Dedicated to My Beloved Parents & Sisters

Declaration by the candidate

The thesis entitled "Design and Development of a Continuous Ohmic Heating System for Thermal Processing of Pineapple Juice" is being submitted to the School of Engineering, Tezpur University in partial fulfilment for the award of the degree of Doctor of Philosophy in the Department of Food Engineering and Technology is a record of research work accomplished by me under the supervision of Prof. Brijesh Srivastava and co-supervision of Dr. Md. Rahat Mahboob.

All helps from various sources have been duly acknowledged.

No part of the thesis has been submitted elsewhere for award of any other degree.

Date: 24.12.2024 Place: Tezpur University Amardeep Heima Amardeep Kumar Roll No.: FEP19110 Department of Food Engineering and Technology School of Engineering, Tezpur University Napaam (784028), Tezpur, Assam, India



तेजपुर विश्वविद्यालय (केंद्रीय विश्वविद्यालय)

TEZPUR UNIVERSITY

(A Central University) Napaam, Tezpur - 784 028, Assam, India

नपाम, तेजपुर - 784 028, असम, भारत

(सर्वोत्तम विश्वविद्यालय के लिए कुलाध्यक्ष पुरस्कार, 2016, भारत के 100 श्रेष्ठ उच्च शिक्षण संस्थानों में पंचम स्थान और 'नाक' द्वारा 'ए' ग्रेड प्राप्त विश्वविद्यालय) (Awardee of Visitor's Best University Award, 2016, 5th among India's Top 100 Universities, MHRD-NIRF Ranking, 2016 and NAAC Accredited with "A" Grade)

Certificate of the Supervisor

This is to certify that the thesis entitled "Design and Development of a Continuous Ohmic Heating System for Thermal Processing of Pineapple Juice" submitted to the School of Engineering, Tezpur University in partial fulfilment for the award of the degree of Doctor of Philosophy in the Department of Food Engineering and Technology is a record of research work carried out by Mr. Amardeep Kumar under co-supervision of Dr. Md. Rahat Mahboob and my supervision and guidance

All helps received by him from various sources have been duly acknowledged.

No part of this thesis has been submitted elsewhere for the award of any other degree.

Signature by Supervisor

Date: 24-12.24 Place: Tezpur University

Prof. Brijesh Srivastava Professor Department of Food Engineering and Technology School of Engineering, Tezpur University Napaam (784028), Tezpur, Assam, India



तेजपुर विश्वविद्यालय (केंद्रीय विश्वविद्यालय)

TEZPUR UNIVERSITY

(A Central University)

नपाम, तेजपुर – 784 028, असम, भारत

Napaam, Tezpur - 784 028, Assam, India

(सवोत्तम विश्वविद्यालय के लिए कुलाध्यक्ष पुरस्कार, 2016, भारत के 100 श्रेष्ठ उच्च शिक्षण संस्थानों में पंचम स्थान और 'नाक' द्वारा 'ए' ग्रेड प्राप्त विश्वविद्यालय) (Awardee of Visitor's Best University Award, 2016, 5th among India's Top 100 Universities, MHRD-NIRF Ranking, 2016 and NAAC Accredited with "A" Grade)

Certificate of the Co-supervisor

This is to certify that the thesis entitled "Design and Development of a Continuous Ohmic Heating System for Thermal Processing of Pineapple Juice" submitted to the School of Engineering, Tezpur University in partial fulfilment for the award of the degree of Doctor of Philosophy in the Department of Food Engineering and Technology is a record of research work carried out by Mr. Amardeep Kumar under the supervision and guidance of Prof. Brijesh Srivastava as supervisor and myself as co-supervisor.

All helps received by him from various sources have been duly acknowledged.

No part of this thesis has been submitted elsewhere for the award of any other degree.

724/12/24

Signature by Co-supervisor

Date: Place: Tezpur University Dr. Md. Rahat Mahboob Assistant Professor Department of Electrical Engineering School of Engineering, Tezpur University Napaam (784028), Tezpur, Assam, India

Acknowledgements

I would like to express my deepest gratitude to all those who have supported and guided me throughout the course of my PhD journey.

Firstly, I am profoundly grateful to my supervisor Prof. Brijesh Srivastava, Professor, Department of Food Engineering and Technology, Tezpur University, Tezpur, Assam for his unwavering support, insightful feedback, guidance, and encouragement that helped me in completing the thesis. I am also grateful to him for all the valuable suggestions during my PhD work. I am also deeply thankful to my co-supervisor Dr. Md. Rahat Mahboob, Assistant Professor, Department of Electrical Engineering, Tezpur University, Assam for his consistent support and guidance throughout my PhD work.

I express my sincere gratitude to Prof. Shambhu Nath Singh, Vice Chancellor, Tezpur University, Assam for providing the opportunity to carry out the PhD work. I also want to thank Prof. Partha Pratim Sahu, Dean, School of Engineering, Tezpur University and Prof. Sankar Chandra Deka, Controller of Examination, Tezpur University for their constant support throughout the PhD work.

I sincerely want to thank the esteemed member of my Doctoral Committee, Dr. Manuj Kumar Hazarika, Professor, Department of Food Engineering and Technology, Tezpur University, Dr. Nandan Sit, Professor, Department of Food Engineering and Technology, Tezpur University, and Dr. Paragmoni Kalita, Associate Professor, Department of Mechanical Engineering, Tezpur University for their valuable suggestions and encouragement at various stages of PhD journey.

My sincere gratitude and thanks also go to the members of the Departmental Research Committee for their valuable suggestions and help throughout my research work. I also want to thank all the faculty members from the Department of Food Engineering and Technology, Tezpur University, for their regular suggestions and encouragement.

I also want to thank UGC, Ministry of Education, Government of India, for the award of National Fellowship for Other Backward Classes 2020-21 (No. F. 82-44/2020 (SA-III); UGC-Ref. No.: 200510218872; Dated: 30.11.2020) during my PhD work. My thanks also go to the Prof. Brijesh Srivastava, Principal Investigator of the ICAR NASF funded project (NASF-7010), for hiring me as Senior Research Fellow during the initial stage of my PhD work. Without the financial assistance received from the stated sponsors, it would not have been possible for me to conduct the present research.

I want to thank my colleagues who supported and encouraged me during the entire journey of my PhD work whenever needed. Thanks are due to the technical and office staffs of the Department of Food Engineering and Technology, Tezpur University, Assam for providing the necessary help and assistance during my PhD work. I also express my sincere thanks to all whose names have not been mentioned individually but have helped me directly or indirectly during my PhD work.

Finally, on a personal note, I owe a special thanks to my parents, sisters, and my girlfriend for their patience, encouragement, motivation, and understanding throughout this process. Their love and support have been my greatest source of strength.

Above all, I am thankful to "The Almighty" who blessed me with good health and sound mind to complete my PhD thesis.

Anardeep Kumar **Amardeep Kumar**

Date: 24.12.2024

Place: Tezpus University

LIST OF TABLES

Table No.	Title	Page No.
3.1	Dimension parameters of COH system	37
4.1	Physico-chemical properties of the fresh fruit juice used in the present study	50
4.2	Come-up time of different fruit juices at varied EFS and flow rate during COH to achieve a target temperature of 90 °C	53
4.3	Physico-chemical properties of different °Brix/Acid of the pineapple juice	60
4.4	Come-up time of different °Brix/Acid pineapple juices at different EFS and flow rate during COH to achieve a target temperature of 90 °C	63
4.5	Design of volume flow rate of juice	71
4.6	Come-up time for steady temperature state	73
4.7	Location of the outlet port of the isothermal holding section for different treatment conditions	74
4.8	Colour parameters and overall colour change of COH treated pineapple juice	76
4.9	Model parameters of different inactivation kinetic modelling of PPO enzymes in COH-treated pineapple juice	79
4.10	Goodness of fit parameters for different inactivation kinetic modelling of PPO enzymes in continuous ohmic-treated pineapple juice	80
4.11	Model validation of PPO inactivation using accuracy factor (A_f) and bias factor (B_f)	84
4.12	Model selection for PPO inactivation by AIC and Akaike increment (Δ_i)	85
4.13	Model parameters of different inactivation kinetic modelling of POD enzymes in COH-treated pineapple juice	89
4.14	Goodness of fit parameters for different inactivation kinetic modelling of POD enzymes in continuous ohmic-treated pineapple juice	90
4.15	Model validation of POD inactivation using accuracy factor (A_f) and bias factor (B_f)	94
4.16	Model selection for POD inactivation by AIC and Akaike increment (Δ_i)	95

4.17	Model parameters of different inactivation kinetic modelling of bromelain enzymes in COH-treated pineapple juice	99
4.18	Goodness of fit parameters for different inactivation kinetic modelling of bromelain enzymes in continuous ohmic-treated pineapple juice	100
4.19	Model validation of bromelain inactivation using accuracy factor (A_f) and bias factor (B_f)	102
4.20	Model selection for bromelain inactivation by AIC and Akaike increment (Δi)	103
4.21	Model parameters of different inactivation kinetic modelling of microbial load in COH-treated pineapple juice	106
4.22	Goodness of fit parameters for different inactivation kinetic modelling of microbial load reduction in continuous ohmic-treated pineapple juice	108
4.23	Model validation for microbial inactivation using accuracy factor (A_f) and bias factor (B_f)	111
4.24	Model selection for microbial inactivation by AIC and Akaike increment (Δ_i)	112
4.25	Model parameters of different degradation kinetic modelling of vitamin C in COH-treated pineapple juice	114
4.26	Goodness of fit parameters for different degradation kinetic modelling of vitamin C in continuous ohmic-treated pineapple juice	115
4.27	Model selection for vitamin C degradation by using accuracy factor (A_f) and bias factor (B_f)	117
4.28	Model selection for vitamin C degradation by AIC and Akaike increment (Δ_i)	118
4.29	Decimal reduction time of enzyme and microbial inactivation	119
4.30	Activation energy of PPO, POD and bromelain enzymes	121
4.31	Model summary statistics for selecting the best model	123
4.32	ANOVA for enzyme inactivation, microbial load reduction and vitamin C retention using a second order polynomial model	123
4.33	Significance level of the model terms	124
4.34	Statistical parameters of the models	127
4.35	Constraints of the optimization process and best solution	128
4.36	Experimental and predicted values at optimized condition	128
4.37	Model parameters of degradation kinetic modelling of vitamin C during storage study of pineapple juice	133

4.38	Model parameters of kinetic modelling of microbial growth during storage study of pineapple juice	134
4.39	Model parameters of degradation kinetic modelling of enzyme activity during storage study of pineapple juice	138

Figure No.	Title	Page No.
2.1	The basic principle of ohmic heating	8
2.2	Schematic diagram of the ohmic heating set-up	9
2.3	Important parameters of ohmic heating in food processing	9
2.4	Lab scale batch type ohmic heating system. 1-ohmic chamber, 2-K- type thermocouple, 3-electrodes, 4-current and voltage indicator, 5- temperature controller, 6-input power from variac transformer	11
2.5	Lab scale continuous type ohmic heating system. 1-pump, 2-inlet tank, 3-electrodes, 4-K-type thermocouple, 5-ohmic heating chamber, 6-outlet tank, 7-current and voltage indicator, 8- temperature controller, 9-input power from variac transformer	12
2.6	Various applications of ohmic heating in food processing	13
3.1	Overall flow chart of the work. Where CJ, TJ, OJ, PJ, and LJ are cucumber, tomato, orange, pineapple, and lemon juice, respectively. Also, Q, EFS, EC, and T are flow rate, electric field strength, electrical conductivity, and temperature, respectively	23
3.2	Flow chart of the objective 1. Where CJ, TJ, OJ, PJ, and LJ are cucumber, tomato, orange, pineapple, and lemon juice, respectively. Also, Q, EFS, and EC are flow rate, electric field strength, and electrical conductivity, respectively	24
3.3	Flow chart of the objective 2	25
3.4	Flow chart of objective 3	27
3.5	Flow chart of objective 4	28
3.6	Flow chart of objective 5	29
3.7	Steps in thermal treatment of fruit juice	30
3.8	Schematic design of a lab-scale COH chamber	31
3.9	Schematic design of a lab-scale COH chamber equipped with an isothermal holding chamber	31
3.10	Schematic diagram of a heating chamber	33
3.11	Schematic diagram of an isothermal holding chamber	34
3.12	Schematic diagram of a T-shaped hollow jointer	35

3.13	(a) dissembled parts of heating and isothermal holding chamber of COH system, (b) assembled COH and isothermal holding chamber, and (c) electrodes	36
4.1	Actual set-up of a lab-scale COH chamber	49
4.2	Actual set-up of a lab-scale COH chamber equipped with an isothermal holding chamber	49
4.3	Effect of EFS on heating profile of cucumber juice during COH at (a) 80 mL/min, (b) 100 mL/min, and (c) 120 mL/min	52
4.4	Effect of EFS on heating profile of tomato juice during COH at (a) 80 mL/min, (b) 100 mL/min, and (c) 120 mL/min	52
4.5	Effect of EFS on heating profile of orange juice during COH at (a) 80 mL/min, (b) 100 mL/min, and (c) 120 mL/min	52
4.6	Effect of EFS on heating profile of pineapple juice during COH at (a) 80 mL/min, (b) 100 mL/min, and (c) 120 mL/min	52
4.7	Effect of EFS on heating profile of lemon juice during COH at flow rate of (a) 80 mL/min, (b) 100 mL/min, and (c) 120 mL/min	52
4.8	Heating rate curve during COH of different fruit juices at varied EFS at flow rate of (a) 80 mL/min, (b) 100 mL/min, (c) 120 mL/min	54
4.9	System performance coefficient (SPC) of different fruit juices at varied EFS during COH at flow rate of (a) 80 mL/min, (b) 100 mL/min, and (c) 120 mL/min	56
4.10	Electrical conductivity – temperature curve of cucumber juice at different EFS during COH at flow rate of (a) 80 mL/min, (b) 100 mL/min, and (c) 120 mL/min	58
4.11	Electrical conductivity – temperature curve of tomato juice at different EFS during COH at flow rate of (a) 80 mL/min, (b) 100 mL/min, and (c) 120 mL/min	58
4.12	Electrical conductivity – temperature curve of orange juice at different EFS during COH at flow rate of (a) 80 mL/min, (b) 100 mL/min, and (c) 120 mL/min	58
4.13	Electrical conductivity – temperature curve of pineapple juice at different EFS during COH at flow rate of (a) 80 mL/min, (b) 100 mL/min, and (c) 120 mL/min	58
4.14	Electrical conductivity – temperature curve of lemon juice at different EFS during COH at flow rate of (a) 80 mL/min, (b) 100 mL/min, and (c) 120 mL/min	58

4.15	Effect of °Brix/Acid of pineapple juice on heating profile at constant flow rate of 80 mL/min during COH at EFS (a) 25 V/cm, (b) 30 V/cm, (c) 35 V/cm, (d) 40 V/cm, and (e) 45 V/cm	61
4.16	Effect of °Brix/Acid of pineapple juice on heating profile at constant flow rate of 100 mL/min during COH at EFS (a) 25 V/cm, (b) 30 V/cm, (c) 35 V/cm, (d) 40 V/cm, and (e) 45 V/cm	62
4.17	Effect of °Brix/Acid of pineapple juice on heating profile at constant flow rate of 120 mL/min during COH at EFS (a) 25 V/cm, (b) 30 V/cm, (c) 35 V/cm, (d) 40 V/cm, and (e) 45 V/cm	62
4.18	Heating rate curve of different °Brix/Acid pineapple juices at different EFS during COH at flow rate of (a) 80 mL/min, (b) 100 mL/min, and (c) 120 mL/min	64
4.19	The SPC curve of different °Brix/Acid pineapple juices at different EFS during COH at flow rate of (a) 80 mL/min, (b) 100 mL/min, and (c) 120 mL/min	67
4.20	Electrical conductivity – temperature curve of different °Brix/Acid pineapple juice during COH at flow rate of 80 mL/min at different EFS (a) 25 V/cm, (b) 30 V/cm, (c) 35 V/cm, (d) 40 V/cm, and (e) 45 V/cm	68
4.21	Electrical conductivity – temperature curve of different °Brix/Acid pineapple juice during COH at flow rate of 100 mL/min at different EFS (a) 25 V/cm, (b) 30 V/cm, (c) 35 V/cm, (d) 40 V/cm, and (e) 45 V/cm	68
4.22	Electrical conductivity – temperature curve of different °Brix/Acid pineapple juice during COH at flow rate of 120 mL/min at different EFS (a) 25 V/cm, (b) 30 V/cm, (c) 35 V/cm, (d) 40 V/cm, and (e) 45 V/cm	69
4.23	Effect of electric field strength on heating profile during continuous ohmic heating of standardized pineapple juice (22 °Brix/Acid) at different temperature (a) 70 °C, (b) 80 °C, and (c) 90 °C	71
4.24	Effect of electric field strength on current profile during continuous ohmic heating of standardized pineapple juice (22 °Brix/Acid) at different temperature (a) 70 °C, (b) 80 °C, and (c) 90 °C	72
4.25	Lab scale continuous type ohmic heating system with an isothermal holding section	74
4.26	Effect of continuous ohmic heating on PPO inactivation at EFS (a) 30 V/cm , (b) 35 V/cm , and (c) 40 V/cm	77
4.27	Model curve fitting of experimental and predicted values of PPO enzymes at EFS (a) 30 V/cm, (b) 35 V/cm, and (c) 40 V/cm, (d)	82

residual plot of PPO inactivation, (e) relative deviation plot of PPO inactivation, (f) predicted vs experimental residual activity of PPO using Weibull distribution model. Where, FOM, DIM, FCM, WDM, and SLM are first order model, distinct isozymes model, fractional conversion model, Weibull distribution model, and sigmoidal logistic model, respectively Effect of continuous ohmic heating on POD inactivation at EFS (a) 4.28 87 30 V/cm, (b) 35 V/cm, and (c) 40 V/cm Model curve fitting of experimental and predicted values of POD enzymes at EFS (a) 30 V/cm, (b) 35 V/cm, and (c) 40 V/cm, (d) residual plot of POD inactivation, (e) relative deviation plot of POD inactivation, (f) predicted vs experimental residual activity of POD 4.29 92 using Weibull distribution model. Where, FOM, DIM, FCM, WDM, and SLM are first order model, distinct isozymes model, fractional conversion model, Weibull distribution model, and sigmoidal logistic model, respectively Effect of continuous ohmic heating on bromelain inactivation at EFS 4.30 97 (a) 30 V/cm, (b) 35 V/cm, and (c) 40 V/cm Model curve fitting of experimental and predicted values of bromelain enzymes at EFS (a) 30 V/cm, (b) 35 V/cm, and (c) 40 V/cm, (d) residual plot of bromelain inactivation, (e) relative deviation plot of bromelain inactivation, (f) predicted vs 4.31 101 experimental residual activity of bromelain using Weibull distribution model. Where, FOM, WDM, and SLM are first order model, Weibull distribution model, and sigmoidal logistic model, respectively Effect of continuous ohmic heating on microbial inactivation at EFS 4.32 104 (a) 30 V/cm, (b) 35 V/cm, and (c) 40 V/cm Model curve fitting of experimental and predicted values of microbial load reduction at EFS (a) 30 V/cm, (b) 35 V/cm, and (c) 40 V/cm, (d) residual plot of microbial load reduction, and (e) predicted vs 4.33 experimental microbial load reduction using Weibull distribution 109 model. Where, FOM, MGM, and WDM are first order model, modified Gompertz model, and Weibull distribution model, respectively Effect of continuous ohmic heating on vitamin C content at EFS (a) 4.34 113 30 V/cm, (b) 35 V/cm, and (c) 40 V/cm Model curve fitting of experimental and predicted values of vitamin 4.35 116 C at EFS (a) 30 V/cm, (b) 35 V/cm, and (c) 40 V/cm, (d) residual plot of vitamin C, (e) relative deviation plot of vitamin C, (f) predicted vs

ХΧ

	experimental vitamin C using first order model. Where, FOM, WDM, and SLM are first order model, Weibull distribution model, and sigmoidal logistic model, respectively	
4.36	Experimental vs predicted values of (a) PPO (%RA), (b) POD (%RA), (c) bromelain (%RA), (d) microbial load reduction (log reduction), and (e) vitamin C (%)	126
4.37	Residual plots of (a) PPO (%RA), (b) POD (%RA), (c) bromelain (%RA), (d) microbial load reduction (log reduction), and (e) vitamin C (%)	127
4.38	Effect of storage on pH	129
4.39	Effect of storage on TSS	130
4.40	Effect of storage on titratable acidity	131
4.41	Effect of storage on electrical conductivity	131
4.42	Effect of storage on vitamin C	132
4.43	Effect of storage on total microbial load	134
4.44	Effect of storage on PPO activity	136
4.45	Effect of storage on POD activity	136
4.46	Effect of storage on bromelain activity	137
4.47	Effect of storage on colour parameters (a) L^* , (b) a^* , (c) b^* , and (d) total colour change	141