

# **VIBRO-FLUIDIZED BED DRYING OF SMALL CARDAMOM (*ELETTARIA CARDAMOMUM* MATON)**

**SUSHREESMITA MISHRA**



**CENTRE FOR RURAL DEVELOPMENT AND TECHNOLOGY  
INDIAN INSTITUTE OF TECHNOLOGY DELHI**

**MARCH 2024**

© Indian Institute of Technology Delhi (IITD), New Delhi, 2024

# **VIBRO-FLUIDIZED BED DRYING OF SMALL CARDAMOM (*ELETTARIA CARDAMOMUM* MATON)**

by

**SUSHREESMITA MISHRA**

**CENTRE FOR RURAL DEVELOPMENT AND TECHNOLOGY**

*Submitted*

*In fulfillment of the requirements of the degree of*

**Doctor of Philosophy**

to the



**INDIAN INSTITUTE OF TECHNOLOGY DELHI**

**MARCH 2024**

***Dedicated to***

***My Late Father***

**Centre for Rural Development & Technology  
Indian Institute of Technology Delhi**

**CERTIFICATE**

This is to certify that the thesis entitled, “**Vibro-Fluidized Bed Drying of Small Cardamom (*Elettaria Cardamomum* Maton)**” being submitted by **Mrs Sushreesmita Mishra** to the **Indian Institute of Technology Delhi** for the award of “**Doctor of Philosophy**” is a record of bonafide research work carried out by her. She has worked under my guidance and supervision and has fulfilled the requirements for the submission of thesis. To the best of my knowledge, the results contained in the thesis have not been submitted, in part or full, to any other university or institute for the award of any degree or diploma.

**(Prof Jatindra K Sahu)**

Centre for Rural Development & Technology  
Indian Institute of Technology Delhi

## ACKNOWLEDGEMENT

Foremost, I would like to express my sincere gratitude to my supervisor **Prof Jatindra K Sahu**, Centre for Rural Development and Technology, Indian Institute of Technology Delhi for his scrupulous guidance, incessant motivation, valuable suggestions and continuous support throughout my doctoral study and research.

Besides my supervisor, I would like to extend my heartfelt thanks to the members of my Doctoral Committee, **Prof S N Naik** (Chairman), **Prof Hariprasad P** (Internal expert), and **Prof Sampa Saha** (External Expert) for their valuable suggestions provided at various stages of investigation and compilation of the thesis. Sincere thanks are due to **Prof P M V Subbarao**, Head, Centre for Rural Development and Technology, IITD providing me with lab facilities and financial approval as and when required for accomplishment of my research work.

I would like to thank the Science and Engineering Research Board, Govt. of India of for providing me with generous financial support throughout my doctorate.

I would like to extend my heartfelt gratitude and appreciation to Mr Joshy Joseph, Kumily, Kerala, India for providing raw material to conduct my experiments as when required.

I am thankful to my lab mates especially Asutosh, Preeti, Bareen, Satheesh, and my previous lab mates Dr Neha, Anupam, Nitya mam for their long conceptual discussion. I must express my sincere gratitude to Nikita for a continual source of support and consolation throughout the difficulties and obstacles that the pursuit of a PhD has inevitably brought. My heartfelt thanks to Sukirti, Tanya, Achala, Vipasha, Dhruv, and Prasanna for their support whenever I approached them throughout my work. I will never forget the kind and mental support provided by my friends Pooja, Gayatri, Sushant, Dwarika, and Subarni mam for sharing so many moments in my life for the deepest exchange of thoughts.

Final appreciation to IIT Delhi for providing the technology and environment to work. Words are not eloquent to thank other Professors for providing valuable suggestions and guidance in the research work.

Last but most important, my heartiest appreciation is for the moral support given by my entire family, particularly my mother Mrs. Banita Rani Mishra, my sisters Subhasmita and Suchismita, and my brother Sudipta. I made it through the pregnancy, thanks in large part to my mother and father-in-law, Mrs. Sarojinee Purohit and Mr. Sushant K Padhee. The last two people I want to thank are my husband Mr. Suman K Padhee and my son Soumil whose radiant

smile helps me put everything into perspective. There are no words to thank my husband enough for the support and encouragement he has been given throughout my life.

To my late father, I will always be grateful for the enormous influence you had on my life, and I work hard to honor you in everything I do.

This list is obviously incomplete; I once again record my deepest gratitude to all those who have cooperated with me either directly or indirectly during my Doctoral study.

Date: **18 March 2024**

Place: **Delhi**

***Sushreesmita Mishra***

# ABSTRACT

Small cardamom (*Elettaria cardamomum* Maton) is an Indian native and one of the most sought-after spices, maintains a notable place in the global spice market. Cardamom capsules contain about 75% (wb) moisture at the time of harvesting, and the capsules are dried immediately after harvest for prolonged storage. Typically, kiln dryers are used to dry the cardamom capsules which take about 36 h. For optimal retention of color and aroma, this drying time should be significantly shortened by implementing suitable fast drying technologies. Fluidized bed (FB) drying offers significant benefits among different drying techniques, including high heat and mass transfer, consistent moisture reduction with short drying time, and high drying rate. As an advancement to the traditional fluidized beds, vibratory fluidized bed (VFB) drying is an emerging technique which combines vibration and air vertical air movement towards the drying bed. With this background, the objectives of the present investigation were to understand the physio-chemical characteristics of freshly harvested small cardamom capsules, to analyze their colour and aroma changes during convective drying and to develop a VFD assisted drying protocol for the optimum retention of their colour and aroma attributes during drying.

Engineering properties such size, sphericity, thousand capsule mass, density, porosity, angle of repose, and terminal velocity of the freshly harvested small cardamom capsules were measured using standard protocols. Moisture sorption isotherms of cardamom samples were determined at 20, 30 and 40°C with water activity levels ranging from 10 to 90%. Color, and aroma kinetics during convective drying were determined at constant air velocity 1.5 m.s<sup>-1</sup> at 40, 50, and 60 °C. The essential oil was extracted from sample using hydro-distillation technique. Investigations were carried out at temperatures of 40, 50, and 60 °C, air velocities of 1, 3, and 5 m.s<sup>-1</sup>, and vibration amplitudes of 0 (no vibration), 1, and 2 mm in a developed VFB dryer. Artificial neural networks (ANN) and genetic algorithms (GA) were used to optimize the process parameters using MATLAB. The essential oils yield and 1,8-cineole, and  $\alpha$ -terpinyl acetate were maximized while drying time and color change values were minimized. The total energy consumption at different drying experiments in the VFB dryer was obtained by the summation of thermal energy consumed to dry cardamom and the mechanical energy consumed by blower and the drying unit to induce vibration. To investigate the effect of temperature, air velocity and vibration on the drying kinetics, colour change, aroma change (essential oil yield) and quality of essential oil (1,8-cineole and terpinyl acetate), the output surfaces were drawn on the basis of the developed ANN model.

The physical properties of small cardamom were significantly dependent on the moisture content with high correlation coefficients ( $p < 0.05$ ). The sorption isotherm data exhibited type III BET categorization curves. The Caurie model was found to be the most effective empirical model for predicting the moisture adsorption isotherm across the entire range of relative humidity values. The glass transition temperature was found out to be 98.91 °C. During hot air drying (HAD) of cardamom, the total drying period was found out to be 52, 38, and 34 h at the drying air temperature of 40, 50, and 60 °C, respectively. Effective



moisture diffusivity was found out to be  $1.62 \times 10^{-8}$ ,  $2.51 \times 10^{-8}$  and  $3.64 \times 10^{-8} \text{ m}^2 \text{ s}^{-1}$  at 40, 50 and 60 °C, respectively. The activation energy was found to be 34.96 kJ.mol<sup>-1</sup>. The colour change value increased with drying time during convective drying. Essential oil yield increased with drying time and released more variety of volatile components during the drying process. In most samples, the major dominant components 1,8-cineole (>25%) and  $\alpha$ -Terpinyl acetate (>25%) were found. Esters, alcohols, and alkenes were the compounds of small cardamom that were most significantly impacted with longer drying times, according to the PCA loading plot of the compounds at three temperatures. The drying time for VFB drying process of small cardamom ranged from 5.5 to 19 h, which is much shorter time than the conventional drying process. Optimum drying conditions predicted in the VFB dryer were drying temperature of 40 °C, drying air velocity of 3 m.s<sup>-1</sup> and vibration amplitude of 2 mm. The effective moisture diffusivity during VFB drying increased with the increase in drying air temperature, air velocity and vibration amplitude, which indicated that there was an existence of external mass transfer resistances. The activation energy for the VFB dryer was calculated to be 19.26 kJ.mol<sup>-1</sup> in the absence of any vibration, and the value decreased from 21.41 kJ.mol<sup>-1</sup> to 16.17 kJ.mol<sup>-1</sup> when the amplitude of vibration increased from 1 mm to 2 mm. The minimum energy requirement to dry 1 kg cardamom without vibration is 27.48% less than that with vibration. The drying efficiency of VFB drying was found to be more than hot air convective (HAC) drying.

The present research investigated the engineering properties of cardamom which would serve as a basis for the development of dryers like vibro-fluidized bed dryer. The VFB drying would be one of the ideal drying systems for the optimum retention of green colour and typical aroma of cardamom capsules with reduced drying time, thereby would reduce energy consumption, and increase drying efficiency. For drying high-value spices like small cardamom, the VFD dryer could be one of the suitable drying techniques.

**Keywords:** *Spice drying; Small cardamom; Engineering properties; Moisture sorption isotherm; Colour kinetics; Aroma kinetics; Vibro-fluidized bed dryer; Drying efficiency; Cost analysis*

## सारांश

छोटी इलायची (एलेटेरिया इलायचीम मैटन) एक भारतीय मूल निवासी है और सबसे अधिक मांग वाले मसालों में से एक है, जो वैश्विक मसाला बाजार में एक उल्लेखनीय स्थान रखती है। कटाई के समय इलायची कैप्सूल में लगभग 75% (wb) नमी होती है, और लंबे समय तक भंडारण के लिए कटाई के तुरंत बाद कैप्सूल को सुखाया जाता है। आमतौर पर, इलायची कैप्सूल को सुखाने के लिए किलन ड्रायर का उपयोग किया जाता है जिसमें लगभग 36 घंटे लगते हैं। रंग और सुगंध के इष्टतम संरक्षण के लिए, उपयुक्त तेजी से सुखाने वाली प्रौद्योगिकियों को लागू करके इस सुखाने के समय को काफी कम किया जाना चाहिए। द्रवीकृत बिस्तर (एफबी) सुखाने से विभिन्न सुखाने की तकनीकों के बीच महत्वपूर्ण लाभ मिलते हैं, जिनमें उच्च ताप और द्रव्यमान स्थानांतरण, कम सुखाने के समय के साथ लगातार नमी में कमी और उच्च सुखाने की दर शामिल है। पारंपरिक द्रवयुक्त बिस्तरों की प्रगति के रूप में, कंपनयुक्त द्रवीकृत बिस्तर (वीएफबी) सुखाने एक उभरती हुई तकनीक है जो सुखाने वाले बिस्तर की ओर कंपन और वायु ऊर्ध्वाधर वायु गति को जोड़ती है। इस पृष्ठभूमि के साथ, वर्तमान जांच का उद्देश्य ताजी तोड़ी गई छोटी इलायची कैप्सूल की भौतिक-रासायनिक विशेषताओं को समझना, संवहनी सुखाने के दौरान उनके रंग और सुगंध में परिवर्तन का विश्लेषण करना और उनके रंग के इष्टतम संरक्षण के लिए वीएफडी सहायता प्राप्त सुखाने प्रोटोकॉल विकसित करना था। और सुखाने के दौरान सुगंध के गुण।

मानक प्रोटोकॉल का उपयोग करके इंजीनियरिंग गुणों जैसे आकार, गोलाकारता, हजार कैप्सूल द्रव्यमान, घनत्व, सरंध्रता, विश्राम का कोण और ताजा काटे गए छोटे इलायची कैप्सूल के टर्मिनल वेग को मापा गया था। इलायची के नमूनों की नमी सोखने की समताप रेखाएं 20, 30 और 40 °C. पर निर्धारित की गईं, जिसमें जल गतिविधि का स्तर 10 से 90% तक था। संवहन सुखाने के दौरान रंग और सुगंध गतिकी को 40, 50 और 60 °C. पर निरंतर वायु वेग 1.5 एमएस-1 पर निर्धारित किया गया था। हाइड्रो-डिस्टिलेशन तकनीक का उपयोग करके नमूने से आवश्यक तेल निकाला गया। एक विकसित वीएफबी ड्रायर में 40, 50, और 60 °C. के तापमान, 1, 3, और 5 ms<sup>-1</sup> के वायु वेग, और 0 (कोई कंपन नहीं), 1, और 2 mm के कंपन आयाम पर जांच की गई। MATLAB का उपयोग करके प्रक्रिया मापदंडों को अनुकूलित करने के लिए कृत्रिम तंत्रिका नेटवर्क (एएनएन) और आनुवंशिक एल्गोरिदम (जीए) का उपयोग किया गया था। आवश्यक तेलों की उपज और 1,8-सिनेओल, और  $\alpha$ -टेरपिनिल एसीटेट को अधिकतम किया गया जबकि सुखाने का समय और रंग परिवर्तन मूल्यों को कम किया गया। वीएफबी ड्रायर में विभिन्न सुखाने वाले प्रयोगों में कुल ऊर्जा खपत इलायची को सुखाने के लिए खपत की गई तापीय ऊर्जा और कंपन उत्पन्न करने के लिए ब्लोअर और सुखाने वाली इकाई द्वारा खपत की गई यांत्रिक ऊर्जा के योग से प्राप्त की गई थी। सुखाने की गतिकी, रंग परिवर्तन, सुगंध परिवर्तन (आवश्यक तेल उपज) और आवश्यक तेल (1,8-सिनेओल और टेरपिनिल एसीटेट) की गुणवत्ता पर तापमान, वायु वेग और कंपन के प्रभाव की जांच करने के लिए, आउटपुट सतहों को आधार पर तैयार किया गया था विकसित एएनएन मॉडल का।

छोटी इलायची के भौतिक गुण उच्च सहसंबंध गुणांक ( $p < 0.05$ ) के साथ नमी की मात्रा पर काफी हद तक निर्भर थे। सोरशन इज़ोटेर्म डेटा ने प्रकार III बीईटी वर्गीकरण वक्र प्रदर्शित किए। सापेक्ष आर्द्रता मूल्यों की संपूर्ण श्रृंखला में नमी सोखना इज़ोटेर्म की भविष्यवाणी के लिए कौरी मॉडल को सबसे प्रभावी

अनुभवजन्य मॉडल पाया गया। कांच संक्रमण तापमान 98.91 °C. पाया गया। इलायची को गर्म हवा में सुखाने (एचएडी) के दौरान, सूखने वाले हवा के तापमान 40, 50 और 60 °C. पर कुल सुखाने की अवधि क्रमशः 52, 38 और 34 घंटे पाई गई। 40, 50 और 60 °C. पर प्रभावी नमी प्रसार क्रमशः  $1.62 \times 10^{-8}$ ,  $2.51 \times 10^{-8}$  और  $3.64 \times 10^{-8} \text{ m}^2 \cdot \text{s}^{-1}$  पाया गया। सक्रियण ऊर्जा  $34.96 \text{ kJ} \cdot \text{mol}^{-1}$  पाई गई। संवहन सुखाने के दौरान सुखाने के समय के साथ रंग परिवर्तन का मूल्य बढ़ गया। सुखाने के समय के साथ आवश्यक तेल की उपज में वृद्धि हुई और सुखाने की प्रक्रिया के दौरान अधिक प्रकार के अस्थिर घटक जारी हुए। अधिकांश नमूनों में, प्रमुख प्रमुख घटक 1,8-सिनेओल (>25%) और  $\alpha$ -टेरपिनिल एसीटेट (>25%) पाए गए। तीन तापमानों पर यौगिकों के पीसीए लोडिंग प्लॉट के अनुसार, एस्टर, अल्कोहल और अल्केन्स छोटी इलायची के यौगिक थे जो लंबे समय तक सूखने के साथ सबसे अधिक प्रभावित हुए थे। छोटी इलायची की वीएफबी सुखाने की प्रक्रिया के लिए सुखाने का समय 5.5 से 19 घंटे तक है, जो पारंपरिक सुखाने की प्रक्रिया की तुलना में बहुत कम समय है। वीएफबी ड्रायर में अनुमानित इष्टतम सुखाने की स्थिति 40 °C. का सुखाने का तापमान, 3 एमएस-1 का सुखाने वाला वायु वेग और 2 मिमी का कंपन आयाम था। वीएफबी सुखाने के दौरान प्रभावी नमी का प्रसार शुष्क हवा के तापमान, वायु वेग और कंपन आयाम में वृद्धि के साथ बढ़ गया, जिससे संकेत मिलता है कि बाहरी द्रव्यमान स्थानांतरण प्रतिरोधों का अस्तित्व था। किसी भी कंपन की अनुपस्थिति में वीएफबी ड्रायर के लिए सक्रियण ऊर्जा की गणना  $19.26 \text{ kJ} \cdot \text{mol}^{-1}$  की गई थी, और जब कंपन का आयाम 1 से बढ़ गया तो मान  $21.41 \text{ kJ} \cdot \text{mol}^{-1}$  से घटकर  $16.17 \text{ kJ} \cdot \text{mol}^{-1}$  हो गया। मिमी से 2 mm. 1 किलो इलायची को बिना कंपन के सुखाने के लिए न्यूनतम ऊर्जा की आवश्यकता कंपन के साथ 27.48% कम है। वीएफबी सुखाने की सुखाने की क्षमता गर्म वायु संवहन (एचएसी) सुखाने से अधिक पाई गई।

वर्तमान शोध में इलायची के इंजीनियरिंग गुणों की जांच की गई जो वाइब्रो-फ्लुइडाइज्ड बेड ड्रायर जैसे ड्रायर के विकास के लिए आधार के रूप में काम करेगा। VFB सुखाने कम सुखाने के समय के साथ इलायची कैप्सूल के हरे रंग और विशिष्ट सुगंध को अधिकतम बनाए रखने के लिए आदर्श सुखाने प्रणालियों में से एक होगा, जिससे ऊर्जा की खपत कम होगी और सुखाने की दक्षता में वृद्धि होगी। छोटी इलायची जैसे उच्च मूल्य वाले मसालों को सुखाने के लिए वीएफडी ड्रायर उपयुक्त सुखाने की तकनीकों में से एक हो सकता है।

**कीवर्ड:** मसाला सुखाना; छोटी इलायची; इंजीनियरिंग गुण; नमी सोखना इज़ोटेर्म; रंग गतिकी; सुगंध गतिकी; विब्रो-फ्लुइडाइज्ड बेड ड्रायर; सुखाने की दक्षता; लागत विश्लेषण

# CONTENT

|                                                                                           | <b>Page no</b>  |
|-------------------------------------------------------------------------------------------|-----------------|
| <b>Certificate</b>                                                                        | <i>i</i>        |
| <b>Acknowledgement</b>                                                                    | <i>ii-iii</i>   |
| <b>Abstract</b>                                                                           | <i>iv-vii</i>   |
| <b>List of Figures</b>                                                                    | <i>xii-xiv</i>  |
| <b>List of Tables</b>                                                                     | <i>xv</i>       |
| <b>List of Abbreviations</b>                                                              | <i>xvi-xvii</i> |
| <br>                                                                                      |                 |
| <b>Chapter I      Background, Aims and Objectives</b>                                     | <b>1-5</b>      |
| 1.1      Background                                                                       | 1               |
| 1.2      Research Gap                                                                     | 4               |
| 1.3      Research Objectives                                                              | 4               |
| 1.4      Thesis Outline                                                                   | 5               |
| <br>                                                                                      |                 |
| <b>Chapter II      Review of Literature</b>                                               | <b>6-18</b>     |
| 2.1      Importance and Medical Virtues of Cardamom                                       | 6               |
| 2.2      Cardamom Processing                                                              | 6               |
| 2.3      Need of Drying of Cardamom                                                       | 9               |
| 2.4      Conventional Techniques for Drying of Cardamom                                   | 9               |
| 2.5      Experimental Studies on Drying of Cardamom                                       | 11              |
| 2.6      Quality Parameters of Dried Cardamom Capsules                                    | 12              |
| 2.7      Engineering Properties                                                           | 13              |
| 2.8      Storage and Thermodynamic Properties                                             | 13              |
| 2.9      Aroma Profile of Small Cardamom                                                  | 14              |
| 2.10      Novel Convective Drying Techniques                                              | 14              |
| 2.10.1      Vibro-fluidized bed drying                                                    | 14              |
| 2.11      Moisture, Colour and Aroma Kinetics Study during Drying<br>of cardamom capsules | 15              |
| 2.12      Chemometric Based Multivariate Analysis                                         | 16              |
| 2.13      Energy Aspects of Dryers                                                        | 17              |
| 2.14      Scope of Research work                                                          | 18              |

|                    |                                                                                                                                                  |              |
|--------------------|--------------------------------------------------------------------------------------------------------------------------------------------------|--------------|
| <b>Chapter III</b> | <b>Determination of Physico-Chemical, Engineering and Storage Properties of Freshly Harvested Small Cardamom at Different Storage Conditions</b> | <b>19-44</b> |
| 3.1                | Background                                                                                                                                       | 19           |
| 3.2                | Materials and Methodology                                                                                                                        | 20           |
| 3.2.1              | Engineering properties of cardamom                                                                                                               | 20           |
| 3.2.2              | Determination of storage and thermodynamic properties                                                                                            | 22           |
| 3.2.3              | Phytochemical analysis                                                                                                                           | 28           |
| 3.2.4              | Statistical analysis                                                                                                                             | 29           |
| 3.3                | Results and Discussion                                                                                                                           | 30           |
| 3.3.1              | Fruit dimensions                                                                                                                                 | 30           |
| 3.3.2              | Capsule mass                                                                                                                                     | 31           |
| 3.3.3              | Bulk density, true density                                                                                                                       | 31           |
| 3.3.4              | Porosity                                                                                                                                         | 32           |
| 3.3.5              | Angle of repose                                                                                                                                  | 32           |
| 3.3.6              | Terminal velocity                                                                                                                                | 33           |
| 3.3.7              | Phytochemical analysis                                                                                                                           | 33           |
| 3.3.8              | Temporal moisture sorption profile                                                                                                               | 33           |
| 3.3.9              | Moisture sorption isotherms                                                                                                                      | 34           |
| 3.3.10             | Temperature dependence of isotherms                                                                                                              | 34           |
| 3.3.11             | Fitting of empirical and neural network models to experimental data                                                                              | 37           |
| 3.3.12             | Thermodynamic properties                                                                                                                         | 38           |
| 3.3.13             | Glass transition and product stability                                                                                                           | 42           |
| 3.4                | Conclusion                                                                                                                                       | 43           |
| <b>Chapter IV</b>  | <b>Analysis of Moisture, Colour and Aroma Kinetics of Small Cardamom at Different Drying Conditions in A Hot Air Convective Dryer</b>            | <b>45-70</b> |
| 4.1                | Background                                                                                                                                       | 45           |
| 4.2                | Materials and Methods                                                                                                                            | 46           |
| 4.2.1              | Materials                                                                                                                                        | 46           |
| 4.2.2              | Hot air drying                                                                                                                                   | 46           |
| 4.2.3              | Drying characteristic and modelling                                                                                                              | 47           |

|                  |                                                                                                                            |              |
|------------------|----------------------------------------------------------------------------------------------------------------------------|--------------|
| 4.2.4            | Measurement of surface colour and kinetic modelling                                                                        | 49           |
| 4.2.5            | Aroma measurement                                                                                                          | 50           |
| 4.2.6            | Classification of components as per functional group                                                                       | 51           |
| 4.2.7            | Multivariate data analysis using Principal component analysis and hierarchical clustering analysis                         | 51           |
| 4.3              | Results and Discussion                                                                                                     | 51           |
| 4.3.1            | Drying characteristic curves                                                                                               | 51           |
| 4.3.2            | Effective Moisture diffusivity and activation energy                                                                       | 55           |
| 4.3.3            | Kinetics of surface colour                                                                                                 | 56           |
| 4.3.4            | Essential oil analysis                                                                                                     | 60           |
| 4.3.5            | Quantification of essential oil components                                                                                 | 61           |
| 4.3.6            | Classification of essential oil components                                                                                 | 64           |
| 4.3.7            | Multivariate analysis of chemometric data                                                                                  | 65           |
| 4.4              | Conclusion                                                                                                                 | 70           |
| <b>Chapter V</b> | <b>Develop a VFD Assisted Drying Protocol for the Optimum Retention of Their Colour and Aroma Attributes During Drying</b> | <b>71-98</b> |
| 5.1              | Background                                                                                                                 | 71           |
| 5.2              | Materials and Methods                                                                                                      | 72           |
| 5.2.1            | Material collection                                                                                                        | 72           |
| 5.2.2            | VFB assisted drying system for cardamom capsules                                                                           | 72           |
| 5.2.3            | Drying characteristic and modelling of small cardamom capsules in the VFB dryer                                            | 73           |
| 5.2.4            | Optimization of process variables of VFB dryer                                                                             | 77           |
| 5.2.5            | Quality analysis of dried cardamom                                                                                         | 78           |
| 5.2.6            | Phytochemical analysis                                                                                                     | 79           |
| 5.3              | Results and Discussion                                                                                                     | 79           |
| 5.3.1            | Drying kinetics                                                                                                            | 79           |
| 5.3.2            | Mathematical modelling of drying curves                                                                                    | 82           |
| 5.3.3            | ANN modelling                                                                                                              | 84           |
| 5.3.4            | Optimized results of developed VFB dryer                                                                                   | 84           |
| 5.3.5            | Moisture diffusivity                                                                                                       | 89           |
| 5.3.6            | Activation energy                                                                                                          | 89           |

|                    |                                                                                                                                 |         |
|--------------------|---------------------------------------------------------------------------------------------------------------------------------|---------|
| 5.3.7              | Effect of temperature, velocity and vibration on quality parameters of dried cardamom capsules                                  | 91      |
| 5.3.8              | Phytochemical analysis                                                                                                          | 92      |
| 5.4                | Conclusion                                                                                                                      | 98      |
| <b>Chapter VI</b>  | <b>Evaluation of Quality Attributes of Dried Cardamom and Analysis of Energy and Economics of The Vibro-Fluidized Bed Dryer</b> | 99-109  |
| 6.1                | Background                                                                                                                      | 99      |
| 6.2                | Material and Methods                                                                                                            | 99      |
| 6.2.1              | Surface roughness of the dried cardamom capsules                                                                                | 99      |
| 6.2.2              | Energy analysis of VFB dryer                                                                                                    | 100     |
| 6.2.3              | Cost analysis of the VFB dryer                                                                                                  | 101     |
| 6.3                | Results and Discussion                                                                                                          | 104     |
| 6.3.1              | Surface profile analysis of the dried cardamom in the VFB dryer                                                                 | 104     |
| 6.3.2              | Energy characteristics                                                                                                          | 104     |
| 6.3.3              | Drying efficiency                                                                                                               | 107     |
| 6.3.4              | Cost analysis                                                                                                                   | 108     |
| 6.4                | Conclusion                                                                                                                      | 109     |
| <b>Chapter VII</b> | <b>Summary and Conclusion</b>                                                                                                   | 110-115 |
|                    | <b>References</b>                                                                                                               | 116-126 |
|                    | <b>Appendix</b>                                                                                                                 | 127-164 |
|                    | <b>Biodata</b>                                                                                                                  | 165-166 |

# LIST OF FIGURES

| Figure | Description                                                                                                                       | Page No. |
|--------|-----------------------------------------------------------------------------------------------------------------------------------|----------|
| 2.1    | Image of a cardamom plant                                                                                                         | 7        |
| 2.2    | Image showing (a)fresh cardamom, (b) dried cardamom, and (c) cardamom seeds                                                       | 7        |
| 2.3    | Different operations involved in cardamom processing                                                                              | 8        |
| 2.4    | Pictorial view of a conventional dryer used for drying of cardamom capsules                                                       | 10       |
| 2.5    | Schematic diagram of conventional cardamom dryer                                                                                  | 11       |
| 3.1    | A schematic illustration of basic principles of DVS instrument.                                                                   | 23       |
| 3.2    | A schematic diagram of neural structure                                                                                           | 25       |
| 3.3    | Image showing the measurement of (a) length, (b)breadth and (c) thickness of fresh cardamom                                       | 30       |
| 3.4    | Variation of bulk density and true density with moisture content                                                                  | 32       |
| 3.5    | Temporal profile of adsorption and desorption profile of small cardamom at (a) 20, (b) 30 and (c) 40°C                            | 33       |
| 3.6    | Moisture sorption isotherms of small cardamom at (a) 20, (b) 30, and (c) 40°C                                                     | 35       |
| 3.7    | Effect of temperatures on (a) adsorption, and (b) desorption isotherms of small cardamom                                          | 36       |
| 3.8    | Experimental and predicted equilibrium moisture content (%) <i>db</i> ) for (a)adsorption and (b)desorption proposed by ANN Model | 39       |
| 3.9    | Effect of moisture content on the net isosteric heat of sorption and sorption entropy of small cardamom                           | 40       |
| 3.10   | Enthalpy entropy compensation for small cardamom capsules                                                                         | 41       |
| 3.11   | Variation of Gibb's free energy change with moisture content                                                                      | 42       |
| 3.12   | Glass transition and equilibrium moisture content of cardamom capsules with water activity                                        | 43       |



|      |                                                                                                                                                                         |    |
|------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------|----|
| 4.1  | Drying characteristics of small cardamom: (a) moisture content vs drying time, (b) drying rate vs drying time, and (c) moisture ratio vs drying time                    | 53 |
| 4.2  | Drying curve as predicted by the Logistic model at 40, 50, and 60 °C for small cardamom capsules                                                                        | 55 |
| 4.3  | Effect of drying air on effective moisture diffusivity                                                                                                                  | 56 |
| 4.4  | Fresh and dried small cardamom samples                                                                                                                                  | 57 |
| 4.5  | Change of surface colour values (a) <i>L</i> , (b) <i>a</i> , and (c) <i>b</i> of small cardamom                                                                        | 58 |
| 4.6  | Yield of essential oil of small cardamom with drying time at 40, 50, and 60 °C                                                                                          | 60 |
| 4.7  | Gas chromatogram of essential oil obtained from small cardamom drying at (a) 40°C, (b) 50°C, and (c) 60°C                                                               | 63 |
| 4.8  | Radar chart of chemical compounds of essential oil obtained from small cardamom drying at (a) 40 °C, (b) 50 °C, and (c) 60 °C at different drying intervals             | 66 |
| 4.9  | PCA loading plot of essential oil constituents obtained from small cardamom drying at (a) 40 °C, (b) 50 °C, and (c) 60 °C                                               | 68 |
| 4.10 | PCA biplot of small cardamom essential oil compounds with different drying times                                                                                        | 68 |
| 4.11 | HCA-heatmap dendrogram for essential oil compounds obtained from small cardamom drying at different drying times and temperatures of (a) 40 °C, (b) 50 °C and (c) 60 °C | 69 |
| 5.1  | Fresh cardamom capsules of Njallani green gold                                                                                                                          | 72 |
| 5.2  | Experimental setup used for drying cardamom                                                                                                                             | 74 |
| 5.3  | A Schematic illustration of the setup used for cardamom drying                                                                                                          | 75 |
| 5.4  | A CAD model with dimensions of the VFB dryer                                                                                                                            | 76 |
| 5.5  | Drying rate curve of small cardamom VFB dryer at 40°C, (b) 50°C and (c) 60°C                                                                                            | 81 |
| 5.6  | Fitting of the Logistic model during drying of small cardamom capsules in VFB dryer (NB: marker indicates experimental value and line indicates fitted values of MR)    | 83 |

|      |                                                                                                                                                |     |
|------|------------------------------------------------------------------------------------------------------------------------------------------------|-----|
| 5.7  | Post training (a) performance and (b) error histogram                                                                                          | 88  |
| 5.8  | Post training regression analysis of developed ANN model                                                                                       | 89  |
| 5.9  | Moisture diffusivity vs temperature during VFB drying of small cardamom                                                                        | 90  |
| 5.10 | Images of the (a) fresh and (b) dried small cardamom capsules                                                                                  | 91  |
| 5.11 | 3D surface plots showing the effect of process variables on drying time at (a) without vibration (b) 1 mm vibration and (c) 2 mm vibration     | 93  |
| 5.12 | 3D surface plots showing effect of process variables on colour at (a) without vibration (b) 1 mm vibration and (c) 2 mm vibration              | 94  |
| 5.13 | 3D surface plots showing effect of process variables on essential oil yield at (a) without vibration (b) 1 mm vibration and (c) 2 mm vibration | 95  |
| 5.14 | 3D surface plots showing effect of process variables on 1,8-cineol at (a) without vibration (b) 1 mm vibration and (c) 2 mm vibration          | 96  |
| 5.15 | 3D surface plots showing effect of process variables on Terpinyl acetate at (a) without vibration (b) 1 mm vibration, and (c) 2 mm vibration   | 97  |
| 6.1  | 3D surface profiles of (a) fresh, (b) vibro-fluidized bed (VFB) and (c) hot air convective (HAC) dried cardamom samples.                       | 105 |
| 6.2  | Total energy consumption in the VFB assisted drying of small cardamom capsules dried at vibration amplitude of (a) 0mm, (b)1mm and (c) 2mm     | 106 |
| 6.3  | Specific energy consumption in the VFB assisted drying of small cardamom capsules                                                              | 107 |

# LIST OF TABLES

| Table | Description                                                                                          | Page No. |
|-------|------------------------------------------------------------------------------------------------------|----------|
| 3.1   | Models fitted to sorption isotherm data of small cardamom                                            | 24       |
| 3.2   | Physical properties of Cardamom capsule at different moisture content                                | 30       |
| 3.3   | Estimated coefficients and accuracy of fit of sorption isotherm models                               | 38       |
| 3.4   | Nonlinear regression parameters of KMR model for small cardamom                                      | 43       |
| 4.1   | Thin layer-drying models                                                                             | 47       |
| 4.2   | Drying model constants and statistical analysis                                                      | 54       |
| 4.3   | Fitting of the models to the colour values at different drying temperatures                          | 59       |
| 4.4   | Relative content (%) of some major components of essential oil derived from fresh and dried cardamom | 61       |
| 4.5   | Drying time intervals                                                                                | 61       |
| 5.1   | Predictive models for moisture ratio (MR)                                                            | 73       |
| 5.2   | Statistical results of drying model parameters of small cardamom                                     | 85       |
| 6.1   | Cost analysis of the VFB dryer for drying of small cardamom capsules                                 | 108      |

---

## LIST OF ABBREVIATIONS

---

|             |                                              |
|-------------|----------------------------------------------|
| ANN         | Artificial Neural Network                    |
| AOAC        | Association of Official Analytical Chemists  |
| ASAE        | American Society of Agricultural Engineers   |
| BET         | Brunauer-Emmett-Teller                       |
| BIS         | Bureau of Indian Standard                    |
| CMC         | Critical moisture content                    |
| $D_{eff}$   | Effective moisture diffusivity               |
| DSC         | Differential scanning calorimeter            |
| EMC         | Equilibrium Moisture Content                 |
| Eq.         | Equation                                     |
| $E_{total}$ | Total Energy Consumption                     |
| FB          | Fluidized Bed                                |
| FSSAI       | Food Safety and Standards Authority of India |
| GAB         | Guggenheim-Anderson-de Boer                  |
| GAE         | Gallic acid equivalents                      |
| GCMS        | Gas Chromatography Mass Spectroscopy         |
| g dw        | Gram dry weight                              |
| HAC         | Hot air Convective                           |
| HCA         | Hierarchical Cluster Analysis                |
| Ltd.        | Limited                                      |
| MC          | Moisture content                             |
| MR          | Moisture ratio                               |
| MSE         | Mean Square of Error                         |
| MSL         | Mean Sea Level                               |
| MSIs        | Moisture Sorption Isotherms                  |
| MT          | Million Ton                                  |
| MLFFN       | Multi-layer feed-forward network             |
| $p$         | probability                                  |
| PCA         | Principle Component Analysis                 |
| $Q_{st}$    | Isosteric heat of sorption                   |
| R           | Universal gas constant                       |
| $R^2$       | Co-efficient of determination                |

---

---

|                |                              |
|----------------|------------------------------|
| RMSE           | Root mean square error       |
| SEC            | Specific energy consumption  |
| T <sub>g</sub> | Glass transition temperature |
| TFC            | Total flavonoid content      |
| TPC            | Total phenolic content       |
| VFB            | Vibro-fluidized Bed          |
| w/v            | Weight by volume             |
| $\chi^2$       | chi-square                   |
| $\Delta S$     | Sorption entropy             |

---