Contents

Page No.

Dedication

Abstract i-v

Declaration vi

Certificate vii-viii

Acknowledgements ix-x

Contents xi-xxii

Lists of Tables xxiii-xxv

List of Figures xxvi -xxxi

List of Abbreviations xxxii-xxxvi

Chapter 1 Introduction 1.1-1.38

1.1 The background and the biology of *Musa* 1.1

1.2 The production 1.2

1.3 Banana the potential food for health 1.4

1.4 Effect of ripening stages on the biochemical and nutritional properties of banana 1.6

1.5 Utilization of banana and plantain as value added products 1.9

1.6 Banana peel 1.10

1.6.1 Prospects for utilization as by-products 1.10

1.6.2 Chemical properties and bioactive compounds present in banana peel 1.10

1.6.3 Utilization of peel as value added products 1.12

1.6.4 Extraction of cellulose from peel and its utilization 1.14

1.7 Encapsulation of bioactive compounds by co-crystallization and its application in functional food formulation 1.15

1.8 Dehydration of banana and plantains 1.18

1.8.1 Mathematical modeling 1.20

1.8.2 Moisture sorption isotherm (MSI) 1.22

1.9 Scope and objectives of the present investigation 1.25

References 1.26

Chapter 2 **Biochemical composition of pulp and peel of culinary banana at various developmental stages and to identify the best stage** 2.1-2.60

2A) Nutritional composition of culinary *Musa* ABB pulp at different stages of development 2.1

2.1 Introduction 2.1

2.2 Material and methods 2.2

2.2.1 Sample collection and preparation 2.2

2.2.2 Chemical analysis 2.3

2.2.2.1 The proximate composition 2.3

2.2.2.2 Estimation of pH, titratable acidity, ascorbic acid, cellulose and lignin 2.5

2.2.2.3 Starch and sugars 2.5

2.2.2.4 Pectin, tannin, phytic acid estimation 2.5

2.2.2.5 Total polyphenols and antioxidant activity analysis 2.6

2.2.2.6 Estimation of carotenoids, vitamin A and thiamine 2.6

2.2.2.7 Minerals estimation 2.7

2.2.2.8 Fatty acid analysis 2.7

2.2.2.9 Amino acid analysis 2.7

2.2.2.10 Estimation of phenolic compounds by HPLC 2.8

2.2.3 The colour measurement 2.8

2.2.4 Determination of pulp to peel ratio 2.9

2.2.5 Statistical analysis 2.9

2.3 Results and discussion 2.9

2.3.1 Proximate compositions 2.9

2.3.2 pH, ascorbic acid, cellulose and lignin 2.10

2.3.3 Starch, amylose, sugar and pectin contents 2.12

2.2.4 Tannin and phytic acid contents 2.13

2.3.5 Total polyphenols, DPPH radical scavenging activity, total carotenoids, vitamin A and thiamine contents 2.14

2.3.6 Minerals content 2.15

2.3.7 Fatty acids composition 2.15

2.3.8 Amino acids composition 2.16
2.3.9 Estimation of polyphenols by HPLC 2.19
2.3.10 Colour measurement 2.22
2.3.11 Optimum stage of harvesting 2.23
2.4 Conclusions 2.24

2B) Nutritional composition of culinary *Musa* ABB peel at different stages of development 2.25
2.5 Introduction 2.25
2.6 Material and methods 2.26
2.6.1 Sample collection and preparation 2.26
2.6.2 Physiochemical analysis 2.26
2.6.2.1 Estimation of minerals, fatty acids, polyphenols and amino acids 2.27
2.6.2.2 Fourier transform infrared spectroscopy (FT-IR) 2.27
2.6.2.3 Microstructure Study by SEM 2.28
2.6.2.4 X-ray Diffraction (XRD) 2.28
2.6.3 Statistical Analysis 2.28

2.7 Results and discussion 2.28
2.7.1 Physicochemical analysis 2.28
2.7.1.1 Proximate composition 2.28
2.7.1.2 Starch, amylose and sugar content 2.31
2.7.1.3 Cellulose, lignin, hemicelluloses, pectin and tannin content 2.32
2.7.1.4 Total polyphenols, flavonoids and antioxidant activity 2.34
2.7.1.5 Minerals content 2.36
2.7.1.6 Fatty acids and amino acid composition 2.38
2.7.1.6 Polyphenols analysis by HPLC 2.39
2.7.1.7 Fourier transform infrared spectroscopy (FT-IR) 2.43
2.7.1.8 Scanning electron microscopy 2.47
2.7.1.9 X-ray Diffraction Pattern (XRD) 2.47
2.8 Conclusion 2.51
References 2.53

Chapter 3 Resistant starch development from pulp and its application in food model 3.1-3.54

3A) Effect of modified resistant starch of culinary banana on physicochemical, functional, morphological, diffraction and thermal properties 3.1

3.1 Introduction 3.1

3.2 Materials and methods 3.3

3.2.1 Raw materials 3.3

3.2.2 Starch isolation 3.3

3.2.3 Chemical analysis 3.4

3.2.4 Functional Properties 3.4

3.2.4.1 Water holding capacity, starch swelling power and solubility 3.4

3.2.4.2 Freeze-thaw stability and paste clarity 3.5

3.2.4.3 Pasting Properties 3.5

3.2.5 Structural analysis of starch 3.6

3.2.5.1 X- Ray diffraction 3.6

3.2.5.2 Fourier transforms infrared (FT-IR) spectra 3.6

3.2.5.3 Morphological analysis by SEM 3.6

3.2.6 Thermal characteristics by thermogravimetric analysis (TGA) 3.7

3.2.7 Development of type III resistant starch (RS) from culinary banana starch 3.7

3.2.7.1 Autoclaving and cooling method 3.7

3.2.7.2 Enzyme debranching method 3.7

3.2.7.3 Chemical analysis of RS 3.8

3.2.8 Statistical analysis 3.8

3.3 Results and discussion 3.8

3.3.1 Chemical composition of culinary banana starch 3.8

3.3.2 Functional properties of culinary banana starch 3.10

3.3.2.1 Water holding capacity, starch swelling power and 3.10

solubility
3.3.2.2 Freeze-thaw stability and paste clarity 3.11
3.3.2.3 Pasting properties 3.12
3.3.3 Structural analysis 3.13
3.3.3.1 X- Ray diffraction 3.13
3.3.3.2 Fourier transforms infrared (FT-IR) spectra 3.14
3.3.3.3 Morphological analysis by SEM 3.16
3.3.4 Thermal stability by thermogravimetric analysis (TGA) 3.16
3.4 Development of type III resistant starch (RS) from culinary banana starch 3.17
3.4.1 RS production by hydrothermal method 3.17
3.4.2 Effect of enzyme concentration on starch debranching 3.18
3.4.3 Effect of storage temperature on RS content 3.19
3.4.5 Chemical analysis 3.20
3.4.6 Scanning electron microscopy (SEM) 3.21
3.4.7 FT-IR spectra of RS 3.23
3.4.8 Thermogravimetric analysis (TGA) 3.24
3.5 Conclusion 3.27

3B) Effect of partial replacement of wheat flour with type III resistant starch and flour of culinary banana on the chemical composition, textural properties and sensory quality of brown bread 3.28

3.6 Introduction 3.28
3.7 Materials and methods 3.29
3.7.1 Raw materials 3.29
3.7.2 Starch isolation and modification in to RS 3.29
3.7.3 Preparation of brown bread incorporated with RS 3.30
3.7.3.1 Brown Bread Making Procedure 3.31
3.7.4 Chemical composition 3.31
3.7.5 Physical properties 3.31
3.7.5.1 Proofing of dough 3.31
3.7.5.2 Water retention, weight and volume of baked bread loaves 3.32

3.7.5.3 Texture profile analysis of bread crumb 3.33
3.7.5.4 Crumb colour 3.33
3.7.6 Sensory evaluation 3.34
3.7.7 Statistical analysis 3.34

3.8 Results and discussion 3.34
3.8.1 Effect of RS and KF on chemical composition of brown bread 3.34
3.8.2 Physical properties of brown bread 3.35
3.8.2.1 Proofing of dough 3.35
3.8.2.2 Water retention, loaf weight and volume of baked product 3.36
3.8.2.3 Texture profile analysis 3.41
3.8.2.4 Colour attributes 3.44
3.8.3 Sensory analysis 3.45
3.9 Conclusion 3.46
References 3.48

Chapter 4 Isolation and characterization of cellulose nanofiber from peel and its application in developing nanopaper 4.1-4.49

4A) Isolation and characterization of cellulose nanofibers from culinary banana peel using high-intensity ultrasonication combined with chemical treatment 4.1
4.1 Introduction 4.1
4.2 Materials and methods 4.3
4.2.1 Raw materials and chemicals 4.3
4.2.2 Preparation of peel flour 4.3
4.2.3 Isolation of cellulose fibers (CFs) and cellulose nanofibers (CNFs) 4.3
4.2.4 Characterization of cellulose nanofibers (CNFs) 4.6
4.2.4.1 Microstructure evaluation by scanning electron microscopy (SEM) 4.6

4.2.4.2 Transmission electron microscopy (TEM) 4.6
4.2.4.3 X-ray diffraction (XRD) 4.6
4.2.4.4 Fourier transform infrared spectroscopy (FT-IR) 4.7
4.2.4.5 Thermogravimetric analysis (TGA) 4.7
4.3 Results and discussion 4.7
4.3.1 Visual examination on appearance of CNFs suspensions 4.7
4.3.2 Microstructure evaluation by scanning electron microscopy (SEM) 4.10
4.3.3 Transmission electron microscopy (TEM) 4.12
4.3.4 X-ray diffraction (XRD) 4.13
4.3.5 Fourier transform infrared spectroscopy (FT-IR) 4.14
4.3.6 Thermogravimetric analysis (TGA) 4.15
4.4 Conclusion 4.17
4B) Production of renewable high performance cellulose nanopaper from culinary banana (*Musa* ABB) peel and its characterization 4.19
4.5 Introduction 4.19
4.6 Materials and methods 4.20
4.6.1 Raw materials and isolation of CNF 4.20
4.6.2 Preparation of cellulose nanopaper (CNP) 4.20
4.6.3 SEM and TEM micrographs of CNP 4.22
4.6.4 X-ray diffraction (XRD) 4.22
4.6.5 Fourier transform infrared spectroscopy (FT-IR) 4.22
4.6.6 Solid-state ^{13}C nuclear magnetic resonance (NMR) measurements 4.22
4.6.7 Thermogravimetric analysis (TGA) 4.23
4.6.8 Photoluminescence (PL) and uv-vis spectroscopy 4.23
4.6.9 Mechanical properties 4.23
4.6.10 Particle size distribution and zeta potential 4.23
4.7 Results and discussion 4.24
4.7.1 Structural morphology by SEM 4.25
4.7.2 Nanostructure evaluation by TEM 4.26
4.7.3 X-ray diffraction (XRD) 4.27

4.7.4 Fourier transform infrared spectroscopy (FT-IR) 4.29
4.7.5 Cross polarization ^{13}C NMR spectroscopy 4.30
4.7.6 Thermogravimetric analysis (TGA/DTG) 4.34
4.7.7 Photoluminescence (PL) and uv-vis spectroscopy 4.36
4.7.8 Mechanical property 4.37
4.7.9 Particle size distribution 4.40
4.8 Conclusions 4.41
References 4.43

Chapter 5 Encapsulation of natural antioxidant from culinary banana pulp and peel 5.1-5.26

5.1 Introduction 5.1
5.2 Materials and methods 5.2
5.2.1 Raw materials and preparation of the sample extract 5.2
5.2.2 Preparation of cocrystallized powder 5.2
5.2.3 Total polyphenols content 5.3
5.2.4 Loading capacity and entrapment yield 5.3
5.2.5 HPLC analysis of phenolic compounds 5.3
5.2.6 Characterization of the cocrystallized products 5.3
5.2.6.1 Moisture content and water activity 5.3
5.2.6.2 Solubility 5.4
5.2.6.3 Flowability 5.4
5.2.6.4 Colour attributes 5.4
5.2.6.5 Fourier transform infrared spectroscopy (FTIR) 5.5
5.2.6.6 Differential scanning calorimetry (DSC) 5.5
5.2.6.7 X-ray diffraction (XRD) 5.5
5.2.6.8 Microstructure evaluation 5.5
5.2.7 Water gain, hygroscopicity and chemical stability during storage 5.5
5.2.8 Statistical Analysis 5.6
5.3 Results and discussion 5.6
5.3.1 Total polyphenols, antioxidant activity, entrapment yield and loading capacity 5.6

5.3.2 Polyphenols analysis by HPLC 5.8
5.3.3 Characterization of the cocrystallized products 5.8
5.3.3.1 Moisture content and water activity 5.8
5.3.3.2 Solubility and flowability of cocrystal powders 5.10
5.3.3.3 Colour attributes 5.12
5.3.3.4 Fourier transform infrared spectroscopy (FT-IR) 5.13
5.3.3.5 Differential scanning calorimetry (DSC) 5.14
5.3.3.6 X-ray diffraction (XRD) 5.16
5.3.3.6 Microstructure evaluation 5.20
5.3.3.7 Water gain, hygroscopicity during storage 5.22
5.4 Conclusions 5.22
References 5.24

Chapter 6 Drying characteristics by hot air oven, optimization of process parameters in vacuum drying for pulp slices and peel paste and storage study of culinary banana flour 6.1-6.74

6A) Drying characteristics and assessment of physicochemical and microstructural properties of dried culinary banana 6.1

6.1 Introduction 6.1
6.2 Materials and methods 6.3
6.2.1 Sample preparation 6.3
6.2.2 Experimental procedure 6.3
6.2.3 Drying kinetics 6.5
6.2.4 Effective moisture diffusivity 6.6
6.2.5 Activation energy 6.7
6.2.6 Physicochemical analysis 6.7
6.2.6.1 Microstructure evaluation 6.7
6.2.6.2 Texture analysis 6.7
6.2.6.3 Nonenzymatic browning 6.8
6.2.6.4 Rehydration ratio 6.8
6.2.6.5 Determination of DPPH radical scavenging activity and total 6.9

polyphenols
6.2.7 Statistical analysis 6.9

6.3 Results and discussion 6.9
6.3.1 Drying characteristics 6.9
6.3.2 Mathematical modeling for fitting drying curves 6.11
6.3.3 Effective moisture diffusivity 6.14
6.3.4 Activation energy 6.16
6.3.5 Physicochemical analysis 6.17
6.3.5.1 Microstructure evaluation 6.17
6.3.5.2 Textural property 6.19
6.3.5.3 Nonenzymatic browning 6.20
6.3.5.4 Rehydration ratio 6.20
6.3.5.5 Determination of DPPH radical scavenging activity and total polyphenols 6.21
6.4 Conclusions 6.22

6B) Modeling and optimization of the process parameters in vacuum drying of culinary banana pulp slices and peel paste by application of artificial neural network and genetic algorithm 6.23
6.5 Introduction 6.23
6.6 Materials and methods 6.24
6.6.1 Sample preparation 6.24
6.6.2 Experimental design 6.25
6.6.3 Experimental procedure 6.25
6.6.4 Quality evaluation 6.26
6.6.5 Response surface methodology 6.26
6.6.6 Artificial neural network (ANN) development and coding 6.27
6.6.7 Genetic algorithm (GA) as an optimizing tool for process parameters 6.30

6.7 Results and discussion 6.31
6.7.1 Modeling of the process parameters by response surface 6.31

methodology
6.7.2 Modeling of the process parameters by artificial neural network 6.36
6.7.3 Comparative study between RSM and ANN model 6.37
6.7.4 Effect of independent variables on rehydration ratio of dried culinary banana 6.41
6.7.5 Effect of independent variables on DPPH radical scavenging activity 6.42
6.7.6 Effect of independent variables on colour of dried culinary banana 6.43
6.7.7 Effect of independent variables on hardness of dried culinary banana slices 6.43
6.7.8 Microstructure evaluation by scanning electron microscope 6.46
6.7.9 Optimization of process parameters by GA 6.48
6.7.10 Validation of the GA 6.48
6.8 Conclusion 6.49

6C) Moisture sorption isotherm of culinary banana flour and its antioxidant stability during storage 6.51

6.9 Introduction 6.51
6.10 Materials and methods 6.52
6.10.1 Raw materials 6.52
6.10.2 Antioxidant stability during storage 6.52
6.10.3 Moisture sorption isotherm (MSI) studies 6.52
6.10.4 Fitting to existing mathematical models and data analysis 6.54
6.10.5 Determination of net isosteric heat of sorption 6.55

6.11 Results and discussion 6.56
6.11.1 Antioxidant stability during storage 6.56
6.11.2 Moisture sorption characteristics of culinary banana flour 6.57
6.11.3 Mathematical Modeling and Fitting of Moisture Sorption Data 6.59
6.11.4 Net isosteric heat of sorption 6.63

6.12 Conclusions 6.64

References 6.66

Chapter 7 Conclusions and future scope 7.1-7.10

7.1 Conclusions 7.1

7.2 Future scope of the present investigation 7.7

List of publications 7.8