantly lower ($P<0.05$) degrees of shrinkage (13.07±0.10 % compared with 14.52±0.21 and 14.36±0.08 at 130, 120 and 138^{o}C, respectively) possibly due to some expansion produced when the water evaporates from the sample.

In summary, the degree of shrinkage in the mango chips was affected by OD time and by vacuum frying temperature.

Table 4-14 Effect of vacuum frying (P = 1.33 kPa, de-oiled at 225 rpm for 25 s) temperature on the shrinkage (diameter) of mango slices subjected to different OD (mango:syrup ratio = 1:4) times (65w/v at 40^{o}C).

OD Times [min]	**Frying times[s]**	**Frying temperatures [^{o}C]**	**Moisture content [w.b.]**	**Degree of Shrinkage [%]**
45	150	120	$0.02\pm0.00_{a}$	12.02 ± 0.04^{a}
45	130	130	$0.02\pm0.00_{a}$	12.22 ± 0.09^{b}
45	98	138	$0.02\pm0.00_{a}$	12.49 ± 0.05^{c}
60	128	120	$0.02\pm0.00_{a}$	14.52 ± 0.21^{d}
60	120	130	$0.02\pm0.00_{a}$	13.07 ± 0.10^{e}
60	75	138	$0.02\pm0.00_{a}$	14.36 ± 0.08^{d}
70	109	120	$0.02\pm0.00_{a}$	15.00 ± 0.23^{p}
70	115	130	$0.02\pm0.00_{a}$	14.58 ± 0.10^{p}
70	60	138	$0.02\pm0.00_{a}$	16.93 ± 0.04^{q}

$^{a-q}$ Means within a column with different letters are significantly different ($P<0.05$)

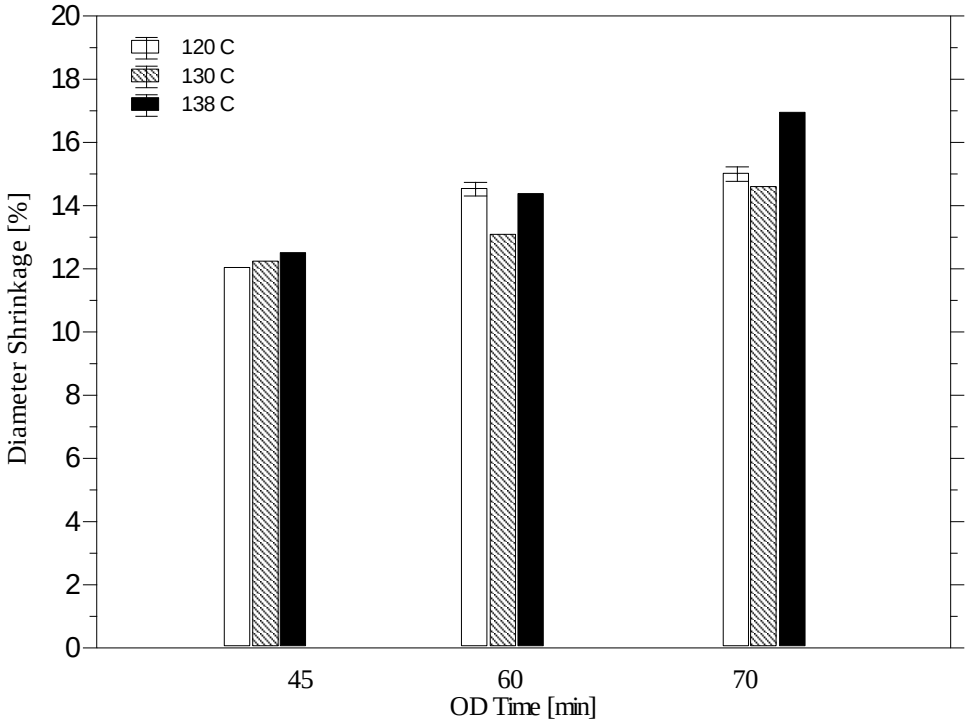


Fig. 4-23. Degree of shrinkage in mango chips after vacuum frying (P = 1.33 kPa, de-oiled at 225 rpm for 25 s) at different frying temperatures and OD (mango:syrup ratio = 1:4) times (65 w/v at 40^{o}C).

4.7.3 Texture

The texture of the sample was obtained when the mango chips final moisture content was around 2%. In most of the cases, the maximum force to break the chips as well as the work increased when the frying temperature was 130^{o}C (Table 4-15 and Figs. 4-24 and 4-25). However, no significant difference (P>0.05) was detected except for 60 min OD. This difference only occurred between 120 and 130^{o}C (6.20±0.79 and 12.66±2.06 N for peak force, and 33.17±4.82 and 45.32±4.31 N*mm for work at 120 and 130 ^{o}C, respectively). No changes were observed (P>0.05) at the same temperature for different OD times. The high variations were caused by uniformity, presence of bubbles, cracks, and shape of the mango chips. At high temperatures (138^{o}C), the chips became brittle; that explains the decrease in peak force and work values when frying at temperatures higher than 120 and 130^{o}C.

In terms of hardness, the OD pre-treatment had an important effect in the samples fried at 120^{o}C. When the OD time increased (from 45 to 60 min) the mango chips hardness also increased (P>0.05) (Figs. 4-24 and 4-25). These results suggest that OD as a pre-treatment increases the product hardness (an effect not expected from a frying process), but not as significantly as reported by Taiwo & Baik (2007) in sweet potatoes chips fried under traditional fryer at 170^{o}C for 0.5 to 5 min.

Table 4-15 Effect of vacuum frying (P =1.33kPa, de-oiled at 225 for 25 s) temperature on texture (force peak (N) and work (N*mm)) of the mango chips subjected to different OD (mango:syrup ratio = 1:4) times (65 w/v and 40^{o}C).

OD Times [min]	Frying temperatures [^{o}C]	Force (Peak)[N]	Work [N*mm]
45	120	$_{w}6.70\pm1.02^{a,c}$	$_{x}32.36\pm3.40^{a}$
45	130	$_{w}11.75\pm2.12^{b,d}$	$_{x}41.58\pm5.84^{a,b}$
45	138	$_{w}9.01\pm2.1^{b}$	$_{x}37.\ 81\pm3.78^{a}$
60	120	$_{w}6.20\pm0.79^{c}$	$_{x}33.17\pm4.82^{a,c}$
60	130	$_{w}12.66\pm2.06^{d}$	$_{x}45.32\pm4.31^{b,c}$
60	138	$_{w}10.18\pm1.72^{d,e}$	$_{x}37.77\pm5.37^{a,b,c}$
70	120	$_{w}7.61\pm1.^{10a,c,e}$	$_{x}37.76\pm4.71^{a,b,c}$
70	130	$_{w}9.26\pm1.94^{e,d}$	$_{x}42.09\pm6.16^{c}$
70	138	$_{w}8.01\pm0.53^{e}$	$_{x}35.19\pm4.79^{c,a}$

[a-e] Means within a column with different superscript letters are significantly different (P<0.05)
[w-x] Means within a column for peak and work with different subscript letters are significantly different (P<0.05)

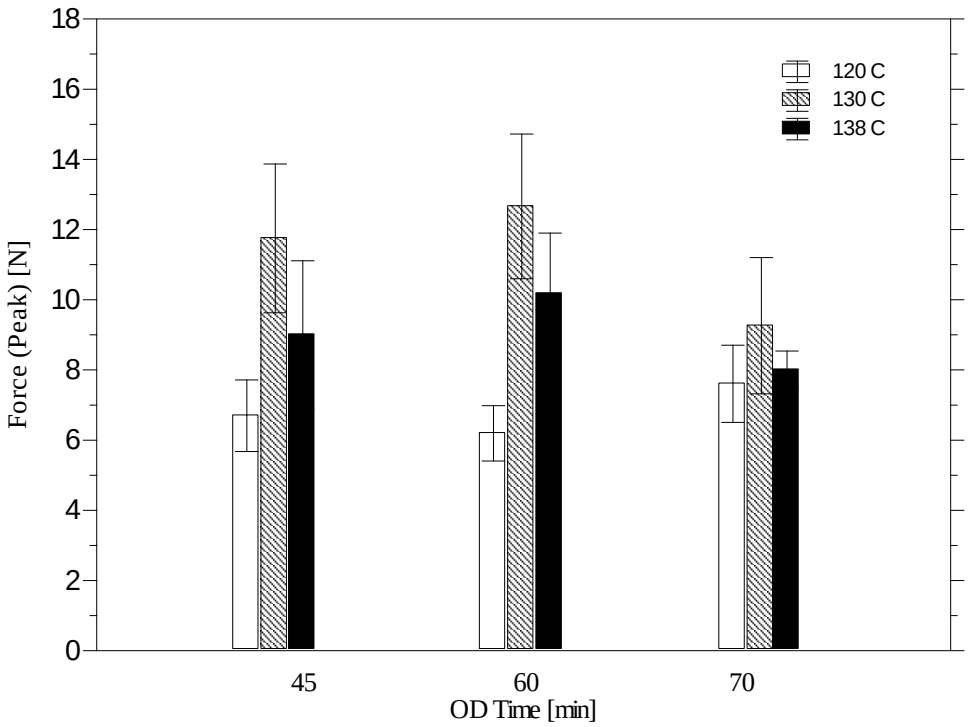


Fig. 4-24. Maximum force (Peak) to compress the mango chips after vacuum frying (P = 1.33 kPa, de-oiled at 225 rpm for 25 s) at different frying temperatures and OD (mango:syrup ratio = 1:4) times (65 w/v and 40^{o}C).

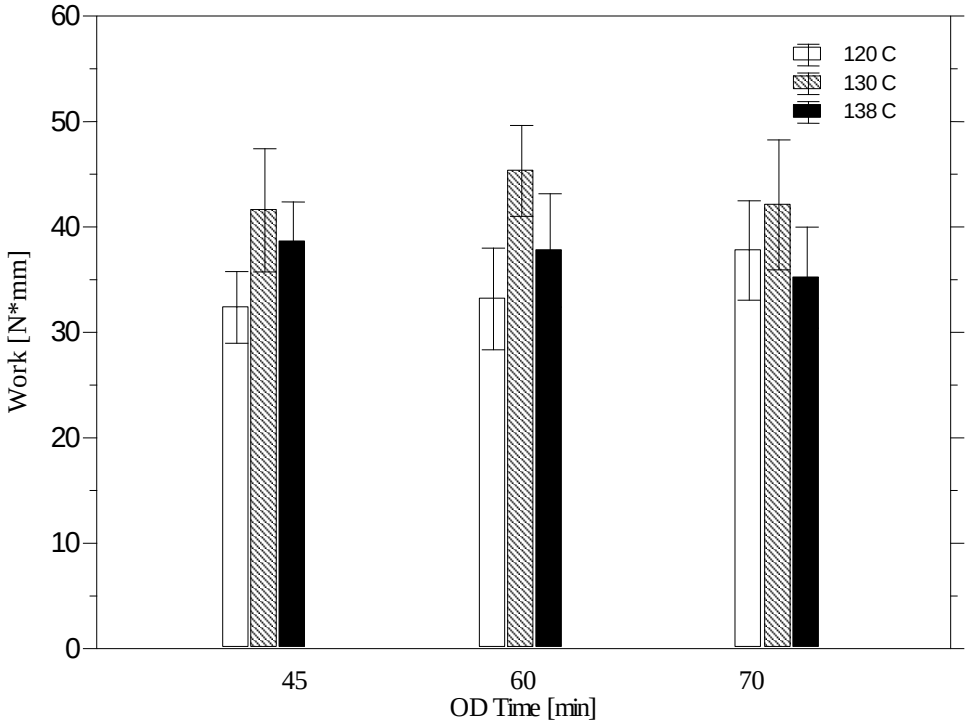


Fig. 4-25. Work done to compress the mango chips after vacuum frying (P = 1.33 kPa, de-oiled at 225 rpm for 25 s) at different frying temperatures and OD (mango:syrup ratio = 1:4) times (65 w/v and 40^{o}C).

4.7.4. Color

Values for **a* and **b* are shown in Table 4-16. There was no significant difference (P>0.05) for the color parameter **a* in mango chips pre-treated with different OD times (45, 60, and 70 min) at vacuum frying temperatures of 120 and 130^{o}C (Fig. 4-25). For 45 and 60 min OD, the color **a* in mango chips vacuum fried at 130^{o}C was lower than those fried at 120 and 140^{o}C, although no significant (P>0.05) different. This result can be explained by the high standard deviation obtained in the raw mango due to low value in color **a* (around 5.6) compared with the majority of the fruit used (around 9.6). This difference was probably attributed to differences in the raw mango when testing mango slices fried at 130^{o}C.

The maximum value for **a* (12.76±0.47) was observed at the highest vacuum frying temperature (138^{o}C) with OD of 45 min. High frying temperatures and long frying times resulted in Maillard reactions in the samples, therefore increasing the value of **a* (Fig. 4-26). Shyu & Hwang (2001) found in fried apple chips an increase in the red color (**a*) when exposing them to vacuum (P = 98.66 kPa)frying temperature of 100 and 110^{o}C. For Hunter color **b*, they observed a small no significant increase when the frying temperature was increased.

The results for color **b* are shown in Table 4-16 and Fig. 4-27. The maximum value found was 63.11±0.5 when mango slices were pre-treated for 70 min and vacuum fried at 120^{o}C. Less time is needed to fry when the samples are dehydrated (OD) for longer time before frying. No significant change (P>0.05) for color **b* was observed at different frying temperatures, however, in Fig. 4-27 a small decrease value in **b* was

obtained when the temperatures increased for each OD time. The *b color in mango can be related to the beta-carotenes present, which gives the characteristic yellow color in the flesh. Beta-carotenes are degraded at high temperatures; for that reason, the lowest vacuum frying temperature used in this study (120^{o}C) should be preferred to vacuum fry mango chips. Frying at 130^{o}C, with an OD pre-treatment of 45 and 60 min, decreased slightly the color *b. Color *b increased at 138^{o}C. This effect can be explained by the intial raw mango color (*b) (around 58) compared with the other raw mangoes used in this experiments which had higher *b's values (around 61).

Table 4-16 Color *a and *b for mango chips pre-treated at different OD (mango:syrup ratio = 1:4) times (65 w/v and 40^{o}C) and different vacuum frying (P = 1.33 kPa, de-oiled at 225 rpm for 25 s) temperatures.

OD Time [min]	**Frying times [s]**	**Frying Temperature [^{o}C]**	**Moisture content [w.b.]**	***a**	***b**
0	0	0	0.85	$8.76\pm2.04^{a,b}$	$61.09\pm2.46^{a,f}$
45	150	120	$0.02\pm0.00_{a}$	$10.89\pm0.50^{a,d}$	$61.50\pm0.47^{a,c}$
45	130	130	$0.02\pm0.00_{a}$	7.14 ± 0.05^{b}	56.73 ± 0.32^{b}
45	98	138	$0.02\pm0.00_{a}$	12.76 ± 0.47^{c}	$60.72\pm0.17^{a,f}$
60	128	120	$0.02\pm0.00_{a}$	10.36 ± 0.31^{a}	61.81 ± 0.17^{c}
60	120	130	$0.02\pm0.00_{a}$	7.27 ± 0.04^{b}	56.69 ± 0.30^{b}
60	75	138	$0.02\pm0.00_{a}$	9.86 ± 0.37^{a}	$60.53\pm1.14^{a,c,f}$
70	109	120	$0.02\pm0.00_{a}$	10.24 ± 0.47^{a}	63.11 ± 0.58^{d}
70	115	130	$0.02\pm0.00_{a}$	11.18 ± 0.24^{d}	62.36 ± 0.08^{e}
70	60	138	$0.02\pm0.00_{a}$	10.02 ± 0.39^{a}	60.76 ± 0.22^{f}

[a-f] Means within a column with different superscript letters are significantly different (P<0.05)

The results obtained in this study for changes in color, *a and *b, can be compared with the results reported by Fan (2005) in carrot chips (fried under vacuum

(60, 80, and 95 kPa at 60, 80, and 100^{o}C). He observed an increase in the color *a (due to Maillard reactions) and a decrease in color *b (due to concentration and degradation of carotenoids) when the frying temperature increased.

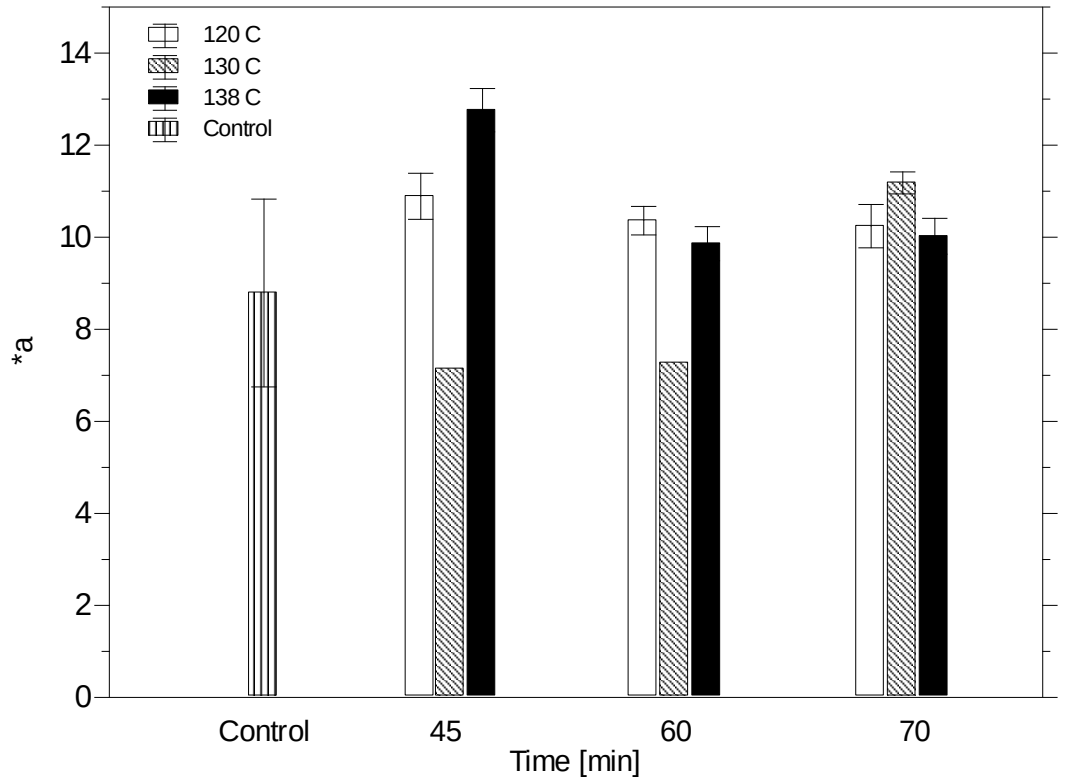


Fig. 4-26. Color *a in mango chips after vacuum (P = 1.33 kPa, de-oiled at 225 rpm for 25 s) frying at different frying temperatures and OD (mango:syrup ratio = 1:4) times (65 w/v and 40^{o}C).

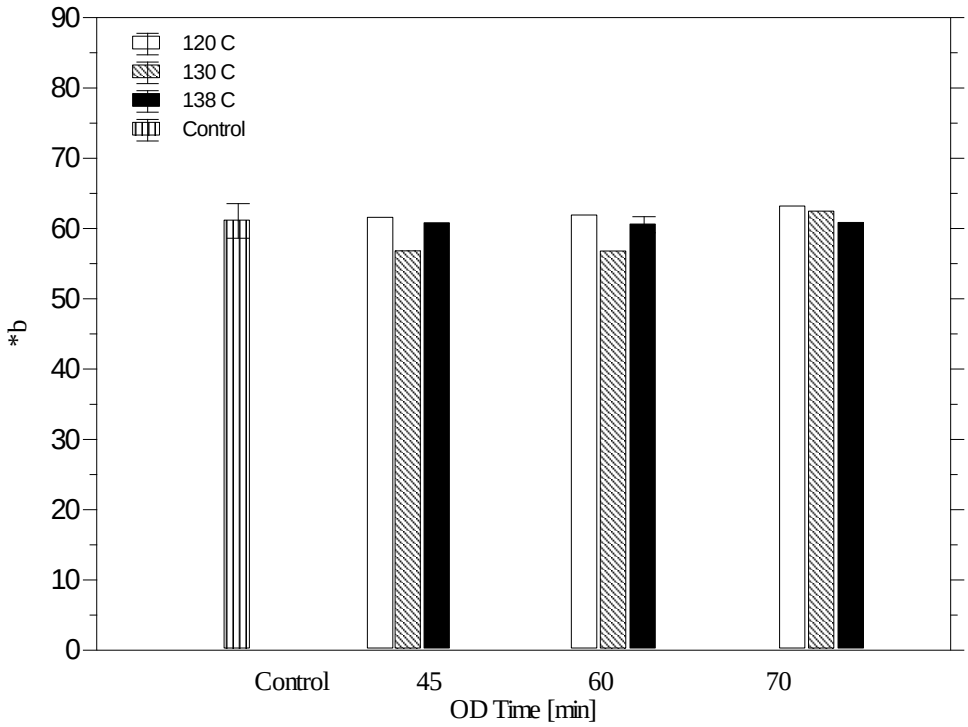


Fig. 4-27. Color **b* in mango chips after vacuum (P = 1.33 kPa, de-oiled at 225 rpm for 25 s) frying at different frying temperatures and OD (mango:syrup ratio = 1:4) times (65 w/v and 40^{o}C).

4.7.5 Sensory evaluation

The sensory analysis was conducted in three days (Table 4-17), which new samples prepared each day the samples were prepared for each OD time (day 1: 45min, day 2: 60min, and day 3: 70 min) and fried at 120, 130, and 138^{o}C frying temperatures. Scores higher or equal to 5 were considered acceptable, based on the nine-point hedonic scale used by Carr, Meilgaard & Civille (1999).

Mango chips color (yellowness) for all frying temperatures and OD times was no significantly different (P>0.05) except for the treatment (score: 5.96±1.92) carried with an OD time of 70 min at 138^{o}C. The highest score in color was 7.34±1.20 when pre-treating the samples for 60 min and frying at 120^{o}C. The preferred temperature (120^{o}C) in the sensory test agreed with the temperature selected for color (*b) in section *4.7.4*. However, no significant difference in color was found for all the OD times when the samples were fried at 120 and 130^{o}C.

Mango chips odor scores were above 5 and no significant change (P>0.05) was found among treatments (3 days). The maximum score given by the panelists was 6.56±1.34 when the mango slices were pre-dehydrated for 60 min and fried at 120^{o}C. Based on consumer comments, low scores for odor were for those chips with high oil content. High oil content was obtained when frying at the highest temperature (138^{o}C) in this study. The highest score for odor was 6.56±1.34 when pre-treated mango slices for 60 min and frying at 120^{o}C. The texture and flavor scores of the mango chips were not significantly different (P>0.05) among the treatments. The highest scores for texture and

flavor were 7.68±0.93 and 6.75±1.77, respectively, for OD for 60 min and frying at 130^{o}C.

No significant difference (P>0.05) was found for color, odor, flavor and overall quality in the mango chips pre-treated with 65 w/v at 40^{o}C for 45, 60, and 70 min and vacuum fried at 120, 130, and 138^{o}C. However; there was a significant difference (P<0.05) in the parameter color when pre-treating for 70 min and vacuum frying at 138^{o}C. The highest scores for all mango chips parameters (color, odor, texture, flavor and overall quality) were when pre-treating the samples for 60 min OD. Fig. 4-28 shows very similar mango chips pre-treated for 60 min and fried at 120, 130, and 138^{o}C. In summary, all samples were found acceptable by the consumer panelists.

Table 4-17 Sensory analysis results for mango chips pre-treated (mango:syrup ratio = 1:4) during 45, 60, and 70 min and vacuum fried (P = 1.33 kPa, de-oiled at 225 rpm for 25 s) at three different temperatures.

Day	Test (Temperature-Time)	Color	Odor	Texture	Flavor	Overall quality
1	**120C-45minOD**	7.16±1.18^{a}	6.45±1.50^{a}	7.02±1.57^{a}	7.05±1.41^{a}	7.20±1.07^{a}
	130C-45minOD	6.54±1.74^{a}	6.35±1.47^{a}	7.33±1.30^{a}	6.48±2.07^{a}	6.54±1.74^{a}
	138C-45minOD	6.58±1.46^{a}	6.13±1.53^{a}	7.08±1.29^{a}	6.74±1.19^{a}	6.66±1.14^{a}
2	**120C-60minOD**	7.34±1.20^{a}	6.56±1.34^{a}	7.56±0.87^{a}	7.59±1.07^{a}	7.50±0.95^{a}
	130C-60minOD	7.22±1.20^{a}	6.50±1.29^{a}	7.68±0.93^{a}	6.75±1.77^{a}	7.06±1.29^{a}
	138C-60minOD	6.40±1.56^{a}	6.34±1.18^{a}	7.09±1.35^{a}	6.59±1.68^{a}	6.62±1.28^{a}
3	**120C-70minOD**	7.23±1.25^{a}	6.30±1.31^{a}	7.16±1.26^{a}	6.60±1.45^{a}	6.96±1.21^{a}
	130C-70minOD	6.40±1.81^{a}	5.90±1.44^{a}	7.31±1.22^{a}	6.70±1.39^{a}	6.86±1.56^{a}
	138C-70minOD	5.96±1.92^{b}	6.13±1.33^{a}	6.90±1.64^{a}	6.44±1.35^{a}	6.58±1.35^{a}

$^{a-b}$ Means within a column with different letters are significantly different (P<0.05)

Treatment: 60 min OD at 120°C

Treatment: 60 min OD at 130°C

Treatment: 60 min OD at 138°C

Fig. 4-28. Comparison of mango chips pre-treated (mango:syrup ratio = 1:4) for 60 min and vacuum fried (P = 1.33 kPa, de-oiled at 225 rpm for 25 s) at 120, 130, and 138°C.

4.7.6. Effect of osmotic dehydration and vacuum frying in mango microstructure

The effect of osmotic dehydration (OD) at 40 and 65 w/v concentrations and vacuum frying (1.33 kPa, de-oiled at 225 rpm for 25 s) on mango microstructure is shown in Figs. 4-29 to 4-31. Environmental scanning electron microscopy of the surface and cross section for all cases was performed to visualize the samples structure.

Raw (A) slices and those pre-treated with 40 w/v (B) and 65 w/v (C) OD concentration at 40^{o}C for 60 min show similar structure on the surface (II) (Fig. 4-29 B and Fig. 4-30 C). Slices pre-treated with 65 w/v concentration (Fig. 4-30 C) had a more packed surface in the fruit than those pre-treated with 40 w/v concentration (Fig. 4-29 B) due to more water removed by higher osmotic pressure difference. For both concentrations (40 and 65 w/v), the cross section (Fig. 4-29 IB and 4-30 IC) looked more compact compared with the raw mango (Fig. 4-29 IA), which shows a more uniform structure. Osmotic dehydration led to the decrease of cellular area (diameter, roundness, and compactness) (Pissarra & Sereno, 2008; Falade & Igbeka, 2007). Giraldo, Talens, Fito, and Chiralt (2003) studied the influence of sucrose concentration during OD in mango cylinders. They noted that the compactness of cells depends on the liquid phase concentration. When the OD concentration is higher, a more compact aspect can be observed. Shyu & Hwang (2001) observed in apple slices fried under vacuum (98.66 kPa) and pre-treated using different methods that the samples should be pre-treated with a sucrose solution before freezing and vacuum frying (100^{o}C, 20 min) to give a better quality and more spongy structure.

Traditional and vacuum frying caused notable structure changes in the cross section (I) and surface (II) areas of the mango slices (Figs. 4-30 E and 4-31 F, G). Vacuum frying caused a rapid water evaporation at the surface and prevented water diffusion from the interior of the chips while the free water inside the mango slices reached the boiling point creating pores and making the chips look more spongy when the internal water evaporated. Bigger pores are observed when vacuum frying at 138^{o}C than at 120^{o}C. This might be because at higher temperature a sudden water phase change occurs increasing the pressure inside the tissue, thus breaking the cell structure and creating bigger holes than at lower frying temperatures (Fig. 4-31 IF). Visual inspection showed slight differences for the mangos fried at different temperature (120 and 138^{o}C) under vacuum. Mango slices (surface area) fried at 138^{o}C showed a more smooth structure (Fig. 4-31 IIF) than those fried at 120^{o}C. This can be attributed to a higher frying temperature causing some rupture in the mango structure matrix.

During atmospheric frying (165^{o}C), surface and inside water evaporates faster creating a complete destruction of the mango tissue structure. Figs. 4-31 IG, IIG show the continuous cross section and surface areas in mango slices fried with a traditional (atmospheric) fryer. The continuous phase is the result of the completely destroyed (collapsed) structure of the fruit. Fig. 4-32 shows the differences in mango chips fried under vacuum and atmospheric pressures. The mango slices fried under vacuum (Fig. 4-32 a,b) show a more uniform (less bubbles) and more spongy structure than those fried under traditional frying (Fig. 4-32 c).

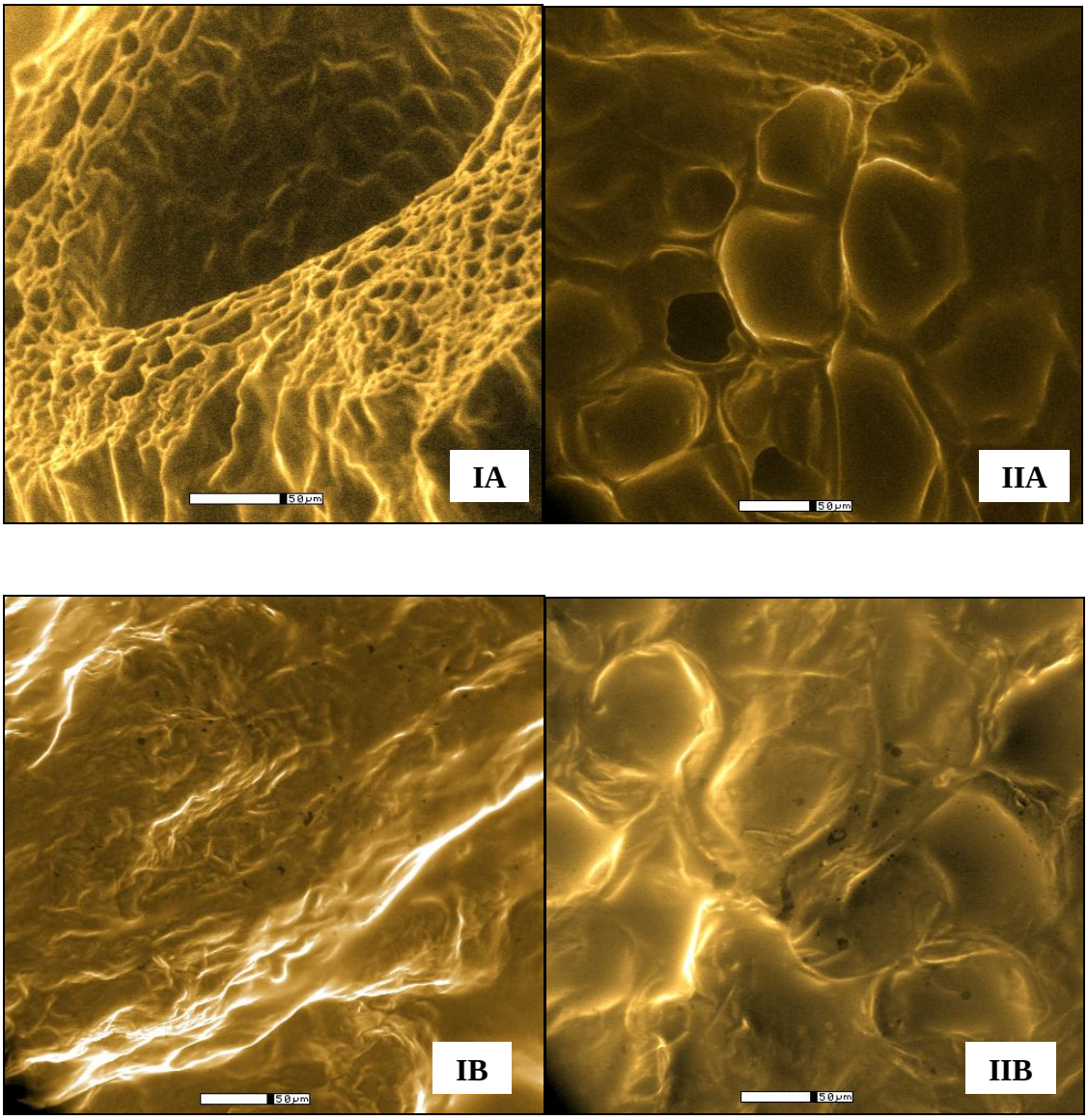


Fig. 4-29 Environmental scanning electron photomicrographs of the cross section (I) and surface (II) of raw (A) and pre-treated (40 w/v OD concentration at 40^{o}C for 60 min) (B) mango slices. Slices were viewed at 15 kV.

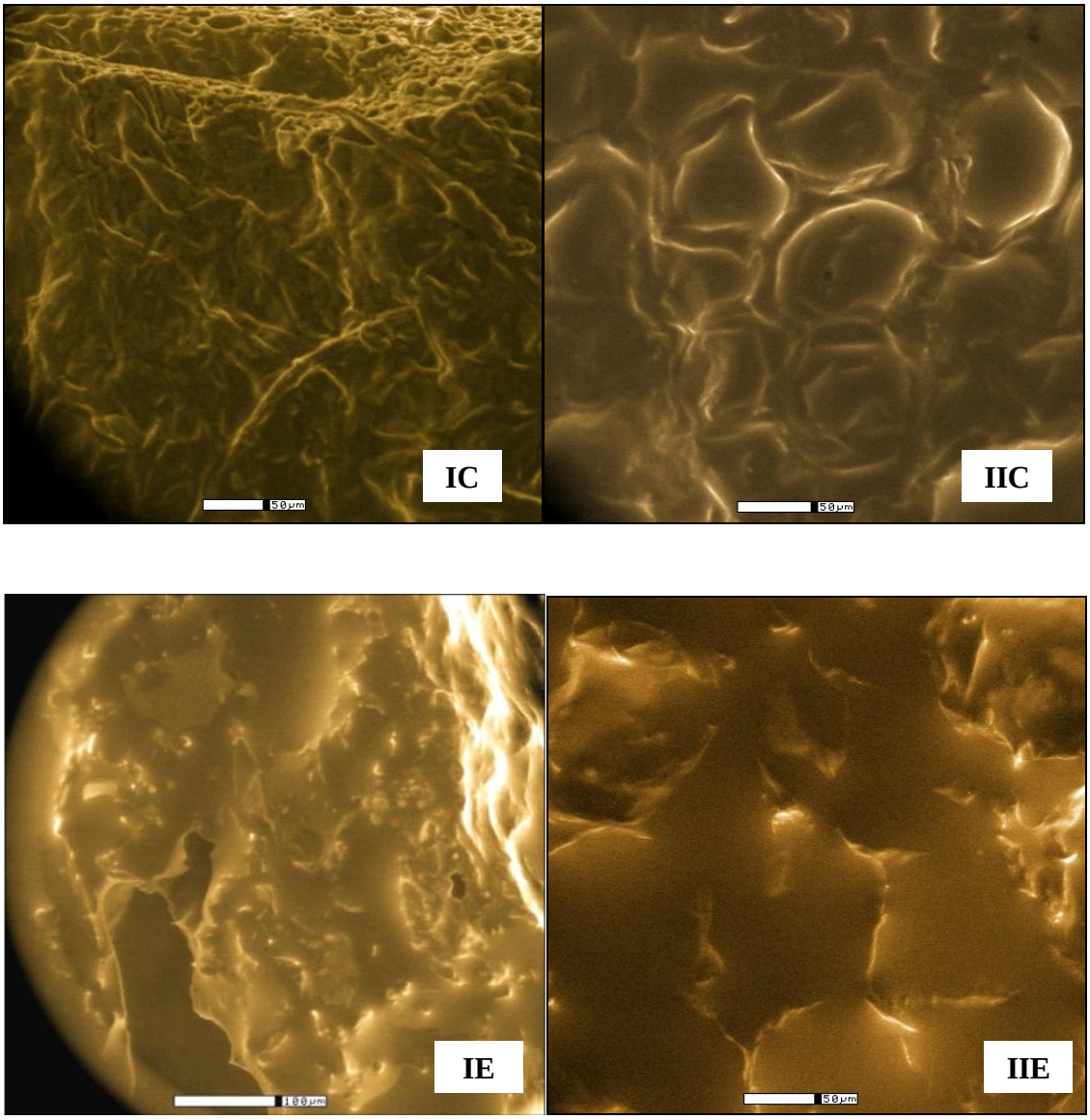


Fig. 4-30 Environmental scanning electron photomicrographs of the cross section (I) and surface (II) of mango slices pre-treated (65 w/v OD concentration at 40^{o}C for 60 min) (C) and vacuum fried at 120^{o}C (1.33 kPa, de-oiled at 225 rpm for 25 s) (E). Slices were viewed at 15 kV.

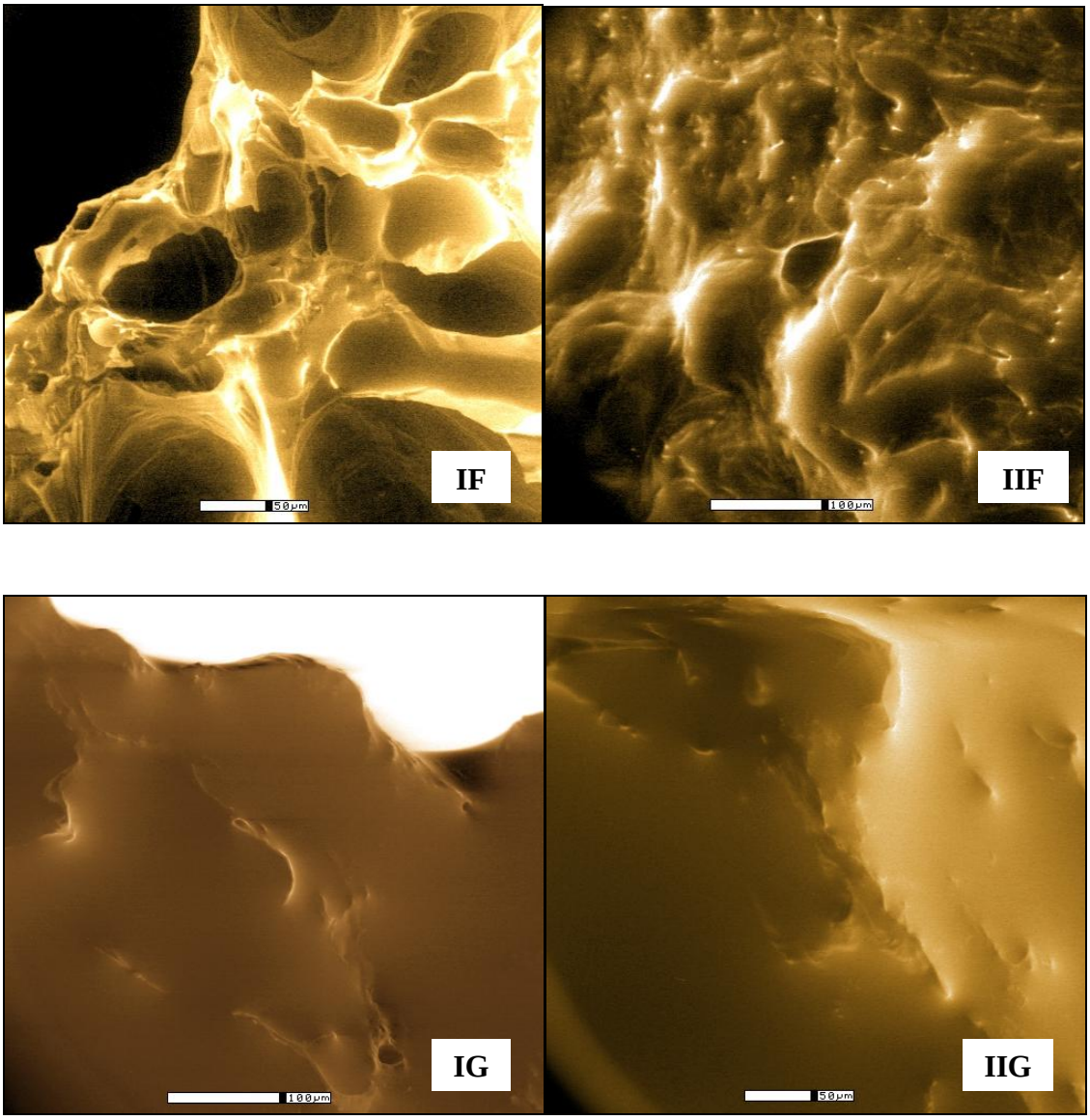


Fig. 4-31 Environmental scanning electron photomicrographs of the cross section (I) and surface (II) of mango slices vacuum fried at 138^{o}C (1.33 kPa, de-oiled at 225 rpm for 25 s) (F) and traditionally fried at 165^{o}C for 2 min (G) . Slices were viewed at 15 kV.

a: Vacuum frying at 120^{o}C b: Vacuum frying at 138^{o}C

c: Traditional frying at 165^{o}C

Fig. 4-32 Mango chips pre-treated (65 w/v, 40^{o}C for 60 min) and fried under vacuum (P = 1.33 kPa, de-oiled at 225 rpm for 25 s) at (a) 120^{o}C and (b) 138^{o}C and (c) atmospheric frying (165^{o}C).

CHAPTER V

KINETIC STUDIES OF PRE-TREATED VACUUM FRIED MANGO CHIPS

5.1 Effect of vacuum frying temperature and time on moisture content in pre-treated mango chips

Fig. 5-1 and Appendix B show the kinetics of moisture loss when frying mango slices under vacuum at different temperatures (120, 130, and 138^{o}C), pre-treated with maltodextrin solution (65 w/v for 60 min at 40 ^{o}C). Results confirm the observation of other authors that the moisture loss during frying follows a typical drying profile (Garayo, 2001; Shyu & Hwang, 2001). Overall, after the OD pre-treatment, the mango slices lost about 31% of water and gained 5% of maltodextrin, thus reducing the frying time to reduce final moisture content around 2% w.b. Goyal, Kingsly, Manikantan, & Ilyas (2006) concluded that OD pre-treatment had an effect on moisture movement from mango slices during drying.

Initially, during the first 30 sec of frying, the rate of water loss is high due to an initial rapid fall of water content mainly attributable to loss of surface water. After 70 sec, water content slowly decreased for the three different temperatures. Vacuum frying causes a rapid moisture loss in mango slices due to a decrease of the water boiling point (in this case for P≈ 1.33 kPa, T_{sat}≈ 12^{o}C). Water loss can be described by an exponential decay (Fig. 5-1) following the Fick's law. This behavior was also observed by Fan (2005) in carrots chips subjected to vacuum frying at different temperatures (60, 80, and 100^{o}C) and pressures (60, 80, and 95 kPa).

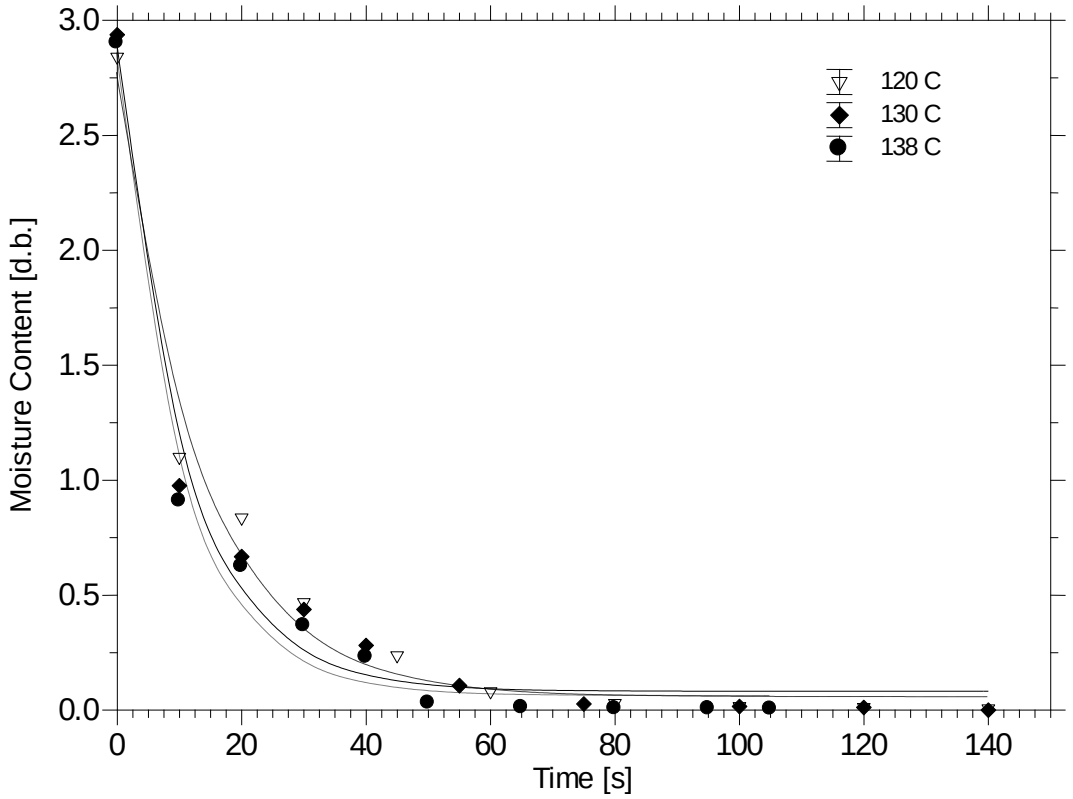


Fig. 5-1. Drying rate on mango chips pre-treated with OD (65 w/v and 40^{o}C) for 60 min and fried under vacuum (P = 1.33 kPa, de-oiled at 225 rpm for 25 s) at different frying temperatures [120^{o} C, MC(t) = 2.715*exp(-0.07351*t) + 0.05482, R^2 = 0.98; 130^{o} C, MC(t)=2.801*exp(-0.0916*t) + 0.08195, R^2 = 0.98; 138^{o} C, MC(t)=2.796*exp(-0.09716*t) + 0.0596, R^2 = 0.98].

The diffusion coefficient (D_e) is a measure of molecular mobility. Therefore, a higher moisture diffusion coefficient in mango slices means a faster drying rate (Datta, 2002). The diffusion coefficient of mango slices fried at different temperatures under vacuum was obtained by the method proposed by Brooker *et al* (1992). The moisture diffusion equation for a flat plate can be described by:

$$MC[d.b.] = (MC_o - MC_e) * \left(\frac{8}{\pi^2}\right) exp\left(-\frac{\pi^2 D_e t}{4a^2}\right) + MC_e \qquad [5\text{-}1]$$

where MC is the moisture content in decimal dry basis [d.b.], M_o is the initial moisture content [d.b.], M_e is the equilibrium moisture content [d.b.], t is the frying time, D_e is the diffusion coefficient, and a is the thickness o the mango slice.

The values of D_e were obtained by using non-linear regression to fit the experimental drying rate curve (Table 5-1 and Fig. 5-2).

As reported by Granda (2005) and Garayo & Moreira (2002), in potato chips, the diffusion coefficient (D_e) increases when the temperatures increases during a drying process. In mango slices fried under vacuum (1.33 kPa) at 138^o C the D_e ($2.43x10^{-6}$ m^2/s) was higher ($P<0.05$) than in mango slices fried under vacuum at 120 ($2.00x10^{-6}$ m^2/s) and 130^o C ($2.27x10^{-6}$ m^2/s) (Table 5-1).

Table 5-1 Diffusion coefficients for mango chips pre-treated with OD (65 w/v and 40°C) for 60 min and fried under vacuum (1.33 kPa) at different temperatures.

Frying Method	**Vacuum Frying**		
Temperature [°C]	**120**	**130**	**138**
MC_o **[d.b.]**	3.48	3.48	3.48
MC_e **[d.b.]**	0.07	0.07	0.07
D_e **(m^2/s)**	2.00×10^{-6}	2.27×10^{-6}	2.43×10^{-6}
R^2	0.99	0.99	0.98

Moisture tests were run in triplicate.
Thickness of the mango slices for D_e calculations was 1.55×10^{-3} m.

The influence of the frying oil temperature on the diffusion coefficient during vacuum frying was modeled using an Arrhenius-type equation:

$$D_e(T) = Aexp\left(\frac{-E_a}{RT}\right) \quad [5\text{-}2]$$

where A is the pre-exponential factor (1/s). E_a is the activation energy, T is the absolute temperature (K), and R is the universal gas constant (8.314 J/molK).

Equation [5-2] can be linearized as:

$$lnD_e = lnA - \frac{E_a}{RT} \quad [5\text{-}3]$$

The following relationship was found for vacuum frying (Eq. [5-3] and Fig. 5-2):

$$\ln D_e = -8.6724 - \frac{1746.48}{T}, R^2 = 0.99 \quad [5\text{-}4]$$

The pre-exponential factors (A) and activation energy (E_a) [J/mol] for mango chips fried under vacuum were 1.7124×10^{-4} 1/s and 1.4520×10^{-4} J/mol, respectively. The

D_e is influenced by temperature during vacuum frying since the boiling point of water during vacuum frying is significantly reduced, and water stars evaporating even before the product is immersed in the oil (Granda, 2005; Garayo & Moreira, 2002).

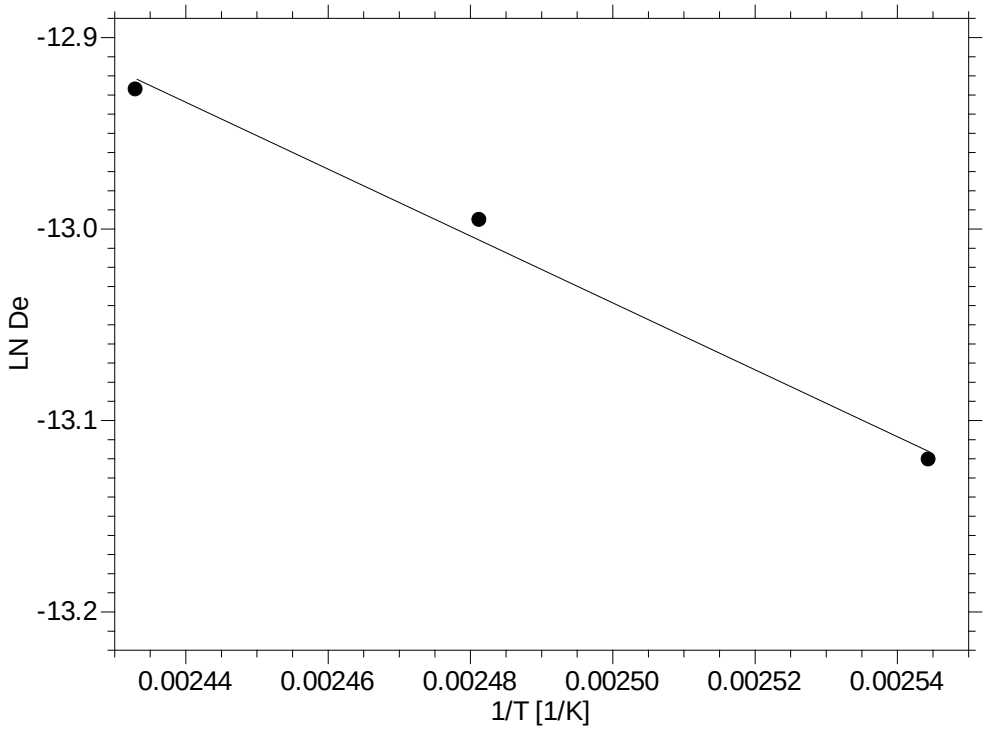


Fig. 5-2. Effect of frying temperature on the diffusion coefficient (D_e) of mango slices pre-treated with OD (65w/v and 40^{o}C) for 60 min and fried under vacuum (P = 1.33 kPa) and de-oiled for 25 s at 225 rpm.

5.2 Effect of oil temperature and frying time on the oil content of pre-treated mango chips

The final oil content of de-oiled mango chips fried under vacuum was about 30% w.b. when frying at 120^{o}C and 130^{o}C for 140 s. However, mango slices fried at 138^{o}C showed higher oil content, about 39% w.b. after frying for 105 s.

The effect of temperature on the oil content in potato chips was also observed by Granda (2005), and Garayo & Moreira (2002). They observed that at high vacuum frying temperature (around 140^{o}C) a fast oil absorption rate in potato chips occurs at the beginning of the frying process. However, by the end of the frying time the final oil content for all temperatures was around the same.

In addition, Bouchon (2008), Shyu & Hwang (2001), and Fan, Zhang, & Mujumdar (2005) found an increase in oil content at higher temperatures for apple and carrot chips pre-treated with a sweet solution, respectively. The significant increase in oil content in mango chips at 138^{o} C could be explained by the tissue damage caused specifically by high temperature during frying of mango slices. Shyu & Hwang (2001) agreed that high temperatures during vacuum frying of apple slices, cause damage in the fruit thus increasing the oil content.

The time period for oil absorption (50 s) coincides with the period at which water evaporates from the mango slices at the fastest rate at this temperature (Figs. 5-1 and 5-4). This was also observed by Granda (2005) and Shyu & Hwang (2001) who found a relationship within the oil and moisture content in potato chips.

Mango slices vacuum fried at 120°C and 130°C show similar trend in the increase in oil content behavior (Fig. 5-3). During the first 50 s of frying at 120°C and 130° C, the oil content increased (from 20 to 60 sec) very fast (around 26% w.b.) reached the maximum oil content at about 140 s (29.5% w.b.).

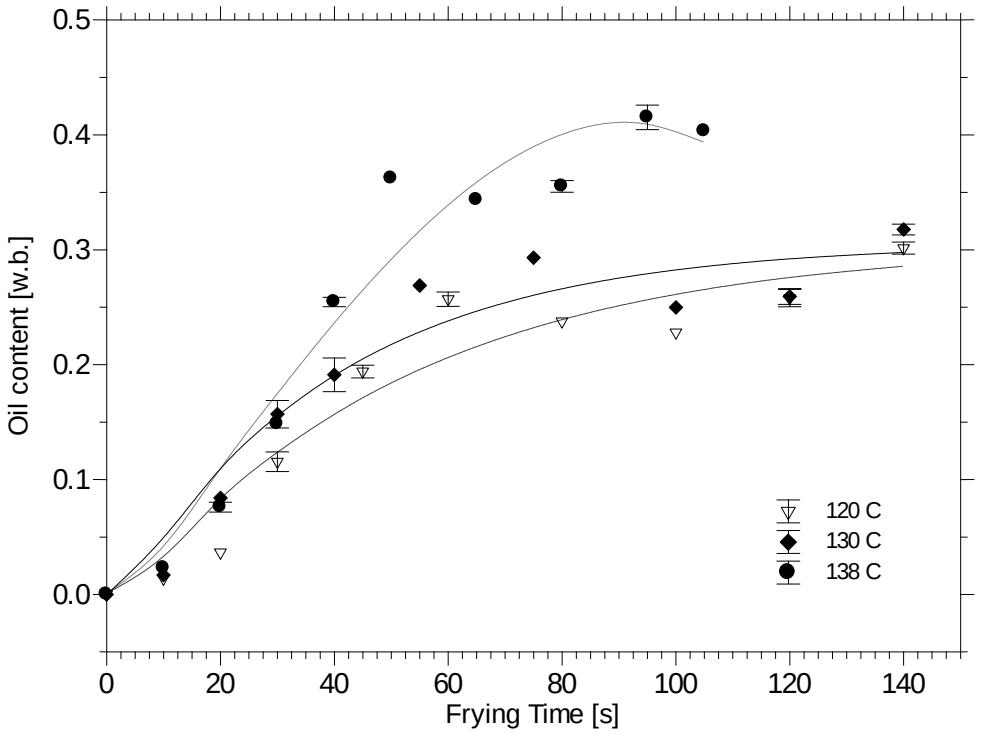


Fig. 5.3. Oil content (OC) of mango chips pre-treated with OD (65 w/v and 40°C) for 60 min and fried under vacuum (P = 1.33 kPa, de-oiled at 225 rpm or 25 s) and de-oiled at 225 for 25 s at different frying temperatures. [120° C, OC(t) =-0.3337*exp(-0.02017t) + 0.3048, R^2=0.93; 130° C, OC(t)= -0.3343*exp(-0.02663t) + 0.3058, R^2 = 0.94; 138° C, OC(t)= -0.02591 + 0.006592t – 1.239*$10^{-5}t^2$ – 3.54*$10^{-7}t^3$, R^2 = 0.96.

The oil absorption in mango chips fried under vacuum at 138^{o} C is different. Granda (2005) also found a different behavior for potato chips fried under vacuum (10 Torr) at 140^{o} C than those vacuum fried at 118 and 125^{o} C.

The author concluded that this difference can be produced during the pressurization period, which can decrease or increase oil absorption depending on the amount of free water and surface oil in the product. However, the mango chips were subjected to a de-oiling process under vacuum after frying to get rid of the superficial oil and diminish this effect.

Table 5-2 Oil absorption rate constant (*k*) values (Eqn. 5-5) for mango chips pre-treated with OD (65 w/v and 40^{o}C) for 60 min and fried under vacuum (P = 1.33 kPa, de-oiled at 225 for 25 s) at different temperatures.

Oil Temperature (^{o}C)	***OCo*[1] (% w.b.)**	***OCe*[2] (% w.b.)**	***A***	***k(1/s)***	**R^2**
120	1.39	31	1.293	0.02268	0.93
130	1.68	32	1.283	0.02631	0.94
138	2.29	42	2.042	0.03163	0.95

[1]Initial oil content. [2]Equilibrium oil content (final oil content)

The rate of oil content absorption was modeled following the same fractional conversion kinetic model used by Granda (2005) (Table 5-2):

$$OR = \frac{OC(t) - OCe}{OCo - OCe} = Aexp(-kt) \qquad [5\text{-}5]$$

where *OR* = oil ratio, *OCe* = equilibrium oil content, *OCo* = initial oil content, *A* and *k* are the regression coefficients, and *t* = frying time (Fig. 5-4).

Mango structure is more sensitive to heat than potato. Therefore, higher oil content in mango slices fried under vacuum at 138^{o} C can also be attributed to tissue/constituents degradation which enhances the oil absorption. Nevertheless, the presence of a mesh in the de-oiling process help to keep the mango slices in the frying basket which also affected the mango chips oil content, as previously discussed in sections *4.6* and *4.7.1*. After frying for 50 s at 138^{o} C, an increase of 37% w.b. in oil content was observed compared with the other temperatures (120 and 130^{o} C). At this frying time and temperature (138^{o}C) most of the water is removed from the mango slices and the oil absorption rate (Table 5-2) suddenly increases.

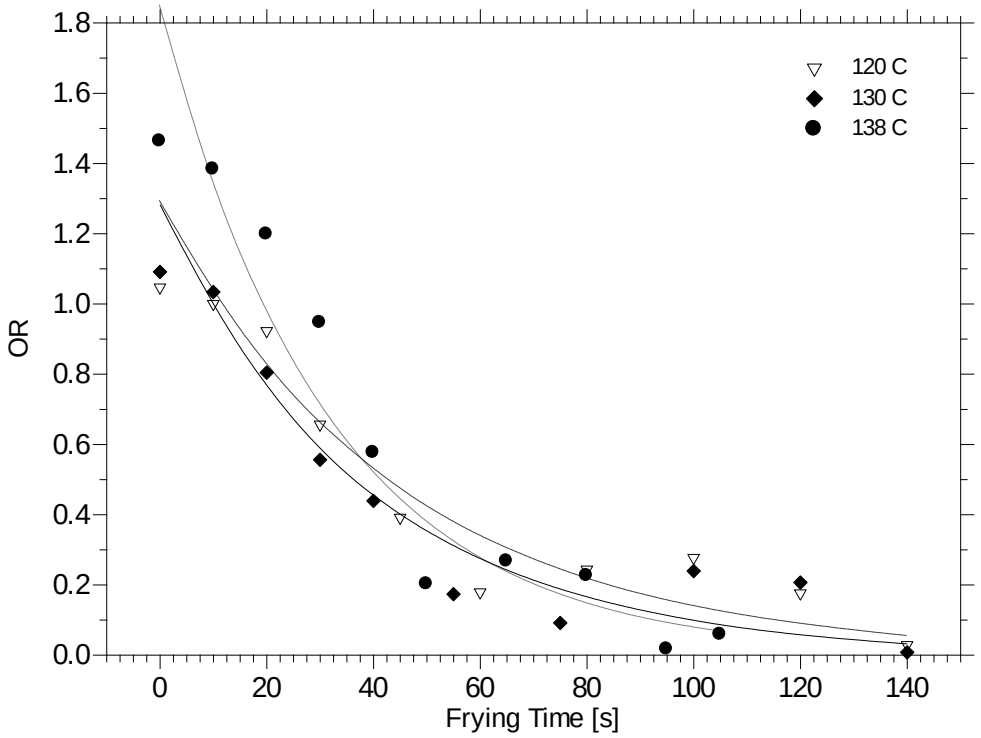


Fig. 5-4. Oil absorption on mango chips pre-treated with OD (65 w/v and 40^{o}C) for 60 min and fried under vacuum (P = 1.33 kPa, de-oiled at 225 for 25 s) at different frying temperatures [120^{o} C, OR(t) = 1.293*exp(-0.02268*t), R^2= 0.93; 130^{o} C, OR(t) = 1.283*exp(-0.02631*t), R^2= 0.94; 138^{o} C, OR(t) = 2.042*exp(-0.03163*t), R^2= 0.95].

5.3 Effect of oil temperature and frying time on the diameter and thickness changes of pre-treated mango chips

5.3.1. Diameter changes

The changes in the mango slices diameter with frying time was analyzed in two periods (Figs. 5-5 and 5-6): during the first 50 s and then from 50 to 140 s. During the initial frying time (50 s) for a frying temperature of 120^{o}C the slices experienced a slight increase ($P>0.05$) in diameter. Due to sudden water evaporation in the mango slices during the first seconds, expansion of the mango tissue was observed. Fig. 5-1 shows that for 50 s vacuum frying most of the water in the mango slices evaporated. At 130^{o}C and 138^{o}C frying temperatures, less expansion in the diameter was observed probably due to a faster crust formation in the mango tissue due to the higher frying temperature.

Yan, Sousa-Gallagher, & Oliveira (2008) observed the relationship between mango shrinkage and the moisture content during air-drying. They found that mango shrinkage increased when less water is present in the sample, though the air-drying process was carried out at 70^{o}C and at this temperature water evaporation does not happen suddenly. Kawas-Escoto (2000) found a sudden decrease in the diameter of freeze-dried and steamed-baked tortilla chips fried for 60 s at high frying temperature (190^{o}C) in the first 8 s.

After the 8 s, no changes in chips diameter occurred for both pre-treatments. After 50 s of frying, when most of the water was removed, a slight exponential decrease in the diameter for all frying temperatures was observed (Fig. 5-6). When frying at 120^{o}C and 130^{o}C similar shrinkage behavior was obtained. However, for 138^{o}C no significant change ($P>0.05$) ocurred.

Da Silva, Moreira, & Gomes (2008) observed a similar shrinkage behavior for vacuum fried potato chips at 120 and 130^{o}C. Fig. 5-6 shows similar diameter change for vacuum frying temperatures of 120 and 130^{o}C.

The changes in diameter during the first period of frying (0 to 45 s) fluctuate up to a maximum diameter expansion due to sudden evaporation of water. For the second frying period (50 to 140 s), an exponential decay (diameter shrinkage) for the three frying temperatures was observed. Mango slices fried at 138^{o}C shrunk more (around 11.81%), compared with 120 and 130^{o}C (1.74 and 2.28%, respectively) due to fast crust formation and less expansion in diameter was observed.

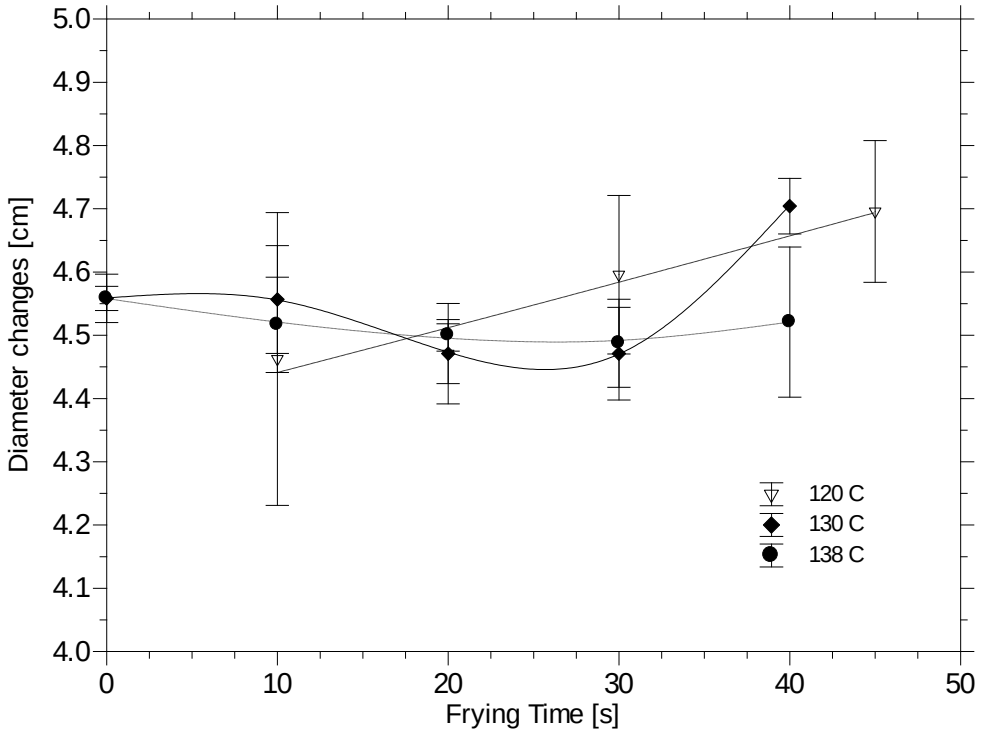


Fig. 5-5. Diameter changes (DC) on mango chips pre-treated with OD (65 w/v and 40^{o}C) for 60 min and fried under vacuum (P = 1.33 kPa, de-oiled at 225 for 25 s) at different frying temperatures [120^{o}C, DC = 4.37*exp (0.001582*t), R^2 = 0.94; 130^{o}C, DC = 4.559 + $8.932x10^{-3}$*t – $1.19x10^{-3}$*t^2 + $2.646x10^{-5}$*t^3, R^2 = 0.99; 138^{o}C, DC = 4.557 + $3.953x10^{-3}$*t – $5.952x10^{-6}$*t^2 + $1.736x10^{-6}$*t^3, R^2 = 0.981].

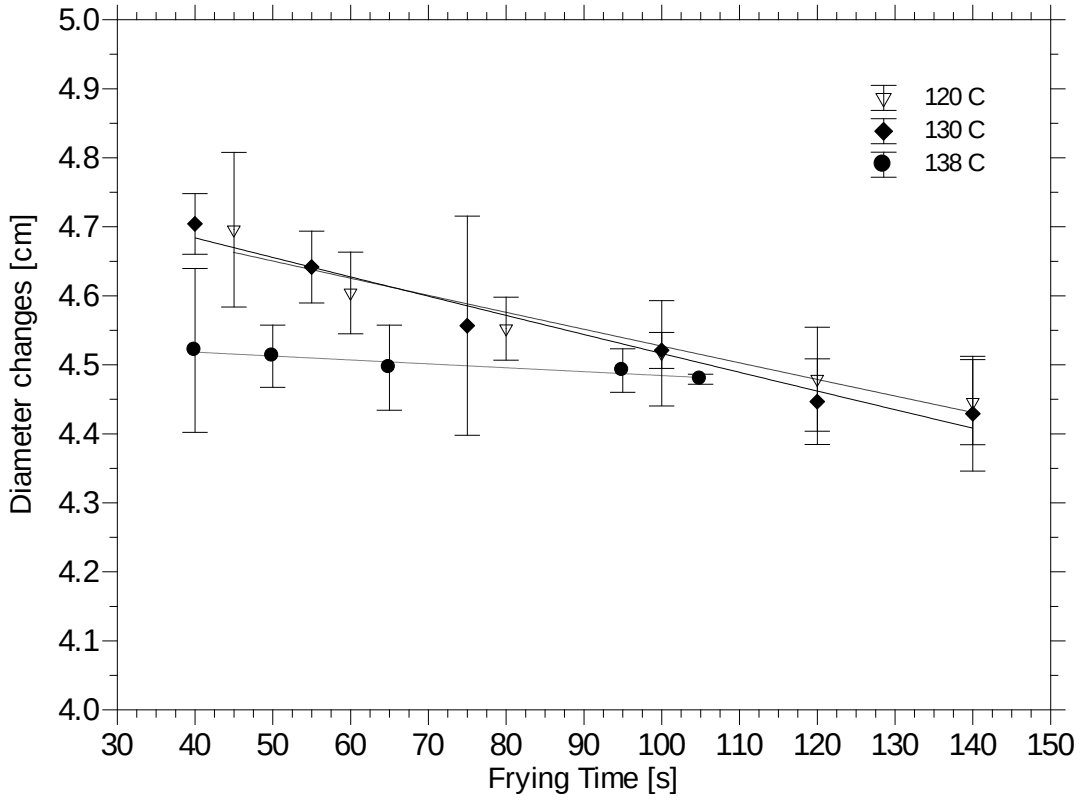


Fig. 5-6. Diameter changes (DC) on mango chips pre-treated with OD (65 w/v and 40^{o}C) for 60 min and fried under vacuum (P = 1.33 kPa, de-oiled at 225 rpm for 25 s) at different frying temperatures [120^{o} C, DC = 4.776*exp(-0.0005372*t), R^2 = 0.94; 130^{o} C, DC = 4.799*exp(-0.0006067*t), R^2 = 0.97; 138^{o}C, DC = 4.54*exp(-0.0001257*t), R^2 = 0.91].

5.3.2 Thickness changes

The changes in mango slices thickness during vacuum frying at different temperatures (120, 130, and 138^{o}C) are presented in Fig. 5-7. Compared with the initial raw mango thickness (about 1.6±1 mm), the thickness increased with frying time for all vacuum frying temperatures. The effect of OD on the mango slices thickness is discussed in section *4.4.1*.

When vacuum frying at 120^{o}C, the thickness of the mango slices increased from 0.7±0.07 mm (frying for 10 s) to 2.19±0.15 mm (frying for 140s). At 130^{o}C frying temperature, the samples puffed from 0.95±0.12 mm (frying for 10 s) to 2.20±0.19 mm (frying for 140s). Frying at 138^{o}C resulted in less thickness expansion of the mango chips, from 0.89±0.12 mm (frying for 10 s) to 1.64±0.17 mm (frying for 105 s). A second order equation (Fig. 5-7) was fitted to describe thickness changes in mango slices during vacuum frying. Mango slices shrunk during the first 40 s, since at this time most of the water evaporates at a faster rate. After vacuum frying for 40 s the mango chips thickness increased (Fig. 5-7). These results have also been obtained by Da Silva, Moreira, & Gomes (2008) and Kawas-Escoto (2000) in vacuum fried potato chips and traditional fried tortilla chips, respectively. They also observed the shrinkage expansion during frying time.

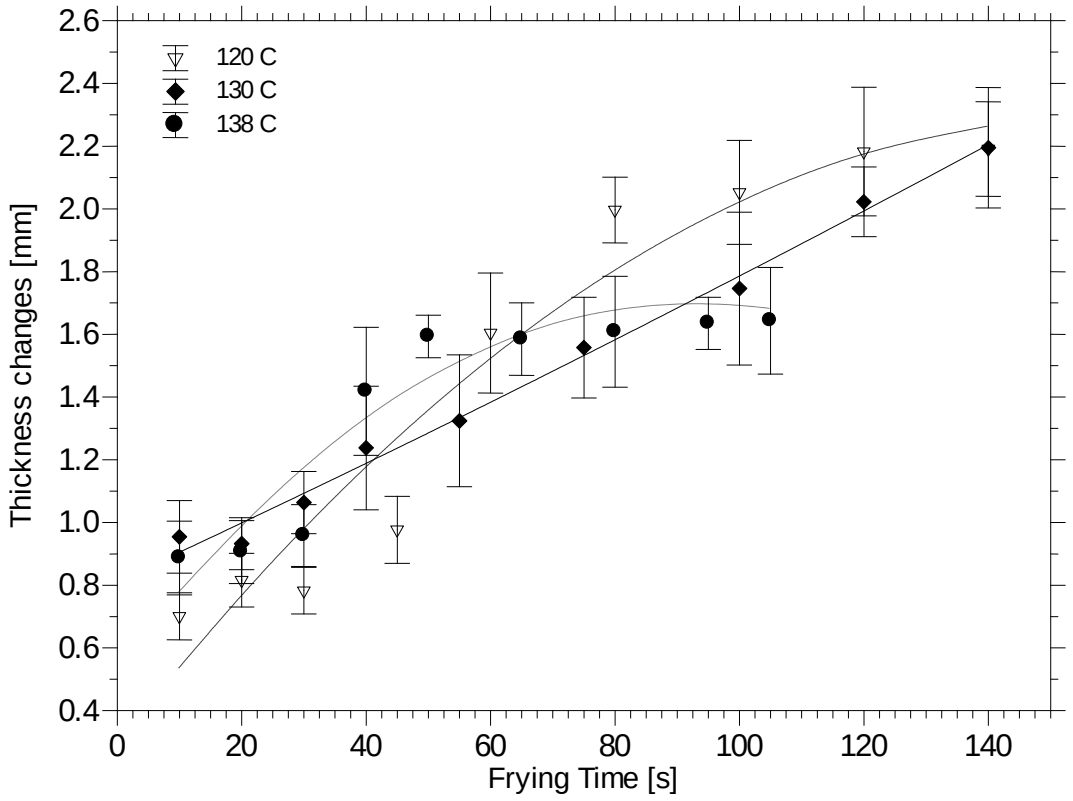


Fig. 5-7. Thickness changes (TC) on mango chips pre-treated with OD (65 w/v and 40^{o}C) for 60 min and fried under vacuum (P = 1.33 kPa, de-oiled at 225 rpm for 25 s) at different frying temperatures [120^{o} C, TC = 0.2873 + 0.02534*t – 8.03x10^{-5}*t^{2} , R^2 = 0.97; 130^{o} C, TC = 0.8128 + 0.009172*t + 5.48x10^{-6}*t^{2}, R^2 =1; 138^{o}C, TC = 0.5334 + 0.02562*t – 0.00014*t^{2}, R^2 = 0.95].

5.4 Effect of oil temperature and frying time on the texture of pre-treated mango chips

Figs. 5-8 and 5-9 show the changes in texture for mango chips fried for 40 s at 120, 130, and 138^{o}C. The mango slices became crispier at a fast rate at the beginning of the frying (40 s). During this time, most of the water, which acts as a plasticizer, (Fig. 5-1) evaporates and crisp texture begins to form. Maximum force peak and work followed a similar exponential decay for frying during 40 s. At higher vacuum frying temperatures, the water lost rate increased and the chips became crispier faster. This effect was also observed by Granda (2005) in potato chips, which became more brittle rather than rubbery earlier in the frying process as the temperature increased. Shyu & Hwang (2001) found in vacuum fried apple chips that at lower breaking force correspond to a higher crispiness. They observed that the lower the moisture content in the samples the lower the force to break them. At higher vacuum frying temperatures, the breaking force decreases resulting in crispier apple chips. Also, Fan, Zhang, & Mujumbar (2005) found a decrease in breaking force of carrot chips when vacuum frying temperatures decreased.

After 40 s (Figs. 5-10 and 5-11), the sugar uptake played an important role in the chips structure. The addition of sugar (maltodextrin) in the mango slices resulted in a more rigid structure. This rigidity can be attributed to some breakage of the matrix in the mango structure due to high pressure in the pores when water was being evaporated. This effect was also observed by Kasahara *et al* (2002) in French fries pre-treated with different soaking solutions. The French fries crust rigidity decreased during the first

three minutes of frying, then after 4 min of frying it increased as the surface crust formed. Also, the texture of on the French fries increased when frying temperature increased.

The kinetics of texture formation based on peak force and work values (from 0 to 40 s) was similar to the model proposed by Pedreschi and Moyano (2005) (two frying periods) for potato chips (Figs. 5-8 and 5-9, and Table 5-3 and 5-4):

$$P = P_o \exp(-kt) \quad [5\text{-}6]$$

Or

$$W = W_o \exp(-kt) \quad [5\text{-}7]$$

where P is the peak force, W the work done to compress the 5 samples, P_o the initial peak force texture, W_o the initial work, k the kinetic constant, and t frying time.

Table 5-3 Texture kinetic coefficients (P_o, W_o, and k) values for the first period ($0 < t < 40$ s) for mango chips pre-treated with OD (65 w/v and 40°C) for 60 min and fried under vacuum (P = 1.33 kPa, de-oiled at 225 rpm for 25 s) at different temperatures.

Oil Temperature (°C)	P_o [1]	W_o [2]	$k[1/s]_p$	$k[1/s]_w$	R^2_p	R^2_w
120	48.99	42.95	0.1172	0.0912	0.99	0.96
130	43.49	38.47	0.0742	0.0833	0.98	0.99
138	43.9	36.26	0.1030	0.1102	0.98	0.98

[1]Initial peak force, [2]initial work. P = peak force, and W= work

For the second period (from 40 to 140 s) the kinetics of texture formation followed this model:

[5-8]

$$P = \frac{P(t) - P_e}{P_o - P_e} = \exp(-kt)$$

Or

[5-9]

$$W = \frac{W(t) - W_e}{W_o - W_e} = \exp(-kt)$$

where $P(t)$ [N] and $W(t)$ [N*mm] are the peak force and work with frying time, respectively. P_e and W_e the peak force and work in equilibrium, respectively. P_o and W_o the peak force and work initial values, respectively. And, k [1/s] and t [s] are the kinetic constant coefficient and frying time, respectively.

Table 5-4 Texture kinetic coefficients (P_o, W_o, P_e, W_e, and k) values for the second period (40< t <140 s) for mango chips pre-treated with OD (65 w/v and 40°C) for 60 min and fried under vacuum (P = 1.33 kPa, de-oiled at 225 rpm for 25 s) at different temperatures.

Oil Temperature (°C)	P_o [1]	W_o [2]	P_e [3]	W_e [4]	$k[1/s]_p$	$k[1/s]_w$	R^2_p	R^2_w
120	-21.25	-141.35	5.85	28.65	0.0405	0.04	0.92	0.90
130	-10.70	-64.84	6.27	29.09	0.0405	0.04	0.94	0.96
138	-15.47	-94.60	7.85	38.00	0.0405	0.04	0.90	0.95

[1]Initial peak force. [2]Initial work. [3]Equilibrium peak force. [4]Equilibrium work. P = peak force, and W= work

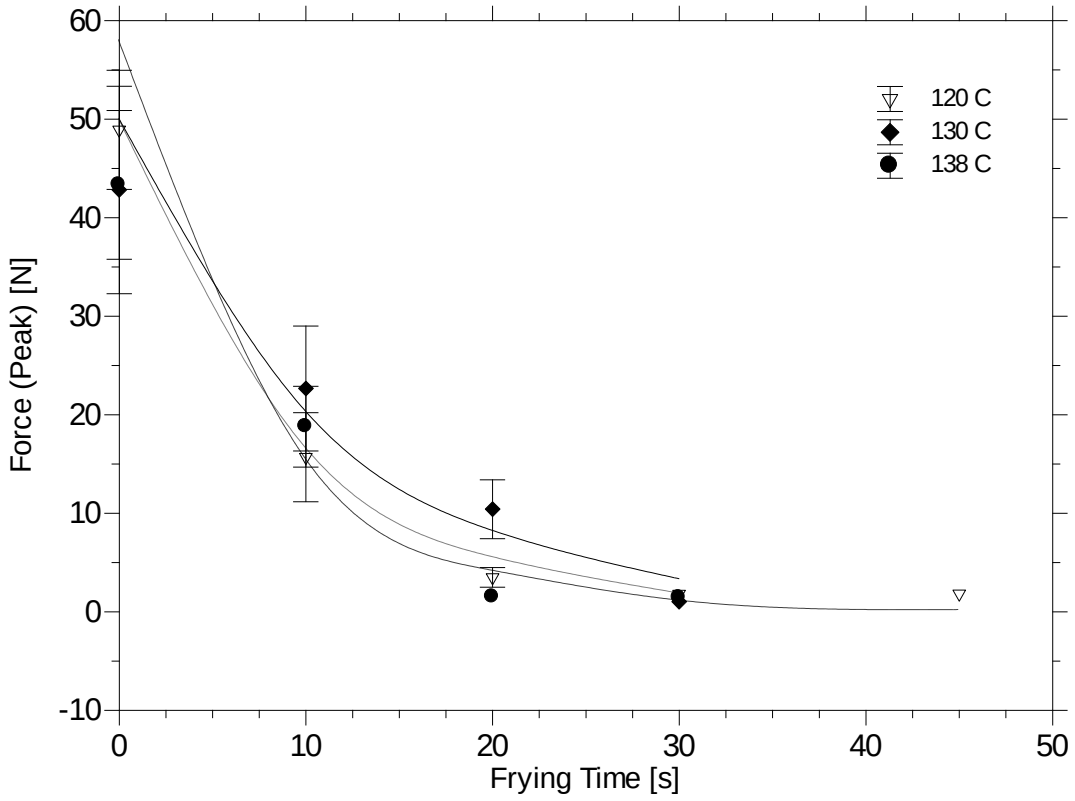


Fig. 5-8. Maximum force (peak (P)) to compress mango chips pre-treated with OD (65 w/v and 40^{o}C) for 60 min and fried under vacuum (P = 1.33 kPa, de-oiled at 225 rpm for 25 s) at different frying temperatures [120^{o} C, P= 48.99*exp(-0.1172*t), R^2 = 0.99; 130^{o} C, P = 43.49*exp(-0.0742*t), R^2 = 0.98; 138^{o}C, P = 43.9*exp(-0.103*t), R^2 = 0.98].

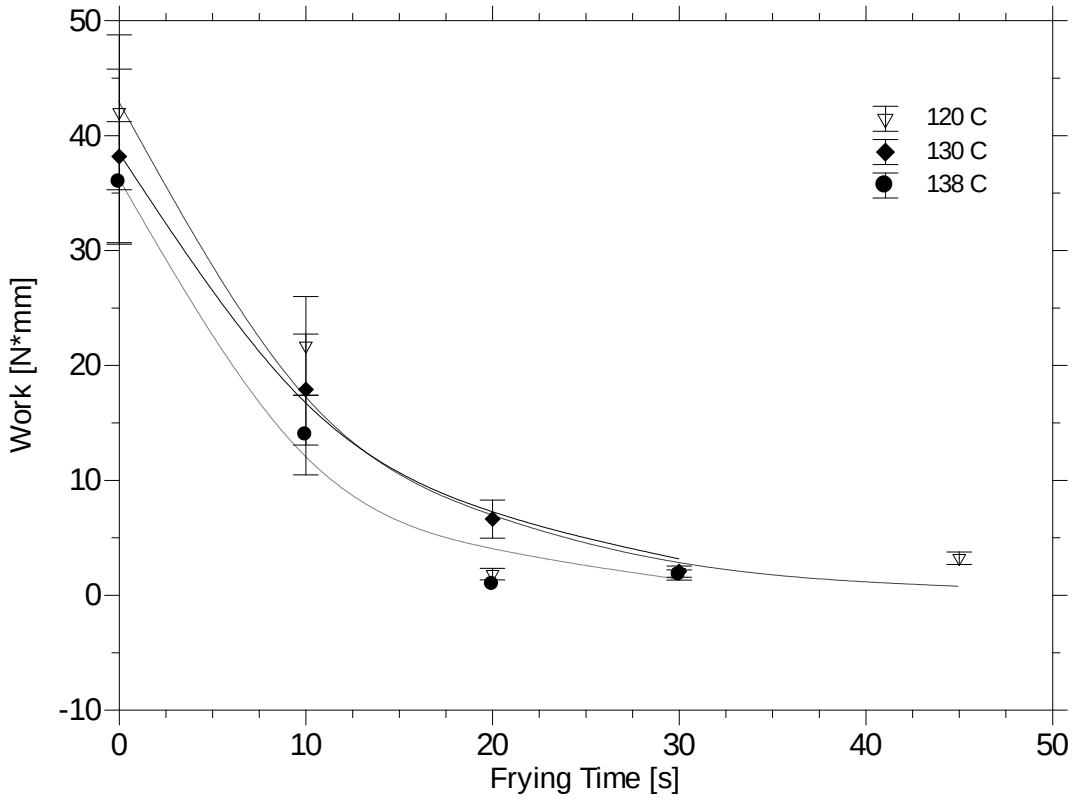


Fig. 5-9. Work required to compress mango chips pre-treated with OD (65 w/v and 40^{o}C) for 60 min and fried under vacuum (P = 1.33 kPa, de-oiled at 225 rpm for 25 s) at different frying temperatures [120^{o} C, W = 42.95*exp (-0.09124*t), R^2 = 0.96; 130^{o} C, W = 38.47*exp (-0.08331*t), R^2 = 0.99; 138^{o}C, W = 36.26*Exp (-0.1102*t), R^2 = 0.98].

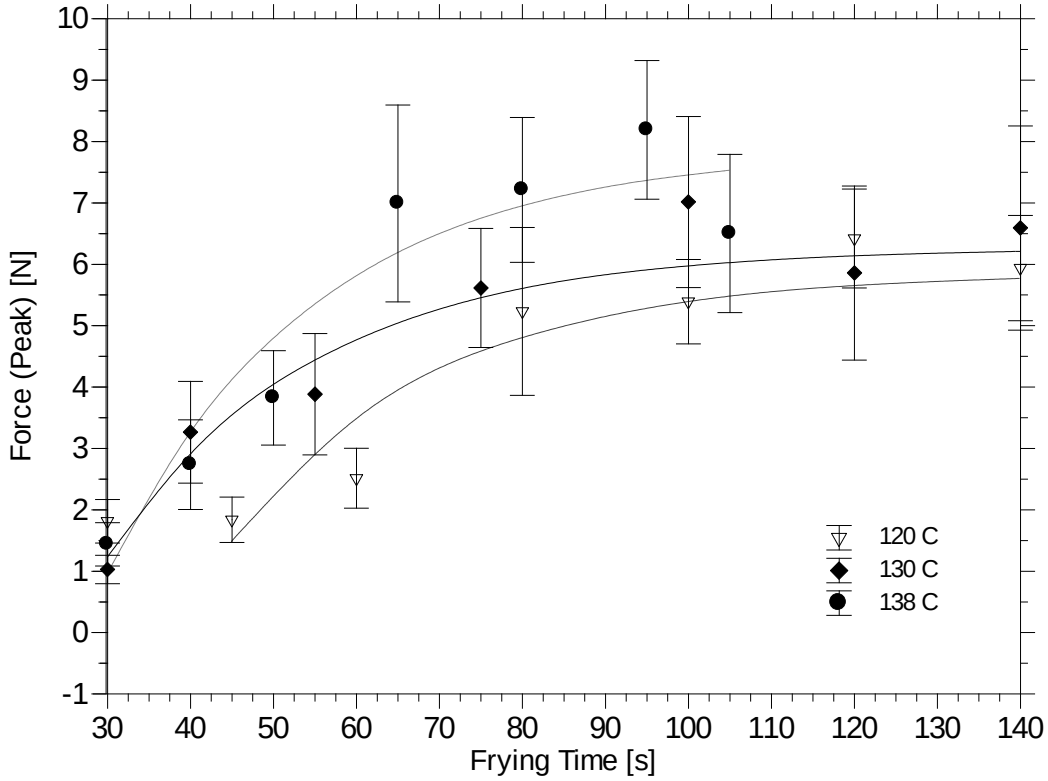


Fig. 5-10. Maximum force (peak (P)) required to compress mango chips pre-treated with OD (65 w/v and 40^{o}C) for 60 min and fried under vacuum (P = 1.33 kPa, de-oiled at 225 rpm for 25 s) at different frying temperatures [120^{o} C, P = -27.1*exp(-0.0405*t) + 5.85, R^2 = 0.91; 130^{o} C, P = -16.97*exp(-0.0405*t) + 6.27, R^2 = 0.94; 138^{o}C, P = -23.32*exp(-0.0405*t) + 7.85, R^2 = 0.90].

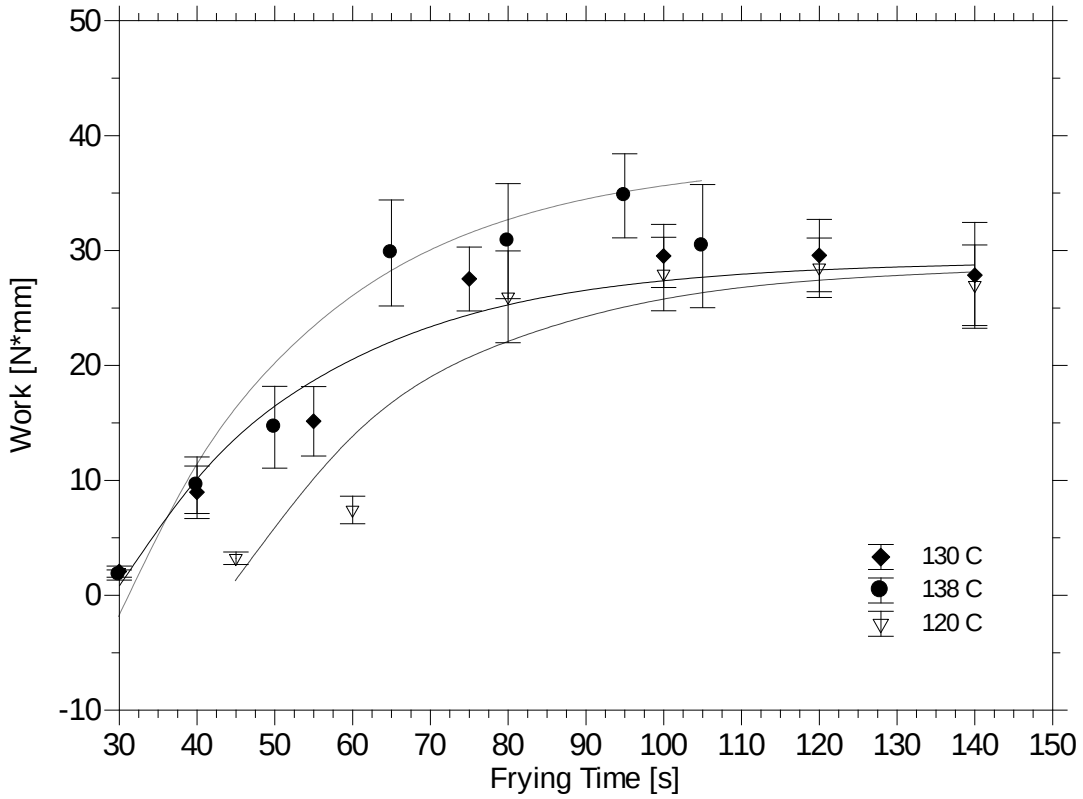


Fig. 5-11. Work required to compress mango chips pre-treated with OD (65 w/v and 40^{o}C) for 60 min and fried under vacuum (P = 1.33 kPa, de-oiled at 225 rpm for 25 s) at different frying temperatures [120^{o} C, W = -170*exp(-0.04*t) + 28.65, R^2 = 0.90; 130^{o} C, W = -93.93*exp(-0.04*t) + 29.09, R^2 = 0.96; 138^{o}C, W = -132.6*exp(-0.04*t) + 38, R^2 = 0.95].

5.5 Effect of oil temperature and frying time on the porosity of pre-treated mango chips

Bulk density and true density changed with frying time for different frying temperatures (120, 130, and 138^{o}C) (Appendix B). Bulk density decreased with frying time for all frying temperatures. The minimum bulk density was 0.52±0.02 g/cm^3 for 80 s, 61±0.02 g/cm^3 for 75 s, and 0.62±0.03 g/cm^3 for 95 s at 120, 130, and 138^{o}C, respectively. The increase in bulk density at the end of frying time at 120^{o}C and 130^{o}C was not significant because of the increase in oil content.

True density increased with frying time for all three temperatures. The maximum values obtained were 1.26±0.03 g/cm^3 for 120 s, 1.25±0.05 g/cm^3 for 75 s, and 1.22±0.01 g/cm^3 for 80 s at 120, 130, and 138^{o}C, respectively. However, fluctuation in the true density measurement, was observed due to water loss and oil absorbed at the beginning and the end of frying. The increase in true density was attributed to the water loss with frying time, although, the presence of oil in the mango chips caused some variation in the results at the end of the frying time. Porosity calculations were based on bulk and true density following Eqn. [3-10]. Fig. 5-12 shows the effect of vacuum frying time and temperature on the porosity of mango chips. The porosity formation rate in mango slices is faster before 40 s frying time. This is related to the time period where most of the water has been evaporated.

The porosity formation rate followed the same behavior for the three frying temperatures. However, at 138^{o}C the water is removed faster than the other two temperatures, and less time is needed to get the required porosity in mango chips. After

40 s of frying, no significant changes in porosity were found for frying temperatures of 130 and 138^{o}C. At 120^{o}C the equilibrium was reached after 60 s.

Yan, Sousa-Gallagher, & Oliveria (2008) observed in mango slices dried in an oven (70^{o}C) that their porosity increased 5-folds up to 12% w.b. and then decreased slowly with further drying to a final moisture content around 5%. The porosity increased with decreased moisture content. The slight decrease in porosity at the end of the drying process was attributed to the ongoing sample shrinkage.

Taiwo & Baik (2007) found an increase in porosity with frying time of sweet potato chips pre-treated (blanching, freezing, air-drying, and osmotic dehydration) compared with the control (decrease in bulk density). Also, Da Silva, Moreira, & Gomes (2008) observed an increase in porosity with frying time in potato chips.

The change in porosity formation rate was modeled following the fractional conversion kinetic model (Table 5-5):

$$PR = \frac{P(t) - Pe}{Po - Pe} = Aexp(-kt) \qquad [5\text{-}10]$$

where *PF* = porous ratio, *Pe* = equilibrium porosity, *Po* = initial porosity, *A* and *k* are the regression coefficients, and *t* = frying time. Fig. 5-13 shows the experimental data and curve fitting using Eqn. [5-10] (Table 5-5).

Table 5-5 Porous formation rate constant (*k*) values (Eqn. 5-10) for mango chips pre-treated with OD (65 w/v and 40°C, mango:syrup ratio = 1:4) for 60 min and fried under vacuum (P = 1.33 kPa, de-oiled at 225 rpm for 25 s) at different temperatures.

Oil Temperature (°C)	***Po*[1]**	***Pe*[2]**	***A***	***k(1/s)***	**R^2**
120	0.01	0.6	1.475	0.02527	0.95
130	0.026	0.52	1.483	0.02899	0.92
138	0.11	0.5	1.663	0.03905	0.95

[1]Initial porosity. [2]Equilibrium porosity

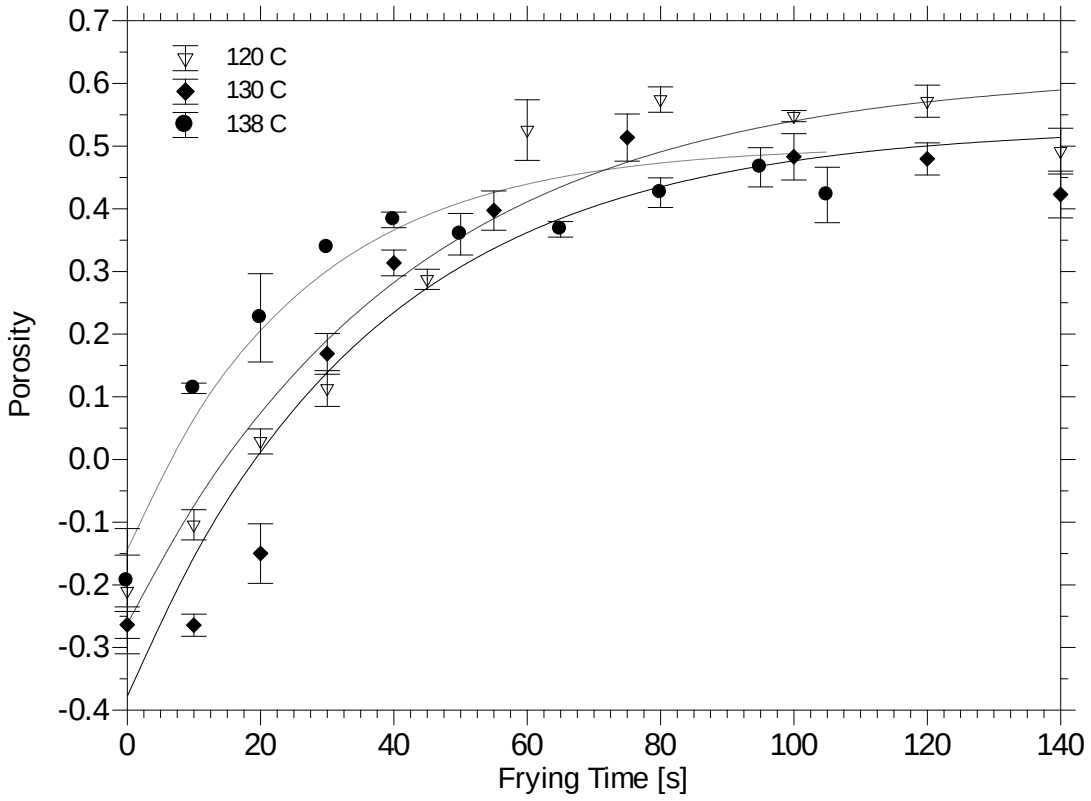


Fig. 5-12. Porosity (Por) change in mango chips pre-treated with OD (65 w/v and 40^{o}C) for 60 min and fried under vacuum (P = 1.33 kPa, de-oiled at 225 rpm for 25 s) at different frying temperatures [120^{o} C, Por = -0.8849*exp(-0.024*t) + 0.6087, R^2= 0.95; 130^{o} C, Por = -0.9098*exp(-0.02797*t) + 0.523, R^2= 0.91; 138^{o}C, Por= -0.6486*exp(-0.03904*t) + 0.503, R^2= 0.95].

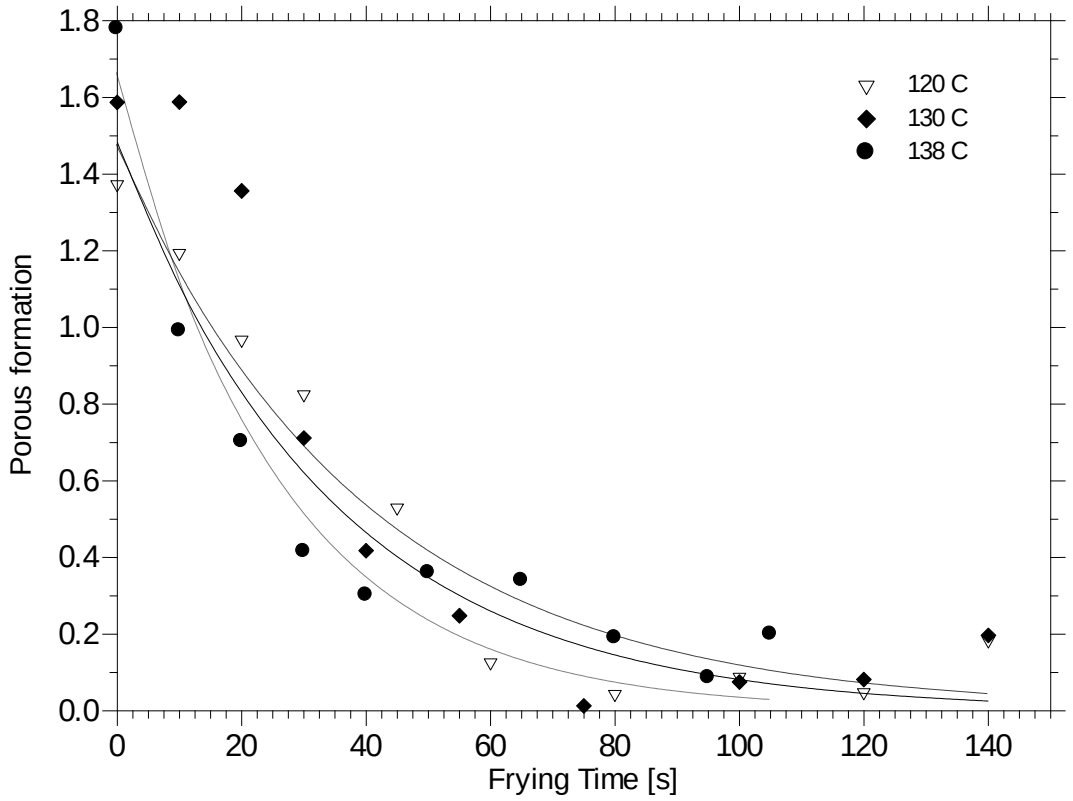


Fig. 5-13. Porous ratio changes (PR) in mango chips pre-treated with OD (65 w/v and 40^{o}C) for 60 min and fried under vacuum (P = 1.33 kPa, de-oiled at 225 rpm for 25 s) at different frying temperatures [120^{o} C, PR = 1.475*exp(-0.02527*t), R^2 = 0.95; 130^{o} C, PR = 1.483*exp(-0.02899*t), R^2 = 0.92; 138^{o}C, PR = 1.663*exp(-0.03995*t), R^2 = 0.95].

5.6 Effect of oil temperature and frying time on the color of pre-treated mango chips

Figure 5-14 shows the changes in color *a with frying time for pre-treated mango chips at different vacuum frying temperatures. The changes for *a color value ranged from 9.97±0.38 to 12.16±0.14, 12.89±0.05, and 14.34±0.12 at 120, 130, and 138^{o}C, respectively. The highest *a values were found at the end of the frying time. Color *a increased with frying time for all frying temperatures. Also, this parameter increased with frying temperature. The changes in color *a can be attributed to the Maillard reaction due to high frying temperatures during frying time (Garayo & Moreira, 2002; Shyu & Hwang, 2001; Taiwo *et al*, 2007). At the highest frying temperature (138^{o}C) the increase in *a value was sharply higher than at 120 and 130^{o}C.

Shyu & Hwand (2001) observed an increase in the *a color of pre-treated apple chips when frying time and temperature increased. They concluded that changes in color *a was produced by Maillard reactions caused by heating during vacuum frying.

Taiwo, Baik, and Farinu (2007) found an increased in *a color of pre-treated sweet potato chips (170^{o}C) due to Maillard reactions with frying time. Osmotic dehydration pre-treatment gave a lower *a value compared with air-drying pre-treatment. They found changes in color *a ranging between 2.73 and 5.18 and final values ranging between 11.38 and 17.13, depending on the pre-treatment. Baik & Mittal (2003) observed an exponential increased in *a value from -1.17 to 2.89-6.72 at the surface of tofu depending on frying conditions. The highest values were found with the highest frying temperature (172^{o}C).

Color *a changes were best described by a logistic model for all vacuum frying temperatures:

[5-11]

$$Color\ a* = A_o + \frac{A}{1 + \exp\left[-k*(t - to)\right]}$$

where A_o, A and k are the first order kinetic coefficients, and t_o the initial frying time. t is frying time. Figure 5-14 and Table 5-6 shows the experimental data and curve fitting using Eqn. [5-11].

Table 5-6 Color *a coefficients (A_o, A, and k) values (Eqn. 5-11) for mango chips pre-treated with OD (65 w/v and 40°C, mango:syrup ratio = 1:4) for 60 min and fried under vacuum (P = 1.33 kPa, de-oiled at 225 rpm for 25 s) at different temperatures.

Oil Temperature (°C)	A_o[1]	A	t_o[2] **[s]**	k**[1/s]**	R^2
120	4	10.21	0	0.006469	0.80
130	3	10.11	0	0.016	0.84
138	4	12.52	0	0.0111	0.88

[1]Initial regression coefficient, [2]Initial time.

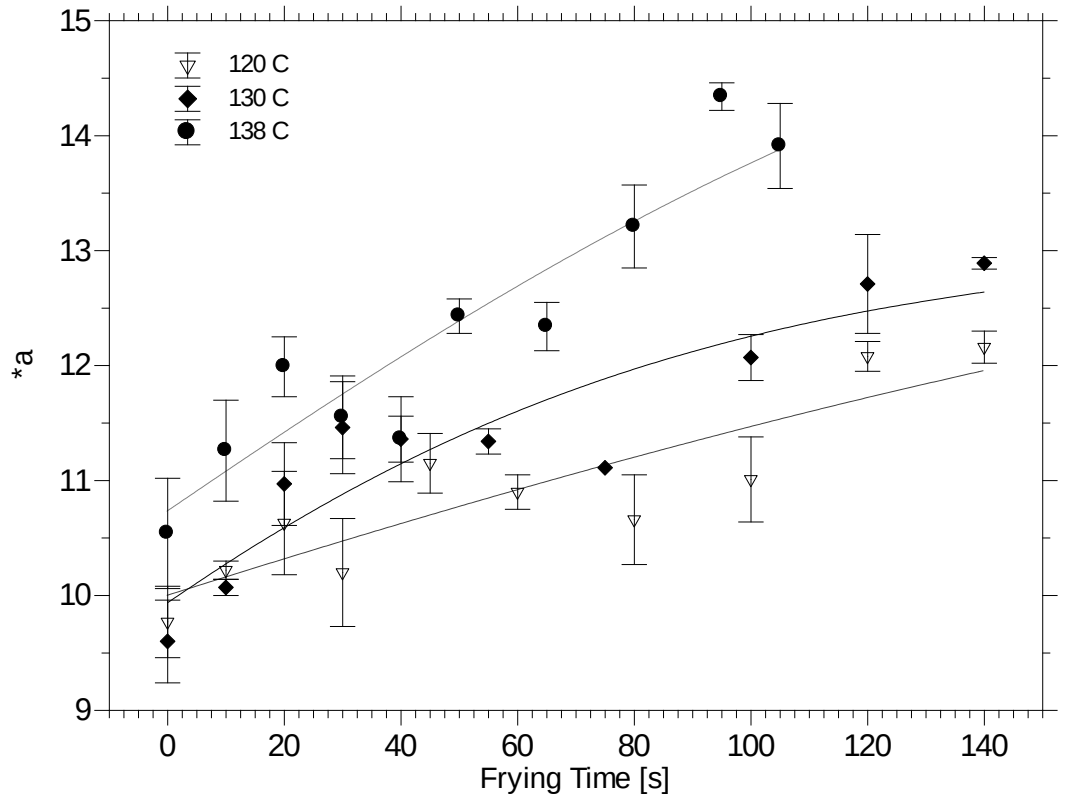


Fig. 5-14. Color *a in mango chips pre-treated with OD (65 w/v and 40^{o}C) for 60 min and fried under vacuum (P = 1.33 kPa, de-oiled at 225 rpm for 25 s) at different frying temperatures [120^{o} C, *a = 4 + 10.21/(1 + 0.7036*exp(-0.006469*t)), R^2 = 0.80; 130^{o} C, *a = 3 + 10.11/(1 + 0.4573*exp(-0.016*t)), R^2 = 0.84; 138^{o}C, *a = 4 + 12.52/(1 + 0.8618*exp(-0.0111*t)), R^2 = 0.88].

Figure 5-15 shows the results for color *b for mango chips fried at different temperatures. For all frying temperatures, *b increased exponentially for the first 20 s and then stared to decrease exponentially until 140 (120 and 130^{o}C) and 105 s (138^{o}C). The yellowness in the mango (associated to *b) is related to the beta-carotenes present in mango (Fan, 2005), which gives its characteristic yellow color. A decrease in color *b means a possible carotenoids degradation in mango. However, during the first 20 s of frying an increase in *b color was found for all frying temperatures. This can be a consequence of the carotenoids concentration due to water removal. Color *b changes were from around 62.8 to 67.5, 61 to 67, and 66 to73 before frying for 30 s at 120, 130, 138^{o}C, respectively. After 30 s, color *b decreased from 67.5 to 62, 67 to 55, and 73 to 58.5 at 120, 130, and 138^{o}C frying temperatures, respectively. High *b values give more yellow color, which is desirable for mango chips. The model used to describe *b color changes (for the two periods, from 0 to 20 s and 30 to 140 s) in the mango slices at different frying temperatures was a first order kinetic model (Fig. 5-15, and Tables 5-7 and 5-8):

[5-12]

$$*b = \frac{*B(t) - *B_e}{*B_0 - *B_e} = \exp(-kt)$$

where $*B_o$ is the initial *b color, $*B_e$ is the equilibrium, k [1/s] is the first order coefficient, and t [s] time.

Table 5-7 Color *b coefficients (B_o, B_e, and k) values for the first period (0< t <20 s) for mango chips pre-treated with OD (65 w/v and 40°C, mango:syrup ratio = 1:4) for 60 min and fried under vacuum (P = 1.33 kPa, de-oiled at 225 rpm for 25 s) at different temperatures.

Oil Temperature (°C)	***B_o**[1]	***B_e**[2]	***k*[1/s]**	**R^2**
120	62.45	69.79	0.053	0.88
130	61.11	66.94	1.112	1
138	66.09	72.27	0.8047	0.99

[1]Initial *b color, [2]Equilibrium *b color.

Table 5-8 Color *b coefficients (B_o, B_e, and k) values for the second period (30< t <140 s) for mango chips pre-treated with OD (65 w/v and 40°C, mango:syrup ratio = 1:4) for 60 min and fried under vacuum (P = 1.33 kPa, de-oiled at 225 rpm for 25 s) at different temperatures.

Oil Temperature (°C)	***B_o**[1]	***B_e**[2]	***k*[1/s]**	**R^2**
120	70.16	57	0.00619	0.97
130	68.55	51	0.00342	0.83
138	78.61	50	0.01055	0.92

[1]Initial *b color, [2]Equilibrium *b color.

Taiwo, Baik, & Farinu (2007) found that *b values in fried sweet potatoes increased initially with frying up to 60 s, after which they decreased to the end of frying. At the end of frying (300 s), control samples had *b values of less than 5.0, while other pre-treated samples had values in the range 19.8 to 23.72, depending on the treatment. OD samples had higher *b values than the control samples. The results obtained for color *b (Table 5-8) in this study are similar to those obtained by Baik & Mittal (2003)

who observed an exponential increase in color *b up to 240, 130, and 150 s frying at 147, 160, and 172^{o}C, respectively. Then *b color decreased exponentially up to 300 s, where the lowest value for this parameter was observed at the highest frying temperature.

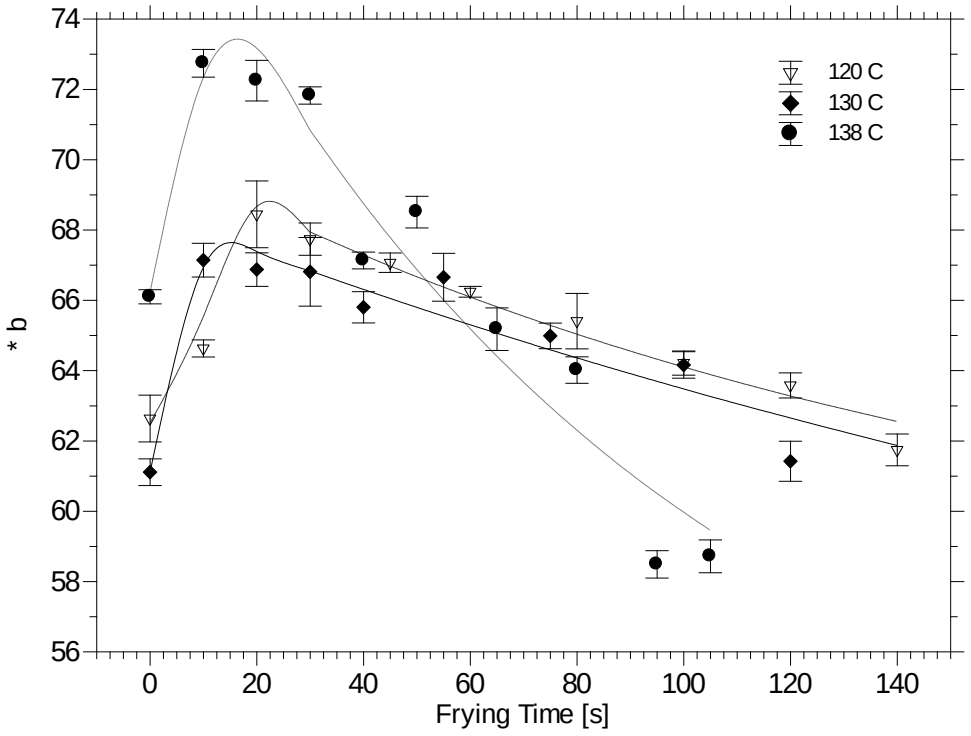


Fig. 5-15. Color *b in mango chips (de-oiled fro 25 s at 225 rpm) pre-treated with OD (65 w/v and 40^{o}C) for 60 min and fried under vacuum (P = 1.33 kPa, de-oiled at 225 rpm for 25 s) at different frying temperatures. For 0< t < 20 s = [120^{o} C, *b = -7.339*exp(-0.053*t) + 69.79, R^2 = 0.88; 130^{o} C, *b = -5.832*exp(-1.112*t) + 66.94, R^2 = 1; 138^{o}C, *b = -6.172*exp(-0.8047*t) + 72.27, R^2 = 0.99]. For 30 < t < 140 s = [120^{o} C, *b = 13.16*exp(-0.006187*t) + 57, R^2 = 0.97; 130^{o} C, *b = 17.55*exp(-0.003421*t) + 51, R^2 = 0.83], and for 30 < t < 105 s , 138^{o}C [*b = 28.61*exp(-0.01055*t) + 50, R^2 = 0.92].

5.7 Effect of oil temperature and frying time on the carotenoids (beta-carotenes) degradation in mango slices

The average beta-carotenes concentration in raw mango was 51.47±2.70 [µg-carotene/g product d.b.] For 140 s vacuum frying, the lowest value for beta-carotenes in mango chips fried at 120 and 130^{o}C was 32.04±1.77 and 31.25±2.40 [µg-carotene/g product d.b.], respectively. At 140^{o}C, the lowest value was 29.59±1.21 [µg-carotene/g product d.b.] for 105 s. When pre-treated mango slices were fried at 165^{o}C for 2.33 min under traditional frying (atmospheric), the beta-carotene concentration was 16.34±1.05 [µg-carotene/g product d.b.] at the end of the process.

Both methods (vacuum and atmospheric frying) caused a decrease in carotenoids. However, mango chips fried under vacuum had higher (around 45% to 49%) carotenoids retention after frying for 140 s. The differences in carotenoids retention can be attributed to higher temperature and absence of oxygen. Carotenoids can degrade with high temperatures, presence of oxygen (oxidation), or/and light. Da Silva and Moreira (2008) found a difference in final carotenoids concentration in mango chips fried under traditional (165^{o}C) and vacuum (121^{o}C, 1.33 kPa) fryers. The difference in the final carotenoid concentration for traditional and vacuum frying was 11.85±0.05 and 14.67±0.52 [µg-carotene/g product d.b.], respectively. Their results are different from those obtained in this study because the samples were fried for longer time (vacuum frying for 180 s at 121^{o}C and traditional frying for 240 s at 165^{o}C).

The rate of change beta-carotene content can be modeled as a first order reaction model, as discussed by Chen and Ramaswamy (2002):

$$\frac{dC}{dt} = -kC \qquad [5\text{-}13]$$

where *k* is the rate constant [1/s] and *C* is the carotenoids concentration.

By integrating Eqn 5-14, a first order equation is obtained:

$$C(t) = A + kt \qquad [5\text{-}14]$$

$$C(t) = A \exp(-kt) \qquad [5\text{-}15]$$

$$C = \frac{C(t) - C_e}{C_o - C_e} = \exp(-kt) \qquad [5\text{-}16]$$

where *C(t)* is the carotenoid concentration at time *t*, and C_o and C_e represent the initial and equilibrium values, respectively.

The rate of carotenoid degradation decreased exponentially with time at all frying temperatures (Fig. 5-16). Table 5-9 shows all the first order coefficients for all frying temperatures.

Table 5-9 Carotenoid degradation coefficients (C_o, C_e, and k) values for the second for mango chips pre-treated with OD (65 w/v and 40°C, mango:syrup ratio = 1:4) for 60 min and fried under vacuum (P = 1.33 kPa, de-oiled at 225 rpm for 25 s) at different temperatures.

Oil Temperature (°C)	C_o[1] **[µg/g]**	C_e[2] **[µg/g]**	k **[1/s]**	R^2
120	53.021	6.651	0.00436	0.94
130	49.82	30.72	0.0117	0.94
138	51.23	28.92	0.0449	0.99

[1]Initial carotenoid concentration, [2]Carotenoid concentration in equilibrium.

The rate constant (k) temperature dependence was determined using the Arrhenius equation (Eqn. 5-18). The following relationship was found by plotting ln (k) vs 1/T (Fig. 5-17):

$$\ln k = 47.2592 - 20750.5\left(\frac{1}{T}\right), \qquad R^2 = 0.97 \qquad [5\text{-}18]$$

From Eqn. 5-18, A = 3.34x10^{20} 1/s and E_a = 172519.65 J/mol. The dependency of k on the frying temperature in mango chips is then given by:

$$k(T) = 3.34x10^{20}[1/S]\exp\left(\frac{-20750.5K}{T}\right) \qquad [5\text{-}19]$$

According to Pesek and Warthessen (1989) established that in an aqueous medium most of ß-carotenes degradation follows a first order equation. Minguez-Mosquera & Jaren-Galan (1995) found a high relationship between beta-carotenes degradation (measure directly by the discoloration of beta-carotene pigments in their

experiment) and temperature. Hiranvarachat, Suvarnakuta & Devahastin (2008) observed by different drying techniques that hot air drying had more ß-carotenes degradation than vacuum drying in carrots dried from 60 to 80°C.

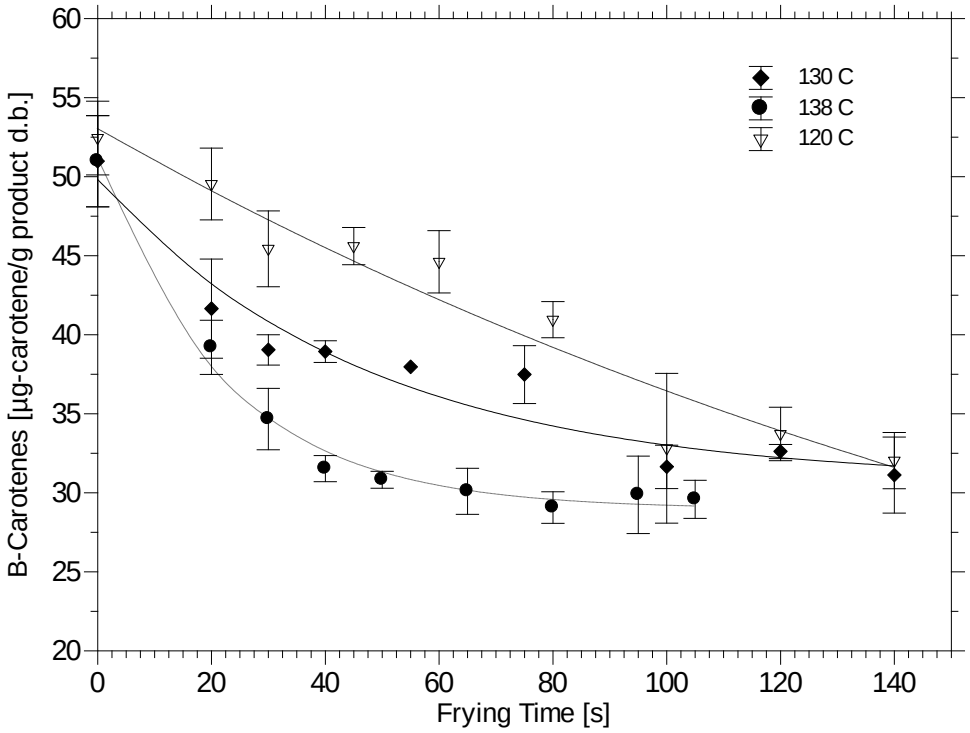


Fig. 5-16. Beta-carotenes (C) in mango chips pre-treated with OD (65 w/v and 40°C) for 60 min and fried under vacuum (P = 1.33 kPa, de-oiled at 225 rpm for 25 s) at different frying temperatures. [120° C, C = 46.37*exp(-0.004367*t) + 6.651, R^2 = 0.94; 130° C, C = 19.1*exp(-0.02117*t) + 30.72, R^2 = 0.94; 138°C, C = 22.31*exp(-0.0449*t) + 28.92, R^2 = 0.99].

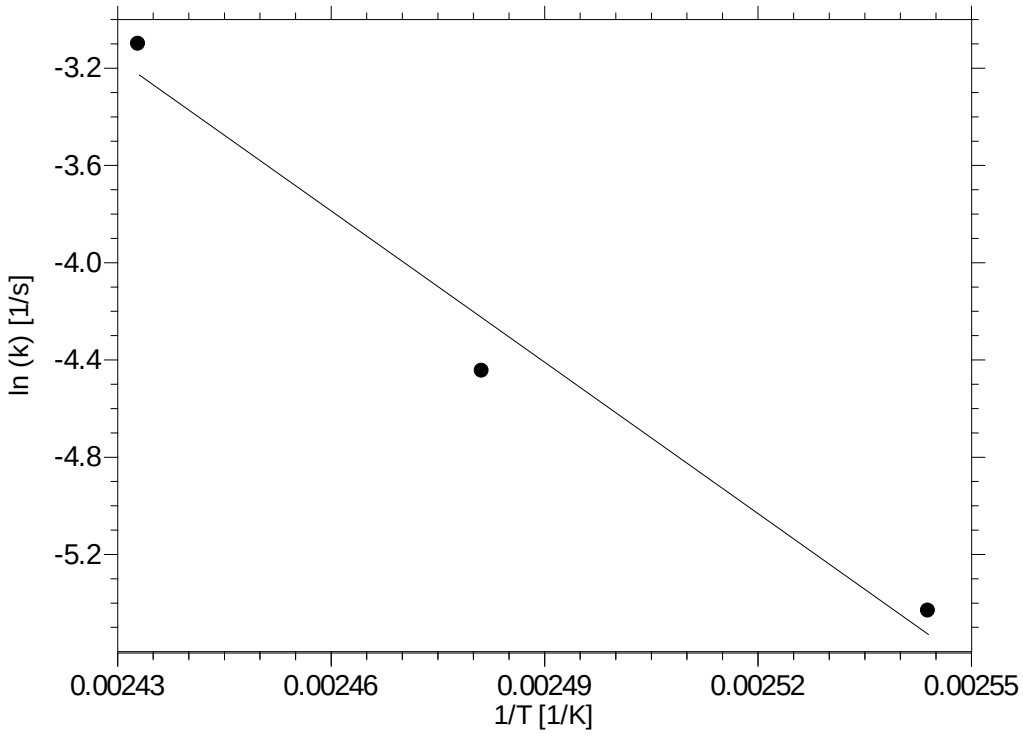


Fig. 5-17. Effect of frying temperature on the rate constant *k* for carotenoid degradation in mango chips pre-treated (OD concentration 65 w/v at 40^{o}C for 60 min) and fried under vacuum (P = 1.33 kPa, de-oiled at 225 rpm for 25 s).

CHAPTER VI

CONCLUSIONS

This study was focused on evaluating the effect of osmotic dehydration and vacuum frying process affect the final product quality attributes (oil content, color, texture, chemical retention (carotenoids), and structure) of mango chips.

The osmotic dehydration variables such as osmotic solution concentration, temperature, time, and fruit to syrup ratio were evaluated to find the best pre-treatment to obtain high quality vacuum fried mango chips. Study of the chemical (pH, ^{o}Brix, a_w, sugar gain, and water loss) and physical properties (degree of shrinkage, bulk and true density) for osmotic dehydration were also performed.

The effect of vacuum frying temperature and time on mango chips was evaluated based on product characteristics such as moisture loss, oil absorption, texture, diameter and thickness changes, porosity (bulk and true density), color, carotenoid degradation, microstructure, and sensory analysis. These parameters were important to determine the final quality in mango chips. A de-oiling system was used to remove the oil at the surface of the chips thus decreasing the final oil content.

The main results obtained in the study were:

- High osmotic dehydration temperatures (57^{o}C) increased ($P<0.05$) the final oil content of mango chips.
- There was no effect on the final water loss and sugar uptake when pre-treating raw mango slices with 1:10 or 1:4 fruit:syrup ratios.

- Water loss during osmotic dehydration was affected by OD concentration and temperature.
- Lower slice water activity was only obtained at high OD concentrations, temperatures, and times. The ^{o}Brix increased with high OD concentrations.
- The OD concentration and temperature with the highest *dehydration efficiency index* (water loss/ sugar gain) was 65 w/v at 40^{o}C.
- The diameter degree of shrinkage during OD increased at high OD concentration (65 w/v) and temperature (40^{o}C).
- Texture (maximum force (peak) and work) for 2 min frying increased at higher OD concentrations, temperatures and times. At 60 min OD not a significant ($P>0.05$) change was observed at different OD concentrations and temperatures. Mango chips vacuum fried for 2 min for low OD concentrations were soggy.
- The lowest oil content (22% w.b.) was found at the highest OD concentration (65 w/v), temperature (40^{o}C), and time (70 min).
- Color *a (redness) and *b (yellowness) increased in the chips with higher OD concentration and time. This change was attributed to the water loss when vacuum frying for 2 min. Color *b decreased at higher OD temperature in mango chips.
- The de-oiling system decreased the final oil content from 44% d.b. (without de-oiling) to 23% d.b. in the fried samples. Centrifuging at 225

rpm for 25 s resulted in the best mouth feeling property of the mango chips.

- Vacuum frying temperature affected the final oil content in the mango chips. Oil content increased at the highest frying temperature (138^{o}C). No significant differences were observed in the final oil content of mango slices fried at 120 and 130^{o}C. Texture in the fried samples was not affected by the frying temperature. Color *a (redness) slightly increased with frying temperature. Color *b (yellowness) decreased with frying temperature. However, no significant changes for color *a and *b were observed when comparing with the control.
- Mango chips pre-treated (65 w/v concentration at 40^{o}C) at different OD times and frying temperatures were subjected to testing using an acceptability test. All treatments were accepted ($P>0.05$) by the consumer panel and no significant differences for color, flavor, texture, odor, and overall quality parameters were found. The highest sensory scores (around 7.50) were for those chips pre-treated by OD for 60 min and fried at 120^{o}C.
- Osmotic dehydration with 65 w/v concentration for 60 min at 40^{o}C was the best pre-treatment selected to fry mango slices. This choice was based on the product quality characteristics such as color, texture, oil content, flavor, and sensory evaluation.

- Changes in microstructure of mango chips were observed using ESEM method. Frying under vacuum resulted in more uniform samples than for atmospheric frying, where chips showed completely destruction of the mango tissue structure.
- The diffusion coefficient (*De*) for moisture loss in mango chips increased as vacuum frying oil temperature increased. This diffusion coefficient was modeled using an Arrhenius-type relationship.
- The oil absorption rate increased when oil temperature increased. The final oil content was lower when frying at 120^{o}C.
- The texture in mango chips was modeled in two periods based on the frying process. During the first period (40 s), texture became crispier due to water removal. During the second period (up to 140 s), the samples became more rigid and hard to break. This effect was observed for all frying temperatures.
- Changes in the diameter of the fried chips were modeled in two frying periods. During the first period, up to 45 s, the mango slices diameter fluctuated to a maximum expansion for all frying temperatures; however, at 138^{o}C the crust formation occurred fast and the chips did not expand very much. During the second period, up to 140 s, the samples shrank for each temperature.

- The thickness of the mango slices with frying time increased (expanded). Frying at 120 and 130^{o}C caused more expansion in the chips than at 138^{o}C, probably due to fast crust formation at the higher temperature.
- The porosity in mango slices increased for all frying temperatures. Bulk density decreased with frying time. No significant changes were obtained for true density for all frying temperatures.
- Color *a increased with frying temperature. Color *b was modeled in two frying periods. The first 20 s, and increased in *b was observed due to fast water removal rate causing the concentrations of carotenoids in the samples. The maximum value was found for the highest vacuum frying temperature (138^{o}C). For the second period (up to 140 s), an exponential decay was observed due to carotenoid degradation. The lowest value was found at 138^{o}C.
- Carotenoids degradation was modeled using a first order model for all frying temperatures. Vacuum frying at 120^{o}C for 140 s (< 2% moisture content) resulted with the highest carotenoid retention (around 62%). Mango chips fried under atmospheric fryer had less carotenoid concentration (25% less) than with the vacuum fryer.
- Overall, the best way to fry mango chips is when using a OD concentration of 65 w/v at 40^{o}C for 60 min as a pre-treatment and vacuum fried at the lowest temperature to improve color, flavor, and carotenoid content in the final product.

CHAPTER VII

RECOMMENDATIONS FOR FURTHER STUDY

Recommendations for future research on vacuum frying of vegetable-based chips include:

- Evaluate the effect of mango variety on pre-treatment and vacuum frying parameters and the product quality attributes.
- Study the effects of using different molecular sizes for the agent used in the osmotic dehydration process.
- Pre-treat the mango slices using more than one osmotic dehydration agent.
- Develop an optimization model to select the best pre-treatment based on osmotic dehydration time, concentration, and temperature.
- Determine the effects of different vacuum frying pressures on the oil absorption, texture, and porosity of mango chips.
- Create mango chips from mango puree to decrease the waste.
- Study the effect of vacuum frying and pre-treatment in other tropical fruits.
- Study the relationship between the $*b$ color and carotenoids concentration.
- Develop a better and more efficient method for performing texture kinetics in chips.
- Determine the effect of pressurization and de-oiling process on the oil absorption mechanism of mango chips.

REFERENCES

AACC. (1986). *Approved Methods of American Association of Cereal Chemists.* Minneapolis, MN: AACC.

Ahmed, J., Shivhare, U. S., & Sandhu, K. S. (2002). Thermal degradation kinetics of carotenoids and visual color of papaya puree. *Journal of Food Science, 67*(7), 2692-2695.

AOAC. (1990). Official method 930.04. Moisture in plants. *Official methods of analysis*. AOAC.

Azuara, E., & Beristain, C. (2002). Osmotic dehydration of apples by immersion in concentrated sucrose/maltodextrin solutions. *Journal of Food Processing Preservation, 26*(4), 295-306.

Baik, O. D., & Mittal, G. S. (2005). Heat and moisture transfer and shrinkage simulation of deep fat tofu frying. *Food Research International, 38,* 183–191.

Baik, O.D., & Mittal, G.S. (2003). Kinetics of tofu color changes during deep-fat frying. *Lebensmittel-Wissenschaft und-Technologie, 36,* 43-48.

Behsnilian, D., & Spiess, W. E. (2006). Osmotic dehydration of fruits and vegetables. IUFOST. *13th World Congress of Food Science and Technology*, Nantes, France.

Bouchon, M. M. P. (2008). Comparison between atmospheric and vacuum frying of apple slices. *Food Chemistry, 107*(4), 1561-1569.

Bouchon, P., & Pyle, D. L. (2004). Studying oil absorption in restructured potato chips. *Journal of Food Science, 65*(3), 115-122.

Brooker, D. B., Bakker-Arkema, F. W., & Hall, C. W. (1992). *Drying ans Storage of Grains and Oilseeds*. New York: Van Nostrand Reinhold, Inc.

Browner, W. S., Westenhouse, J., & Tice, J. A. (1991). What if Americans ate less fat? A quantitative estimate of the effect on mortality. *Journal of the American Medical Association, 265*, 3285–3291.

Bunger, A., Moyano, P., & Rioseco, V. (2003). NaCl soaking treatment for improving the quality of French-fried potatoes. *Food Research International, 36,* 161-166.

Caixeta, A. T., Moreira, R., & Castell-Perez, M. E. (2002). Impingement drying of potato chips. *Journal of Food Process Engineering, 25*(1), 63-90.

Campbell, C. W. (1973). The 'Tommy Atkins' mango. *Florida State Horticultural Society*. 348-350.

Cano, P., & de Ancos, B. (1994). Carotenoid and carotenoid ester composition in mango fruit as influenced by processing method. *Journal of Agriculture and Food Chemistry, 42,* 2737-2742.

Carr, B.T., Meilgaard, M., & Civille, G.V. (1999). *Sensory Evaluation Techniques*. Washington, DC: CRC Press.

Chiralt, A., & Talens, P. (2005). Physical and chemical changes induced by osmotic dehydration in plants tissue. *Journal of Food Engineering, 67,* 167-177.

Chirife, J., & Fontan, F. C. (1982). The water activity of fresh foods. *Journal of Food Science, 47*, 661-663.

Chen, C.R. & Ramaswamy, H.S. (2002). Color and texture change kinetics in ripening bananas. *Lebensmittel-Wissenschaft und-Technologie, 35*, 415-419.

Conway, J., Castaigne, F., Picard, G. & Voxan, X. (1983). Mass transfer considerations in the osmotic dehydration of apples. *Canadian Institute of Food Science and Technology Journal, 16,* 25-29.

Costa, R. M., Oliveira, F. A. R., & Bouthcheva, G. (2001). Structural changes and shrinkage of potato during frying. *International Journal of Food Science and Tehcnology, 36,* 11–23.

Da Silva, P. F., & Moreira, R. G. (2008). Vacuum frying of high-quality fruit and vegetable-based snacks. *LWT-Food Science and Technology.* Article in press: 1-10.

Da Silva, P.F., Moreira, R.G., & Gomes, C.F. (2008).Vacuum frying of potato chips: The de-oiling effect. Article in press.

Datta, A. (2002). *Biological and Bioenvironmental Heat and Mass Transfer.* New York: Marcel Dekker.

Dermesonlouoglou, E. K., Grannakourou, M. C., & Taoukis P. (2007). Stability of dehydrofrozen tomatoes pretreated with alternative osmotic solutes. *Journal of Food Engineering, 78*(1), 272-280.

Edward, C., Lulai, & Paul, H. O. (1979). Influence of potato specific gravity on yield and oil content of chips. *American Journal of Potato Research,* 56(8), 379-390.

Falade, K. O., Babalola, S. O., Akinyemi, S. O. S. & Ogunlade, A. A. (2004). Degradation of quality attributes of sweetened Julie and Ogbomoso mango juices during storage. *European Food Research and Technology,218*(5), 456-459.

Falade, K.O. & Igbeka, J.C. (2007). Osmotic dehydration of tropical fruits and vegetables. *Food Reviews International, 23,* 373-405.

Fan, L., Zhang, M., & Mujumdar, A. S. (2005). Vacuum frying of carrot chips. *Drying Technology, 23*, 645-656.

Farkas, D. F. & Lazar, M. E. (1969). Osmotic dehydration of apple pieces: Effect of temperature and syrup concentration on rates. *Food Technology, 23,* 688-90.

Gabriel, A. A. (2007). Estimation of water activity from pH and ^{o}Brix values of some food products. *Food Chemistry, 108*, 1006-1113.

Gamble, M.H., & Rice, P. (1987). Effect of pre-fry drying on oil uptake and distribution in potato chip manufacture. *International Journal of Food Science and Technology, 22*, 535-548.

Garayo, J & Moreira, R. (2002). Vacuum frying of potato chips. *Journal of Food Engineering*, *55*(2), 181-191.

Garayo, J. (2001). Production of low-fat potato chips using vacuum frying. M.S. Thesis. Texas A&M University, College Station, Texas.

Giraldo, G., Talens, P., Fito, P. & Chiralt, A. (2003). Influence of sucrose solution concentration on kinetics and yield during osmotic dehydration of mango. *Journal of Food Engineering 58*(1), 33-43.

Goyal, R.K., Kingsly, A.R.P., Manikantan, M.R. & Ilyas, S.M. (2006). Thin-layer drying kinetics of raw mango slices. *Biosystems Engineering*, *95*(1), 43-49.

Granda, C. E. (2005). Kinetics of acrylamide formation in potato chips. MS thesis, Biological and Agricultural Department, Texas A&M University, College Station.

Granda, C., Moreira R. G. & Tichy, S.E. (2004). Reduction of acrylamide formation in potato chips by low-temperature vacuum frying. *Journal of Food Science*, *69*(8), 405-411.

Heng, W., Guilbert, S. & Cuq, J. L. (1990). Osmotic dehydration of papaya: influence of process variables on the quality. *Sciences des Aliments, 10*, 831-848.

Hidaka, T., Fukuda, N., & Sakamoto, K. (1991). Evaluations of quality of oils and fats used in vacuum frying. *Bulletin of the Faculty of Agriculture*, Miyazaki University, *38*, 35-38.

Hiranvarachat, B., Suvarnakuta, P. & Devahastin, S. (2008). Isomerisation kinetics and antioxidant activities of β-carotenes in carrots undergoing different drying techniques and conditions. *Food Chemistry, 107*, 1538-1546.

Ibarz, A., Pagan, J. & Garza, S. (1999). Kinetic models for colour changes in pear puree during heating at relatively high temperature. *Journal of Food Engineering. 39*(4), 415-422.

Jung, M. Y., Choi, D. S., & Ju, J. W. (2006). A novel technique for limitation of acrylamide formation in fried and baked corn chips and in French fries. *Journal of Food Science*, 68, 1287-1290.

Kasahara, I., Osorio, F., Moyano, P., Pizarro, G., & Beltran, J. (2002). Study of texture and glass transition of French fries potatoes pretreated with soaking solutions. *Journal of Food Processing and Preservation*, *26*(4), 237-257

Kato, E., & Sato, K. (1991). Vacuum frying tempeh. *Bulletin of the Faculty of Agriculture,* Meiji University, *88*, 25-32.

Kawas, M. L., & Moreira, R. G. (2001). Characterization of product quality attributes of tortilla chips during the frying process. *Journal of Food Engineering, 47*(2), 97–107.

Kawas-Escoto, M. L. (2000). Characterization of product quality attributes of tortilla chips during the frying process. MS thesis, Biological and Agricultural Department, Texas A&M University, College Station, Texas.

Kayacier, A. & Singh R. K. (2003). Texture properties of baked tortilla chips. *LWT-Food Science and Technology, 36,* 463-466.

Keller, C., Escher, F. & Solms, J. A. (1986). Method of localizing fat distribution in deep-fat fried potato products. *Lebensmittel-Wissenschaft and Technologie 19*(4), 346–348.

Krokiba, M. K., Oreopoulous, V., Maroulis, Z. B., & Marinos-Kouris, D. (2001a). Effect of pre-drying on quality of French fries. *Journal of Food Engineering,* 49, 347-354.

Krokiba, M. K., Oreopoulous, V., Maroulis, Z. B., & Marinos-Kouris, D. (2001b). Effect of osmotic dehydration pre-treatment on quality of French fries. *Journal of Food Engineering, 49,* 339-345.

Lazarides, H. N. (2001). Reasons and possibilities to control solids uptake during osmotic treatment of fruits and vegetables. *In* Osmotic *Dehydration and Vacuum Impregnation*, Fito P., Chiralt A., Barat J.M., Spiess W.E., and Behsnilian D. (Editors), Inc. Lancaster, PA: Technomic Publishing Company.

Lazarides, H. N., Katsanidis, E. & Nickolaidis A. (1995). Mass transfer kinetics during osmotic preconcentration aiming at minimal solid uptake. *Journal of Food Engineering, 25,* 151-166.

Lazarides, H. N. & Mavroudis, N. E. (1996). Kinetics of osmotic dehyration of a highly shrinking vegetable tissue in a salt-free medium. *Journal of Food Engineering, 30*, 61-74.

Lisinska, G. (1989). Manufacturing of potato chips and Frech fries. *In Potato Science and Technology*, Lisinska, G., & Leszczynski, W. (Editors), New York. Springer.

Lombard, G. E., Oliveira, J. C., Fito, P., & Andres A. (2008). Osmotic dehydration of pineapple as a pre-treatment for further drying. *Journal of Food Engineering, 85*, 277-284.

Madamba, P. S., & Lopez, R. I. (2002). Optimization of the osmotic dehydration of mango (*Mangifera Indica L.)* slices. *Drying Technology*, *20*(6), 1227-1242.

Maltini, E., Torregiani, D., Venir, E., & Bertolo, G., (2003), Water activity and the preservation of plant foods, *Food Chemistry, 82*, 79-86.

National Mango Board. "Mango Varieties and Availability", 6 September, (2007). < http://www.mango.org/about/varieties.php>

Marousis, S. N., & Saravacos, G. D. (1990). Density and porosity in drying starch materials. *Journal of Food Science, 55*, 1367–1372.

Mavroudis, N. E., Gekas, V. & Sjoholm, I. (1998). Osmotic dehydration of apples. Shrinkage phenomena and the significance of initial structure and mass transfer rates. *Journal of Food Engineering*, *38*(1), 101-123.

Mavroudis, N. E., Lee, K-M., Sjoholm, I., & Hallstrom B. (2001). Osmotic treatment of apples: cell death and some criteria for the selection of suitable apple varieties for industrial processing. *In Osmotic Dehydration and Vacuum Impregnation*, Fito P.,

Chiralt A., Barat J.M., Spiess W.E., and Behsnilian D. (Editors), Inc. Lancaster, PA: Technomic Publishing Company, Inc.

Mayor L., Moreira R., Chenlo, F. & Sereno, A. M. (2005). Kinetics of osmotic dehydration of pumpkin with sodium chloride solutions. *Journal of Food Engineering. 74*(2), 253-262.

Mercadante, A. Z. & Rodriguez-Amaya, D. B. (1998). Effect of ripening, cultivar differences, and processing on the carotenoid composition of mango. *Journal of Agriculture and Food Chemistry, 46,* 128-130.

Minguez-Mosquera, M.I. & Jaren-Galan M. (1995). Kinetic of the discoloration of carotenoid pigments. *Journal of Science and Food Agriculture, 67,*153-161.

Moreira R. G., & Barrufet, M. (1998). A new approach to describe oil absorption in fried foods: a simulation study. *Journal of Food Engineering, 35,* 1-22.

Moreira, R. G., Sun, X., & Chen Y. (1997). Factors affecting oil uptake in tortilla chips in deep-fat frying. *Journal of Food Engineering 31*(4), 485-498.

Moreira, R. G., Castell-Perez, M. E. & Barrufet M. A. (1999). *Deep-Fat Frying: Fundamentals and Aplications*. Gaithersburg, MD: Aspen Publishers.

Moreno-Tinjaca, M. A. (2005). Effect of electron beam irradiation on quality and shelf-life of Tommy Atkins (*Mangifera indica L*) and blueberry (*Vaccinium corymbosum L.*). MS thesis. Biological and Agricultural Department, Texas A&M University, College Station.

Mujica-Paz, H., Valdez-Fragoso, A., Lope-Malo, A., Palou, E., & Welti-Chanes, J. (2003). Impregnation and osmotic dehydration of some fruits: effect of the vacuum pressure and syrup concentration. *Journal of Food Engineering, 57*, 305-314.

Pedreschi, F. & Moyano, P. (2005). Oil uptake and texture development in fried potato slices. *Journal of Food Engineering, 70*(4), 557-563.

Perez-Tinoco, M. R., Perez, A., Salgado-Cervantes, M., Reynes, M., & Vaillant F. (2008). Effect of vacuum frying on main physicochemicals and nutritional quality parameters of pineapples chips. *Journal of Food and Agriculture, 88*, 945-953.

Perkins, V., P. M. (2007). Carotenoids in watermelon and mango. *Acta Horticulturae, 746*, 259-264.

Pesek, C.A. & Warthessen, J.J. (1989). Characterization of the photodegradation of ß-carotene in aqueous models systems. *Journal of Food Science, 53*, 1517-1520.

Pissarra, L.M. & Sereno, A.M. (2008). Microestructural changes during osmotic dehydration of parenchymatic pumpkin tissue. *Journal of Food Engineering, 85*(3), 326-339.

Reynes, M., Aymard, C., & Aw, B. (1997). Production de chips d'ananas par le procede combine deshydratation osmotique-friture. Recents progress en genie des procedes. La friture-Maitrise du procede et de la qualite des produits. *11*, (59): 139-150. Centre de Cooperacion Internacional en Recherche Agronomique pour le Developpement (CIRAD), Montpellier, France.

Rodriguez-Amaya, D. B. (1989). Critical review of provitamin A determination in plant foods. *Journal of Micronutrients Analysis, 5*, 191-225.

Sablani, S. S., & Rahman, M. S. (2003). Effect of syrup concentration, temperature and sample geometry on equilibrium distribution coefficients during osmotic dehydration of mango. *Food Research International*, *36*, 65-71.

Saputra, D. 2001. Osmotic dehydration of pineapple. *Drying Technology*, *19*(2), 415-425.

Sauco, V. G. (2004). Mango production and world market: Current situation and future prospects. *Acta Horticulturae, 1,* 107-116.

Shi, J., Le Maguer, M., Kakuda, Y., Liptay, A., & Nickamp, F. (1999). Lycopene degradation and isomerization in tomato degradation. *Food Research International, 32*, 15-21.

Shi, J. X. & Maguer, M. L. E. (2001). Stability of lycopene in tomato dehydration. *In Osmotic Dehydration and Vacuum Impregnation*, Fito P., Chiralt A., Barat J.M., Spiess W.E., and Behsnilian D. (Editors), Lancaster, PA: Technomic Publishing Company, Inc.

Shyu, S. L., & Hwang, L. S. (2001). Effects of processing conditions on the quality of vacuum fried apple chips. *Food Research International, 34,* 133-142.

Singh, L. B. 1960. *The Mango: Botany, Cultivation, and Utilization*. Polunin, N. (Editor), New York: Interscience Publishers, Inc.

Steffe, J. F. (1996). *Rheological Methods in Food Process Engineering* (2nd ed.). East Lansing, MI: Freeman Press, Inc.

Taiwo, K. A. & Baik, O. D. (2007). Effects of pre-treatments on the shrinkage and texture properties of fried sweet potatoes. *LWT-Food Science and Technology, 40*(4), 661-668.

Taiwo, K. A., Baik, O-D., & Farinu, A. O. (2007) Kinetics of heat and mass transfer and color development of pre-treated sweet potatoes during frying. *American Society of Agricultural and Biological Engineers, 50*(1), 129-135.

Torezan, G. A., Campos-Favareto, P., Pallet, D., & Castle de Menezes, H. 2004. Use of a combined process of osmotic dehydration and deep-fat-frying to obtain mango chips from the cultivar Tommy Atkins. *Acta Horticulturae, ISHS*, 285-291.

Torreggiani, D. (1993). Osmotic dehydration in fruits and vegetables processing. *Food Research International*, *26*, 59-68.

Torreggiani, D. & Bertolo, G. (2001a). High-quality fruit and vegetable products using combined processes. *In Osmotic Dehydration and Vacuum Impregnation*, Fito. P., Chiralt. A., Bara.t J. M., Spiess. W. E., and Behsnilian. D. (Editors). Lancaster, PA: Technomic Publishing Company, Inc.

Torreggiani, D. & Bertolo, G. (2001b). Osmotic pre-treatment in fruit processing: Chemical, physical and structural effects. *Journal of Food Engineering, 49*, 247-253.

Tovar, B., Garcia, H. S., & Mata, M. (2001). Physiology of pre-cut mango. I. ACC and ACC oxidase activity of slices subjected to osmotic dehydration. *Food Research International, 34*(2,3), 207-215.

Tran, M. T. T., Chen, X. D., & Southern, C. (2007). Reducing oil content of fried potato crisps considerably using a 'sweet' pre-treatment technique. *Journal of Food Engineering, 80*, 719-726.

USDA. (1990). Building for the future: Nutrition guidance for the child nutrition programs. FNS-279, Washington, DC: US Dept. Agric.

USDA & USDHHS. (1990). *Dietary Guidelines for Americans* (3rd ed.) Washington, DC: US Dept. of Agric. and US Dept. of Health and Human Services.

USDA/ARS. (2007). Nutrient Database for Standard Reference. Nutrient Data Laboratory. http://www.nal.usda.gov/fnic/foodcomp. Last accessed on October 28th, 2008.

Wang J., Jiang W., Wang B., Liu S., Gong Z. & Luo Y. (2007). Partial properties of polyphenol oxidase in mango (*Mangifera Indica L*. CV. "Tainong") pulp. *Journal of Food Biochemistry, 31*(1), 45-55.

Wilberg, V.C., & Rodriguez-Amaya, D. B. (1995). HPLC Quantitation of major carotenoids of fresh and processed guava, mango and papaya. *Lebensm.-Wiss. u.-Technology, 28*, 474–480.

Yan, Z., Sousa-Gallagher, M. J., & Oliveira, F. A. R. (2007). Shrinkage and porosity of banana, pineapple and mango slices during air drying. *Journal of Food Engineering, 84*(3), 430-440.

APPENDIX A

Acceptance Test: 587

Place a mark in the box which you feel best describes how you like the sample.
An honest expression of your personal feelings will help us. Thank you.

Color (Yellowness)	☐ Like extremely	☐ Like Very much	☐ Like moderately	☐ Like slightly	☐ Neither like nor dislike	☐ Dislike slightly	☐ Dislike moderately	☐ Dislike very much	☐ Dislike extremely
Odor	☐ Like extremely	☐ Like Very much	☐ Like moderately	☐ Like slightly	☐ Neither like nor dislike	☐ Dislike slightly	☐ Dislike moderately	☐ Dislike very much	☐ Dislike extremely
Texture (Crispiness)	☐ Like extremely	☐ Like Very much	☐ Like moderately	☐ Like slightly	☐ Neither like nor dislike	☐ Dislike slightly	☐ Dislike moderately	☐ Dislike very much	☐ Dislike extremely
Flavor (Natural)	☐ Like extremely	☐ Like Very much	☐ Like moderately	☐ Like slightly	☐ Neither like nor dislike	☐ Dislike slightly	☐ Dislike moderately	☐ Dislike very much	☐ Dislike extremely
Overall Quality	☐ Like extremely	☐ Like Very much	☐ Like moderately	☐ Like slightly	☐ Neither like nor dislike	☐ Dislike slightly	☐ Dislike moderately	☐ Dislike very much	☐ Dislike extremely

Comments:……

APPENDIX B

Effect of frying time and oil temperature on moisture content and oil content in mango chips pre-treated (OD concentration of 65 w/v at 40°C for 60 min) and fried under vacuum (10 Torr and de-oiled at 225 rpm for 25 s).

Toil (°C)	Frying Time [s]	FMC[%w.b.]	OC[%w.b.]
120	0	*85.28±0.04	ND
120	0	73.96±0.46	0
120	10	52.40±0.18	1.39±0.16
120	20	45.55±0.13	3.67±0.09
120	30	31.89±0.13	11.56±0.86
120	45	19.19±1.27	19.41±0.55
120	60	7.52±0.17	25.70±0.69
120	80	2.89±0.36	23.77±0.33
120	100	1.59±0.18	22.80±0.29
120	120	1.24±0.027	25.79±0.75
120	140	0.68±0.098	30.16±0.52
130	0	*85.15±0.35	ND
130	0	74.60±0.44	0
130	10	49.39±0.49	1.68±0.095
130	20	40.08±0.25	8.41±0.092
130	30	30.42±0.28	15.69±1.20
130	40	21.91±0.23	19.11±1.47
130	55	9.65±0.27	26.91±0.16
130	75	2.60±0.02	29.31±0.33
130	100	1.54±0.16	24.98±0.36
130	120	1.16±0.07	25.93±0.68
130	140	0.28±0.00	31.77±0.47
138	0	*85.25±0.92	ND
138	0	74.37±0.41	0
138	10	47.63±0.36	2.29±0.045
138	20	38.45±0.70	7.60±0.43
138	30	26.84±0.88	14.83±0.04
138	40	18.69±0.23	25.46±0.41
138	50	2.95±0.22	36.20±0.25
138	65	1.05±0.10	34.33±0.18
138	80	0.58±0.042	35.52±0.51
138	95	0.56±0.01	41.52±1.07
138	105	0.42±0.01	40.32±0.03

Tests were performed in triplicate. T_{oil} = oil temperature, FMC = final moisture content, OC = oil content.
*= Initial moisture content. ND = no determined

Effect of frying time and oil temperature on shrinkage (diameter and thickness) in mango chips pre-treated (OD concentration of 65 w/v at 40°C for 60 min) and fried under vacuum (10 Torr and de-oiled at 225 rpm for 25 s).

Toil (°C)	Frying Time [s]	Diameter [cm]	Thickness [mm]
120	0	5.08±0.00	1.67±0.06
120	0	4.59±0.03	1.35±0.12
120	10	4.46±0.23	0.70±0.07
120	20	4.47±0.08	0.82±0.09
120	30	4.60±0.13	0.78±0.07
120	45	4.70±0.11	0.98±0.11
120	60	4.60±0.06	1.60±0.19
120	80	4.55±0.05	1.10±0.10
120	100	4.517±0.08	2.05±0.17
120	120	4.48±0.08	2.18±0.21
120	140	4.45±0.06	2.19±0.15
130	0	5.08±0.00	1.68±0.06
130	0	4.56±0.02	1.34±0.03
130	10	4.56±0.09	0.95±0.12
130	20	4.47±0.05	0.93±0.08
130	30	4.47±0.07	1.06±0.10
130	40	4.70±0.04	1.24±0.20
130	55	4.64±0.05	1.32±0.21
130	75	4.56±0.16	1.56±0.16
130	100	4.52±0.03	1.75±0.24
130	120	4.45±0.06	2.02±0.11
130	140	4.43±0.08	2.20±0.19
138	0	5.08±0.00	1.65±0.06
138	0	4.56±0.04	1.33±0.04
138	10	4.52±0.08	0.89±0.12
138	20	4.50±0.02	0.91±0.10
138	30	4.49±0.07	0.96±0.10
138	40	4.52±0.12	1.42±0.20
138	50	4.51±0.05	1.59±0.07
138	65	4.50±0.06	1.59±0.12
138	80	4.51±0.03	1.61±0.18
138	95	4.49±0.03	1.64±0.08
138	105	4.48±0.01	1.64±0.17

Tests were performed in triplicate. T_{oil} = oil temperature.

Effect of frying time and oil temperature on porosity (bulk and true density) in mango chips pre-treated (OD concentration of 65 w/v at 40°C for 60 min) and fried under vacuum (10 Torr and de-oiled at 225 rpm for 25 s).

Toil (°C)	Frying Time [s]	Bulk density (g/cm^3)	True density (g/cm^3)	Porosity
120	0	1.27±0.07	1.05±0.05	-0.21±0.09
120	10	1.19±0.01	1.08±0.01	-0.10±0.02
120	20	1.08±0.01	1.11±0.03	0.03±0.03
120	30	1.02±0.03	1.15±0.01	0.11±0.02
120	45	0.86±0.02	1.21±0.00	0.29±0.01
120	60	0.54±0.02	1.14±0.07	0.52±0.04
120	80	0.52±0.02	1.23±0.04	0.57±0.02
120	100	0.54±0.02	1.19±0.02	0.55±0.01
120	120	0.54±0.04	1.26±0.03	0.57±0.02
120	140	0.60±0.03	1.17±0.03	0.49±0.03
130	0	1.36±0.01	1.08±0.01	-0.26±0.02
130	10	1.35±0.03	1.07±0.01	-0.26±0.02
130	20	1.21±0.05	1.05±0.03	-0.15±0.04
130	30	0.90±0.03	1.08±0.01	0.17±0.03
130	40	0.79±0.01	1.16±0.02	0.31±0.02
130	55	0.71±0.02	1.18±0.03	0.40±0.03
130	75	0.61±0.02	1.25±0.05	0.51±0.03
130	100	0.64±0.05	1.24±0.00	0.48±0.03
130	120	0.63±0.03	1.22±0.01	0.48±0.02
130	140	0.68±0.03	1.17±0.02	0.42±0.04
138	0	1.29±0.01	1.08±0.05	-0.2±0.02
138	10	1.01±0.01	1.14±0.01	0.11±0.01
138	20	0.92±0.02	1.19±0.09	0.22±0.07
138	30	0.74±0.00	1.12±0.01	0.34±0.00
138	40	0.74±0.01	1.20±0.01	0.38±0.01
138	50	0.74±0.04	1.15±0.01	0.36±0.03
138	65	0.74±0.01	1.18±0.01	0.37±0.01
138	80	0.70±0.02	1.22±0.01	0.43±0.02
138	95	0.62±0.03	1.18±0.01	0.47±0.03
138	105	0.68±0.06	1.17±0.01	0.42±0.04

Tests were performed in triplicate. T_{oil} = oil temperature.

Porosity = $1 - \frac{\rho_b}{\rho_s}$ where ρ_b is the bulk density and ρ_s the true density.

Effect of frying time and oil temperature on mango chips texture (peak and work) pre-treated (OD concentration of 65 w/v at 40°C for 60 min) and fried under vacuum (10 Torr and de-oiled at 225 rpm for 25 s).

Toil (°C)	**Frying Time [s]**	**Force Peak (N)**	**Work (N*mm)**
120	0	48.93±6.04	42.03±6.74
120	10	15.69±4.52	21.71±4.30
120	20	3.50±0.99	1.84±0.50
120	30	1.81±0.35	2.00±0.40
120	45	1.84±0.37	3.22±0.54
120	60	2.51±0.49	7.42±1.20
120	80	5.23±1.37	25.98±3.99
120	100	5.39±0.69	27.96±3.20
120	120	6.42±0.81	28.50±2.59
120	140	5.94±0.86	26.98±3.51
130	0	42.82±10.53	38.17±7.61
130	10	22.67±6.35	17.90±4.83
130	20	10.42±2.99	6.63±1.65
130	30	1.03±0.23	2.06±0.49
130	40	3.26±0.83	8.96±2.28
130	55	3.88±0.99	15.13±3.02
130	75	5.61±0.97	27.52±2.78
130	100	7.01±1.39	29.53±2.75
130	120	5.86±1.42	29.57±3.15
130	140	6.59±1.66	27.84±4.60
138	0	43.33±7.55	35.95±5.26
138	10	18.80±4.10	13.94±3.46
138	20	1.51±0.38	0.93±0.18
138	30	1.44±0.35	1.77±0.44
138	40	2.73±0.73	9.57±2.47
138	50	3.82±0.77	14.62±3.56
138	65	6.99±1.60	29.80±4.61
138	80	7.21±1.18	30.82±5.01
138	95	8.19±1.13	34.76±3.66
138	105	6.50±1.29	30.39±5.36

Tests were performed in triplicate. T_{oil} = oil temperature.

Effect of frying time and oil temperature on color (*a* and *b*) in mango chips pre-treated (OD concentration of 65 w/v at 40°C for 60 min) and fried under vacuum (10 Torr and de-oiled at 225 rpm for 25 s).

Toil (°C)	**Frying Time [s]**	***a***	***b***
120	0	9.77±0.31	62.64±0.67
120	10	10.22±0.08	64.63±0.24
120	20	10.63±0.45	68.45±0.95
120	30	10.20±0.47	67.74±0.46
120	45	11.15±0.26	67.07±0.28
120	60	10.90±0.15	66.25±0.15
120	80	10.66±0.39	65.41±0.79
120	100	11.01±0.37	64.22±0.34
120	120	12.08±0.13	63.58±0.36
120	140	12.16±0.14	61.75±0.45
130	0	9.60±0.36	61.11±0.38
130	10	10.07±0.07	67.14±0.48
130	20	10.97±0.36	66.88±0.48
130	30	11.46±0.40	66.81±0.98
130	40	11.36±0.37	65.80±0.45
130	55	11.34±0.11	66.66±0.68
130	75	11.11±0.03	64.99±0.36
130	100	12.07±0.20	64.16±0.38
130	120	12.71±0.43	61.42±0.57
130	140	12.89±0.05	55.24±0.18
138	0	10.54±0.48	66.10±0.20
138	10	11.26±0.44	72.74±0.39
138	20	11.99±0.26	73.05±2.23
138	30	11.55±0.36	71.83±0.25
138	40	11.36±0.20	67.13±0.24
138	50	12.43±0.15	68.51±0.45
138	65	12.34±0.21	65.18±0.60
138	80	13.21±0.36	64.02±0.38
138	95	14.34±0.12	58.49±0.39
138	105	13.91±0.37	58.72±0.47

Tests were performed in triplicate. T_{oil} = oil temperature.

Effect of frying time and oil temperature on carotenoid degradation in mango chips pre-treated (OD concentration of 65 w/v at 40°C for 60 min) and fried under vacuum (10 Torr and de-oiled at 225 rpm for 25 s).

Toil (°C)	Frying Time [s]	Carotenoid [µg/g d.b.]
120	0	52.45±2.34
120	20	49.54±2.27
120	30	45.44±2.40
120	45	45.61±1.17
120	60	44.62±1.97
120	80	40.96±1.15
120	100	32.82±4.74
120	120	33.73±1.69
120	140	32.04±1.77
130	0	50.98±2.89
130	20	41.66±3.13
130	30	39.04±0.96
130	40	38.94±0.68
130	55	37.98±0.14
130	75	37.48±1.83
130	100	31.65±1.38
130	120	32.62±0.45
130	140	31.13±2.40
130	0	50.98±2.89
138	20	39.21±1.71
138	30	34.67±1.94
138	40	31.53±0.83
138	50	30.83±0.54
138	65	30.10±1.45
138	80	29.07±1.00
138	95	29.87±2.45
138	105	29.59±1.21

Tests were performed in triplicate. T_{oil} = oil temperature.

VITA

Yolanda Nunez Gallegos is originally from Monterrey, Nuevo Leon, Mexico. She graduated with a B.S. in Industrial Chemical Engineering in November 2005 from Faculty of Chemical Engineering of the Autonomous University of Yucatan with a major in Industrial Chemical Engineering. She obtained her Master of Science degree in Biological and Agricultural Engineering (Food Engineering option) at Texas A&M University in May 2009.

Her permanent address is:
Yolanda Nunez Gallegos
Calle 13 No. 65 Mexico Norte
Zip code: 97128
Merida, Yucatan, Mexico.