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INVESTIGATION OF MICROWAVE ASSISTED HOT AIR DRYING BEHAVIOUR OF CTC TEA (*CAMELLIA ASSAMICA*)

A THESIS SUBMITTED IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF DOCTOR OF PHILOSOPHY

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Registration Number 005 of 2013

SCHOOL OF ENGINEERING

DEPARTMENT OF ENERGY

TEZPUR UNIVERSITY

MAY, 2013

I dedicate this thesis to

my wife (Deepa)

and

daughters (Ankita and Arpita)

whose love inspired me

to complete this work successfully.

Diganta Hatibaruah

DECLARATION

I do hereby declare that the thesis entitled "**Investigation of Microwave Assisted Hot Air Drying Behaviour of CTC Tea (*Camellia assamica*)**", being submitted to the Department of Energy, Tezpur University, is a record of original research work carried out by me. All sources of assistance have been assigned due acknowledgment. I also declare that neither this work as a whole nor a part of it has been submitted to any other University or Institute for any other degree, diploma or award.

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This is to certify that the matter embodied in the thesis entitled "**Investigation of Microwave Assisted Hot Air Drying Behaviour of CTC Tea (*Camellia assamica*)**", submitted by Diganta Hatibaruah for the award of degree of Doctor of Philosophy of Tezpur University is a record of bona-fide research work carried out by him under my supervision and guidance. The results embodied in this thesis have not been submitted to any other University or Institute for the award of any degree or diploma.

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The committee recommends for the award of the degree of Doctor of Philosophy.

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Diganta Hatibaruah

ABSTRACT

Tea industry is one of the traditional plantation based industries in India and holds a prime position in production, consumption and export. It employs more than 1 6 million people in India and contributes to the welfare and development of the region besides contribution to the national economy. Thus, growth and development of the tea industry require appropriate attention Technical innovation and supply of sustainable energy to ensure economical and quality tea production is considered crucial aspects for sustainable growth of the tea industry. Understanding of the behaviour of the tea sample is pre-requisite for application of such innovation. Therefore, focus of the present study is to examine some basic properties of tea and also to investigate the prospect of a new tea drying technique ensuring quality production at optimum energy use.

Processed tea also called made tea is classified as white tea, green tea, oolong tea and black tea based on the processing technique. CTC tea is a typical black tea which is prepared through some specific processing steps *viz.*, (i) withering (ii) CTC (iii) fermentation and (iv) drying.

The present research work is carried out with dry ready CTC tea samples of T3E3 cultivar obtained from a reputed tea research organization (Tea Research Association, Tocklai Experimental Station, Assam India) for (i) identifying best fit desorption isotherm model, (ii) investigation of drying kinetics using (a) hot air with varying temperature and (b) microwave radiation with varying microwave power level, (iii) optimizing the variable process parameter for best quality at least specific energy consumption for combine mode (microwave-hot air) of CTC tea drying. Standard experimental procedure and analysis are followed for all of the above as discussed in brief below.

Drying some food products like tea, which require careful hygienic attention, availability of water for growth of microorganisms, germination of spores, and participation in several types of chemical reaction becomes a critical issue. This water availability depends on water activity (a_w), which is the equilibrium relative humidity of the food material. Water activity (a_w) is one of the most critical factors that affect the shelf life, safety, texture, flavor, and smell of foods. Water activity of a food product can be determined from the sorption isotherms of the food product. The sorption isotherm is a graphical relationship between the equilibrium moisture content of a material and its equilibrium relative humidity at a specific temperature. Sorption isotherm of food product is useful for designing of the dryer and specifies optimum drying, storage and packaging conditions to assure long-term stability of dehydrated foods. Sorption isotherms are determined by the standard static gravimetric technique, which is based on the use of saturated salt solutions to maintain constant relative humidity. Nine salts (*viz.*, KOH, $MgCl_2$, K_2CO_3, $NaNO_3$, KCl, $BaCl_2$, LiBr, LiCl and KI) have been used to achieve varying degree of ambient relative humidity (RH) around identical CTC tea samples kept in the temperature-controlled cabinet. Reduction of moisture contents corresponding to 30, 40, 50, 80 and 90 ^{0}C ambient temperature for each of the above nine ambient RH conditions is recorded for investigating temperature dependent desorption behavior of CTC tea sample. Six available models, *viz.*, BET, GAB, Halsey, Pleg, Oswin and Henderson have been used for fitting the experimental data. However, Oswin model has been found as the best-fit for predicting the desorption data of the CTC tea. The monolayer moisture content of CTC tea has been found as 0.0477, 0.0457, 0.0420, 0.0321 and 0.0311 kg kg^{-1} (d.b.) at 30, 40, 50, 80 and 90 ^{0}C, respectively. Correlation between net isosteric heat of desorption and equilibrium moisture content has also been derived from experimental data. Further, theoretical energy required for drying is assessed from net isosteric heat of desorption data.

Drying is a critical step amongst these CTC tea manufacturing processes - considering its impact on quality and energy requirement. In drying, moisture of the fermented tea-leaf particles is reduced from about 2.33 to 0.03 kg kg^{-1} (d.b.). Hot air drying has been the most common method in tea drying, requiring maximum share from thermal source of energy. Longer time required, particularly during the falling rate period of drying, has been the characteristic feature of traditional hot air tea drying. Attempt to shorten drying time, aiming to improve energy efficacy and quality of processed tea, is desirable for the tea industry. Ideally, such attempt requires comprehensive investigation of drying phenomena, taking into account of the physical and chemical changes of tea samples during drying and their relationships with energy consumption and quality. However, in the present investigation, reduction of moisture content with time and associated energy consumption could be assessed with experimental set-up.

The laboratory scale experimental set-up simulates thin layer hot air drying of tea. The set-up consisted of an electrical heater, a blower, a flow controller, a humidity controller and weighing device. Hot air streams with three levels of temperature (80, 90 and 95 ^{0}C) and 70% RH can be generated for drying CTC tea samples maintaining constant air flow rate (2.33×10^{-3} kg s^{-1}). Repeated experiments are conducted with identical tea samples (ready-to-dry) at varying temperature. The generated data are used to fit in six popular thin layer drying models, *viz.*, Henderson and Pabis model, Lewis model, Page model, Logarithmic model, Two term model and Midilli et al. model. Drying curves and subsequently best-fit drying model for CTC tea is identified. Out of six available drying models, the Midilli et al. model has been found the best fitted for thin layer drying of CTC tea samples. The higher temperature of hot air stream resulted relatively quicker drying and consumed lesser specific energy.

Microwave drying has been reported as rapid and energy efficient drying technique compared to conventional hot air drying of food materials, such as apple, carrot, banana, garlic, potato *etc.* resulting more uniform end product quality. Microwave drying is suggested for the "falling rate period" to take care of the overall economy of the process. Prospect of application of microwave drying technique for CTC tea has been the central focus of the present investigation. A domestic microwave oven is used as a drying chamber for investigating microwave drying behaviour of CTC tea. Ready-to-dry CTC tea samples are kept in the tray of the microwave oven. Losses of moisture with time are recorded while exposing samples to microwave in the chamber. The experiments are repeated varying microwave power level (175, 350, 525, 700 and 875 W). Observed data are also fitted in the available drying models. Among all drying models used in this study, the Page model is found the best fitted model to represent microwave drying of CTC tea. Higher the microwave power resulted quicker drying while reducing the moisture reduction from 2.33 to 0.03 kg kg^{-1} (d.b.). Further, irrespective of the microwave power level, "constant drying rate period" is observed during 2.33 to 0.26 kg kg^{-1} (d.b.) moisture reductions accounting about 88% of the total moisture removal.

Drying kinetics in microwave drying is different from hot air drying of CTC tea. A combination drying (hot air and microwave) is decided on the basis of the observation on two individual mode of drying. Microwave mode of drying is used for reduction of moisture beyond 0.2 kg kg^{-1} (d.b.). Partially dried samples at 0.2 kg kg^{-1} (d.b.) from the hot air drying set up are transferred to the microwave oven for the final phase of drying. The experiments are conducted using varying hot air temperature (first phase) and microwave power level (final phase). The observations pertaining total drying time and energy consumption are recorded for combined drying.

The made tea samples are further tested for quality as per the prevailing industrial procedure in a reputed tea research laboratory. The procedure consists of providing score values for each sample of made tea corresponding to all treatments. Ten point scoring scale for five quality parameters (*viz.*, colour, strength, brightness, briskness and thickness) of the CTC samples corresponding to the treatment under consideration is used by professional tea tasters.

The specific energy consumption (MJ kg^{-1}) corresponding to all experimental treatments are also assessed from related observed data on energy consumption. An optimization procedure is used to identify the optimum process variable (hot air temperature and microwave power level) for best quality and least specific energy consumption in case of combine mode of drying. In general, increased in microwave power and hot air temperature reduces specific energy consumption. However, while higher drying temperature favourably influenced quality, higher microwave power have a negative effect on tea quality. The optimisation exercise predicts a temperature of 95 ^{0}C (first phase hot air drying) and 225 W microwave power (final phase) for the best quality with minimum specific energy consumption of 3.23 MJ kg^{-1}.

Finally, the observation on specific energy consumption recorded from three local tea factories are compared with the results of the present investigation. The comparative assessment indicates the prospect of reducing energy consumption using microwave assisted hot air drying.

The outcomes of the present investigation are expected to be useful for development of new drying process vis-à-vis techniques for preparation of made tea.

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LIST OF ABBREVIATIONS AND SYMBOLS

List of abbreviations

Abbreviations	Description
ANOVA	Analysis of variance
BET	Brunauer-Emmett-Teller
CHD	Conventional hot air drying
CTC	Crush-tear-curl
DF	Degree of freedom
DOE	Design of experiment
ERH	Equilibrium relative humidity
FBD	Fluidised bed dryer
GAB	Guggenheim-Anderson-de Boer
IMPI	International Microwave Power Institute
MAHD	Microwave-assisted hot air drying
PCD	Pressure chamber dryer
RH	Relative humidity
SEC	Specific energy consumption
SSE	Sum of square error
VFBD	Vibro fluidised bed dryer

List of symbols

Symbols	Description
^0C	degree centigrade
a and b	model coefficients (dimensionless)
A, B, C and K	model coefficients

a_w	water activity, (dimensionless)
$BaCl_2$	barium chloride
cm	centimeter
d.b.	dry basis, kg kg^{-1}
D_{eff}	effective moisture diffusivity, $m^2 s^{-1}$
D_0	Arrhenius factor ($m^2 s^{-1}$)
E_a	activation energy for diffusion, kJ mol^{-1}
g	gram
kg	kilogram
kJ	kilo Joule
k and k_1	drying coefficients, $minute^{-1}$
kW	kilo Watt
kWh	kilo Watt hour
KCl	potassium chloride
K_2CO_3	potassium carbonate
KI	potassium iodide
KOH	potassium hydroxide
l	half thickness of the thin layer bed, m
ln	natural logarithm
LiBr	lithium bromide
LiCl	lithium chloride
m	meter
mm	millimeter
M	material moisture content, kg kg^{-1} (d.b.)
M_e	equilibrium moisture content, kg kg^{-1}(d.b.)
$MgCl_2$	magnesium chloride
MHz	mega Hertz
MJ	mega Joule
M_m	monolayer moisture content, kg kg^{-1}(d.b.)
MR	moisture ratio, dimensionless
MWh	mega Watt hour
n	exponent (dimensionless)

$NaNO_3$	sodium nitrate
Q	quality
R	universal gas constant, kJ mol^{-1} K^{-1}
R_s	specific gas constant of water, kJ kg^{-1} K^{-1}
R^2	coefficient of determination
s	second
t	time, s
t_1	time, minute
T	temperature, ^0C
T_k	temperature, Kelvin.
W	Watt
w.b.	wet basis, kg kg^{-1}
Δh_d	net isosteric heat of sorption, kJ kg^{-1}

CHAPTER 1

INTRODUCTION

Chapter 1

Introduction

Keeping appropriate balance between economic growth and sustainable development seems to be one of the crucial challenges of the present time. Accordingly, research and development (R&D) focuses need to be prioritized. It is needless to mention about the impact of industrial growth on development. Traditionally, mere economy is seen as a yardstick of development. Now, sustainability has also been identified equally essential factor to judge the efficacy of industrial development. Amongst the industries, food and beverage industry is one of the leading industrial sector contributing to the economy and hence development. Quality and cost are the utmost concern for such industry. The energy requirement for processing contributes to the cost of production. Keeping this in mind, any effort to minimize energy consumption and quality enhancement, either through an innovative process or through new technology, would be considered welcome. However, targeted research would require materializing such innovation, particularly while handling biological materials as inputs for processing.

Tea industry is one of the traditional plantation based beverage industries and India holds a prime position in production, consumption and export of tea. In India, it employs more than 1.6 million people. This industry contributes to the national economy by paying central and state taxes, excise duty *etc.*, apart from earning colossal foreign exchange through export. Tea production consumes a considerable amount of chemical inputs (fertilizers, pesticides *etc.*) and hence, influencing growth of such chemical sectors. Moreover, it is also creating employment in goods transport sector for haulage of the processed products. Thus, uninterrupted growth of the tea industry is desirable for economic development of the region.

Traditionally, India has been the largest tea consumer and largest tea producers in the world. For over a century, Indian tea has commanded a towering position in the world tea economy. India produced about 986.43 million kg tea in 2007. However, a decreasing trend of production with about 966.40 million kg in 2010 has been observed [1], which requires appropriate attention. There are only few pockets, including the state of Assam (located in north-eastern part of the country) in India where tea is grown. Assam contributes about 45% of total Indian tea production. The total area under tea cultivation in Assam is accounting for more than half of the country's total area under tea. There are 830 registered tea gardens run by both Indian and multinational companies in Assam. Assam tea has characteristic feature and has a good reputation in domestic and international market. However, there have been some challenges experienced by Assam tea industry pertaining to cost and quality in recent times. Keeping this in mind a research programme is undertaken for appropriate research intervention in processing of a locally grown tea variety. Overall goal of the present work is to attempt reduction of energy consumption of tea processing by keeping quality intact.

The research is performed through a systematic procedure with an attempt to understand comprehensively the existing pool of knowledge, which is introduced in this Chapter through discussion on the following aspects.

- Tea as a plantation crop and different products of tea
- Processing of tea
- Theory of drying of food product and importance of material characterisation
- Recent innovation in drying of food material
- Drying technology and existing tea dryer

1.1 Tea: a plantation crop of economic importance

The place of origin of tea is still a matter of speculation. Knowledge of tea in the distant past is derived from China. The information available from the Chinese sources does not through much light on it's place of origin. Discovery of a wild prototype of the plant cultivated in China would have assisted the search for it's original home, but no wild tea plant appears to have been discovered in China. Since the early part of the Nineteenth century, discovery of 'wild' plants of tea has been reported from India (Assam, Manipur, Mizoram), Thailand, Burma, South Vietnam and Laos. It is, however, not certain whether the plants were wild or relics of plantations abandoned by the migratory tribes of these regions [2]. As per report, in 1823, Robert Bruce (a British Army Major) had discovered tea tracts in Assam.

The inhabitants of northern Burma use tea as a vegetable (*Letpet* Tea) for chewing as well as for making a drink out of it. In the Indo-China peninsula, tea is a prominent village industry for many centuries long before the discovery of the Assam plant. Hence it is doubtful whether the plant discovered in this region was truly wild. These discoveries indicate three races of tea, *i.e.* China race has one origin and the Assam and Cambodia races together, another common origin. Thus, there are three basic races of tea *viz.*, (i) *Camellia sinensis* for China race, (ii) *Camellia assamica* for Assam race and (iii) *Camellia assamica lasiocalyx* for Cambod race cultivated all over the world [3]. With the advent of plant breeding technology, there has been some purposeful development of new tea cultivars all over the tea growing regions. In Assam also there are many tea cultivars and T3E3 is one of the popular cultivars with distinguished biological characteristics.

The tea leaf and bud plucked from tea plants undergo distinct processing steps in the factory to convert it to the final product *i.e.* made tea. On the basis of processing techniques adopted in the manufacturing process, tea is further classified as white tea, green tea, oolong tea and black tea [4]. A brief discussion of these tea types is given below.

Classification of processed Tea

White tea is harvested from the youngest hand-picked leaf tips and buds of the Chinese *Camellia sinensis* plant. These give a snowy/silver coloured brew from which white tea gets its name. The processing steps involve steaming and drying. It is claimed that due to less processing steps, white tea contains more nutrients than other tea [4].

Green tea processing steps involve withering, pan frying, rolling and drying. It is made from tea leaves without fermentation (to be discussed in the next Section). So, green tea contains the highest concentration of antioxidants than black or oolong tea. It is claimed that, the antioxidants present in green tea are useful for health including cancer prevention, cholesterol reduction *etc*.

Oolong tea processing steps involve withering, rolling, fermentation, pan frying and drying. The fermentation time in oolong tea manufacturing is shorter than black tea. Due to semi-fermentation, oolong tea contains caffeine, which is reported to increase body metabolism.

Black tea manufacturing process involves withering, maceration, fermentation and drying. The complete fermentation causes the leaves to turn black and give them their characteristic flavor. Black tea is further classified as CTC (crush-tear-curl) tea and Orthodox tea. The difference between CTC and Orthodox manufacturing lies in maceration process (to be discussed in the next Section). CTC tea is macerated in CTC machine, whereas Orthodox tea is macerated in rolling table.

Black tea dominates the Indian tea industry [1]. Again share of CTC tea is more than the orthodox types of black tea in this region. A brief description of prevailing CTC tea manufacturing process is presented below.

1.2 Processing of CTC tea

Freshly harvested tea leaves and buds contain about 75% to 83% (w.b.) moisture and number of bio-chemicals. The desirable chemical reactions are induced, and moisture content is reduced to 3% (w.b.) through a series of processes to facilitate incorporation of required liquor quality characteristics and safe storage of the final product which is called made tea [5]. The tea manufacturing processes involve withering, maceration, fermentation and drying, which are discussed below.

Withering

In withering process of CTC tea manufacturing, moisture content of tea leaves is reduced to 70% (w.b.). During withering, leaf conditions become limp and flaccid which are essential for the subsequent step of processing. Withering is done by spreading the tea leaves on trays, racks or shelves. Withering is either conducted in open sheds by utilizing the effect of natural air currents or, in withering trough with controlled heating and ventilating equipment. Thermal energy for generation of hot air and electrical energy for operation of blower are required for withering process.

Maceration

In maceration process, the withered tea leaf cells are ruptured to facilitate chemical reaction. As discussed earlier, maceration is carried out by two methods, *viz.*, (i) Orthodox, and (ii) CTC. In CTC method, maceration is carried out in CTC machine. The withered tea leaves are crushed, tear and curled by the teeth on the two rollers of the CTC machine. Electricity is required for operation of CTC machine.

Fermentation

Fermentation of tea is the most significant step of tea processing since the liquoring characters of tea are developed during this process [6]. This process involves enzymic oxidation/degradation of polyphenols, lipids, carotenoids and terpene-glycosides and their subsequent condensation/degradation leading to the formation of coloured polymers and aroma and flavor compounds [7]. Fermentation is carried out in custom-designed fermentation rooms or fermentation racks. Tea colour becomes coppery after completion of fermentation. Fermentation time is varied from 45 to 180 minutes depending on the temperature, maceration technique and the style of tea desired [8].

Drying

Drying is the process of removal of moisture by evaporation from fermented leaf. During this process, fermented leaf turns black or blackish brownish from coppery red and loses its moisture to about 3% (w.b.) in the final product [9]. Drying process stops all the chemical reaction that starts during the fermentation process. Also, removal of moisture from the leaf particle produces a stable product with superior keeping quality.

All the processing steps become crucial to maintain quality output at minimum processing cost. However, drying, which is a thermal energy dominant processing step, is particularly crucial for quality and energy perspective. Therefore, a detailed discussion on the theory of drying with specific reference to hygroscopic materials is presented below.

1.3 Theory of drying

Drying food products like tea, require careful attention, as water could stimulate growth of microorganisms, germination of spores, and participation in several types of chemical reactions. Available water depends on relative pressure or water activity (a_w), which is defined as the ratio of the partial pressure of water over the wet food surface, to the equilibrium vapor pressure of water at the same temperature [10]. The water activity can be thought of as the equilibrium relative humidity of the food product. When a food product comes into equilibrium with the ambient atmosphere, the water activity in the food product becomes equal to the relative humidity of the ambient atmosphere. Once this equilibrium is reached, the food product neither gains nor loses moisture over time. Water activity (a_w) is one of the most critical factors that affect the shelf life, texture, flavor, and smell of food products [10]. Water activity of a food product can be determined from the sorption isotherms of the food product, which is briefly discussed below.

Sorption isotherms

The moisture in a food product exerts a vapour pressure. A food product lose (desorb) or gain (adsorb) moisture until the vapour pressure of the moisture in the product equals the vapour pressure of the surroundings. The moisture content of the product at this point is known as the equilibrium moisture content. A graphical relationship between the equilibrium moisture content of a material and its equilibrium relative humidity (ERH) at a specific temperature is termed as the equilibrium moisture curve [11] or sorption isotherm [12]. Each material has a unique shape of sorption isotherm at a specific temperature. The physical structure, chemical composition and extent of water binding within the material governs the shape of the isotherms.

Knowledge of desorption isotherms of food product, corresponding to probable condition (temperature and relative humidity) inside dryer, is highly essential either to analysis the performance of an existing dryer or to propose a new dryer. The equilibrium moisture content of the product is the lowest moisture content that can be achieved under a given set of drying conditions [13, 14]. The difference between the total moisture and the equilibrium moisture content represents the amount that can be removed by drying and is called the free moisture content. This may include both bound and unbound moisture. Desorption isotherms can also distinguish between the bound and unbound moisture of foods. Bound moisture is defined as that moisture which exerts a lower vapour pressure than that of pure water at the same temperature. While unbound moisture has a vapour pressure equal to that of water [14, 15].

Sorption isotherm of food product at a specific temperature can be predicted with the help of sorption isotherm models. These models of food products are of particular interest in the prediction of drying times and the shelf life of packaged dried products [16, 17]. Chirife and Iglesias [18] have reviewed twenty three models for fitting sorption isotherms of different foods. Six available isotherm models, *viz.*, (i) Brunauer-Emmett-Teller, (ii) Guggenheim-Anderson-de Boer, (iii) Peleg,

(iv) Halsey, (v) Oswin and (vi) Henderson, which are applicable for hygroscopic food materials are used for present investigation, and, therefore, presented in Table 1.1 and discussed below. Some more isotherm models are discussed in Appendix A11.

Table 1.1 Some isotherm models used for predicting sorption isotherm of food product

Name of Model	Model	Model Parameters	References
Brunauer-Emmett-Teller (BET)	$M_e = \frac{a_w M_m C}{(1-a_w)(1+Ca_w - a_w)}$	M_m, C	[19]
Guggenheim-Anderson-de Boer, (GAB)	$M_e = \frac{a_w M_m CK}{(1-Ka_w)(1+CKa_w - Ka_w)}$	M_m, C, K	[19]
Peleg	$M_e = A - B\ln(1-a_w)$	A, B	[20]
Halsey	$M_e = \left(\frac{A}{\ln(a_w)}\right)^{\frac{1}{B}}$	A, B	[21]
Oswin	$M_e = A\left(\frac{a_w}{1-a_w}\right)^{B}$	A, B	[22]
Henderson	$M_e = \left(-\frac{\ln(1-a_w)}{A}\right)^{\frac{1}{B}}$	A, B	[11]

where,

M_e = equilibrium moisture content, kg kg^{-1}(d.b.)

a_w = water activity, (dimensionless)

M_m = monolayer moisture content, kg kg^{-1}(d.b.)

A, B, C and K = model coefficients

The BET isotherm model is one of the most widely used model and gives a reasonable fit for a variety of food product over the wide range of water activities (0.05 to 0.45) [19]. It is a two parameter model that provides an estimation of monolayer moisture content of the product. Monolayer moisture is the portion of water strongly bound in food. It predicts the lower limit of moisture in food for the most dehydration process. The theory behind the development of the BET model has been questioned due to the assumptions that (a) the rate of condensation on the first layer is equal to the rate of evaporation from the second layer; (b) the binding energy of all of the adsorbates on the first layer is same; and (c) the binding energy of the other layers is equal to the one of pure adsorbates. The assumptions of a uniform adsorbent surface and the absence of lateral interactions between adsorbed molecules are incorrect, considering the heterogeneous food surface interactions. Nevertheless, the theoretical basis that provided this isotherm stimulated the investigation for developing alternatives that broaden the scope of the BET model, or for reformulating the model to find new physical approaches. An extension of the BET model is the GAB model. This model takes into account the modified properties of the adsorbate in the multi-layer region and bulk liquid (free water) properties through the introduction of one additional parameter [19]. The GAB model can apply to a wide range of water activities from 0.1 to 0.9 and to various materials including inorganic materials and foods. It has been recommended as the fundamental equation for the characterization of water sorption by food product [23]. The GAB model underestimates the water content values at high water activities ($a_w > 0.93$). The discrepancy underlines two facts: (a) this type of model is unsuitable for high humidity range, and (b) the saturated salt solution method does not afford sufficient information to get a complete sorption curve. Two-parameter Peleg model [20] can describe the sorption curves with two constants. Semi empirical Halsey model [21] can be used to describe sorption isotherms of different food products with water activity ranging from 0.10 to 0.80. The Oswin model [22] is a mathematical series expansion for a sigmoid-shaped curve. Henderson model [11] can also apply to food product, but the applicability of this model is stated as limited compared to Halsey model [24].

The sorption isotherm models discussed above can be used for determining some of thermodynamic properties (*viz.*, monolayer moisture content and net isosteric heat of sorption) of food product. As reported earlier, monolayer moisture is the portion of water strongly bound in food product. It represents the minimum moisture to prevent auto-oxidation and to enhance product stability during storage [25]. A food product is most stable at its monolayer moisture content. Monolayer moisture content varies with chemical composition and structure of food particles.

Energy required to remove water from the food product is the sum of energy required to remove free water through evaporation and energy required to remove water bound with the food product [26]. The energy required to remove water bound with the food product is called the net isosteric heat of sorption. The equilibrium moisture content of food product derived from desorption isotherms is used in standard mathematical expression (Clausius-Clapeyron equation) for finding the net isosteric heat of desorption [27]. So, theoretical energy required to remove water from a food material is the summation of net isosteric heat of desorption and latent heat of evaporation [28]. Thus, performance of a drying technology or dryer can be analysed with the knowledge of theoretical energy requirement for drying a given material. In the absence of specific information of these parameters (equilibrium moisture content, monolayer moisture content, isosteric heat of desorption) in most of the cases, the process engineers either assume or make arbitrary design of the drying process.

Apart from the knowledge of desorption isotherms; the moisture transfer mechanism within the food product, which is characteristics of the material, also a vital area of concern for the present study and therefore discussed below.

Moisture transfer mechanism in food product during drying

Existing theory stated that, moisture is transferred from food to the drying medium through two distinct phases *viz.*, (i) constant rate period and (ii) falling rate period [26]. In constant rate period, moisture is removed from the food surface. The surface of the food is saturated by the internal moisture transfer. Therefore, the rate of evaporation remains constant during this period. Drying in the constant rate period is governed by the external conditions *viz.*, (i) temperature difference between the drying medium (dry air) and wet food surface and (ii) amount of contact area of food with drying medium (dry air) [29, 30]. In falling rate period, the rate of moisture movement from the interior towards the surface is less than the rate of evaporation from the surface. Therefore, the surface of the material is not saturated. Thus drying in the falling rate period is an internally controlled mechanism [30]. Depending on drying rate, falling rate period is further divided into two parts *viz.*, (i) first falling rate period and (ii) second falling rate period.

The first falling rate period starts as soon as the critical moisture content (moisture content at which the drying rate first begins to drop) is reached within the product, and the surface film of moisture on the product is reduced. Further drying causes dry spots to appear on the surface. This is the period of unsaturated surface drying. This stage proceeds until the surface film of the liquid is entirely evaporated [30]. The second falling rate period appears on further drying. The rate of drying falls rapidly during this period. The rate is mainly limited by diffusion of moisture from within the product to the surface. It is controlled by the mass diffusion [30]. The drying rate in this period is extremely slow. Therefore, the time required to remove the last part (below 10%) of food moisture is almost equivalent to the time required to remove the first 90% of moisture. Some biological and most food materials experience this second falling rate drying period [30, 31, 32].

It is almost conclusively evident that, most of the moisture from food materials removes in falling rate period [33] and the moisture transfer during drying is controlled by internal diffusion [34]. Fick's second law [35] of diffusion, as shown in Eq. 1.1 has been widely used to describe the drying process during falling rate period for most biological material [34, 36, 37]

$$\frac{\partial M}{\partial t} = D_{eff} \nabla^2 M \qquad \dots\dots\dots(1.1)$$

where, D_{eff} is the effective moisture diffusivity, $m^2\ s^{-1}$, which represents the conductive term of all moisture transfer mechanism; M is the material moisture content at a specific time, kg kg^{-1} (d.b.) and t is the drying time, s.

The effective moisture diffusivity can be estimated from the knowledge of moisture ratio (ratio of moisture content of the grain at any level and at any time, (d.b.) to initial moisture content of the wet grain (d.b.) at any specific time (Appendix A8). The effective moisture diffusivity is determined from the slope of the plot of experimental drying data expressed in terms of the natural logarithm of moisture ratio, ln (MR) against drying time [38, 39, 40, 41]. The estimated slope is equated with the D_{eff} as given below.

$$\text{Slope} = \frac{D_{eff}\pi^2}{4l^2} \qquad \text{... ... .. (1.2)}$$

where,

l = half thickness of the thin layer bed, m.

Further, effective moisture diffusivity is dependent on temperature and can be described by Arrhenius relationship as given below [34, 42].

$$D_{eff} = D_0 \times e^{-\frac{E_a}{RT_k}} \qquad \text{... ... ... (1.3)}$$

where,

D_0 = Arrhenius factor, $m^2\ s^{-1}$

E_a = activation energy for diffusion, kJ mol^{-1}

R = universal gas constant, kJ mol^{-1} $Kelvin^{-1}$

T_k = temperature, Kelvin.

Thus, activation energy can be determined from the Eq. 1.3 by plotting $\ln(D_{eff})$ against $(1/T_k)$. The slope of the line is $(-E_a/R)$, from which the activation energy (E_a) can be calculated [43].

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It is seen that, knowledge of sorption isotherm and moisture diffusivity of specific food product become a useful tool for investigation of drying kinetics. In addition to these aspects, there has been consistent effort either to develop or to fit drying kinetics using mathematical models. These models reflect not only material properties but also system characteristics of the drying process and become useful tools for investigation. A brief discussion of some existing drying models is given below.

Drying models used for food products

Drying process involves complex heat and mass transfer phenomena, which are difficult to describe mathematically. However, it is often sufficient to use simple semi-empirical expressions/models to describe the drying kinetics of a food product [44]. The semi-empirical models were derived by simplifying general series solutions of Fick's second law [45]. These models do not require assumptions of geometry of a typical food product, its mass diffusivity and conductivity [46]. Among semi-empirical thin-layer drying models, the six models *viz.*, (i) Two-term model, (ii) Henderson and Pabis model, (iii) Lewis model, (iv) Page model, (v) Logarithmic model and (vi) Midilli et al. model are found to use extensively in literature and, therefore, presented in Table 1.2.

Table 1.2 Some prominent thin-layer drying models used for modeling drying kinetics of food products

Model name	Model description	Parameters estimated from model	Reference
Two Term	$MR = a \times e^{(-k \times t_1)} + b \times e^{(-k_1 \times t_1)}$	*a*, *b*, *k* and k_l	[47]
Henderson and Pabis	$MR = a \times e^{(-k \times t_1)}$	*a*, *k*	[48]
Lewis	$MR = e^{(-k \times t_1)}$	*k*	[49]
Page	$MR = e^{(-k \times t_1^n)}$	*k*, *n*	[50]
Logarithmic	$MR = a \times e^{(-k \times t_1)} + c$	*a*, *k* and *c*	[51]
Midilli et al.	$MR = a \times e^{(-k \times t_1^n)} + b \times t_1$	*a*, *b*, *k* and *n*	[44]

where,

MR = moisture ratio (dimensionless)

k and k_1 = drying coefficient, minute^{-1}

n = exponent (dimensionless)

t_1 = time, minute

a and b = model coefficients (dimensionless)

Experimental drying data is used to determine the model co-efficient to make the model usable. Drying models are applied for whole regime of drying including constant rate period. Identification of the best fit model for a given drying condition is required, when investigating new products and proposing new drying technique.

Discussion on drying theory made so far, basically pertain to the thin layer drying. However, there have been some efforts of investigation of innovative drying technology apart from the thin layer hot air drying; a brief account is presented below.

1.4 Recent innovation: Microwave drying of food

With the advancement in technology and considering the continual demand for more and more energy efficient processes, the introduction of new technology in food drying becomes indispensible. Some of such new drying technologies are centrifugal fluid bed dryer, vacuum dryer, flash-cum-fluidised bed dryer, microwave dryer, radio frequency dryer. Microwave drying has been successfully utilized in drying of food products, such as carrot [52], banana [53], garlic [54], potato [55], white mulberry [56], okra [57], spinach [58], parsley [59] *etc*. Thus, Microwave drying has been projected one of the promising drying technologies for food products.

Microwaves are forms of energy that are manifested as heat through their interaction with materials. In a specific frequency regime (915 MHz to 2450 MHz) there is primarily two physical mechanisms [60] *viz*., (i) ionic conduction and (ii) dipolar rotation through which energy can be transferred to a non-metallic material.

In ionic conduction, ions are accelerated by electric fields. All the ions in a salt solution move in the opposite direction to their own polarity by the electric field. In doing so, they collide with non ionized water molecules and, thus, giving up kinetic energy. As a result, the water molecules accelerate and collide with other water molecules. When the polarity changes, the ions accelerate in the opposite fashion. Since this phenomenon occurs many millions of times per second, large numbers of collisions and transfers of energy occur. The kinetic energy thus converts to heat energy. The theory of dipolar rotation is different. Water is dipolar in nature. Dipoles are influenced by the rapidly changing polarity of the electric field. Although they are normally randomly oriented, the electric field attempts to pull them into alignment. However, as the field decays to zero, the dipoles return to their random orientation. They again align as the electric field builds up to its opposite polarity. This build up and decay of the field, occurring at a frequency of many millions of times per second, causes the dipoles similarly to align and misalign millions of times per second. This causes an energy conversion from electrical field energy to potential energy in material and then to kinetic or thermal energy in the material.

It is also postulated that, a complete microwave drying process consists of three drying period [61] *viz*., (i) heating-up period, (ii) rapid drying period and (iii) reduced drying rate period. During microwave drying process, the heating-up period is relatively short, and moisture loss is small. In this period, microwave energy is converted into thermal energy within the moist food products. As a result, the product temperature increases with time. The material starts to lose moisture at relatively smaller rate when the moisture vapor pressure in food product is above that of the environment. In rapid drying period, a stable temperature profile is established. Thermal energy converted from microwave energy is used for the vaporization of moisture. Much of the moisture loss takes place during the second period of microwave drying [62]. In reduced drying rate period, the local moisture is reduced to a point. Local temperature then may rise above the boiling temperature of water, resulting in overheating or charring of the food product.

Microwave drying alone has some serious drawbacks that include uneven heating, possible textural damage, and limited product penetration of the microwave radiation into the product. Other drying methods can be combined to overcome these drawbacks [63]. Increasing concerns over product quality and production costs have motivated the researchers to investigate, and the industry to adopt combination drying technologies.

Microwave assisted combination drying has drawn attention claiming the advantages of (i) short drying time and (ii) improved product quality. It is reported that microwave assisted combination drying takes advantages of conventional drying methods and microwave heating, leading to better processes than microwave drying alone [61]. There are three stated ways in which microwave energy may be combined with conventional drying methods [60] *viz.*, (i) preheating, (ii) booster drying and (iii) finish drying. In preheating, microwave energy is applied at the entrance to the dryer. The heat generated at the interior of the food product force moisture to the surface and permitting conventional dryer to operate at higher temperatures. The drying curve is steeper, and drying time is shortened. In booster drying, microwave energy is added to the conventional dryer when the drying rate begins to fall. The drying rate is sharply increased. It is reported that, this is the most effective on thick, hard to heat materials. The least efficient portion of a conventional drying system is near the end, when two thirds of time may be spent removing the last one third of the water [30]. The inefficiency of hot air drying can be addressed by adding microwave energy near the end of the conventional dryer. This method also provides close control of the final moisture without over drying.

As discussed earlier, there are some efforts to use microwave energy for drying through a variety of modes. However, its application on tea drying could not be found. Tea industries use different types of conventional dryer for drying its products. A brief account of different dryers used in tea industries is given below.

1.5 Tea dryers used in tea factory

The tea industry is one of the energy intensive food-processing sectors consuming both electrical and thermal energy. About 12–15% of the total energy requirement is electrical energy, and the rest is thermal energy. The electrical energy is used to run the machineries, and the thermal energy is used to reduce the moisture content of the leaves from 70–80% (w.b.) down to 3% (w b.) [5]. In most cases, thermal energy requirement is derived from firewood, coal, fuel oil and natural gas. Among all the tea processing steps, drying is the most energy consuming process. About 86% of total thermal energy in tea manufacturing is consumed by dryers alone. A brief review of different types of tea dryers used in tea factory *viz.*, (i) pressure chamber dryer (PCD), (ii) fluidised bed dryer (FBD), (iii) vibro-fluidised bed dryer (VFBD) are discussed below.

Pressure chamber dryer

The schematic of a pressure chamber dryer is shown in Fig. 1.1, which consists of a closed rectangular chamber known as drying chamber. Top part of the chamber is kept open for feeding the fermented tea leaves in trays. Fermented leaves fed to the top are carried forward by the conveyor. At the end of the run, the trays tilt one by one and discharge the leaves to the lower run. The process is repeated till the leaves are discharged by the bottom run onto a discharge valve, which delivers the made tea outside the chamber. Hot air circulating by a blower from bottom passes through the trays, and dries the leaves.

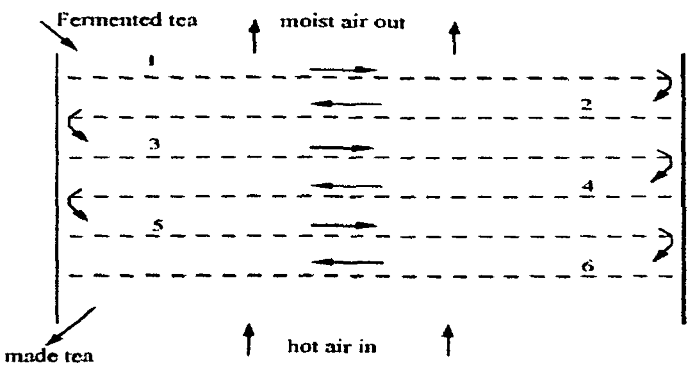


Fig. 1.1 Schematic diagram of Pressure Chamber Dryer

Fluidised Bed Dryer (FBD)

In fluidised bed dryer, fermented tea to be dried is placed on perforated screen. Hot air is blown through the screen. At certain air velocity, the pressure drop across the tea bed becomes equal to the total tea weight. At this point, the tea bed begins to expand. Further increase in air velocity causes the individual tea particles to separate from one another and float. The tea particles in this condition are said to be under fluidisation. Fluidisation helps the fermented tea to dry from all sides, increases heat transfer rate and thus, reduces drying time.

The fluidised bed tea dryer shown in Fig. 1.2, consists of a drying chamber, plenum chamber, dust collectors and air blowers. Fermented tea leaf particle is loaded on the grid plate of the drying chamber. In the initial portion of the dryer, the moisture of the fermented tea leaf particle is reduced rapidly. Hence maximum volume of air is introduced at this stage. The density of the tea leaf particles is reduced with the loss of moisture. These low density particles tend to move away from the feed end, and are replaced by high moisture fresh fermented tea leaf particles. The air also acts as a carrier of the tea particles through the drier, making the bed of tea particles move forward until the dried tea is discharged at the opposite end.

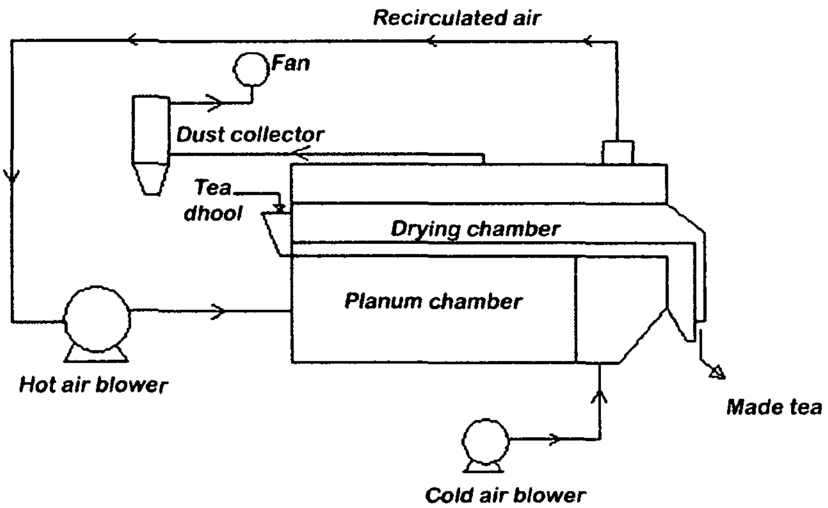


Fig. 1.2 Schematic diagram of Fluidised Bed Dryer

Vibro Fluidised Bed Dryer (VFBD)

Fermented tea particles with high initial moisture content require a higher air velocity than similar bed of dry particles for fluidisation. Due to dominant cohesive forces exerted by wetted tea surfaces, only the top layer of the bed of tea particle is fluidised. The bottom layers may remain stationary during the initial stage of drying when tea leaf particles are quite wet. To overcome this problem, VFBD is introduced, where mechanical forces are added for vibrating the material [64].

A continuous VFBD as shown in Fig. 1.3 consists of a drying chamber, plenum chamber, dust collectors, air blowers and excitation system. The vibrating plate inside the plenum chamber makes a small angle to the horizontal. The vertical component of vibration helps to fluidize the solids in the bed while the horizontal component facilitates the particle movement towards the outlet of VFBD

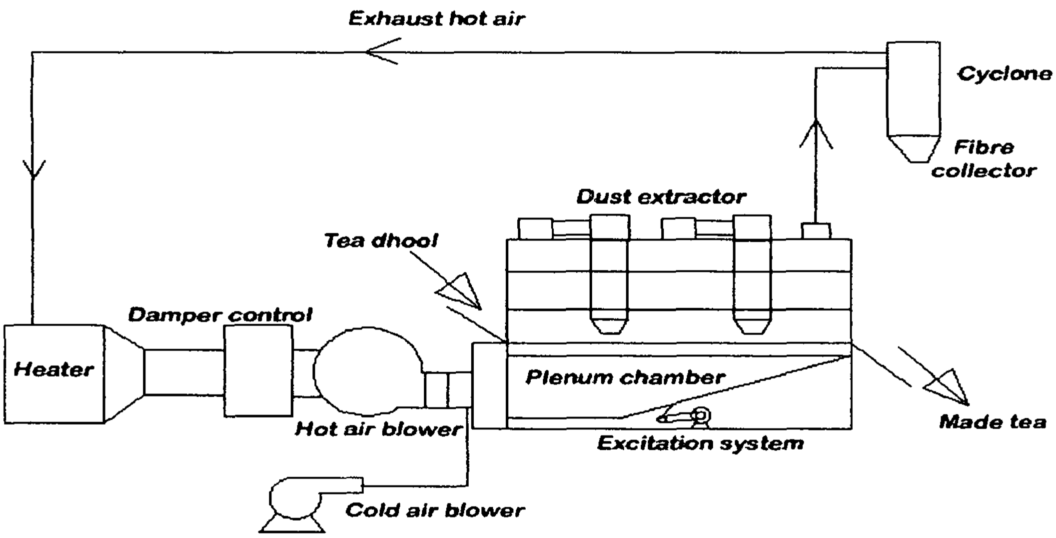


Fig. 1.3 Schematic diagram of Vibro Fluidised Bed Dryer

It is seen that development of drying technology and hence tea dryer is still progressing in this century old industry. It is also noticed that knowledge of material characteristics related to drying kinetics is essential for understanding and assessing drying performance using the existing theory of drying. However, there exist knowledge gaps, with reference to drying kinetics of tea specially, for local varieties grown in Assam (India). Innovation in tea drying should be based on the appropriate knowledge on its drying kinetics. Investigation of drying kinetics and related material properties of local tea variety has been considered as required area of research. The above discussion is summarized with the following points:

- Tea is an important beverage product of Assam (India) and drying is a significant processing step requiring urgent research attention with reference to energy optimisation and quality enhancement

- Existing theory of drying implies the requirement of information on fundamental material characteristics pertaining to drying and drying kinetics which are material and/or system dependent. Such information is not available for local variety of tea and, therefore, need to be determined through precise experimentation.

- Microwave drying is getting attention for a variety of food products due to certain advantages, and, therefore, its prospect of tea drying needed investigation.

1.6 Objectives of the research

Keeping in view of the discussion made in this Chapter, the focus of the present study has been to investigate the prospect of a new tea drying technique ensuring quality production at optimum energy use. Therefore, this research work has been undertaken through a systematic procedure with the following objectives:

❖ Characterisation of CTC tea of T3E3 cultivar (ready-to-dry sample) through desorption isotherm at some predetermined and controlled temperature conditions

❖ Investigation of the best-fit drying model for conventional hot-air drying of CTC tea of T3E3 cultivar under varying drying environment

- Investigation of the best-fit drying model for microwave drying of CTC tea of T3E3 cultivar under varying level of microwave power

- Investigation of the drying behaviour of CTC tea of T3E3 cultivar using a combination of hot-air and microwave drying

- Analysis of the results of drying experiments pertaining to specific energy consumption in comparison with energy consumption pattern of industrial drying prevalent in some representative local tea factories.

1.7 Organization of the thesis

The text of the thesis has been arranged in six chapters as follows·

- **Chapter 1**

In this chapter, tea classification and different processing steps of manufacturing made tea has been discussed. Theory of drying (*viz.*, desorption isotherm, moisture transfer mechanism in thin layer drying and thin layer drying model) has also discussed here. Recent innovation in the field of food drying along with the common tea dryers used in tea factory is highlighted, leading to the statement of the problem and objective of the research work undertaken.

- **Chapter 2**

Literature pertaining to desorption isotherm of food product, hot air drying characteristics of food product, microwave drying of food product and microwave assisted hot air drying of food product have been reviewed and presented in Chapter 2.

- **Chapter 3**

Chapter 3 covers in detail the methodology adopted for characterisation of CTC tea sample (ready-to-dry sample) through desorption isotherm Also, the result of desorption isotherm model, monolayer moisture content and net isosteric heat of desorption are provided in this chapter.

- **Chapter 4**

Chapter 4 covers in detail the methodology adopted and results, for investigation of the best-fit drying model for both conventional hot-air drying and microwave drying of CTC tea.

- **Chapter 5**

Investigation of the drying behaviour of CTC tea sample using a combination of hot-air and microwave drying has been discussed in Chapter 5. The process parameters (*viz.*, temperature of hot air and microwave power) have been optimised to achieve the objective has been discussed in this chapter.

- **Chapter 6**

This chapter enlists the summary of the results obtained to achieve the objectives of the thesis. It also discusses the limitations and possible future extensions of the work.

The thesis ends with references and a set of appendices.

CHAPTER 2

REVIEW OF LITERATURE

Chapter: 2

Review of literature

Tea is a biologically derived material which would have some similarities with other biological products. Since studies on tea drying are limited, it is necessary to review the literature on drying of other biological materials. Knowledge gained from this review would give some ideas applicable to tea drying. In the context of the present scope of work, the literature survey is presented in the following sections.

- Sorption isotherms of food products
- Hot air drying of food products
- Microwave drying of food products
- Microwave assisted hot air drying of food products

2.1 Sorption isotherms of food products

Many research workers have been demonstrated the usefulness of the investigation of sorption isotherms of agricultural materials (potato [33], mulberry [65], Black tea by [25, 66, 67], apple and garlic [68], mushroom [69] etc. Though the results of these studies are useful for processing and handling of the concerned product, the methodology provides useful guidelines for extending the work to CTC tea. The literature describing the desorption isotherms and thermodynamic properties of different food product are discussed below.

Panchariya et al. (2001) [66] studied desorption isotherms of black tea (Darjeeling, India) particles at 25, 40, 60 and 80 ^{0}C using the static gravimetric method. The equilibrium moisture content of black tea was found to decrease with the increase in air temperature. Also, Oswin equation was found to predict best fit experimental desorption isotherm data of CTC tea. The monolayer moisture content at different temperatures (*viz.*, 25, 40, 60 and 80 ^0C) was found 0.04354, 0.04237, 0.04103 and 0.03803 kg kg^{-1} (d.b.) respectively.

Ghodake et al. (2007) [67] determined sorption isotherms of withered leaves, black and green tea at 20, 30, and 40 ^0C by using static gravimetric method within the water activity range of 0.10-0.90. At constant equilibrium relative humidity, equilibrium moisture content was observed to increase with decrease temperature. Also, modified Halsey model was found better fit for predicting desorption data for withered leaves, black and green teas. The net isosteric heat of sorption of withered leaves varied between 30.8 and 29.5 kJ mol^{-1} with the variation of moisture level between 8% and 9% (d.b.). For black tea and green tea, it varied between 25.5-16.8 kJ mol^{-1} and 34.8-20.7 kJ mol^{-1} respectively, at moisture levels varied between 6% and 8% (d.b.).

Mulet et al. (2002) [69] determined moisture desorption isotherms of mushrooms (*Morchella esculenta*) at 5, 15, 25 and 35 ^0C and within the range of 0.11-0.92 water activity using a standardized conductivity hygrometer. The GAB model was found the best model to describe desorption isotherms of mushrooms. The estimated monolayer moisture content was found 0.0978 kg kg^{-1} (d.b.). The net isosteric heat was determined (2812.5 kJ kg^{-1}) by using the Clausius–Clapeyron equation.

Igathinathane et al. (2007) [70] determined moisture sorption thermodynamic properties of the major corn stover fractions such as leaf, stalk skin, and stalk pith, utilizing the static gravimetric sorption isotherms data in the temperature range of 10 to 40 ^0C. Mean values of monolayer moisture contents were determined in the range from 3.8% to 4.9% (d.b.) by using BET model. Net isosteric heat of sorption was found to decrease gradually when the moisture in the material was greater than 20% (d.b.). Increased heat of sorption values at reduced moisture levels indicated high binding energy for removal of water. In the moisture range of 10% to 40% (d.b.), mean net isosteric heat of sorption values for leaf, stalk skin, and stalk pith were calculated 4.60, 2.32, and 4.00 kJ mol^{-1}, respectively. It was concluded that reduced energy is required to extract moisture from stalk skin, followed by leaf and stalk pith.

Botheju et al. (2008) [25] determined desorption isotherms of fermented tea at 50, 55, 60, and 70 ^{0}C by using static gravimetric method within the water activity range of 0.05-0.81. Results indicated that, the equilibrium moisture contents were decreased with the increase in temperature. Desorption isotherm curves obtained were S-shaped curve that could be predicted by Oswin model. Also, the net isosteric heat of sorption of the tea was found to decrease exponentially with the increase in moisture. A decrease in monolayer moisture content from 6.0% (w.b.) at 50 ^{0}C to 5.2% (w.b.) at 70^{0}C was observed. This decrease can be attributed to reduction in the number of sites available for water binding as a result of physical and chemical changes caused by temperature increase.

Ethmane Kane et al. (2008) [71] investigated moisture sorption isotherms of two Mint varieties (*Mentha pulegium* and *Mentha rotundifolia*) at 30, 40 and 50 ^{0}C by using the static gravimetric method. The shape of the isotherms was sigmoid shape and GAB model was found most suitable for predicting sorption isotherm of both the varieties. The sorption capacity was found to decrease with an increase in temperature. Activation of the water molecules due to the increase in temperature causes them to break away from the water binding sites, thus lowering the equilibrium moisture content. Net isosteric heats of sorption were calculated through direct use of moisture isotherms by applying the Clausius-Clapeyron equation. The net isosteric heat of sorption was varied with the variety of Mint under study.

Janjai et al. (2010) [72] experimentally determined the equilibrium moisture contents of Litchi (*Litchi Chinensis Sonn*) at temperatures of 30, 40, and 50 ^{0}C over a range of relative humidity values of 12 to 95%. The GAB model was found the best fitted model to experimental isotherm data of Litchi. It was observed that, equilibrium moisture content decreased with the increase in temperature at all levels of relative humidity. The kinetic energy associated with water molecules present in litchi was found to increase with the increase in temperature. This in turn, resulted in decreasing attractive forces, and consequently, escapes of water molecules. This led to a decrease in equilibrium moisture content with the increase in temperature at a given relative humidity.

Gazor (2011) [73] determined moisture desorption isotherms of canola cultivar (Option 500) at 30, 40, 50 and 60 ^{0}C using the standard gravimetric static method over a range of relative humidity from 11 to 81%. The Oswin model was found the best model to describe desorption isotherms of canola. The net isosteric heat of desorption of canola was observed to vary between 1.58-10.41 kJ mol^{-1} at moisture varying between 1.0-12.5 % (d.b.).

Filho (2011) [74] determined moisture desorption isotherms of fresh and heat blanched pumpkins (*Cucurbita moschata*) at three temperatures (*viz.*, 30, 50 and 70 ^{0}C), using the standard static-gravimetric method. The GAB model was used to analyze the fitting ability to describe the isotherm type. The net isosteric heat of desorption was found 17.29 and 9.02 kJ mol^{-1} with fresh and blanched one.

Chiste et al. (2012) [75] determined adsorption and desorption isotherms of tapioca flour in the range of water activity (a_w) from 0.22 to 0.92 at 25 ^{0}C. The tapioca flour presented Type II isotherm, and Handerson model fitted the best to experimental isotherm data. The monolayer moisture content was found 4.92% (w.b.).

2.2 Hot air drying of food products

Hot air drying is popular and age old method for preservation of food. There are a number of literatures available to describe the drying kinetics of different food products with hot air. Some of the literature is discussed below.

Temple et al. (2001) [76] studied the effect of hot air on black tea quality with 102 g tea samples at different air temperatures (*viz.*, 60, 80, 100, 120 and 140 ^{0}C) and fixed air flow rate of 0.095 m s^{-1}. The quality was judged by the commercial Tea Taster. A ten point scale for each five parameters *viz.*, (i) colour, (ii) strength, (iii) brightness, (iv) briskness and (v) thickness of liquor was used by the Tea Taster. The total quality scores of 25.5, 23.5, 26, 21.5 and 20.5 were achieved with air temperatures of 60, 80, 100, 120 and 140 ^{0}C respectively. It was observed that quality of made tea was reduced at drying air temperature above 110 ^{0}C and to give a black appearance, the minimum hot air temperature of 80 ^{0}C was required.

Gupta et al. (2002) [77] studied the use of various pre-treatments on chillies before drying and their impact on drying kinetics as well as product quality. A tray dryer was used to dry pre-treated chillies at different air temperatures (*viz.*, 55, 60, 65 and 70 ^{0}C). The drying rate was found to decrease continuously throughout the drying period. Also, no constant rate period was reported for the entire duration of drying. Drying of red chillies took place only in the falling rate period, and the Page model was used to describe the drying behavior of red chillies. An improvement on product quality at drying temperature of 55 ^{0}C was claimed.

Panchariya et al. (2002) [78] examined drying characteristics of black tea with 100 g tea sample at different hot air temperature (*viz.*, 80, 90, 100, 110 and 120 ^{0}C) and air velocity (*viz.*, 0.25, 0.45 and 0.65 m s^{-1}). It was observed that, increase of external parameters (temperature and air velocity) increases the drying rate. The experimental results also illustrate the absence of constant drying period and drying takes place only in the falling rate period The Lewis model adequately described the single-layer drying behaviour of black tea particles.

Togrul & Pehlivan (2003) [79] investigated the drying behaviors of single apricot (sample range 15.38 to 15.77 g) in a laboratory tea dryer at different air temperatures (*viz.*, 50, 60, 70 and 80 ^{0}C) and air velocities (*viz.*, 0.2, 0.5, 1.0 and 1.5 m s^{-1}). It was reported that, air velocity has negligible effect on drying rate of apricots. Drying took place only in the falling rate period. The Logarithmic model adequately described the drying kinetics of apricot.

Naheed (2007) [80] studied the effects of drying on the quality of black tea. The drying experiments were conducted in a pressure chamber dryer at three hot air temperatures (*viz.*, 80, 100 and 110 ^{0}C). Quality of made tea (*viz.*, flaviour, aroma and strength) was judged by a Tea Taster. It was concluded that, drying of black tea at air temperature 110 ^{0}C produced superior quality tea.

Mohammadi et al. (2009) [81] investigated drying behaviour of kiwifruit slices in a laboratory dryer at five different drying air temperatures (*viz.*, 40, 50, 60, *70 and 80* ^{0}*C) and constant air velocity 1 m* s^{-1} *Midilli et al. model was found to* describe the drying kinetics of kiwifruit in the above range. Drying time was reduced by 60% with the increase in drying air temperature from 40 to 80 ^{0}C.

Taheri-Garavand et al. (2011) [82] investigated thin-layer drying kinetics of tomato at three different air temperatures (*viz.*, 40, 60, and 80 ^{0}C) and three levels of relative humidity (*viz.*, 20%, 40% and 60%) with constant air velocity of 2 m s^{-1}. Drying characteristics of tomato in the above experimental range were described by Midilli et al. model. A decrease in drying time was observed with the increase in air temperature. Also, at a constant temperature, decrease in drying time was observed with decreasing air relative humidity.

Radhika et al. (2011) [83] investigated drying behavior of finger millet (100 g) in a conventional tray dryer at three different air temperatures (*viz.*, 50, 70 and 80 ^{0}C). Drying kinetics of the millet was satisfactorily described by the logarithmic model. Further, it was observed that drying air temperature significantly affects the rate of drying and the total drying process was found to be occurred in the falling rate period only. Also, effective diffusivity was evaluated by using Fick's law, which varied from 1.526×10^{-10} to 2.85×10^{-10} m^2 s^{-1}. Temperature dependence of diffusivity was found by Arrhenius type of relationship, and the activation energy for the diffusion of the moisture associated with the millet was found to be 35.37 kJ mol^{-1}.

Motevali et al. (2012) [84] investigated the influence of hot air temperature (*viz.*, 50, 60 and 70 ^{0}C) and air velocities (*viz.*, 0.5, 1 and 1.5 ms^{-1}) on drying kinetics of jujube. Drying time was found to decrease with the increase in air temperature and air velocity. It was also observed that, the major part of the drying process occurs at the falling rate period. Two well-defined falling rate periods with constant slope were observed. Effective moisture diffusivity of jujube fruit during the drying process was found in the range of $(1.1532\text{-}5.1895)\times10^{-10}$ m^2 s^{-1} for the first period and $(0.4036\text{-}2.3064)\times10^{-10}$ m^2 s^{-1} for the second period. Also, the activation energy in both periods was determined as 34.97 and 74.20 kJ mol^{-1}, respectively. The specific energy consumption was found in the range of 2.04-9 (MWh kg^{-1}). The optimum air temperature and velocity for minimum energy consumption was found at 70 ^{0}C and 0.5 m s^{-1}.

EL-Mesery & Mwithiga (2012) [85] investigated drying kinetics of onion slices in gas-fired hot air dryer and electrically heated hot air dryer. Three air temperatures (*viz*., 50, 60 and 70 ^{0}C) and air velocities (*viz*., 0.5, 1.0 and 2.0 m s^{-1}) were selected for the study. It was observed that, in case of hot air dryer, drying time was reduced by 28%, when drying air temperature increased from 50 to 70 ^{0}C at constant air velocity (0.5 m s^{-1}). For the electrical dryer, these drying durations decreased by 50%, when the air velocity was increased from 1.0 to 2.0 m s^{-1}. In the electrical dryer, when the temperature of drying air was increased from 50 to 70 ^{0}C while holding the air velocity constant at 0.5 m s^{-1}, the specific energy consumption decreased from 65.45 to 43.34 MJ kg^{-1}. At the fixed air velocity of 2 m s^{-1} and for the same air temperature range of 50 to70 ^{0}C, the specific energy consumption of the electrical dryer decreased from 84.64 to 70.59 MJ kg^{-1}. For the gas dryer, raising the drying air temperature from 50 to 70 ^{0}C at a fixed air velocity of 0.5 m s^{-1} caused the specific energy consumption to decrease from 41.22 to 33.56 MJ kg^{-1}. At a fixed velocity of 2 m s^{-1}, the specific energy consumption in the gas dryer decreased from 50.89 to 42.52 MJ kg^{-1}, when the air temperature was increased from 50 to 70°C. It was concluded that, the specific energy consumption of the gas heated dryer was lower than that of the electrically heated dryer.

2.3 Microwave drying of food products

Microwave drying is a rapid dehydration technique that can be applied to specific foods, particularly to fruits and vegetables [61]. There is extensive research on the microwave drying of fruits and vegetables, some of which are discussed below.

Soysal (2005) [86] studied microwave drying of mint leaves with 90 g weight at seven different microwave power densities (*viz*., 4, 5, 6, 7, 8, 9 and 10 W g^{-1}). It was observed that, by working microwave power density at 10 W g^{-1} instead of 4 W g^{-1}, drying time was reduced by 2.7 times. Depending on drying conditions, average drying rate of mint leaves was found to vary from 0.48 to 1.14 kg kg^{-1} (d.b.) $minute^{-1}$ for the microwave power density between 4 and 10 W g^{-1} respectively. Higher drying rate was obtained with higher microwave power. After a short heating period, relatively long constant period was observed. Midilli et al. model was found best suited to predict the drying behaviour of the mint leaves.

Alibas Ozkan et al. (2007) [87] studied microwave drying behaviour of spinach leaves (50 g) in a microwave oven using eight different microwave power levels (*viz.*, 90, 160, 350, 500, 650, 750, 850 and 1000 W). Drying at 1000 W, instead of 500 W was found to reduce drying time by 33%. Energy consumption was found constant (0.12 kWh) within the power range of 350-1000 W. A significant increase in energy consumption was noticed at 160 and 90 W. Microwave power of 750 W produced the least energy consumption (0.12 kWh). The best quality in terms of colour and ascorbic acid values were obtained with microwave power of 750 W. Page thin layer drying model was found best suited for predicting microwave drying behaviour of spinach leaves.

Dadali et al. (2007) [57] investigated the effects of microwave power level on drying kinetics of okra (100 g sample) at 5 microwave power levels (*viz.*, 180, 360, 540, 720, and 900 W). By working at 900 W instead of 180 W, the drying time was shortened by 72%. It was observed that, sample mass has an effect on drying time. The drying time was shortened by 73% with the increase in sample mass from 25 to 100 g. It was also, noticed that, drying of okra took place both in the constant rate and falling rate periods after a short heating period. The moisture removed in the constant rate period varied from 13 to 40% for all drying conditions. Average drying rates for okra in the constant rate period was found to vary from 0.08 to 0.44 kg kg^{-1} (d.b.) $minute^{-1}$ at various microwave power levels (from 180 to 900 W). The semi-empirical Page model was found best suitable to describe the drying kinetics of okra.

Lin, X. et al (2010) [145] investigated quality of green tea by comparing four drying processes (*viz.* hot-air drying, vacuum drying, microwave drying, and microwave vacuum drying). Microwave vacuum drying reduced drying time by 20 times than hot air drying. The green tea with low phenol- amino acid ratios has a good taste. The lowest phenol- amino acid ratio of 5.86 was obtained by microwave vacuum drying; while the highest ratio of 7.87 was found in green tea from air hot drying. The highest score of sensory evaluation was calculated for green tea by microwave vacuum drying with a score of 93.15, followed by microwave drying, vacuum drying, and hot air drying, with the values of 90.95, 89.55, and 87.70, respectively. Results indicated that using microwave drying not only retained more nutrients but also produced green teas with less astringent taste with the lowest phenol-ammonia ratio among four different drying methods. The structure of tea cells was uniform and better maintained by microwave drying with or without vacuum.

Evin (2011) [56] investigated microwave drying kinetics of white mulberry at five microwave power (*viz.*, 90, 180, 360, 600, and 800 W). Drying time was shortened by 88% with the increase in microwave power from 90 to 800 W. It was observed that, at constant microwave power level (180 W), the increase of sample mass from 50 to 150 g increases the drying time by 82%. No constant rate period was observed. Drying process took place only in the falling rate period. The semi-empirical Midilli et al. model was found best suitable to describe the drying kinetics of white mulberry.

Darvishi et al. (2012) [88] investigated the influence of microwave power on the drying kinetics of Alfalfa (sample weight 30 g), at different microwave (*viz.*, 180, 360, 540, 720 and 900 W). Drying time was found to shorten by 56% while working at 900 W instead of 180 W. Results indicated that drying took place in the falling rate period. The least specific energy consumption (3.87 MJ kg^{-1}) was observed at microwave power of 180 W. It was observed that, specific energy consumption increases with increases in power. The maximum value was found 9.98 MJ kg^{-1} at microwave power of 900 W.

Darvishi et al. (2013) [55] studied drying characteristics and energy requirement of potato slices (15 mm thickness) with different microwave power (*viz.*, 200, 250, 300, 350, 400, 450 and 500 W). It was found that, increase in microwave power from 200 to 500 W significantly reduces the drying time from 9.5 to 3.25 min. Experimental drying curves showed only a falling drying rate period. The minimum and the maximum specific energy consumption for drying of potato slices were determined 4.645 MJ kg^{-1} for 500 W and 5.882 MJ kg^{-1} for 300 W, respectively. The semi-empirical Page model was found best suitable to describe the drying kinetics of potato slice.

2.4 Microwave assisted hot air drying of food products

Microwave drying alone has some serious drawbacks that include uneven heating, possible textural damage, and limited product penetration of the microwave radiation into the product. Other drying methods can be combined to overcome these drawbacks [63]. Increasing concerns over product quality and production costs have motivated the researchers to investigate, and the industry to adopt combination drying technologies. Some of the literature dealt with combine microwave-hot air drying is discussed below.

Funebo et al. (1998) [89] studied microwave-assisted hot-air dehydration of apple by the combination of hot air parameters (air temperature 40, 60 and 80 ^{0}C, air velocity 0.5 and 1 m s^{-1} and microwave power level 0.1 and 1 W g^{-1}). The drying time for apples could be reduced to 60% by the combination of microwave power. The air velocity was found to influence the drying rate. Microwave drying with high (1.5 m s^{-1}) and low (0.5 m s^{-1}) air velocity for apple revealed a difference in drying time with a factor 1.5-3 in favour of the higher air velocity.

Maskan, M. (2000) [53] investigated microwave finish drying of banana. Banana sample with 4.3 mm thick was dried at 60 ^{0}C and 1.45 m s^{-1} air velocity to 1.25 kg kg^{-1} (d.b.) moisture content. Microwave power of 350 W was applied for finish drying. Compared to hot air drying, microwave finish drying, was found to reduce the drying time by 64.3%. The increase in drying rate was also observed with microwave finish drying. The colour quality of the fresh bananas was found to maintain in microwave finish drying.

Sharmah et al. (2001) [54] carried out combined microwave-hot air drying experiments of garlic cloves at varying temperatures (*viz.*, 40, 50, 60 and 100 ^{0}C), air velocities (1 and 2 m s^{-1}) and continuous microwave power of 40 W. Combined microwave-hot air drying reduced the drying time up to 80-90% in comparison to hot air drying. Further, combined microwave-hot air drying was found to increase quality of garlic.

Kaensup et al. (2004) [90] compared drying kinetics of peeper seed by using a combined microwave/fluidized bed dryer (microwave power 500 W, air temperature 40, 60 and 90 ^{0}C, air velocity 5 to 8 m s^{-1}) with a conventional fluidised bed dryer (FBD). The results from FBD showed that the drying time required were 145, 29.7 and 17.5 minutes for the air temperature of 40, 60 90 ^{0}C, respectively. On the other hand, combined microwave/fluidised bed dryer, the drying times were 86.3, 25 and 13 minutes for the air temperature of 40, 60 90 ^{0}C, respectively. For all the inlet air temperature examined, combined microwave/fluidised bed dryer provided more effective drying rate compared with FBD.

Wang et al. (2007) [91] evaluated characteristics of thin layer microwave drying of apple pomace with and without hot air pre-drying in a laboratory scale microwave dryer. The drying experiments were carried out at 150, 300, 450 and 600 W, and the hot air pre-drying experiment was performed at 105 ^{0}C. Compared to fresh apple pomace, the pre-dried apple pomace required 25% less energy consumption.

Karaaslan (2008) [92] investigated drying of spinach leaves in a combined microwave–fan-assisted convection oven. The effect of microwave drying (microwave power level 180 360, 540, 720 and 900 W), fan assisted convection (100, 180 and 230 ^{0}C) and combined fan assisted convection (100, 180 and 230 ^{0}C) and microwave (180 and 540 W) was investigated. The most significant effect of microwave power in the combined system was found to an increase in the drying rate compared with hot air. According to these results, fan-dried spinach leaves were significantly darker in colour than microwave and microwave–fan combination dried spinach leaves.

Noor et al. (2008) [93] investigated the effects of microwave vacuum drying of guavas by applying three different microwave power densities (*viz.*, 0.5, 1 and 1.9 kW kg^{-1}). It was observed that, the higher microwave power densities reduced drying time with poor product quality. Microwave vacuum dried samples exhibits better appearance and texture when compared to conventionally dried sample.

Dev et al., (2011) [94] studied drying behaviour of fresh *Moringa oleifera* pods (Drumsticks) by microwave-assisted hot air drying (MAHD) and conventional hot air drying (CHD) methods. The samples were dried at three different temperatures, (*viz.*, 50, 60, and 70 ^{0}C) with and without the application of microwaves. Microwave power density of 1 W g^{-1} was used for the MAHD. The drying time was found to reduce 80% in microwave-assisted hot air drying compared to hot air drying. Microwave-assisted drying (60 ^{0}C and 1 W g^{-1}) was found to increase the colour quality of the product.

Nadee, A. et al. (2011) [95] studied, drying kinetic and specific energy consumption of Pandanus leaf in microwave combined hot air drying (*viz.*, 472 W-45 ^{0}C, 472 W-55 ^{0}C and 472-65 ^{0}C). It was noticed that, with the increase in drying air temperature at a given microwave power, the drying rate increases. The specific energy consumption was found to decrease from 43.85 to 38.47 MJ kg $^{-1}$ with the increase in temperature from 45 to 65 ^{0}C for the above hot air-microwave combination.

Ranjbaran & Zare (2012) [96] examined the drying characteristics of soybean in combined hot air-microwave drying. The experiments were carried out for combination of five microwave power densities (*viz.*, 0.89, 1.6, 3.2, 4.3, 5.3 W g^{-1}) and four levels of air temperatures (*viz.*, 30, 40, 50 and 60 ^{0}C). It was also observed that increased in microwave power density decreases the drying time in comparison with hot air drying.

CHAPTER 3

THERMODYNAMIC CHARACTERISATION OF CTC TEA (*CAMELLIA ASSAMICA*)

Chapter 3

Thermodynamic characterisation of CTC tea

(*Camellia assamica*)

3.1 Description of tea cultivars and its samples

Tea cultivars: T3E3

Tea is produced from harvested shoots plucked from bushes planted in the fields. There are many types, varieties and cultivars of saplings which are grown for tea production. The three basic types of tea cultivated all over the world are (1) *Camellia sinensis* (L.) for the China type, (2) *Camellia assamica* for the Assam type and (3) *Camellia assamica lasiocalyx* for the Cambod type [3, 97]. Present day cultivars (*viz.*, T3E3, S3A1, S3A3, TV1 to TV31 etc.) are mostly developed from breeding of these three basic types of tea. These cultivars have different properties, like, rate of loss of moisture, drought resistance, pest and disease resistance, distinguishing processing characteristics, *etc.* [98]. T3E3 is a popular yield clone for CTC tea production in Assam and samples of this cultivar are used for the present investigation.

Tea samples

Dry-ready CTC samples processed from fresh tea shoots, harvested from bushes of T3E3 cultivar, are collected from a reputed tea-processing cum research unit (Tea Research Association, Tocklai Experimental Station, Assam India). For the present investigation 15 number of tea samples are needed to perform a series of experiments. Attempts are made to collect identical samples details of which are presented in Appendix A1. Utmost care is taken to minimize the duration between collection of sample and experiments. Moreover, to avoid the changes of properties during the collection process, standard sample bags are used for carrying the tea samples. The experiments analysis and findings concerning some thermodynamic characterisation are presented in this chapter.

3.2 Thermodynamic characteristics of CTC tea

Some important thermodynamic characteristics *viz*., (i) desorption isotherms, (ii) monolayer moisture content and (iii) heat of desorption of CTC tea are estimated by using standard procedure and analysis. These parameters are useful for understanding the drying behaviour of the CTC tea. The detail procedure analysis and corresponding results are presented and discussed below.

3.2.1 Temperature varying desorption isotherm behaviour of CTC tea

Procedure and experimental set-up for determination of equilibrium moisture content

Desorption isotherms of CTC tea are determined by the standard static gravimetric method available in literature [23]. In this method, saturated salt solutions are used to maintain a fixed relative humidity around the tea sample. Nine salts *viz*., KOH, $MgCl_2$, K_2CO_3, $NaNO_3$, KCl, $BaCl_2$, LiBr, LiCl and KI are used for the present investigation. These salts (Appendix A2) have a range of water activity from 0.0520 to 0.8980 [99]. At equilibrium condition, the water activity of the sample is identical to the relative humidity of the ambient air, and the moisture inside the food product is transferred to the ambient air by natural diffusion of the water vapor [26].

Experimental setup consists of nine glass containers of 500 mL capacity, each with an insulated lid. Each glass container contains a specific salt as mention earlier. Each tea sample of 10 g is weighed and placed into the glass containers. The containers along with the tea sample and salt are placed in a temperature-controlled cabinet. The cabinet has provision for setting temperature. Each individual tea sample under consideration is weighed daily in an analytic balance (Model Als-120-4N, KERN, Balingen-Frommern, Germany, ±0.001 g sensitivity). The weight measurement is continued until the difference of weight between two successive measurements is less than 0.001 g. The moisture contents of the samples at the end of the observation are determined by oven-dry method [100], which is discussed in Appendix A3. The change of moisture contents of all the tea samples is observed (Appendix A4) at five different levels of temperature *viz*., 30, 40, 50, 80 and 90 ^{0}C with three replications for each level of temperature.

Desorption isotherms of CTC tea at different temperatures

The results of the experiments as discussed above are plotted in Fig. 3.1. The plots are corresponds to five different level of temperatures *viz*., 30, 40, 50, 80 and 90 ^{0}C. It is seen that, the desorption isotherms have a sigmoid shape for all the temperature under study. According to Brunauer-Emmett-Teller (BET) classification, a sigmoid shape isotherm is type II isotherm and characteristics of hygroscopic products [101]. General shape of BET isotherm is presented in Appendix A5. The CTC tea sample used for the present investigation is hygroscopic in nature, and, therefore, exhibition of type II isotherm confirms the above BET classification.

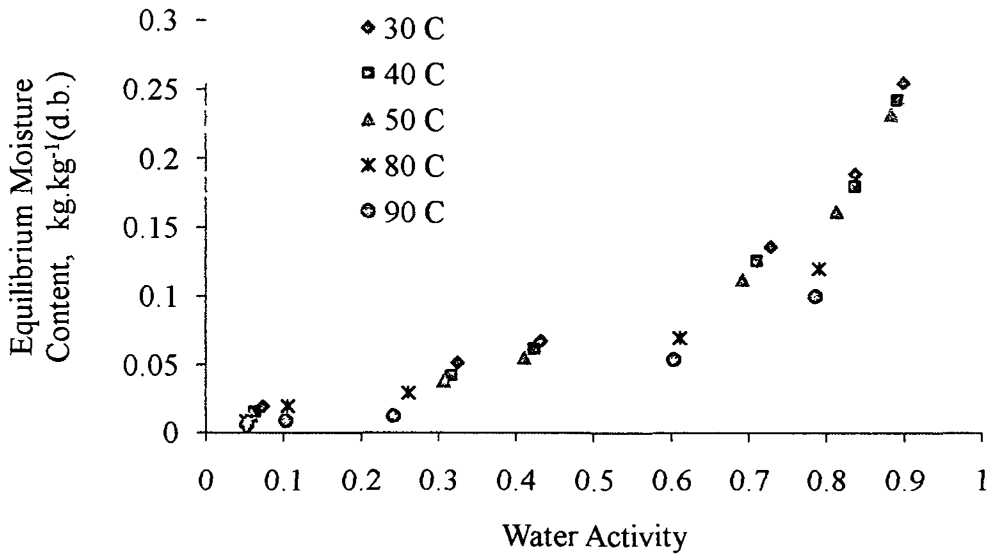


Fig. 3.1 Equilibrium moisture content vs. water activity at different temperatures

The results also reveal the temperature dependence of the desorption behavior of CTC tea. Equilibrium moisture content of the sample decreases with an increase in ambient temperature. Similar behaviour of black tea at different temperature has already been reported earlier by other researchers [25, 66, 67]. Increase in temperature activates the water molecules inside the food. As a result, water binding sites break away and lower the equilibrium moisture content [26].

3.2.2 Modeling desorption behavior of CTC tea

Equilibrium moisture content depends upon many factors including chemical composition, the physical structure and the status of surrounding air [102]. Attempts have been made by earlier researchers, to model the desorption isotherms mathematically in terms of these factors. Some models have been derived theoretically based on thermodynamic concepts; others are empirical or semi empirical models. For the present investigation, six available isotherm models, widely used for solid foods, have been considered for fitting experimental data. The models, *viz.*, (i) Brunauer-Emmett-Teller, (ii) Guggenheim-Anderson-de Boer, (iii) Peleg, (iv) Halsey, (v) Oswin and (vi) Henderson are presented in Table 1.1 (Chapter 1).

A nonlinear regression analysis is used to estimate the best-fit values of model parameters using experimental data through statistical software JMP 7.0.1 (SAS Institute Inc., Cary. NC, USA). The analysis also uses to identify the best fit model through determination of SSE as per standard statistical procedure. The model with the minimum SSE is considered as the best-fit model for predicting desorption isotherm of CTC tea. The estimated model parameters together with the corresponding SSE from nonlinear regression analysis for all the models tested at each level of temperature, i.e., 30, 40, 50, 80 and 90 ^{0}C are presented in Tables 3.1a (GAB and BET model) and 3.1b (Oswin, Pleg, Halsey, and Henderson models) and discussed below.

Table 3.1a Model coefficients and SSE of desorption isotherms of CTC tea (GAB and BET models)

Isotherm model	Temperature (^{0}C)	M_m	C	K	SSE
	30	0.0477	8.7865	0.9093	0.000021
GAB	40	0.0457	6.3488	0.9159	0.000095
	50	0.0420	6.2675	0.9343	0.000036
	80	0.0321	8.8561	0.9416	0.000011
	90	0.0311	1.7190	0.8989	0.000028
	30	0.0285	179.2681	---	0.002310
	40	0.0284	44.2255	----	0.001430
BET	50	0.0291	26.7287	----	0.000770
	80	0.0264	14.0259	----	0.000048
	90	0.0235	3.6258	----	0.000045

On and average, all the models are showing some degree of fitting to the experimental data. On the basis of estimated SSE, variation of fitting condition is observed amongst the models as well as amongst the temperature for a given model. Further, there is an agreement that Oswin model indicated the lowest SSE for entire temperature range, i.e. from 30 to 90 ^{0}C (Tables 3.1a and 3.1b). Several researchers successfully used Oswin model for describing desorption isotherm of many food products (*viz*., Potato [103], Black tea [66], Mango [104], Banana [105], Garlic and Apple [68], Black tea [25], Yam [106], Canola [73]. However, Ghodake et al. (2007) [67] reported Halsey model as the best fitted model for withered tea leaves, black tea and green tea. There can be significant differences between the equilibrium moisture content relationships for different grain varieties of the same grain type due to many factors such as composition and characteristics of materials [107]. Thus, the fitting of Oswin model for CTC tea samples of T3E3 cultivar, might be due to its inherent composition characteristics.

Table 3.1b Model coefficients and SSE of desorption isotherms of CTC tea (Oswin, Pleg, Halsey and Henderson models)

Temperature(^{0}C)	Isotherm model	*A*	*B*	SSE
	Oswin	0.0787	0.5399	0.000006
	Pleg	0.0091	0.1034	0.000216
30	Halsey	-0.0139	1.5169	0.000260
	Henderson	10.0018	1.0524	0.000360
	Oswin	0.0721	0.5747	0.000061
	Pleg	0.0042	0.1026	0.000260
40	Halsey	-0.0157	1.4202	0.000310
	Henderson	9.4159	0.9939	0.000300
	Oswin	0.0675	0.6108	0.000019
50	Pleg	0.0012	0.1022	0.000360
	Halsey	-0.0181	1.3352	0.000190
	Henderson	8.7053	0.9372	0.000310
	Oswin	0.0483	0.7148	0.000022
	Pleg	0.0008	0.0705	0.000049
80	Halsey	-0.0181	1.2204	0.000056
	Henderson	21.3530	1.2171	0.000110
	Oswin	0.0381	0.7497	0.000029
	Pleg	-0.00061	0.0635	0.000066
90	Halsey	-0.0256	0.9828	0.000069
	Henderson	11.5473	0.8732	0.000390

As presented in the Table 3.1b, the values of Oswin model coefficient vary with temperature. To represent temperature dependency of coefficients (*A* and *B*) of Oswin model, further analysis is carried out using the tabulated values of the coefficients for different temperatures (Table 3.1b). The analysis result following two linear equations for the coefficients *A* and *B*, respectively.

$$A = 0.099 - 0.00066 \times T \qquad R^2 = 0.992 \qquad \ldots\ldots\ldots (3.1)$$

$$B = 0.4352 + 0.0035 \times T \qquad R^2 = 0.999 \qquad \ldots\ldots\ldots (3.2)$$

where,

T = Temperature of the surrounding, ^0C

R^2 = Coefficient of determination

Finally, the equilibrium moisture content of CTC tea as a function of ambient temperature and water activity could be modeled by using results of the above analysis as given below.

$$M_e = (0.099 - 0.00066 \times T) \times \left(\frac{a_w}{1-a_w}\right)^{(0.4352+0.0035\times T)} \qquad \ldots\ldots\ldots (3.3)$$

where,

M_e = equilibrium moisture content, kg kg^{-1}(d.b.)

a_w = water activity, dimensionless

T = temperature of the surrounding air, ^0C

Eq. 3.3 can be used to predict equilibrium moisture content of CTC tea at the prevailing temperature and relative humidity (a_w) inside the dryer. The equilibrium moisture content of the product is the lowest moisture content that can be achieved under a given set of drying conditions [13, 14]. The difference between the total moisture and the equilibrium moisture content represents the amount of moisture that can be removed by drying under certain condition, and is called the free moisture content. Further analysis of the isotherm data generated from the above model could provide valuable information regarding the dehydration process and energy requirements [108]. Thus, the model will be useful for understanding the CTC tea of T3E3 cultivar, which is a major type of tea grown in India.

During storage, the final moisture content of tea is determined by the temperature and relative humidity of the air that has surrounded the tea. If the made tea is not protected from the humidity, particularly during the rainy season when the relative humidity is high, the tea moisture content will rise and, this will lead to deterioration in tea quality. The equilibrium moisture content derived for CTC tea (Eq. 3.3) will be useful for the process engineer to design storage system.

3.2.3 Estimation of monolayer moisture content of CTC tea

Studies have shown that critical moisture content exists in foods in which water molecules are bound strongly to the surface of the monolayer. This monolayer moisture content (M_m) is considered as the optimal minimum moisture content that prevents the alteration of the product quality [25]. Some of the Isotherm models, as discussed in the previous section, are a suitable tool for determination of monolayer moisture content. Oswin model can successfully predict desorption isotherm of CTC tea, but, this model is silent about the monolayer moisture content of food product. However, both GAB and BET models could provide an estimation of monolayer moisture content. In the present investigation, the GAB model is considered for the estimation of monolayer moisture content because of its lower SSE compared to BET model (Table 3.1a). The values of monolayer moisture content are found to decrease with the increase in temperature. Iglesias, H.A., & Chirife, J. (1978) [28], also reported similar behaviour for almost 100 different food materials. Using the tabulated value for the GAB model the following temperature dependent linear relationship is proposed for monolayer moisture content of CTC tea.

$$M_m = 0.0568776 - 0.0002958 \times T, \quad R^2 = 0.989 \quad \ldots\ \ldots\ \ldots (3.4)$$

where,

T = Temperature of surrounding, ^0C

R^2 = Coefficient of determination

Monolayer moisture is the portion of water strongly bound in food. It represents the minimum moisture to prevent auto-oxidation and to enhance product stability during storage.

A food product is most stable at its monolayer moisture content. Monolayer moisture content varies with chemical composition and structure of food particles. Monolayer moisture content is used to predict the end point of drying. It predicts the lower limit of moisture in food product for most dehydration process. Further, water removal beyond this point through normal drying processes becomes very costly and time consuming. Therefore, it is very important to identify this point of distinction in order to design and specify optimum drying, storage and packaging conditions to assure long-term stability of dehydrated foods. Eq. 3.4 will help process engineers and dryer manufacturer for determining monolayer moisture content of CTC tea.

3.2.4 Estimation of net isosteric heat of desorption of CTC tea

The net isosteric heat of desorption (Δh_d) is an indicator of the state of water absorbed by the solid material. It is calculated by using the Clausius-Clapeyron equation [27].

$$\left[\frac{d(\ln a_w)}{d(1/T_k)}\right]_M = \frac{-\Delta h_d}{R_s} \qquad \ldots\ \ldots\ \ldots\ (3.5)$$

where,

a_w = water activity, dimensionless

T_K = temperature of surrounding, Kelvin

Δh_d = net isosteric heat of sorption, kJ kg^{-1}

R_s = specific gas constant of water, kJ kg^{-1} Kelvin^{-1}

M = moisture content, kg kg^{-1}(d.b.)

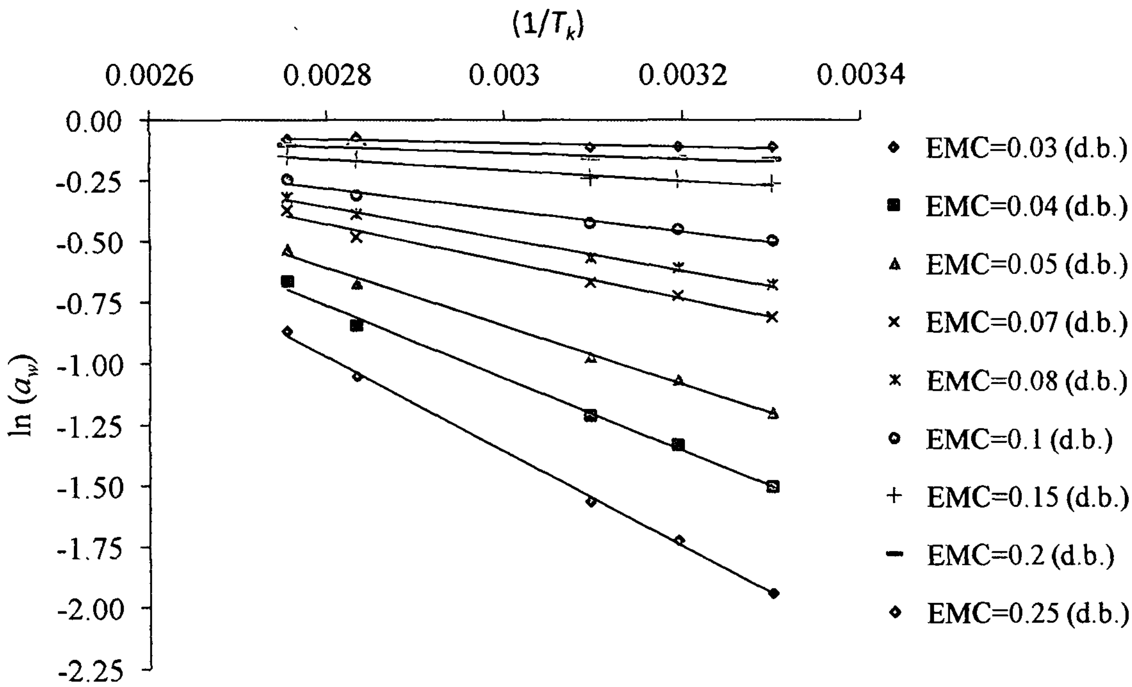


Fig. 3.2 Estimation of net isosteric heat of desorption using equilibrium data obtained from Eq. 3.3.

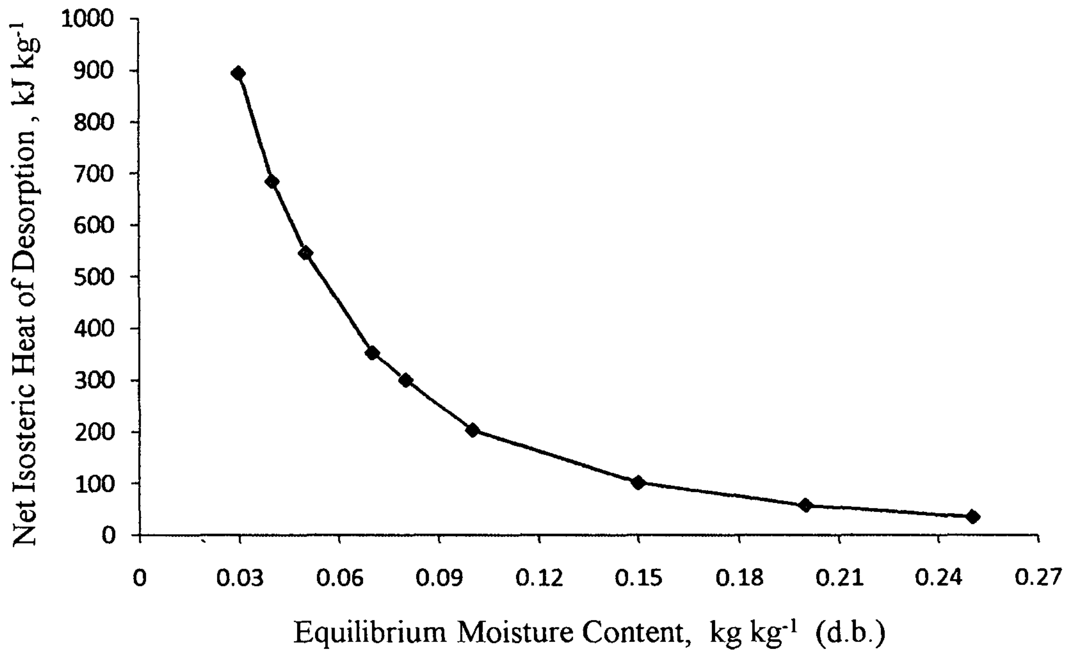


Fig. 3.3 Net isosteric heat of desorption vs. equilibrium moisture content for CTC tea

This calculation procedure assumed that heat of desorption is independent of temperature change. Desorption model (Eq.3.3) derived for CTC tea of T3E3 cultivars is used to plot ln (a_w) against $(1/T_k)$ for nine levels of equilibrium moisture content (*viz*., 0.03, 0.04, 0.05, 0.07, 0.08, 0.10, 0.15, 0.20 and 0.25) as shown in Fig. 3.2. The slope of the plot of ln (a_w) vs. $(1/T_k)$ at specific moisture content (M) gives the net isosteric heat of desorption (Eq. 3.5). Thus, net isosteric heat of desorption corresponding to each level of equilibrium moisture content are calculated from the slope of these straight lines of Fig. 3.2.

Further the estimated values of net isosteric heat of desorption are plotted against moisture content (Fig.3.3). It is observed that, the net isosteric heat of desorption decreases from 896 to 35 kJ kg^{-1} with the increase of equilibrium moisture content from 0.03 to 0.25 kg kg^{-1} (d.b.). The decrease of net isosteric heat of desorption with the increase in moisture content is exponential and can be considered stabilized, when the moisture in tea is greater than 0.20 kg kg^{-1} (d.b.). This behavior is due to the presence of strongly bound water molecules to the food at lower moisture levels. Cenkowski et al. (1992) [109] reported that the energy required to remove water from grain is close to latent heat of vaporization for moisture above 0.25 kg kg^{-1} (d.b.). Similar behavior was also reported for fermented tea [25], rice [110] etc. The variations of net isosteric heat of desorption with moisture content of CTC tea can be expressed using the following relationship derived from Fig. 3.3.

$$\Delta h_d = 5.167 \times M_e^{-1.53} \qquad R^2 = 0.981 \quad \dots \dots \dots (3.6)$$

where,

M_e = equilibrium moisture content, kg kg^{-1}(d.b.)

R^2 = coefficient of determination

Depending on the initial moisture of the material and the desired final moisture, the removal of water from food products may require more energy than that required to vaporize free water [26, 42]. Similar findings were reported for different food (*viz*., rice [111], dried fruits like sultana raisins, currants, figs, prunes and apricots [27], cauliflower and potato starch [112], melon seed and cassava [113].

CHAPTER 4

BEST FIT DRYING MODEL FOR CONVENTIONAL HOT AIR DRYING AND MICROWAVE DRYING OF CTC TEA

Chapter 4

Best fit drying model for conventional hot air drying and microwave drying of CTC tea

In this chapter, drying kinetics of CTC tea of T3E3 cultivar is investigated under conventional hot air drying and microwave drying. Best fit thin layer drying model is also proposed for the above mentioned drying methods. As mentioned in the chapter 3, sixteen number of CTC tea samples are collected from Tea Research Association, Tocklai Experimental Station, Assam India (Appendix A1) for all the experiments.

4.1 Experimental set-up and methodology used for determining drying kinetics of CTC tea

As discussed in Chapter 1, the tea industry is one of the energy intensive food-processing sectors consuming both electrical and thermal energy. About 12–15% of the total energy requirement is electrical energy, and the rest is thermal energy. The electrical energy is used to run the machineries, and the thermal energy is used to reduce the moisture content of the tea leaves from 70–80% (w.b.) down to 3% (w.b.). Most of the thermal energy requirement is derived from firewood, coal, fuel oil and natural gas. Among all the tea processing steps, drying is the most energy consuming process. About 86% of total thermal energy in tea manufacturing is consumed by dryers alone. The different types of tea dryers used in tea factory are elaborately discussed earlier (Chapter 1, Sec. 1.5). These conventional tea dryers use hot air as the drying medium. Longer time required, particularly during the last part of drying, has been the characteristic feature of traditional hot air tea drying. Though these tea dryers have been used for many years, but information on drying behaviour of different types of tea are limited. The inadequacy in research information seems to create a gap either to investigate the performance of existing tea dryer or to propose innovation to drying.

Uniform external conditions are the key aspect to gain an insight into the behavior of a material subjected to drying. The drying rates could be obtained experimentally as it is difficult to predict from heat and mass transfer theories alone. Moreover, in actual drying operations in the industry, the affect of variable parameters on drying behaviour is difficult to estimate. Fluctuations of feed rate, complicated air flows, changing air temperature and humidity caused difficulty to achieve desired uniform drying environment. Therefore, experimental condition conducive to control and record the variable parameters is required for generating data and subsequent analysis of tea drying phenomena. Such product specific characteristic information would be useful for the process engineer, factory engineer and dryer designer.

4.1.1 Experimental set-up for simulation of industrial thin layer tray drying of CTC tea

An experimental tray dryer is fabricated for hot air drying experiments, and its layout is presented in Fig. 4.1. The experimental set-up consists of four basic sections: *viz.*, (i) humidity control section, (ii) flow control section, (iii) heating control section and (iv) drying section. Loss of moisture with time under varying but controllable drying environment has been a primary purpose of the set-up. Electrical power is used to operate the experimental set-up. Provision is made to measure the electricity consumption in generation and flow of hot air for tea drying using an energy meter (Model: D02A, China).

Brief descriptions of the different section of the set-up are discussed below.

i Humidity control: Air humidity control section consist of silica gel filled dehumidifying chamber and temperature-humidity sensor (Model No. TS33F, Meade Instruments Corporation, USA). Air is dehumidified with the help of silica gel. The display unit connected with the temperature cum humidity sensor displays the temperature and humidity of the incoming air.

ii. Flow Control: Air flow control system consists of a blower (Model No. EBC 40 Electrex, 335 W, Planet Power Tools Pvt. Ltd. India), flow regulator, orifice plate and U-tube mercury manometer. The blower circulates controlled air flow through the dryer. The air flow rate passing through the drying chamber is determined from the manometer installed in the pipe.

iii. Air heating and control: Air heating and control section consists of three electric heaters (1 kW each), temperature controller (DTC 303) and temperature sensor. The temperature sensor sends signals to regulate air temperature according to preset value by switching on/off the electric heaters.

iv. Drying chamber: The drying section consists of a drying chamber (20 cm × 20 cm × 50 cm), temperature sensor (PID 528), thermocouples, temperature-humidity sensor, perforated tray (15 cm x 15 cm) for holding tea sample and a digital balance (5 kg ± 0.1 g, Akshar Digi Scale, India). Glass wool is used as an insulator in the air ducting and also in the drying chamber.

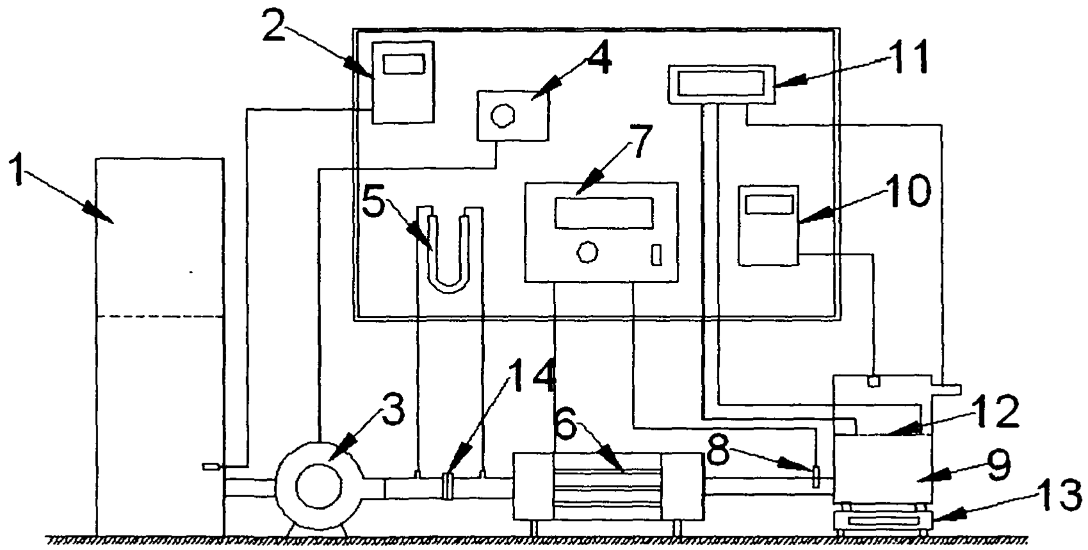


Fig. 4.1 Layout of experimental tray dryer showing Dehumidifying chamber (1), Temperature-Humidity sensor (2, 10), Blower (3), Blower speed regulator (4), U-tube manometer (5), Electric heater (6), Temperature controller (7), Temperature sensor (8), Drying chamber (9), Temperature display Unit (11), Perforated tray for Tea sample (12), Digital balance (13), Orifice plate (14).

4.1.2 Working of experimental drying set-up and recording of observations for hot air drying characterisation of CTC tea

Experiments are performed to determine the effect of temperature on the thin-layer drying characteristics of CTC tea. Drying of tea involves both physical and chemical changes, which are temperature dependent. Therefore, tea drying temperature has to be selected properly. Case hardening and blistering are the two common phenomena at high initial drying temperature. On the other hand, dull and soft products are formed at low initial drying temperature [15]. In general, recommended range of inlet air temperatures between 80 and 140 ^{0}C is reported [114]. No specific recommendation of drying temperature for processing of CTC tea of T3E3 cultivar could be known. In line with the prevailing industrial practices three temperature levels *viz.*, 80, 90 and 95 ^{0}C are selected for investigating thin layer drying behaviour of CTC tea of T3E3 cultivar

In the set-up of thin layer drying, each particle is exposed to as near identical conditions as possible, where continuous monitoring of bed weight gives moisture monitoring in real time The air approaching the product should not displace the particles in the thin-layer holder during the test [115]. Therefore, care is taken to maintain thin layer drying condition during all experiments maintaining constant air flow and controlled air temperature as mentioned in the previous paragraph.

Atmospheric air is allowed to flow through the dehumidifying chamber, to reduce the relative humidity up to about 70%. Dehumidified air is blown at controlled flow rate (2.33×10^{-3} kg s^{-1}) by adjustable blower. The U-tube manometer is used to check any deviation of set flow throughout the experiment.

Moisture content of the CTC tea sample before drying is measured by oven dry method (detail is given in Appendix A3).

To obtain steady state condition, the system is run for 20 minutes for each set of new experiment. Once the temperature has stabilized, and the mass flow rate (2.33×10^{-3} kg s^{-1}, Appendix A6) and air humidity are at the set values (70%), 100 g

CTC tea sample is placed on the mesh tray of the drying chamber. A thickness of the bed of CTC tea sample is kept 6 mm to ensure thin layer drying. Weights are recorded with the digital balance at every 2 minutes till the end point of drying, which is set at 0.03 kg kg^{-1} (d.b.) as per prevailing industrial practice. The experiment is replicated twice for each level of temperature (*viz.*, 80, 90, and 95 ^{0}C). Average of the values obtained from each temperature is used for data analysis.

4.1.3 Experimental set-up for microwave drying of CTC tea

A domestic digital microwave oven (Model : MC-7648WSH, R.F. Output 900 W, Frequency 2450 MHz, LG electronics India Pvt. Ltd. India) is used for the present investigation, and its photograph is presented in Fig 4.2. The oven has the facility to adjust the power level at 180, 360, 540, 720 and 900 W and also the time of processing. The dimensions of microwave oven are 582 mm × 550 mm × 354 mm. A borosilicate glass container 200 mm × 200 mm × 40 mm is used as sample container in the microwave oven. An electronic balance (5 kg ± 0.1 g, Akshar Digi Scale, India) is used for weight measurement of tea samples.

Fig. 4.2 Microwave Oven used for microwave drying CTC tea

4.1.4 Working of experimental drying set-up and recording of observations for microwave drying characterisation of CTC tea

Some of the microwaves that are not absorbed by the sample can be reflected back to the magnetron and damage it. As a result, the power output of the magnetron may decrease. Therefore, it is necessary to verify the output power of the magnetron. The microwave oven power is determined by using standard IMPI 2-Liter Test (discussed details in Appendix A7).

The initial moisture contents of the samples are determined by oven-dry method (discussed details in Appendix A3). Drying trial is carried out for 100 g sample at five different microwave power levels *viz.*, P1 (175 W), P2 (350 W), P3 (525 W), P4 (700 W) and P5 (875 W). Container with the sample is put on the centre of rotating glass plate. The moisture loss is determined by repeated weighing of the sample at 1 minute interval by using an electronic balance. The moisture content of the sample is calculated according to the loss of mass and the initial moisture content value. Drying is carried out until the moisture content of the sample reduced to 0.03 kg kg^{-1} (d.b.).

4.2 Results of investigation relating to hot air drying and microwave drying of CTC tea

Both hot air and microwave drying behaviour of CTC tea is investigated using the data generated through experimental set-up as discussed in the previous section. Hot air drying results corresponds to (i) temperature varying drying kinetics; (ii) estimated moisture diffusivity and (iii) best-fit drying model for CTC tea. The microwave drying results corresponds to (i) microwave power varying kinetics and (ii) best-fit drying model for CTC tea. The data generated from both drying modes are presented and discussed below.

4.2.1 Effect of air temperature on drying kinetics of CTC tea in hot air drying

As discussed earlier, drying of biological material is a complicated process involving simultaneous heat and mass transfer. Knowledge of the drying kinetics is essential for modeling of drying processes [116, 117]. Thin layer drying kinetics with three levels of varying temperature is investigated using the data recorded as discussed in the previous section. The changes of moisture contents of tea sample with time during the thin layer drying process are presented in Fig. 4.3 for all the three levels of temperature and discussed below.

As seen in the Fig. 4.3, all the drying curves have two stages. The moisture content rapidly reduces and then slowly decreases with the increase in drying time. In addition, it is obvious from the figure that drying temperature has a significant affect on the total drying time. The rate of moisture loss is higher at higher temperatures, and the total drying time is reduced substantially with the increase in air temperature. The drying time required to reduce the moisture content of CTC tea from the initial value of 2.33 kg kg^{-1} (d.b.) to a final value of 0.03 kg kg^{-1} (d.b.) are 46, 36 and 32 minutes at 80, 90 and 95 ^{0}C, respectively. Thus, CTC tea drying at 95 ^{0}C instead of 80 ^{0}C can reduce drying time by 30%.

The plots in Fig. 4.3 follow the general trend of drying curves as reported for black tea in similar investigation earlier [78, 118]. The trends are similar irrespective of temperature of hot air. However, there exists variation in the rates of moisture reduction amongst the three curves representing three levels of drying temperature.

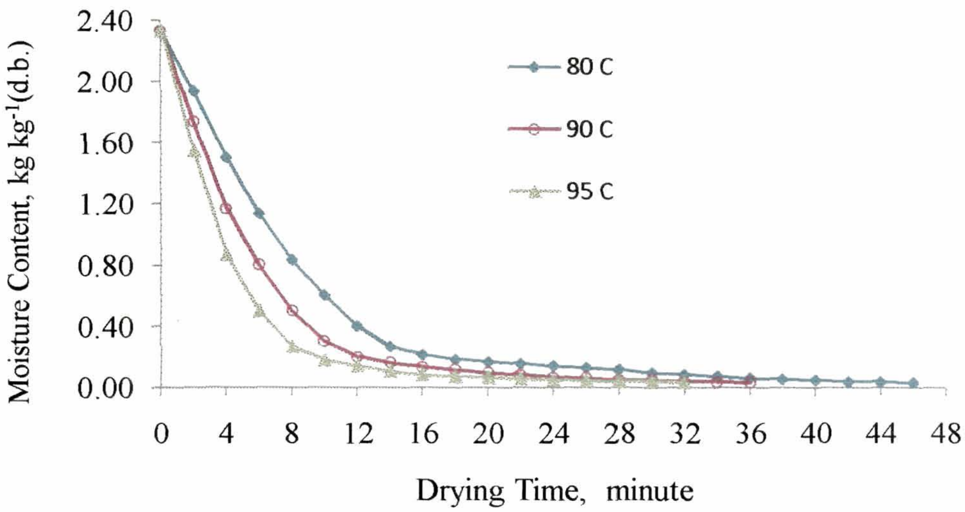


Fig. 4.3 Variation of moisture content (d.b.) with time at different drying air temperatures

Fig. 4.4 illustrates the variation of drying rate with moisture content for three levels of temperature. The drying rate values at a particular moisture content level is calculated from the data corresponding to Fig. 4.3. An increase of drying rate, given by the curve slope, with the increase in temperature is observed. This is in agreement with the earlier results for onions [119], garlic [120] and lettuce and cauliflower leaves [121].

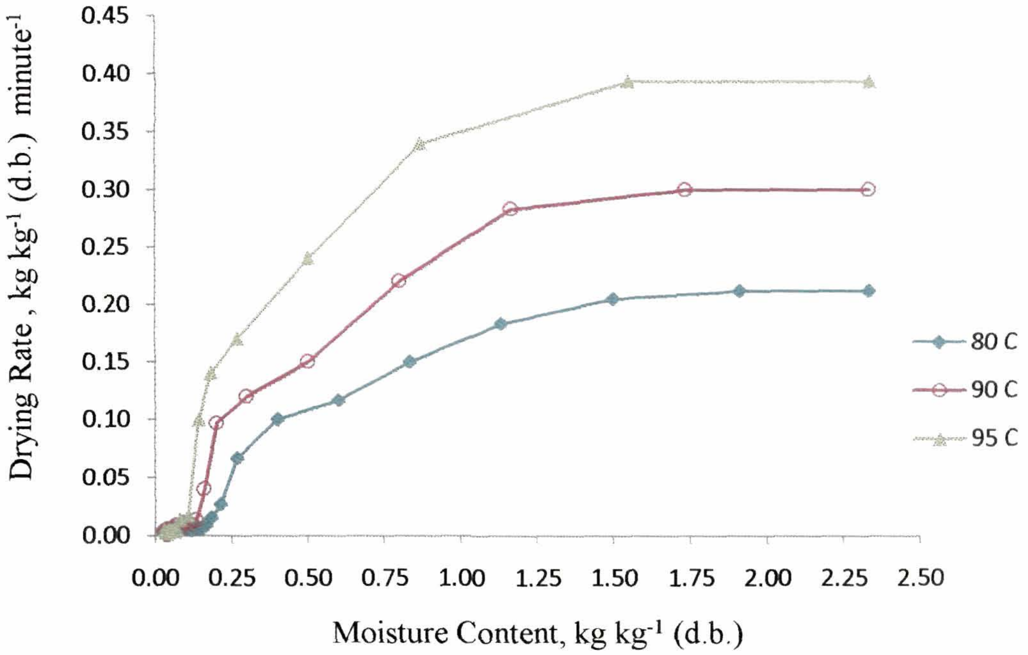


Fig. 4.4 Variation of drying rate with moisture content at different drying air temperatures

Relatively flat curve up to 1.5 kg kg^{-1} (d.b.) moisture content for all the three levels of temperature illustrated the presence of constant drying rate period. The moisture removal in the falling rate is also substantial for all the drying temperature. Similar drying trends have also been reported earlier for fruits [65,120].

4.2.2 Effect of microwave power on drying kinetics of CTC tea in microwave drying

Five different microwave power levels *viz.*, 175, 350, 525, 700 and 875 W are used to investigate the effect of microwave power on moisture loss and drying rate for CTC tea. Variation of moisture content (d.b.) of the sample with drying time at different microwave power level is shown in Fig. 4.5. From the figure, it is observed that reduction of moisture content is dependent on microwave power level. This is in line with the earlier report for various foods under microwave drying (51, 52, 53, 54, 57].

The time required to reduce the moisture contents of tea sample from 2.33 to 0.03 kg kg^{-1} (d.b.) for microwave power level of 175, 350, 525, 700 and 875 W are 40, 20, 12, 9 and 7 minutes respectively. Thus by working at 875 W power level instead of 175 W power level, the drying time is shortened by 78%. Drying time reduces significantly with the increase in the microwave power.

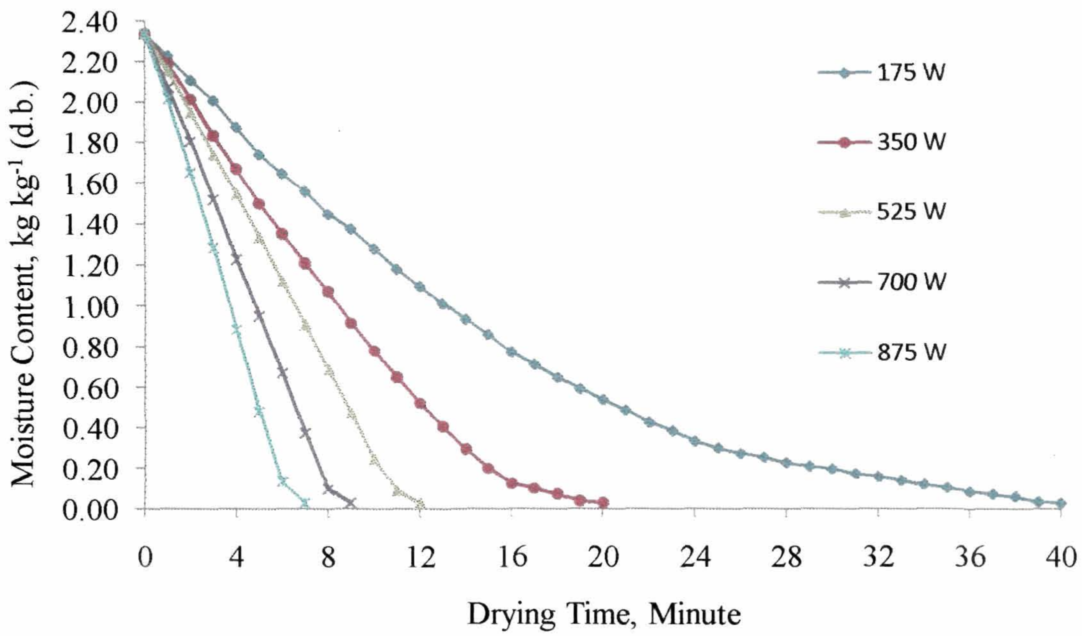


Fig. 4.5 Variation of moisture content (d.b.) with time at various microwave power levels

In general, a complete microwave drying process consists of three drying periods, *viz.*, (i) heating-up period, (ii) constant drying rate period and (iii) reduce drying rate period [61]. Fig. 4.6 shows the effect of microwave power level on drying rate for CTC tea. It is observed that, drying rate is increased with the increase in microwave power. Constant drying rate period for moisture content 2.33 to 0.26 kg kg^{-1} (d.b.) is observed for all the microwave power level. About 88% moisture is removed during this period. The constant rate period is followed by a falling rate period in which moisture content changes from 0.26 to 0.03 kg kg^{-1} (d.b.). In the initial phase, the moisture content of the material is high which results in higher absorption of microwave power. High absorbed microwave power leads to increase rates of evaporation and moisture loss. As the drying progresses, the loss of moisture in the product causes a decrease in the absorption of microwave power and results in the decrease in the drying rate [122]. Similar findings are reported in several studies [51, 57, 87].

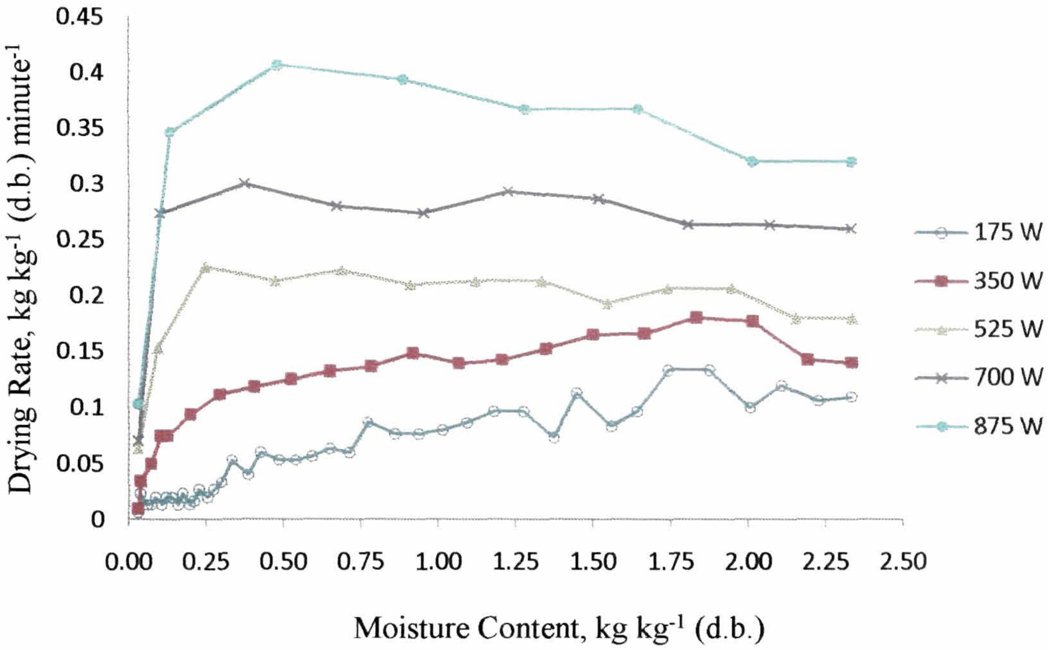


Fig. 4.6 Variation of drying rate with moisture content (d.b.) at various microwave power levels

4.2.3 Effective moisture diffusivity and activation energy of CTC tea in hot air drying

Knowledge of product moisture diffusivity is essential in simulation and optimization of the drying process. The moisture diffusivity of food is estimated by using Fick's diffusion equation [123] as discussed in Chapter 1. The effective moisture diffusivity is determined by plotting the experimental drying data in terms of the natural logarithm of moisture ratio values at different drying temperature *viz.*, 80, 90 and 95 ^{0}C against drying time [38, 39, 41]. The calculation of moisture diffusivity is presented in Appendix A8.

In the present investigation, experimental results are used to plot ln (MR) vs. t as shown in Fig. 4.7. The effective moisture diffusivity increases with temperature. Similar results are found during hot air drying of different food products presented in Table 4.1.

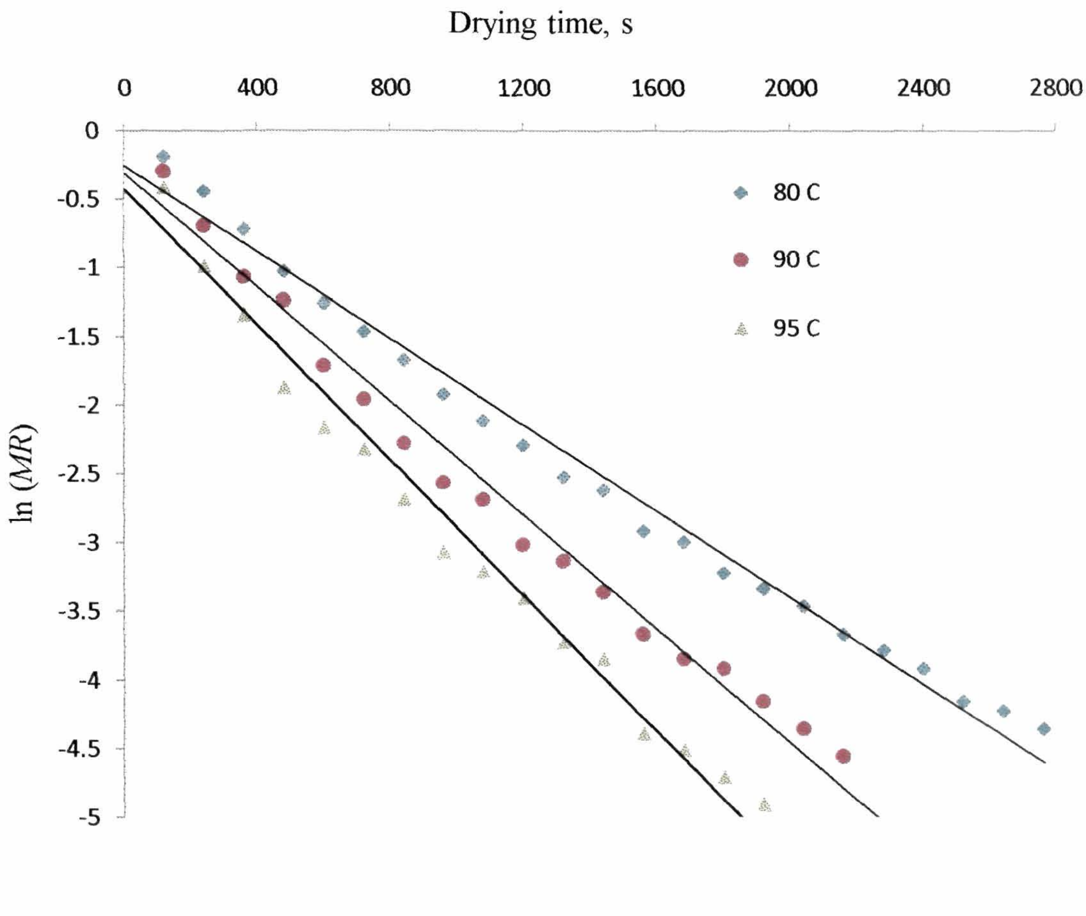


Fig. 4.7 Plot of ln (MR) vs. drying time used for the determination of effective moisture diffusivity

Table 4.1 Effective moisture diffusivity for hot air drying of different food products

Food	Temp, ^{0}C	Effective moisture diffusivity, D_{eff} ($m^2 s^{-1}$)	Reference
	80	5.5162×10^{-9}	
CTC tea (T3E3)	90	7.1569×10^{-9}	
	95	7.739×10^{-9}	
	40	4.29×10^{-9}	
Potato	70	1.57×10^{-9}	[124]
	50	1.15×10^{-10}	
Jujube	60	1.72×10^{-10}	[84]
	70	2.88×10^{-10}	
	50	5.09×10^{-9}	
Apricot	60	5.59×10^{-9}	
	70	5.60×10^{-9}	[79]
	80	6.51×10^{-9}	
	40	1.57×10^{-10}	
Grape	50	2.51×10^{-10}	
(Riesling variety)	60	3.96×10^{-10}	
	40	3.89×10^{-10}	
Grape	50	5.33×10^{-10}	[125]
(Cab variety)	60	8.03×10^{-10}	
	40	2.93×10^{-10}	
Grape	50	4.21×10^{-10}	
(Concord variety)	60	5.91×10^{-10}	

The temperature dependency diffusion characteristics can be used to examine the diffusion kinetics and also to estimate activation energy, which is discussed in Chapter 1. The ln (D_{eff}) vs. ($1/T_k$) plot of CTC tea is presented in Fig. 4.8. The graph shows a linear relationship, therefore; the diffusion kinetics follows Arrhenius type relationship. The slope of this line gives the value of E_a/R, where, R is the universal gas constant (8.314×10^{-3} kJ mol^{-1} Kelvin^{-1}), from which the activation energy (E_a) is evaluated as 24.88 kJ mol^{-1}. The activation energy for other food products is reported as follows: 28.36 kJ mol^{-1} for carrot [40], 62.96 kJ mol^{-1} for mint [126] and 37.76 kJ mol^{-1} for chillies [127].

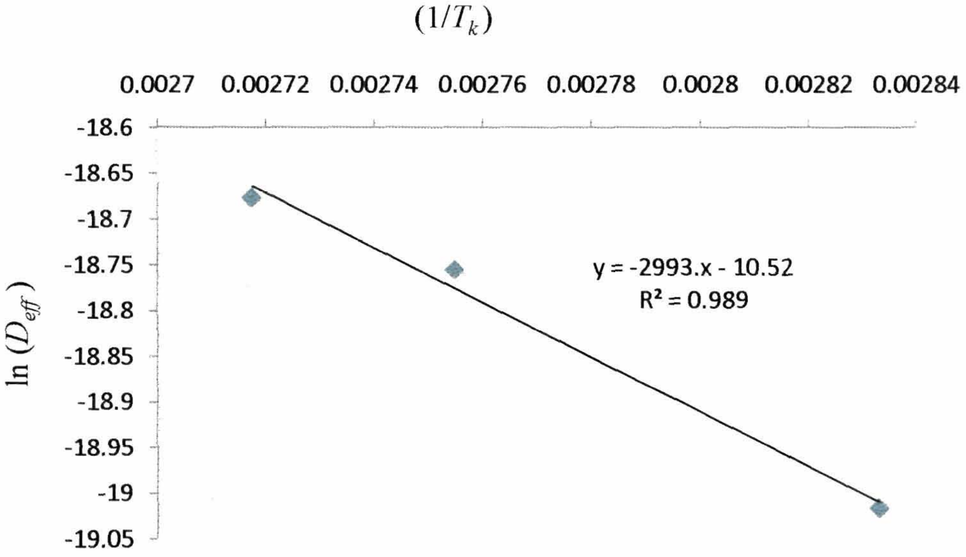


Fig. 4.8 Plot of effective moisture diffusivity for estimation of activation energy

4.3 Modeling thin layer drying behaviour of CTC tea in both hot air drying and microwave drying

For the purpose of design and analysis of drying technology, it is required to have drying models. The results of thin layer drying process are used to model drying kinetics of CTC tea, both in hot air and microwave drying. Data of the experiments is fitted to six widely used thin layer drying models *viz*., (i) Henderson and Pabis model, (ii) Lewis model, (iii) Page model (iv) Logarithmic model (v) Two term model and (vi) Midilli et al. model, which are presented, in Table 1.2 (Chapter 1).

The nonlinear regression analysis is used to estimate the best-fit values of model parameters as discussed in Chapter 3. The model with the minimum SSE is considered as the best-fit model for predicting drying kinetics of CTC tea.

4.3.1 Modeling thin layer drying behaviour of CTC tea in hot air drying

The estimated model parameters together with the corresponding SSE from nonlinear regression analysis for all the models tested at each level of drying temperature, i.e., 80, 90 and 95 ^{0}C in hot air drying are presented in Table 4.2 and discussed below.

Table 4.2 Estimated model coefficients and SSE of different thin-layer model in hot air drying

Model name	Drying air temperature ^{0}C	Model coefficient				SSE
Henderson	80	a=1.0393		k=0.1339		0.0132
& Pabis	90	a= 1.0238		k=0.1850		0.0064
	95	a=1.0166		k=0.2457		0.0061
	80	k=0.1290				0.0156
Lewis	90	k=0.1809				0.0071
	95	k= 0.2420				0.0064
	80	k = 0.0968		n=1.1309		0.0113
Page	90	k =0.1498		n=1.1005		0.0053
	95	k = 0.2106		n=1.0873		0.0054
	80	a= 1.0325		k= -0.1401	c= 0.0136	0.0113
Logarithmic	90	a=1.0170		k= -0.1922	c= -0.0118	0.0052
	95	a=1.0068		k= -0.2577	c= -0.0148	0.0041
	80	a= 1.483	b= -0.1471	k= 0.1467	k_1= 0.9299	0.0088
Two Term	90	a= -0.4160	b= 1.4396	k= 0.1705	k_1= 0.1806	0.0064
	95	a= -1.3735	b= 2.3900	k= 0.2454	k_1= 0.2455	0.0061
	80	a= 1.0044	k= 0.0873	n= 1.991	b= 0.0007	0.0045
Midilli et al.	90	a= 1.0044	k= 0.1403	n= 1.1533	b= 0.0007	0.0017
	95	a= 1.0045	k= 0.2000	n= 1.1395	b= 0.0008	0.0018

On and average, all the models are showing some degree of fitting to the experimental data. On the basis of estimated SSE, variation of fitting condition is observed amongst the model as well as amongst the temperature for a given model. Further, there is an agreement that Midilli et al. model indicated the lowest SSE for all the temperature under study, i.e. 80, 90 and 95 ^{0}C (Table 4.2). Several researchers successfully used Midilli et al. model for describing hot air drying kinetics of different food products *viz.*, apple [128], kiwifruit [81], Tomato [82], Potato [124].

As presented in the Table 4.2, the value of the drying coefficient (k), of Midilli et al. model increases with the increase in air temperature. So with an increase in air temperature drying curves become steeper indicating faster drying of the product. To incorporate the temperature dependency of coefficients (k and n) of selected Midilli et al. model, further analysis is carried out using the tabulated values of the coefficients for different temperatures. Following two linear equations for the coefficients k and n, as a function of temperature are estimated.

$$k = -0.4932 + 0.0072 \times T \qquad R^2 = 0.950 \quad \dots \dots \dots \quad (4.1)$$

$$n = 1.5226 - 0.0041 \times T \qquad R^2 = 0.988 \quad \dots \dots \dots \quad (4.2)$$

where,

T = temperature of the drying air, ^{0}C

R^2 = coefficient of determination

The variations of the coefficients a, b are minimum and, equal to 1.0044 and 0.0007 respectively.

Finally, the moisture ratio (MR) of CTC tea as a function of drying air temperature could be modeled by using the results of above analysis as given below.

$$MR = \left[1.0044 \times e^{\{(0.4932-0.0072\times T)\times t_1^{(1.5226-0.0041\times T)}\}}\right] + 0.0007 \times t_1 \quad \dots \dots \quad (4.3)$$

where,

T = temperature of hot air, ^{0}C

t_1 = drying time, minute.

4.3.2 Hot air drying model validation

The variations of experimental and predicted moisture ratio (*MR*) with drying time are presented in Figure 4.9. The established model is validated by comparing the predicted moisture ratios with a different set of experimental data at 90 ^{0}C, which are not used for model development. A reasonable agreement was found between the experimental and fitted *MR* values with the coefficient of determination, $R^2 = 0.996$.

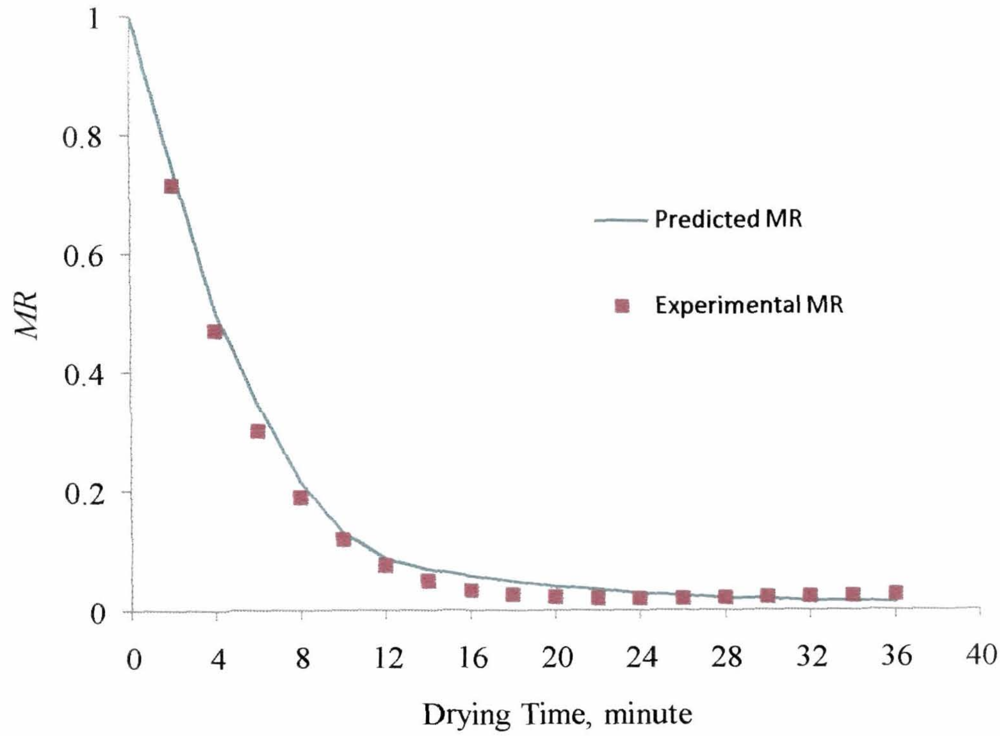


Fig. 4.9 Variation of moisture ratio (*MR*) with drying time based on Midilli et al. model and the experimental data

4.3.3 Modeling thin layer drying behaviour of CTC tea in microwave drying

The estimated empirical parameters together with the corresponding SSE from nonlinear regression analysis for all the models tested at each microwave power level 175, 350, 525, 700 and 875 W are presented in Table 4.3 and discussed below.

Table 4.3 Estimated model coefficients and SSE of different thin-layer model in microwave drying of CTC tea

Model name	Microwave power level, W	Model Co-efficient				SSE
Henderson & Pabis	175	a =1.0752			k =0.0758	0.0388
	350	a = 1.1043			k=0.1281	0.0780
	525	a =1.1082			k=0.1649	0.0936
	700	a = 1.0963			k= 0.2231	0.0742
	875	a = 1.0922			k= 0.2915	0.0670
Lewis	175	k = 0.0707				0.0615
	350	k = 0.1162				0.1067
	525	k = 0.1477				0.1182
	700	k = 0.2028				0.0902
	875	k = 0.2670				0.0797
Page	175	k = 0.0344		n=1.2569		0.0042
	350	k = 0.0375		n=1.4991		0.0129
	525	k = 0.0453		n=1.6224		0.0195
	700	k = 0.0624		n=1.7271		0.0140
	875	k = 0.0895		n=1.8003		0.0095
Logarithmic	175	a = 1.1510	k= −0.0582		c= −0.1155	0.0086
	350	a =1.4860	k= −0.0637		c= −0.4511	0.0198
	525	a =7.0504	k= −0.0133		c= −6.0335	0.0196
	700	a = 4.7411	k= −0.0276		c= −3.7249	0.0179
	875	a = 3.8185	k= −0.0461		c= −2.7953	0.0098
Two Term	175	a = 1.1011	b=−0.0997	k=0.0777	k_1=29.4688	0.0315
	350	a = 13.2272	b=−12.2533	k=0.2298	k_1=0.2480	0.0190
	525	a = 19.2211	b=−18.2508	k=0.3254	k_1=0.3452	0.0303
	700	a = 14.4497	b=−13.4710	k=0.4368	k_1=0.4723	0.0238
	875	a= 15.1549	b=−14.1685	k=0.5839	k_1=0.6309	0.0191
Midilli et al.	175	a= 0.9882	k= 0.0348	n= 1.2342	b= −0.0006	0.0048
	350	a= 0.9744	k= 0.0362	n= 1.4397	b= −0.0038	0.0131
	525	a= 0.9920	k= 0.0380	n= 1.3909	b= −0.0259	0.0198
	700	a= 0.9925	k= 0.0635	n= 1.3876	b=−0.0304	0.0184
	875	a= 0.9908	k= 0.0897	n= 1.5420	b= −0.0248	0.0097

On the basis of estimated SSE, variation of fitting condition is observed amongst the model as well as amongst the temperature for a given model. Further, there is an agreement that Page model indicated the lowest SSE for all the microwave power under study, i.e. 175, 350, 525, 700 and 875 W (Table 4.3).

Several researchers successfully used Page model for describing microwave drying kinetics of different food products *viz.*, garlic cloves [54], potato slice [55], okra [57], spinach [87], apple pomace [91], carrots [129].

As presented in the Table 4.3, the value of the drying coefficient (k), of Page model increases with the increase in microwave power. So with an increase in microwave power drying curves become steeper indicating faster drying of the product. To incorporate the microwave power dependency of coefficients (k and n), of selected Page model, further analysis is carried out using the tabulated values of the coefficients for different temperatures. Following equations for the coefficients (k and n) as a function of microwave power are estimated.

$$k = 10^{-7} \times P^2 - 6 \times 10^{-5} \times P + 0.041 \qquad R^2 = 0.998 \qquad \ldots \ldots \ldots (4.4)$$

$$n = 0.336 \ln P - 0.478 \qquad R^2 = 0.999 \qquad \ldots \ldots \ldots (4.5)$$

Finally, the moisture ratio (MR) of CTC tea as a function of microwave power (P) could be modeled by using the results of the above analysis as given below.

$$MR = e^{[-\{10^{-7} \times P^2 - 6 \times 10^{-5} \times P + 0.041\} \times t_1^{(0.336 \ln P - 0.478)}]} \qquad \ldots \ldots \ldots (4.6)$$

where,

P = microwave power, W

t_1 = Drying time, minute.

4.3.4 Microwave drying model validation

The variations of experimental and predicted moisture ratio (MR) with drying time are presented in Fig. 4.10. The established model is validated by comparing the predicted moisture ratios with a different set of experimental data at the five microwave power level which are not used for model development. A good agreement is found between the experimental and fitted *MR* values.

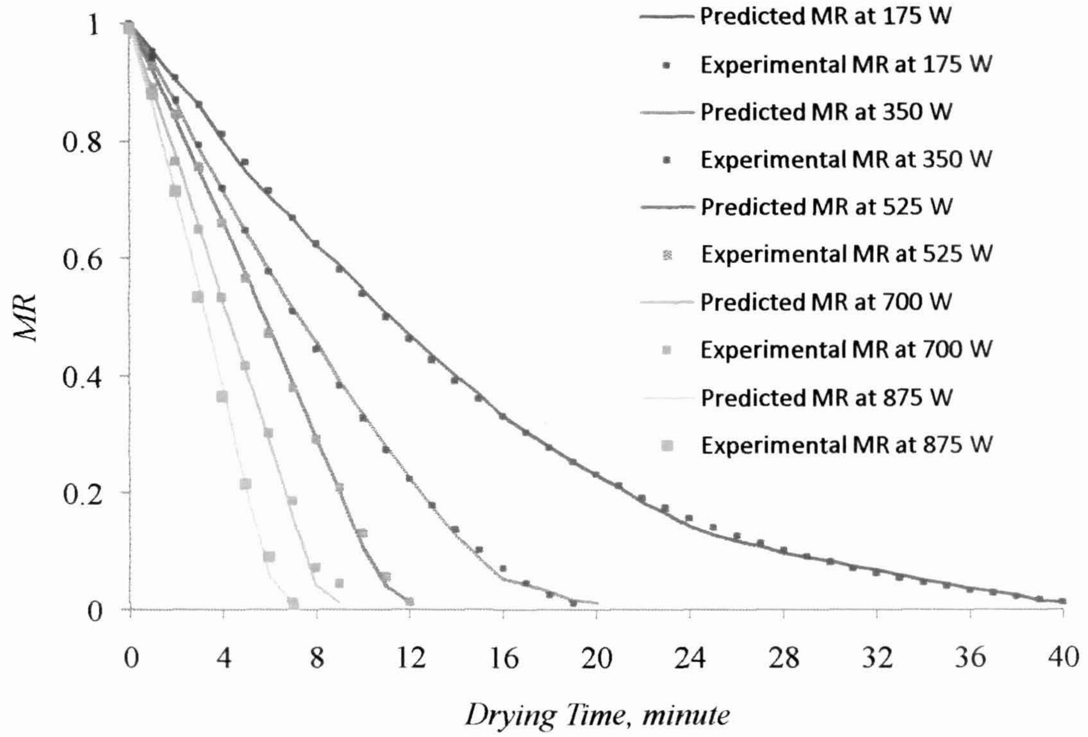


Fig. 4.10 Variation of moisture ratio with drying time based on] Page l. model and the experimental data

CHAPTER 5

MICROWAVE ASSISTED HOT AIR DRYING OF CTC TEA: INVESTIGATION AND ITS PROSPECT

Chapter 5

Microwave assisted hot air drying of CTC tea: investigation and its prospect

In the previous Chapter, the drying kinetics of CTC tea of T3E3 cultivar has been presented, while undergoing (i) hot air drying and (ii) microwave drying separately for the entire range of moisture. In this chapter prospect of combined mode (microwave assisted hot air drying) of drying of CTC tea of T3E3 cultivar is presented. The procedure and results of (i) selection of end points of drying for combined mode, (ii) assessment of specific energy consumption and quality with individual and combined modes of drying, (iii) determination of optimum operating parameters for combined mode and (iv) comparison of specific energy consumption of the above mention drying method with industrial tea dryer are presented below.

5.1 Microwave assisted hot air drying: Decision on end points from results of individual (hot air drying and microwave drying) drying experiments on CTC tea

The results of drying with identical tea samples from 2.33 to 0.03 kg kg^{-1} (d.b.) using hot air and microwave are already discussed in Chapter 4. It is observed that, drying of the CTC tea samples required 40, 20, 12, 9 and 7 minute at microwave power levels of 175, 350, 525, 700 and 875 W, respectively. In conventional hot air drying, the drying of CTC tea samples required 46, 38 and 32 minutes at 80, 90 and 95 ^{0}C, respectively. The required need of a combined mode, where initial hot air drying would follow microwave drying, was also discussed in Chapter 1. The end point of hot air drying should be optimally decided for such a combine mode. The decision of this end point is taken from the results of individual drying mode and discussed below.

Microwave power level at 350 W is selected as representative of microwave drying, and operating temperature of 90 ^{0}C taken for hot air drying mode. The variation of moisture content with time for the two modes of drying (hot air drying at 90 ^{0}C and microwave drying at 350 W power level) is presented in Fig. 5.1. For same moisture loss i.e. from 2.33 to 0.03 kg kg^{-1} (d.b.), microwave drying reduces drying time by 44% than conventional drying. This is due to the difference between the drying mechanisms (both types of drying mechanisms are discussed elaborately in Chapter 1).

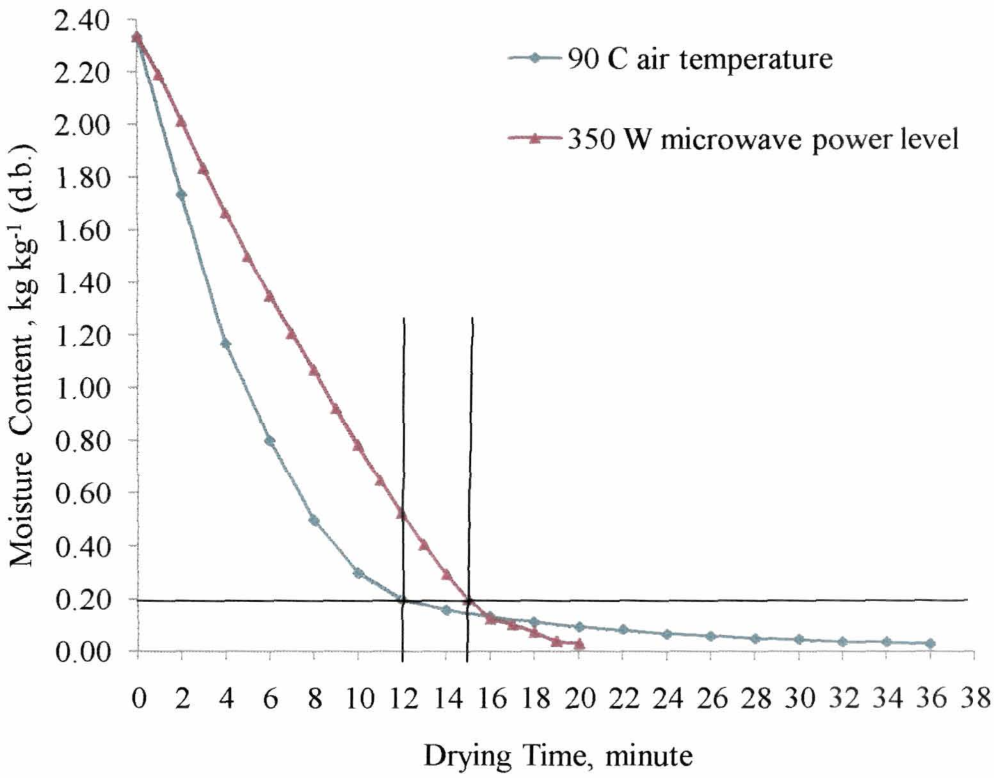


Fig. 5.1 Variation of moisture content (d.b.) with time at air temperatures of 90 ^{0}C and microwave power level of 350 W.

The variation of drying rate with moisture content for the two modes of drying (hot air drying at 90 ^{0}C and microwave drying at 350 W power level) is presented in Fig. 5.2. It is observed that, drying rate is higher in hot air drying than microwave drying up to moisture content of 0.2 kg kg^{-1}(d.b.), but microwave drying can remove moisture faster than hot air drying after crossing the moisture content of

0.2 kg kg^{-1} (d.b.). Further it is found that, drying time is reduced by 79%, when using microwave to dry CTC tea from 0.2 to 0.03 kg kg^{-1} (d.b.) compared to hot air drying.

It is also reported elsewhere earlier that, microwave drying of foods or food ingredients at high moisture content (over 20% moisture) is not economical [53, 130, 131]. While citing a special case, it is reported that, at high moisture content the cost of natural gas heated hot-air process is only 30% of the microwave energy cost [131]. Conventional heating methods remove water more effectively than microwaves at high moisture contents. Higher specific heat of water suppresses the advantage of higher dielectric constant of water to absorb microwave. Therefore, considerable amount of microwave energy would be needed to raise the temperature for dehydration if the bulk of water is high [132].

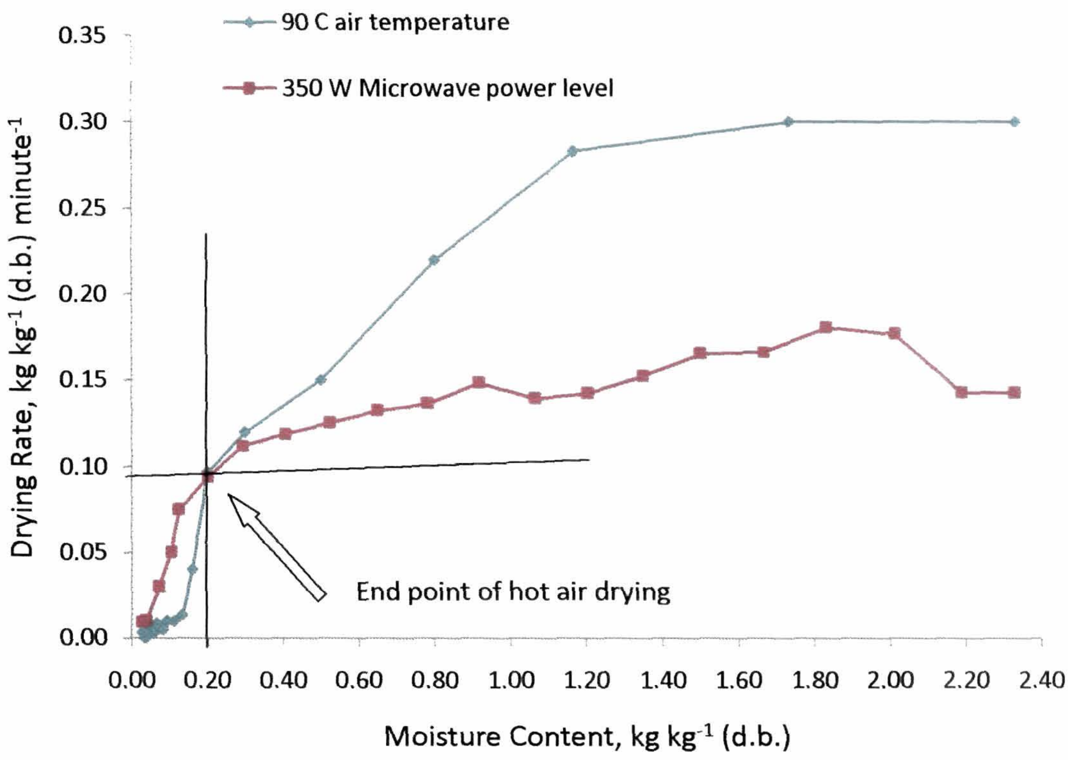


Fig. 5.2 Variation of drying rate with moisture (d.b.) content for two different modes of drying

From the above analysis, it is observed that for CTC tea (i) hot air drying is more efficient than microwave drying up to 0.2 kg kg^{-1} (d.b.) moisture content and (ii) microwave drying is more efficient than hot air drying from 0.2 kg kg^{-1} (d.b.) moisture content up to end point.

Based on this analysis the combined mode of drying is planned such that (i) hot air drying is carried out up to 0.2 kg kg^{-1} (d.b.) and then (ii) sample is subjected to microwave heating up to 0.03 kg kg^{-1} (d.b.) to complete the drying process. The details of the microwave assisted hot air drying experiments are presented below.

5.2 Experimental set-up and methodology used in microwave assisted hot air drying of CTC tea

As mentioned in the Chapter 3, CTC tea samples are collected from Tea Research Association, Tocklai Experimental Station, Assam India (Appendix Table A1) for all the experiments. Such tea samples are dried in a tray dryer (details are described in Chapter 4) subjected to variation of air temperature (80, 90 and 95 ^{0}C). For each level of temperature drying are continued up to tea moisture of 0.2 kg kg^{-1} (d.b.). Moisture loss is measured by a digital balance. The partially dried tea samples at 0.2 kg kg^{-1} (d.b.) are then transferred to a microwave oven. In the microwave oven, samples are further dried at three levels of power *viz.*, 170, 350 and 525 W. The moisture loss is determined by repeated weighing of the sample with a digital balance. Drying is carried out until the moisture content of the sample reduced to 0.03 kg kg^{-1} (d.b.). Drying time of each experiment is recorded. Total drying time in microwave assisted hot air drying is calculated by adding drying time required for hot air drying (from 2.33 to 0.2 kg kg^{-1} (d.b.)) and microwave drying (from 0.2 to 0.03 kg kg^{-1} (d.b.)) for each combination. There are altogether nine treatments of drying with variation of temperature of hot air and microwave power level as summarized in Table 5.1. The treatments are named as E1, E2, E3, E4, E5, E6, E7, E8 and E9 for convenience of discussion. Running order for each run is randomized in order to minimize possible systematic errors.

Table 5.1 Drying treatments for combine hot air-microwave drying

SI. No.	Representation of experiments	Experimental variables	
		Hot air temperature, ^{0}C	Microwave power, W
1	E1	80	175
2	E2	90	175
3	E3	95	175
4	E4	80	350
5	E5	90	350
6	E6	95	350
7	E7	80	525
8	E8	90	525
9	E9	95	525

5.3 Determination of specific energy consumption in hot air, microwave and microwave assisted hot air drying of CTC tea

As discussed earlier, energy consumption is a crucial aspect in tea drying. Specific energy consumption (*SEC*) is one of the performance indicators of drying method. It is defined as the amount of energy needed to evaporate a unit mass of water during drying. Apart from the characteristic features of the sample, there are many system dependent factors which influence the magnitude of *SEC*. The variation of *SEC* results of the laboratory scale drying and industrial drying will be presented later.

The CTC tea samples used in the three modes of drying of *viz.*, (i) hot air drying, (ii) microwave drying and (iii) microwave assisted hot air drying are identical with reference to sample weight, tea types and processing techniques prior to drying. Moreover, electrical energy is used for operation of all three experimental set-ups. While conducting the drying experiments as discussed earlier (Chapter 4), observation on energy consumption and time of drying are recorded for estimation of specific energy consumption. The energy meter (Model: D02A, China) reading given in kW (average power consumption) during drying operation is suitably converted to MJ kg^{-1} of water removed using the corresponding observation of (i) amount of moisture remove, kg and (ii) time taken in minute. In case of microwave assisted hot air drying, the observation of power, moisture removes and time are separately taken for both mode and added up.

The specific energy consumptions (*SEC*) of hot air drying for different air temperatures are presented in Fig. 5.3. The *SEC* for hot air drying of CTC tea at air temperatures of 80, 90 and 95 ^{0}C are 7.80, 6.63 and 6.12 MJ kg^{-1} respectively. It is observed that, *SEC* decreases 15% with every 10 ^{0}C rise (from 80 to 90 ^{0}C) of air temperature. On the other hand, for the next 5 ^{0}C rise (from 90 to 95 ^{0}C) of air temperature, *SEC* decreases by 7.7%. *SEC* decreases linearly with an increase in air temperature within the temperature range of 80 to 95 ^{0}C. Similar trends are reported for different food products *viz.*, onion [85], potato [124], rice [133] during hot air drying and presented in Appendix A9.

The specific energy consumptions for drying of CTC tea at different microwave power level *viz.*, 175, 350, 525, 700 and 875 W are presented in Fig. 5.4. Highest *SEC* (6.00 MJ kg^{-1}) is observed for microwave power levels of 175 and 350 W. *SEC* decreases with the increase in microwave power level. The least *SEC* (5.20 MJ kg^{-1}) is observed with 875 W microwave power level, which is 13% less than the highest value. The lower microwave drying power consumes the highest energy for the same moisture loss. One of many reasons might be that the drying time is longer under lower power and results in the increased energy consumption. Similar findings of reduction of energy consumption with the increase of microwave power are reported for microwave drying of carrot [52], potato slice [55] and spinach [87].

The specific energy consumption for drying of CTC tea at different microwave assisted hot air drying combination is presented in Fig. 5.5. It is observed that the treatment E9 (95 ^{0}C, 525 W) under study resulted least specific energy consumption (2.60 MJ kg^{-1}). On the other hand, highest *SEC* of 4.17 MJ kg^{-1} is observed with E1 (80 ^{0}C, 175 W) treatment, which is 60% more than E9 treatment. For, fixed microwave power, high drying temperature reduces specific energy consumption. Another notable observation is that, highest specific energy is consumed in CTC tea drying, when hot air with 80 ^{0}C is combined with any level of microwave power.

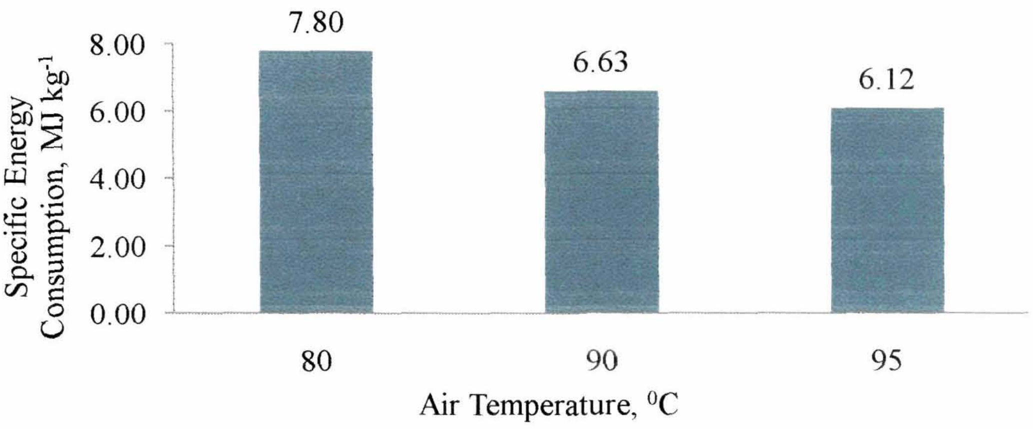


Fig. 5.3 Specific energy consumption during hot air (thin layer) drying of CTC Tea

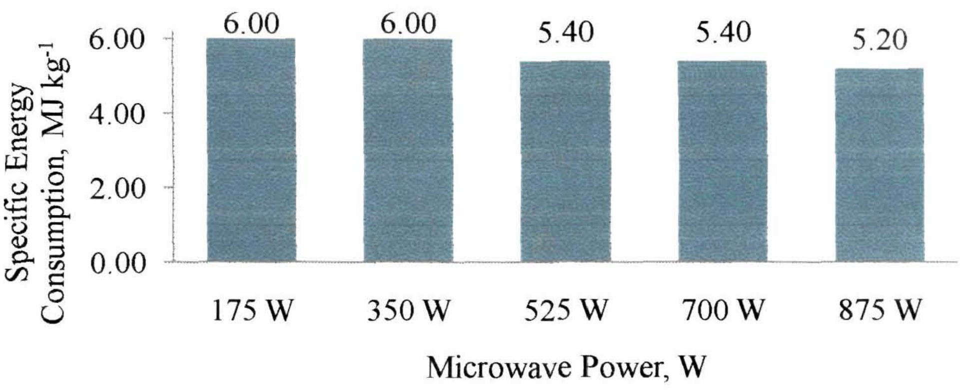


Fig. 5.4 Specific energy consumption during microwave drying of CTC Tea

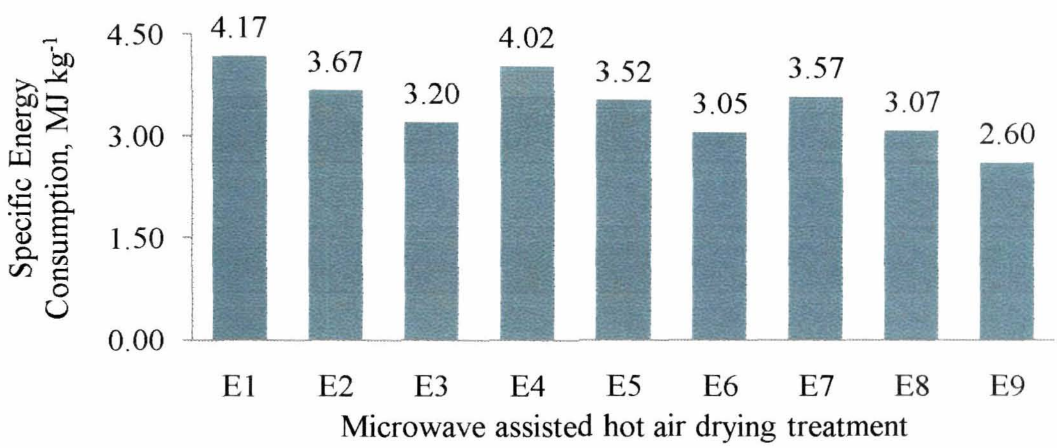


Fig. 5.5 Specific energy consumption of microwave assisted hot air drying of CTC Tea

5.4 Assessment of tea quality of CTC tea

In the present investigation, drying experiments are conducted using laboratory scale drying set up which have already been discussed (Section 4). The moisture content of the dried sample is a parameter to decide the end of the drying process for all the drying options/experiments used in the present study. Further, the specific energy consumptions are assessed to analyse the relative merits. Quality of the final product is also, influential and significant parameters to reflect the efficiency of the process. However, quality assessment of tea is relatively difficult due to the absence of universal methods of standard. The established procedure of assessing tea quality for commercial purpose has been an assessment of the sensory quality through designated Tea Taster.

Sensory quality characteristics of black tea are assessed by using either sight, smell, and/or taste of the beverage [134]. Several studies have demonstrated linkages between the sensory quality characteristics of black tea, chemical composition of the green leaf and the black tea processing parameters [135, 136]. In assessing tea quality, appearance of made tea is used as one of the criteria, primarily because it gives an idea of the standard of manufacture. However, a sample of tea is judged mainly from its liquor characteristics. Designated Tea Tasters evaluate the quality by considering specific characteristics of liquor *viz.*, (i) colour, (ii) strength, (iv) brightness, (iv) briskness and (v) thickness in tea [137]. Tea Tasters assess the quality in tea by three sensory methods i.e. eye (sight), tongue (taste) and nose (smell). The quality parameters perceived by the eye and the tongue are collectively called black tea quality parameters [138], which include brightness, briskness, thickness and the colour of the infusions. It is reported that these attributes are due to the presence of biochemicals like catechins, theaflavins, thearubigins, residual chlorophylls and caffeine [134]. Moreover, flavour of black tea determined by nose is due to volatile flavor compounds.

Table 5.2 Taster's score on made tea from three modes of drying (hot air drying, microwave drying and microwave assisted hot air drying)

Mode of drying	Variable process parameters, *T*- *P*	Taster's score					
		colour	strength	brightness	briskness	thickness	Total
Hot air drying	80 ^{0}C	5	3	4	5	4	21
	90 ^{0}C	6	4	5	6	5	26
	95 ^{0}C	6	4	5	5	5	25
Microwave drying	175 W	6	6	6	4	4	26
	350 W	6	6	5	4	4	25
	525 W	6	6	5	4	4	25
	700 W	4	5	3	4	4	20
	875 W	4	5	3	4	4	20
Microwave assisted hot air drying	E1 (80 ^{0}C - 175 W)	5	5	5	5	4	24
	E2 (90 ^{0}C - 175 W)	8	7	5	5	5	30
	E3 (95 ^{0}C - 175 W)	8	7	5	5	5	30
	E4 (80 ^{0}C - 350 W)	5	5	5	5	4	24
	E5 (90 ^{0}C - 350 W)	8	7	5	5	5	30
	E6 (95 ^{0}C - 350 W)	8	7	5	5	5	30
	E7 (80 ^{0}C - 525 W)	5	5	4	4	4	22
	E8 (90 ^{0}C - 525 W)	6	5	4	4	4	23
	E9 (95 ^{0}C - 525 W)	6	5	4	4	4	23

Sensory quality characteristics are assessed for the processed tea samples of all the experimental treatment considered for this investigation. The dryer mouth samples are selected randomly from two replications of each temperature (*viz.*, 80, 90 and 95 ^{0}C) in hot air drying and each microwave power level (*viz.*, 175, 350 and 525 W) in microwave drying. On the other hand, one sample from each microwave assisted hot air drying treatment (*viz.*, E1, E2, E3, E4, E5, E6, E7, E8 and E9) is collected. Samples are kept in air tight plastic bags and sent for quality assessment.

The made tea sample is evaluated by the designated Tea Taster from a recognized laboratory (Tea Research Association, Tocklai Experimental Station, India). A ten point scale for five parameters *viz.*, (i) colour, (ii) strength, (iii) brightness, (iv) briskness and (v) thickness of liquor are used by Tea Taster [76]. The five individual parameter scores are added to obtain the total score out of 50 points. The Tea Taster's scores for three sets of hot air, five sets of microwave drying and nine sets of microwave assisted hot air drying experiments are presented in Table 5.2 and discussed below.

The performance of individual quality parameters are also investigated and presented in Table 5.2 for all the drying treatments of three modes of drying. No distinguishing trend could be observed amongst the group as well as treatment within the group in general. However, it appears two quality parameters; namely colour and strength have dominated influence on overall quality score. All the four treatments (*viz.*, E2, E3, E5 and E6) bearing highest colour and strength scores belongs to combine mode of drying. On the other hand, the colour scores at higher levels (750 and 875 W) of microwave power in microwave mode of drying result lowest score. Further, it is noted that deterioration of strength scores occurs with hot air drying.

5.5 Optimisation of process parameters (hot air temperature and microwave power) for combine drying mode

The specific energy consumption and quality of made tea in three modes of drying (*viz.*, hot air drying, microwave drying and microwave assisted hot air drying) are discussed earlier in this Chapter. It is observed that, in general microwave assisted hot air drying consumes less specific energy than the other two modes of drying. Quality of made tea processed from microwave assisted hot air drying is also better than that processed from hot air and microwave drying alone. Thus, microwave assisted hot air drying seems to be a potential option for CTC tea processing. Further, it is noticed that, temperature of hot air and level of microwave power affect both specific energy consumption and quality of made tea. Therefore, in microwave assisted hot air CTC tea drying the process variable (*viz.*, temperature of hot air and microwave energy) has to be optimised for least specific energy consumption and better quality.

Design of experiment (DOE) is one of the reliable decision making tools used by researchers for identifying optimal process parameters. This tool has gained a wide application in the field of control, modeling and optimisation of process parameters probably due to its capability to handle multiple process parameters [139].

The methodology of DOE available in literature [140] is used to identify optimum process parameters in the present study. The principal steps followed in the DOE method are shown in Fig. 5.6 and 5.7. For a successful experiment, it is crucial that key parameters have to be identified. In microwave assisted hot air CTC tea drying, the control parameters (hot air temperature and microwave power), and response parameters (specific energy consumption and quality of made tea) are identified from the knowledge of previous experiments as discussed earlier in this Chapter. The next step is to specify an experimental range and a suitable level for each control parameter. This step is crucial because the use of an inappropriate experimental range or unsuitable parameter levels generally leads to result of poor quality and difficult to analyse [141]. The results of earlier experiments for (i) specific energy consumption and (ii) quality of made tea enables to identify the range of control parameters *viz.*, (i) temperature and (ii) microwave power level. Once all the parameters and their experimental domains have been identified, the next step is to prepare the list of experiments to be performed. The list, also called planning matrix, should contain treatments of all the possible combinations of the parameters to be evaluated. In the present case, nine possible treatments comprising three levels of temperature (80, 90 and 95 ^{0}C) and microwave power level (175, 350 and 525 W) are combined as planning matrix.

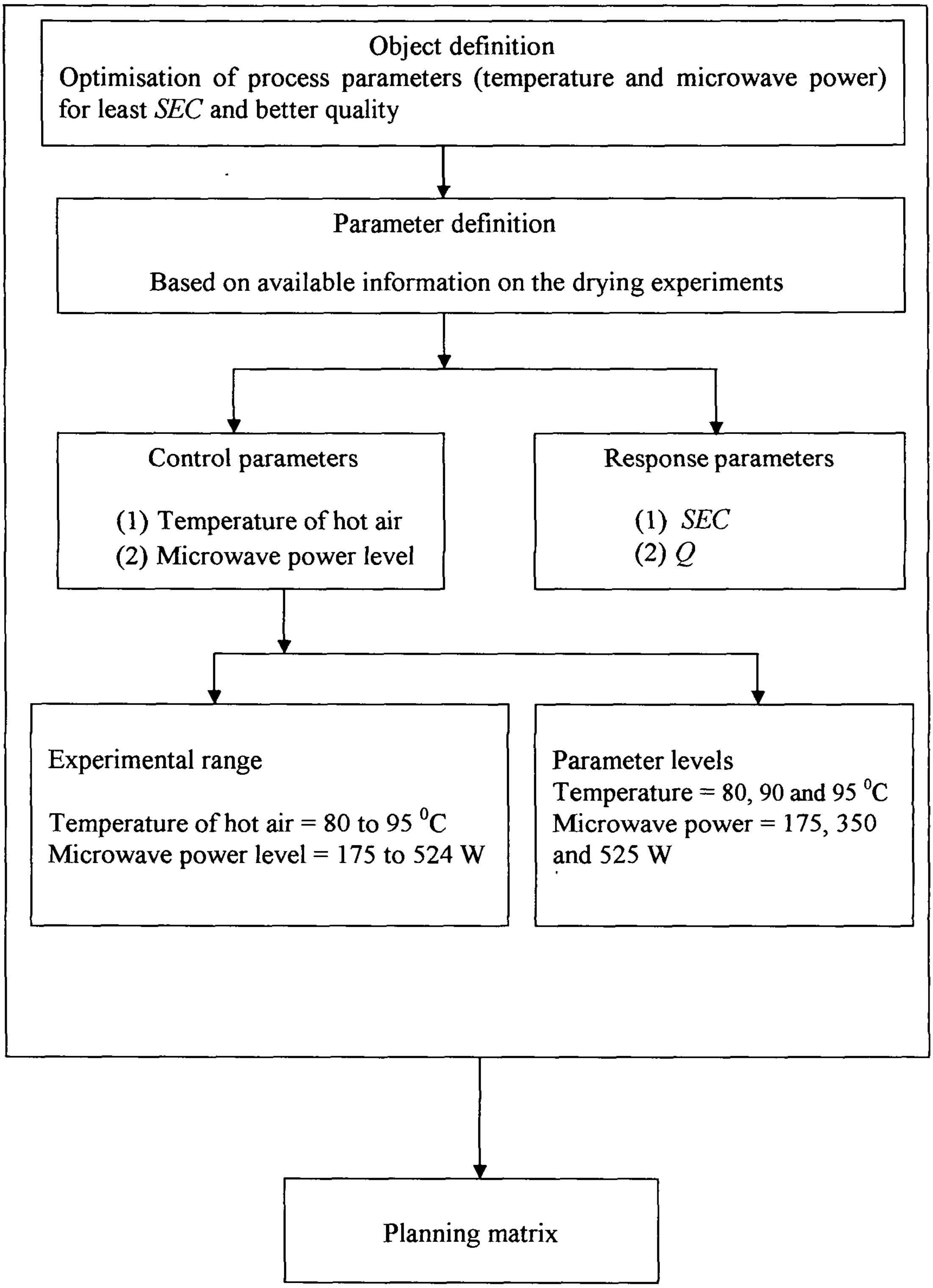


Fig. 5.6 Planning for application of DOE in optimising process parameters of CTC tea drying

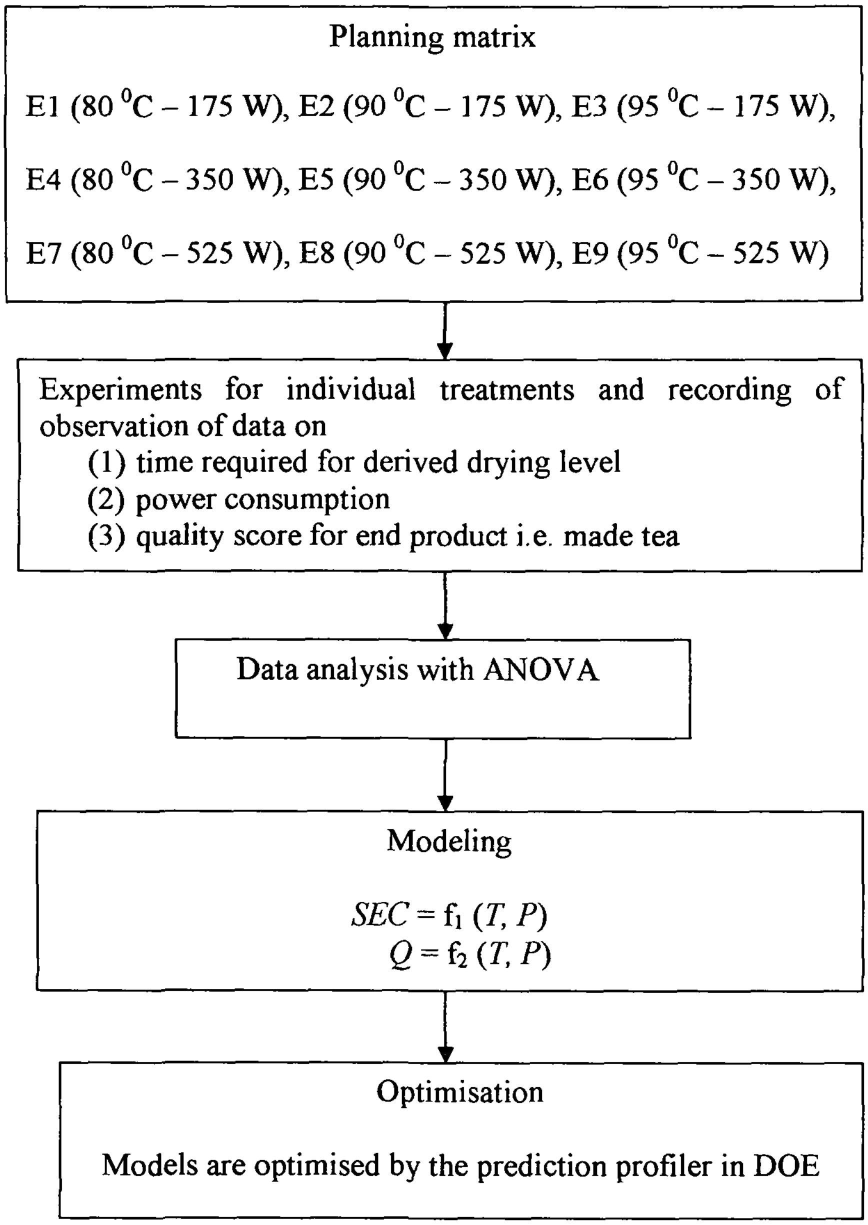


Fig. 5.7 Steps of execution of DOE in optimising process parameters

Fig. 5.7 provides a schematic depiction of the steps required to optimise the control parameters in microwave assisted hot air drying. The microwave assisted hot air drying experiments are performed according to the planning matrix. The experimental set-up and methodology are described earlier in this chapter. The response parameters (*viz.*, specific energy consumption and quality of made tea) of the experiment are estimated as discussed earlier and presented in Table 5.3.

Table 5.3 Experimental matrix of the factorial design and the results (response parameters) obtained from the drying experiments

	Control parameters		Response parameters	
Treatment	Hot air temperature (T), ^{0}C 2.33 to 0.2 (d.b.)	Microwave power (P), W 0.02 to 0.03 (d.b.)	Combine *SEC*, MJ kg^{-1}	Total quality score
E1	80	175	4.17	24
E2	90	175	3.67	30
E3	95	175	3.20	30
E4	80	350	4.02	24
E5	90	350	3.52	30
E6	95	350	3.05	30
E7	80	525	3.57	22
E8	90	525	3.07	23
E9	95	525	2.60	23

The results (Table 5.3) are statistically analysed by analysis of variance (ANOVA) using statistical software JMP 7.0.1. The results of ANOVA for quality and specific energy consumption are given in Tables 5.4a and 5.4b respectively. Statistical analysis (Table 5.4a and 5.4b) implies that the variability of microwave power level and hot air temperature has influence on quality of made tea and its specific energy consumption.

Table 5.4a Analysis of variance for the factorial model (Response parameter: Q).

Source	DF	Sum of square	F Ratio	Prob > F
Model	3	83.63889	6.3604	0.0369 *
P	1	42.666667	9.7338	0.0263 *
T	1	33.531746	7.6498	0.0396 *

Table 5.4b Analysis of variance for the factorial model (Response parameter: *SEC*)

Source	DF	Sum of square	*F* Ratio	Prob > *F*
Model	3	1.9103	36.8137	0.00008 *
P	1	0.5400	31.2190	0.0025 *
T	1	1.3703	79.2220	0.0003 *

Regression models are fitted for the response parameters (Q and *SEC*) as given below.

$$Q = 4.2143 - 0.01524 \times P + 0.3095 \times T \quad \dots \dots \dots (5.1)$$

$$SEC = 9.55714 - 0.0017 \times P - 0.06257 \times T \quad \dots \dots \dots (5.2)$$

These models describe the effect of variable process parameters and their interactions on the responses i.e. quality and specific energy consumption. It is found that, increase in drying air temperature T, increases quality. The quality of made tea decreases with increases in microwave power (Eq.5.1). On the other hand, increase in microwave power and hot air temperature reduces specific energy consumption (Eq. 5.2). However, the modeling outcomes would be valid within the operating range of the present investigation.

In the present investigation variability have been limited to three levels for each of the variables *viz*., temperature (80, 90 and 95 ^{0}C) and microwave power level (175, 350 and 525 W). Accordingly, the corresponding responses (*viz*., Q and *SEC*) are recorded. The module of the DOE and software is used to predict the responses for all the possible combinations of interpolated values within the set ranges of T and P. The graphical outputs of the prediction are presented in Fig. 5.8.

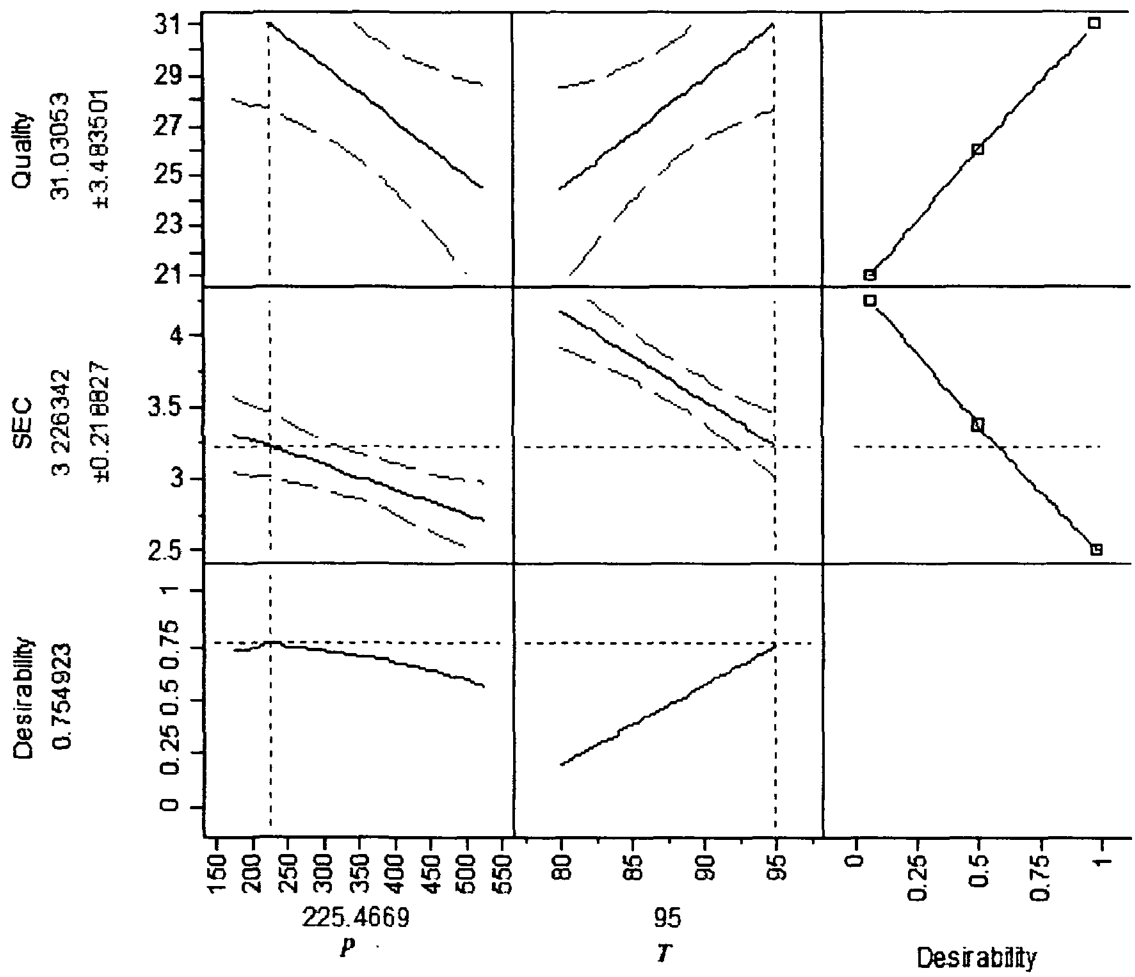


Fig. 5.8 Application of experimental results for determination of optimum Prediction profiler

It is to be noted that the desirability of the present investigation is to maximize quality and minimize specific energy consumption. From the graphical outputs, it is seen that, the best quality (with a corresponding score = 31.03) and least specific energy consumption (3.23 MJ kg^{-1}) can be obtained with 95 ^{0}C hot air drying for the first phase and operating microwave at 225 W for the next phase of drying.

Results presented so far concerns laboratory scale experiment. The findings give useful information on different aspects concerning drying parameters and also comparison between different modes of drying kinetics. The findings and comparative performance of CTC tea drying, using different options (hot air alone, microwave alone, microwave assisted hot air drying) are valid and useful indicator for the process engineer dealing with tea processing. The projection of information for industrial scale may not be realistic. To assess the validation of laboratory experimental results, particularly on specific energy consumption, an attempt is made to collect data from local CTC tea process industries. The data (total drying time, weight of made tea produce, fuel consumption and electrical energy consumption) was collected from three tea processing industries in Assam, India (details of which is presented in Appendix A10) and is used for estimation of specific energy consumption. In these industrial units, natural gas is used as for generating thermal energy for tea drying. Moreover, electricity is used to operate blower for handling hot air and motor for driving drying machinery. The input thermal and electrical energy and quantity of processed tea along with the initial and final moisture content of tea are collected daily basis. Finally, the thermal energy (MJ) and electrical energy (MJ) per kg of moisture removal for all the three processing units are assessed, and results are presented, and discussed below. Details estimation procedure is presented in Appendix A10.

The specific thermal and electrical energy consumption in tea drying for the selected three tea factories are presented in the Fig. 5.9. Dominance of thermal energy is prominent in all the three processing units as seen from the Fig. 5.9. The variation of specific energy consumption amongst the three factories may be due to variation in capacity and machinery available in these factories. Further investigation of the reasons of these variations is not in scope of the present study.

As discussed earlier, energy consumption in tea drying has been one key consideration of the present study. Specific energy consumption is used as a parameter to assure different modes of laboratory scale drying considered in this study. *SEC* is also used as a response variable for optimizing process parameter while investigating prospects of combine mode of drying consisting hot air drying and microwave drying. Further, *SEC* for drying in three industrial tea processing unit is also assessed. The results of *SEC* for drying with different options have already been presented earlier. A summarized comparison is made among *SEC* for drying of

CTC tea in three industrial units, hot air drying, microwave drying and drying with optimal process variable.

In general, it is observed that specific energy consumption of industrial units is higher than corresponding experimental results. All the factories use hot air drying and factory C exhibits lowest *SEC* (6.968 MJ kg^{-1}). The experimental hot air drying consumes 12% lower *SEC* than factory C.

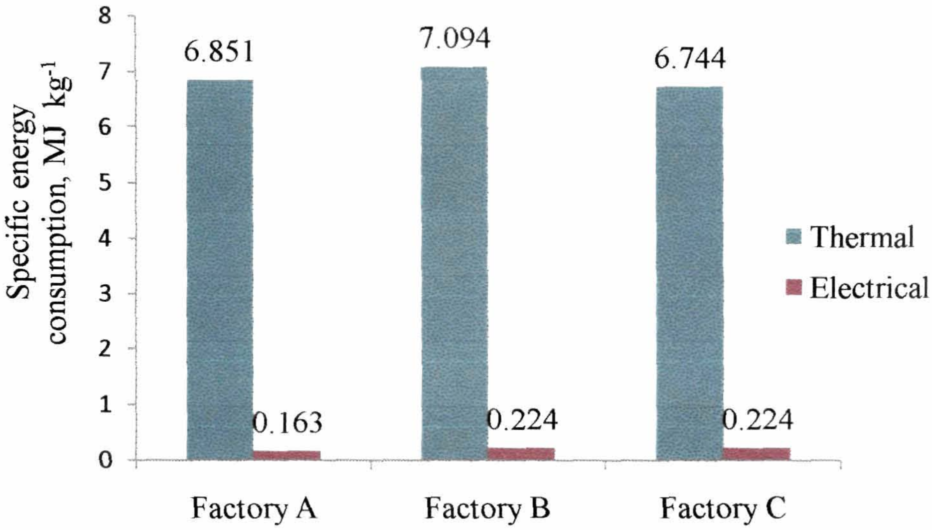


Fig. 5.9 Specific energy consumption in tea drying at three different factories

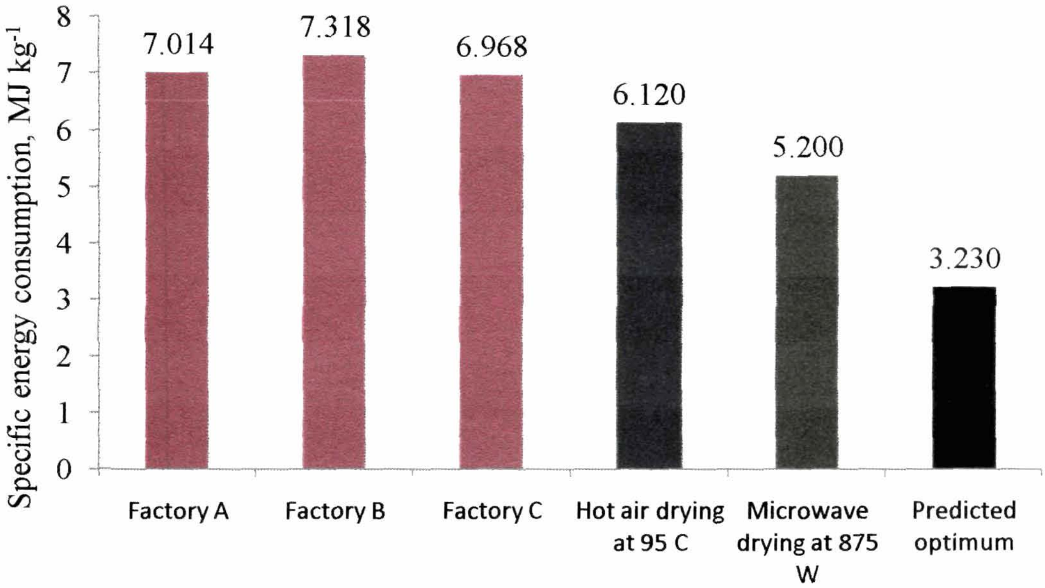


Fig. 5.10 Comparison of specific energy consumption in tea drying

Experimental unit operated on electrical heating and electrical energy recorded through energy meter is used for assessment of energy, whereas industrial units use natural gas. The difference in the energy conversion devices along with the scale of production might have cause the variation of *SEC* between industrial hot air drying and experimental hot air drying. These may require further investigation.

However, the minimum *SEC* is exhibited by optimal scenario (predicted performance of combine mode of hot air and microwave drying with optimal process parameter), amongst all the options investigated in the present study. The use of microwave energy during the tail end of drying might have substantially reducing the drying time and hence the energy in combine mode of drying. Thus, this result is an indication of the prospect for combine mode of CTC tea drying, i.e. microwave assisted hot air drying.

CHAPTER 6

SUMMARY AND CONCLUSIONS

Chapter 6

Summary and conclusions

The focus of the present study has been to investigate the prospect of a new tea drying technique ensuring quality production at optimum energy use. A series of experiments (using standard experimental set-up) is conducted taking dry ready CTC tea samples of a local cultivar (T3E3) to investigate (i) desorption isotherm, (ii) best fit thin layer drying model with (a) hot air and (b) microwave as drying medium and (iii) prospects of microwave assisted hot air drying using optimization for minimum specific energy consumption and achieve best quality. The findings of the investigation are summarized below.

6.1 Modeling desorption isotherm behaviour of CTC tea

The CTC tea of T3E3 cultivar exhibits type II isotherm of BET classification. Equilibrium moisture content of the sample decreases with an increase in ambient temperature. All the models under study (*viz.*, (i) BET, (ii) GAB, (iii) Peleg, (iv) Halsey, (v) Oswin and (vi) Henderson) are showing some degree of fitting to the experimental data. However, Oswin model is found the best fitted model to predict desorption isotherm behaviour of CTC tea for the entire temperature range of 30 to 90 ^{0}C.

The equilibrium moisture content of CTC tea as a function of ambient temperature (T) and water activity (a_w) could be modeled using Oswin model as given below.

$$M_e = (0.099 - 0.00066 \times T) \times \left(\frac{a_w}{1-a_w}\right)^{(0.4352+0.0035\times T)}$$

Desorption isotherm model for CTC tea of T3E3 cultivar, which is not available, would be a useful tool for analyzing the drying process of this type of tea.

6.2 Estimation of monolayer moisture content of CTC tea

The monolayer moisture content (M_m) of CTC tea of T3E3 cultivar is found to decrease with the increase in temperature. Although, Oswin model can successfully predict desorption isotherm of CTC tea, but this model is silent about the monolayer moisture content of food product. Both GAB and BET models could provide an estimation of monolayer moisture content. However, GAB model is better fitted with the experimental results and therefore, considered for the estimation of monolayer moisture content. A temperature dependent linear relationship is found for predicting monolayer moisture content of CTC tea as given below.

$$M_m = 0.0568776 - 0.0002958 \times T$$

The lower safe limit of moisture content for a given storage condition (*i.e.* temperature) could be predicted for CTC tea of T3E3 cultivar using the above relation.

6.3 Estimation of net isosteric heat of desorption of CTC tea

The outcome of desorption isotherm is extended to determine net isosteric heat of desorption using standard procedure available in the literature. The net isosteric heat of desorption of CTC tea of T3E3 cultivar decreases from 896 to 35 kJ kg^{-1} with the increase of equilibrium moisture content from 0.03 to 0.25 kg kg^{-1} (d.b.). The decrease of net isosteric heat of desorption with an increase in moisture content is exponential and can be considered stabilized, when the moisture in tea is greater than 0.20 kg kg^{-1} (d.b.). The variations of net isosteric heat of desorption (Δh_d) with equilibrium moisture content (M_e) of CTC tea can be expressed using the following relationship.

$$\Delta h_d = 5.167 \times M_e^{-1.53}$$

The above information seems to be useful for assessing theoretical energy requirement in drying CTC tea of T3E3 cultivar.

6.4 Drying kinetics of CTC tea in thin layer hot air drying

In hot air drying the moisture content rapidly reduces and then reduction becomes slow with drying time. Drying temperature has distinguished effect on the total drying time. The rate of moisture loss is higher at a higher temperature, and the total drying time is reduced substantially with the increase in air temperature. The drying time required to reduce the moisture content of CTC tea from 2.33 to 0.03 kg kg^{-1} (d.b.) are 46, 36 and 32 minutes at 80, 90 and 95 ^{0}C, respectively. Thus, drying at 95 ^{0}C instead of 80 ^{0}C can reduce drying time by 30%. It is observed that, drying rate increases with an increase in temperature, however, the steps are not uniform throughout the entire range of drying. Relatively flat curve up to 1.5 kg kg^{-1} (d.b.) moisture content for all the three levels of temperature illustrated the presence of constant drying rate period. The moisture removal in the falling rate is also substantial for all the drying temperatures.

The existing theory on drying hygroscopic material is also applicable for CTC tea, using the experimental results to estimate effective moisture diffusivity and activation energy. The generation of new findings on moisture diffusivity is expected to provide a better understanding on drying of this product and then would be useful for the process engineer. The effective moisture diffusivity increases with an increase in temperature. At air temperature of 80, 90 and 95 ^{0}C, value of effective moisture diffusivity of CTC tea are estimated as 5.5162×10^{-9}, 7.1569×10^{-9} and 7.739×10^{-9} m^2 s^{-1}, respectively. The estimated value of activation energy of CTC tea is 24.88 kJ mol^{-1}.

6.5 Drying kinetics of CTC tea in microwave drying

Drying time reduces significantly with the increase in the microwave power within the range used in the present investigation. The time required to reduce the moisture contents of tea sample from 2.33 to 0.03 kg kg^{-1} (d.b.) for microwave power level of 175, 350, 525, 700 and 875 W are 40, 20, 12, 9 and 7 minutes respectively. Thus, highest level of power (875 W) reduces the drying time by 78% compared to lowest power (175 W). It is also observed that, drying rate is increased with the increase in microwave power. Constant drying rate period (2.33 to 0.26 kg kg^{-1} (d.b.)) for a given moisture range is observed, which is true for all the microwave power levels. About 88% moisture is removed is attributed to this period of drying The constant rate period is followed by a falling rate period in which moisture content changes from 0.26 to 0.03 kg kg^{-1} (d.b.).

There is a distinct difference of drying kinetics between hot air drying and microwave drying of CTC tea.

6.6 Modeling thin layer drying behaviour of CTC tea

The experimental results of the thin layer drying process are used to model drying kinetics of CTC tea, both in hot air and microwave drying.

Midilli et al. model is found the best fit model to predict thin layer drying behaviour of CTC tea, in hot air drying. Moisture ratio (*MR*) of CTC tea as a function of drying air temperature (*T*) is modeled by using the experimental results in Midilli et al. model as given below.

$$MR = \left[1.0044 \times e^{\left\{(0.4932-0.0072\times T)\times t_1^{(1.5226-0.0041\times T)}\right\}}\right] + 0.0007 \times t_1$$

Page model is found the best fit model to predict thin layer drying behaviour of CTC tea, in microwave drying. Moisture ratio (*MR*) of CTC tea as a function of microwave power (*P*) is modeled by using the experimental results in Page model as given below.

$$MR = e^{\left[-\{10^{-7}\times P^2-6\times10^{-5}\times P+0.041\}\times t_1^{(0.336\ln P-0.478)}\right]}$$

Similar to the information on desorption isotherm, the drying model would be a useful tool for the process engineer and dryer designer while considering CTC tea.

6.7 Microwave assisted hot air drying

The variation of drying rate with moisture content for the two modes of drying (hot air drying at 90 ^{0}C and microwave drying at 360 W power level) indicates that, drying rate is higher in hot air drying than microwave drying up to moisture content of 0.2 kg kg^{-1} (d.b.). After crossing the moisture content of 0.2 kg kg^{-1} (d.b.), microwave drying can remove moisture faster than hot air drying. Further it is found that, drying time is reduced by 79%, when using microwave to dry CTC tea from 0.2 to 0.03 kg kg^{-1} (d.b.) compared to hot air drying for this range of moisture.

The need of combine mode of drying, such that (i) hot air drying is carried out up to 0.2 kg kg^{-1} (d.b.) and then (ii) microwave heating up to 0.03 kg kg^{-1} (d.b.) is realized for the comparison of results of drying experiments.

6.8 Specific energy consumption in drying

In hot air drying, specific energy consumption (*SEC*) decreases linearly with an increase in air temperature within the temperature range considered in this study. *SEC* for hot air drying of CTC tea at air temperatures of 80, 90 and 95 ^{0}C are 7.80, 6.63 and 6.12 MJ kg^{-1} respectively. It is observed that, *SEC* decreases 15% with 10 ^{0}C rise (80 to 90 ^{0}C) of air temperature. On the other hand, for the next 5 ^{0}C rise (90 to 95 ^{0}C) of air temperature, *SEC* decreases by 7.7%.

In general, *SEC* decreases with the increase in microwave power level. The least *SEC* (5.20 MJ kg^{-1}) is observed with 875 W microwave power level, which is 13% less than the highest value. The lower microwave drying power consumes the highest energy for the same moisture loss.

The results of combine mode of CTC tea drying (hot air and microwave) indicate a prospect of reduction of *SEC*. Amongst the different experimental combination of (hot air temperature and microwave power), least *SEC* (2.60 MJ kg^{-1}) is resulted while initial drying is performed at 95 ^{0}C air temperature and subsequently exposed to 525 W microwave power.

6.9 Assessment of tea quality of CTC tea in hot air, microwave and microwave assisted hot air drying

No distinguishing trend of overall quality score could be observed amongst different treatment (*i.e.* hot air drying, microwave drying and hot air assisted microwave drying). However, it appears two quality parameters namely colour and strength have dominating influence on overall quality score. In general, combine mode of drying resulted highest colour and strength scores. On the other hand, the colour scores at a higher level (750 and 875 W) of microwave power in microwave mode of drying result lowest score. Further, it is noted that deterioration of strength scores occurs with hot air drying alone.

6.10 Optimisation of process parameters (hot air temperature and microwave power) for combine drying mode

The variability of microwave power level (*P*) and hot air temperature (*T*) has influence on quality of made tea and its specific energy consumption. Quality (*Q*) and specific energy consumption (*SEC*) for CTC tea in microwave assisted hot air drying are modeled using experimental results and standard model tool as given below.

$$Q = 4.2143 - 0.01524 \times P + 0.3095 \times T$$

$$SEC = 9.55714 - 0.0017 \times P - 0.06257 \times T$$

Increase in drying air temperature (*T*) increases quality. The quality of made tea decreases with increases in microwave power. On the other hand, increase in microwave power and hot air temperature reduces specific energy consumption. Best quality represented by the highest quality score and least specific energy consumption (3.23 MJ kg^{-1}) are predicted with 95 ^0C hot air drying (first phase) and operating microwave at 225 W (next phase) of drying of CTC tea. The specific energy consumption of CTC tea drying using combine mode of drying is lower than the values estimated for the industrial scale drying.

6.11 Conclusions

Some specific conclusions of the present work are listed below.

1. Oswin model in found the best fit model to predict desorption isotherm behaviour of CTC tea of T3E3 cultivar for temperature range from 30 to 90 ^0C.
2. The monolayer moisture content of CTC tea of T3E3 cultivar is found to decrease with the increase in temperature.
3. The decrease of net isosteric heat of desorption of CTC tea with the increase in moisture content is exponential and can be considered stabilized, when the moisture in tea is greater than 0.20 kg kg^{-1} (d.b.).
4. Midilli et al. model represents the thin layer hot air drying of CTC tea with specific model parameters. The Page model with a different set of model parameters is also represented the microwave drying.
5. Temperature of hot air has an effect on drying kinetics of CTC tea. The effective moisture diffusivity of CTC tea increases with the increase in temperature.
6. Microwave power level of e has an effect on drying kinetics of CTC tea.
7. A combined mode of drying (95 ^0C-225 W) is better than the individual drying, both in terms of quality and specific energy consumption of CTC tea.

6.12 Suggestions for future works

1. The present investigation is related to a certain tea cultivar T3E3 of *Camellia assamica*. However, there are other tea races and cultivars with varying physical and chemical properties. Usefulness of the result of T3E3 cultivar for other tea races and cultivars needs to be investigated.

2. The effect of temperature and microwave power on specific energy consumption (*SEC*) and quality of made tea is estimated for fixed air velocity. It is expected that, hot air velocity has a certain effect on *SEC* and quality. So, there is scope for extending this work to investigate the effect of air velocity on these two parameters.

3. The reason behind the change of quality parameters due to change of drying mode need further investigation.

4. The data for combine mode of drying used for the analysis is generated using two laboratory scale individual experimental set-up having provision for batch mode of drying. In spite of care taken, error might be incorporated while transferring sample from one mode of drying to the other mode. So, for better result, a single unit (combining the hot air dryer and microwave dryer) is suggested for further investigation.

REFERENCES

[1] ITC Annual Bulletin Supplement 2012. http: // www. teaboard.gov.in /pdf / Global Tea_prod, Exp and AvPr_29052012.pdf, accessed on 10/02/2013.

[2] Mann, H.H. *The Early History of the Tea Industry in North-East-India*, D.L.Monro, the Calcutta General Printing Co. Ld., Calcutta, 1918.

[3] Mishra, R.K., et al. Molecular analysis of tea clones (Camellia Sinensis) using AFLP markers, *International Journal of Integrative Biology* **5**, 130-135, 2009.

[4] Banerjee, B. *Tea Production and Processing*, Oxford & IB HPublishing Company Pvt. Limited, New Delhi, 1993.

[5] Barbora, D.N. Firing of tea, *Two and A Bud* **9** (2), 9-13, 1962.

[6] Basu, R.P., & Ullah, M.R. Tea fermentation, *Two and A Bud* **25** (1), 7-11, 1978.

[7] Goswami, M.R. & Gogoi, M.N. Fermentation in tea, Lecture Course on Manufacturing of Tea, 1999, Tocklai Experimental Station, Jorhat, Assam.

[8] Muthumani, R., & Senthil, Kumar, R.S. Influence of fermentation time on the development of compounds responsible for quality in black tea, *Food Chemistry* **101**, 98-102, 2007.

[9] Choudhury, R. Drying of tea in N. E. India with conventional commercial driers, *Two and A Bud* **14** (4), 152-153, 1967.

[10] Jangam, S.V., & Muzumdar, A.S. Basic Concepts and Definitions, in *Drying of Foods, Vegetables and Fruits*, Jangam, S.V. et al., eds., 2010, **1**, 1-30.

[11] Henderson, S.M. A basic concept of equilibrium moisture, *Agricultural Eng.* **33**, 29-32, 1952.

[12] Labuza, T.P. Sorption phenomena in foods, *Food Technology* **22**, 263-265, 268, 270 & 272, 1968.

[13] Brennan, J.G. *Food Engineering Operations*, Applied Science Publishers Limited, London, UK, 1976.

[14] Watson, E.L., & Harper, J.C. *Elements of Food Engineering*, Van Nostrand Reinhold Company, New York, 1988, 252-285.

[15] Williams-Gardner, A. *Industrial Drying*, Leonard Hill. London. 1971, 1-9 & 20-37.

[16] King, C.J. Rates of moisture sorption and desorption in porous, dried foodstuffs, *Journal of Food Technology* **22**, 509-515, 1968.

[17] Labuza, T.P., et al. Mathematical models for optimization of flexible film packaging of foods for storage, *Transactions of the American Society of Agricultural Engineers* **15** (1), 50-155, 1972.

[18] Chirife, J., & Iglesias, H.A. Equations for fitting water sorption isotherms of foods: Part 1: A review, *Journal of Food Technology* **13**, 159-174, 1978.

[19] Basu, S., et al. Models for sorption isotherms for food: A review, *Drying Technology* **24**, 917-930, 2006.

[20] Peleg, M. An empirical model for the description of moisture sorption curves, *Journal of Food Science* **53**, 1249–1251, 1988.

[21] Halsey, G. Physical adsorption on non-uniform surfaces, *Journal of Chem. Phys.* **16**, 931-937, 1948.

[22] Oswin, C.R. The kinetics of package life III-Isotherm, *Journal of the Society of Chemical Industry* **65**, 419–421, 1946.

[23] Wolf, W., et al. Standardization of isotherm measurements (COST-Project 90 and 90 BIS), in *Properties of Water in Foods*, D. Stimatos & J.L. Multon, eds., Martinus Nijhoff Publishers, Dordrecht, the Netherlands, 1985, 661-679.

[24] Aggarwal, K.K., et al. Investigation into the theories of desorption isotherms for rough rice peanuts, *Journal of Food Science* **36**, 919-924, 1971.

[25] Botheju, W.S., et al. Modeling moisture desorption isotherms and thermodynamic properties of fermented tea dhool, *Drying Technology* **26**, 1294-1299, 2008.

[26] Rizvi, S.S.H. Thermodynamics properties of foods in dehydration, in *Engineering Properties of Food*, 3rd ed., M.A. Rao, et al., eds., CRC Press, NewYork, 2005, 239-326.

[27] Tsami, E. Net isosteric heat of sorption in dried fruits, *Journal of Food Engineering* **14**, 325–327, 1991.

[28] Iglesias, H.A., & Chirife, J. A model for describing the water sorption behavior of foods, *Journal of Food Science* **41**, 984-992, 1976.

[29] Geankoplis, C.J. *Transport Processes and Unit Operations*, 3rd ed., Prentice Hall, USA, 1993.

[30] Chirife, J. Fundamentals of the drying mechanism during air dehydration of foods, in *Advances in Drying*, A.S. Mujumdar, ed., Hemisphere Publishing Corp. Washington DC, 1983, **2**, 73-102.

[31] Vaccarezza, L.M., et al. Kinetics of moisture movement during air drying of sugar beet root, *J. Food Technol* **9**, 317-327, 1974.

[32] Karel, M., & Lund, D.B. *Physical Principles of Food Preservation*, 2nd ed., Marcel Dekker Inc., New York, 2003.

[33] Wang, N., & Brennan, J.G. Effect of water binding on the drying behaviour of potato, in *Drying*, A.S. Muzumdar, ed., Elsevier Science Publishers, London, 1992, 1350-1359.

[34] Saravacos, G.D., & Charm, S.E. A study of the mechanism of fruit and vegetable dehydration, *Food Technology* **16** (1), 78-81, 1962.

[35] Marinos-Kouris, M., & Maroulis, Z.B. Transport Properties in the Drying of Solids, *Handbook of Industrial Drying*, A.S. Mujumdar, ed., CRC Press, Boca Raton, Florida, United States. 2006, 82-145.

[36] Sablani, S., et al. Moisture diffusivity in foods-an overview, in *Drying Technology in Agriculture and Food Science*, Science Publishers, Inc., Enfield, NH, 2000.

[37] Saravacos, G.D., & Maroulis, Z.B. *Transport properties of Foods*, Marcel Dekker Inc., New York, 2001.

[38] Lomauro, C. J., et al. Moisture transfer properties of dry and semi-moist foods, *Journal of Food Science* **50**, 397-400, 1985.

[39] Tutuncu, A.M., & Labuza, T.P. Effect of geometry on the effective moisture transfer diffusion coefficient, *Journal of Food Engineering* **30**, 433-447, 1996.

[40] Doymaz, I. Convective air drying characteristics of thin layer Carrots, *Journal of Food Engineering* **61**, 359-364, 2004.

[41] Doymaz, I. Drying kinetics of white mulberry, *Journal of Food Engineering* **61**, 341-346, 2004.

[42] Okos, M.R., et al. Food dehydration, in *Handbook of Food Engineering*, D.R. Hedman & D.B. Lund, eds., Marcel Dekker, New York, 1992, 439-562.

[43] Rayaguru, K., & Routray, W. Mathematical modeling of thin layer drying kinetics of stone apple slices, *International Food Research Journal* **19** (4), 1503-1510, 2012.

[44] Midilli, A., et al. A new model for single layer drying, *Drying Technology* **20** (10), 1503-13, 2002.

[45] Fortes, M., & Okos, M. R. Non-equilibrium thermodynamics approach to heat and mass transfer in corn kernels, *Transactions of ASAE* **22**, 761-769, 1981.

[46] Parry, J.L. Mathematical modeling and computer simulation of heat and mass transfer in agricultural grain drying, *Journal of Agricultural Engineering Research* **32**, 1–29, 1985.

[47] Sharaf-Eldeen, Y.I., et al. A model for ear corn drying, *Transactions of ASAE* **23**, 1261-1265, 1980.

[48] Henderson, S. M., & Pabis, S. Grain drying theory I. Temperature effect on drying coefficient, *Journal of Agriculture Engineering Research* **6** (3), 169-174, 1969.

[49] Lewis, W.K. The rate of drying of solids materials, *Industrial Engineering Chemistry* **13**, 427, 1921.

[50] Wang, C.Y., & Singh, R.P. Use of variable equilibrium moisture content in modeling rice drying,. *Transactions of ASAE* **78** (6), 6505, 1978.

[51] Soysal, Y. Mathematical modeling and evaluation of microwave drying kinetics of mint (*Mentha spicata L.*), *Journal of Applied Sciences* **5** (7), 1266-1274, 2005.

[52] Wang, J., & Xi, Y.S. Drying characteristics and drying quality of carrot using a two-stage microwave process, *Journal of Food Engineering* **68**, 505-511, 2005.

[53] Maskan, M. Microwave/air and microwave finish drying of banana, *Journal of Food Engineering* **44**, 71-78, 2000.

[54] Sharma, G.P., & Prasad, S. Drying of garlic (*Allium sativum*) cloves by microwave-hot air combination, *Journal of Food Engineering* **50**, 99-105, 2001.

[55] Darvishi, H., et al. Mathematical modeling, moisture diffusion, energy consumption and efficiency of thin layer drying of potato slices, *Journal of Food Process Technology* **4** (3), 2-6, 2013.

[56] Evin, D. Microwave drying and moisture diffusivity of white mulberry: experimental and mathematical modeling, *Journal of Mechanical Science and Technology* **25** (10), 2711-2718, 2011.

[57] Dadali, G., et al. Microwave drying kinetics of okra, *Drying Technology* 25, 917-924, 2007.

[58] Ozkan, I.A., et al. Microwave drying characteristics of spinach, *Journal of Food Engineering* **78**, 577-583, 2007.

[59] Soysal, Y. Microwave drying characteristics of parsley, *Biosystems Engineering* **89**, 167-173, 2004.

[60] Schiffmann, R.F. Microwave and Dielectric Drying, in *Handbook of Industrial Drying*, A.S. Mujumdar, ed., CRC Press, Boca Raton, Florida, United States. 2006, 286-356.

[61] Zhang, M., et al. Trends in microwave related drying of fruits and vegetables, *Journal of Food Science and Technology* **17**, 524-534, 2006.

[62] Bouraoui, M., et al. Microwave and convective drying of potato slices, *Journal of Food Process Engineering* **17**, 353-363, 1994.

[63] Feng, H., & Tang, J. Microwave finish drying of diced apples in spouted bed, *Journal of Food Science* **63** (4), 679-683, 1998.

[64] Han, W., et al. Residence time distribution and drying characteristics of a continous vibro-fluidized Bed, *Drying Technology* **9** (1), 159-181, 1991.

[65] Maskan, M., & Gogus, F. Sorption isotherms and drying characteristics of mulberry (*Morus alba*), *Journal of Food Engineering* **42**, 225-233, 1998.

[66] Panchariya, P.C., et al. Modeling of desorption isotherm of black tea, *Drying Technology* **19**, 1177-1188, 2001.

[67] Ghodake, H.M., et al. Moisture sorption isotherms, heat of sorption and vaporization of withered leaves, black and green tea, *Journal of Food Engineering* **78**, 827-835, 2007.

[68] Moraes, M.A., et al. Moisture sorption isotherms and thermodynamic properties of apple Fuji and garlic, *International Journal of Food Science Tech*nology **43** (10), 1824-1831, 2008.

[69] Mulet, A., et al. Equilibrium isotherms and isosteric heats of morel (*Morchella esculenta*), *Journal of Food Engineering* **53**, 75–81, 2002.

[70] Igathinathane, C., et al. Moisture sorption thermodynamic properties of corn stover fractions, *American Society of Agricultural and Biological Engineers* **50** (6), 2157-2160, 2007.

[71] Ethmane Kane, C.S., et al. Moisture sorption isotherms and thermodynamic properties of two mints: Menthapulegium and Mentharetundifolia, *Rev. Energies Renouvelables* **11**, 181-195, 2008.

[72] Janjai, S., et al., Measurement and modeling of moisture morption isotherm of litchi (*Litchi Chinensis Sonn.*), *International Journal of Food Properties* **13**, 251–260, 2010

[73] Gazor, H.R. Moisture isotherms and heats of desorption of canola, *Agricultural Engineering International*, **12** (2), 79-84, 2010.

[74] Filho, L.M., et al., Moisture sorption isotherms of fresh and blanched pumpkin (*Cucurbita moschata*), *Cienc Tecnol. Aliment. Campinas* **31** (3), 714-722, 2011.

[75] Chiste, R.C., et al. Sorption isotherms of tapioca flour, *International Journal of Food Science and Technology* **47**, 870–874, 2012.

[76] Temple, S.J., et al. The effect of drying on black tea quality, *Journal of the Science of Food and Agriculture* **81**, 764-772, 2001.

[77] Gupta, P., et al. Drying characteristics of red chilli, *Drying Technology* **20** (10), 1975-1987, 2002.

[78] Panchariya, P.C., et al. Thin-layer modelling of black tea drying process, *Journal of Food Engineering* **52**, 349-357, 2002.

[79] Togrul, I.T., & Pehlivan, D. Modelling of drying kinetics of single apricot, *Journal of Food Engineering* **58**, 23-32, 2003.

[80] Naheed, Z., et al. Effect of rolling, fermentation and drying on the quality of black tea, *Sarhad Journal of Agriculture* **23** (3), 577-588, 2007.

[81] Mohammadi, A., et al. Moisture content modeling of sliced kiwifruit (c.v. Hayward) during drying, *Pakistan Journal of Nutrition* **8** (1), 78-82, 2009.

[82] Taheri-Garavand, A., et al. Mathematical modeling of thin layer drying kinetics of tomato influence of air dryer conditions, *International Transaction Journal of Engineering, Management, & applied science and technology* **2** (2), 147-160, 2011.

[83] Radhika, G.B. et al. Mathematical model on thin layer drying of finger millet (*Eluesine coracana*), *Advance Journal of Food Science and Technology* **3** (2), 127-131, 2011.

[84] Motevali, A. et al. Effective moisture diffusivity, activation energy and energy consumption in thin-layer drying of jujube (Zizyphus jujube Mill), *J. Agr. Sci. Tech.* **14**, 523-532, 2012.

[85] EL-Mesery, H.S., & Mwithiga, G. Comparison of a gas fired hot-air dryer with an electrically heated hot-air dryer in terms of drying process, energy consumption and quality of dried onion slices, *African Journal of Agricultural Research* 7 (31), 4440-4452, 2012.

[86] Soysal, A., et al. Microwave drying of parsley: modelling, kinetics, and energy aspects, *Biosystems Engineering* **93** (4), 403-413, 2006.

[87] Alibas Ozkan, I., et al. Microwave drying characteristics of spinach, *Journal of Food Engineering* **78**, 577-583, 2007.

[88] Darvishi, H. Mathematical modeling, moisture diffusion and energy consumption in thin layer drying of alfalfa, *Middle-East Journal of Scientific Research* **12** (4), 511-516, 2012.

[89] Funebo, T., & Ohlsson, T. Microwave-assisted air dehydration of apple and mushroom, *Journal of Food Engineering* **38**, 353-367, 1998.

[90] Kaensup, W., & Wongwises, S. Combined microwave/fluidized bed drying of Fresh Peppercorns, *Drying Technology* **22** (4), 779-794, 2004.

[91] Wang, Z., et al. Mathematical modeling on thin layer microwave drying of apple pomace with and without hot air pre-drying, *Journal of Food Engineering* **80**, 536-544, 2007.

[92] Karaaslan, S.N., & Tuncer, I.K. Development of a drying model for combined microwave-fan-assisted convection drying of spinach, *Biosystems Engineering* **100**, 44-52, 2008.

[93] Noor, Z.Z., et al. Microwave vacuum drying of guava, *Jurnal Teknologi* **49**, 567-577, 2008.

[95] Nadee, A., et al. Microwave and combined hot air/infrared radiation of pandanus leaf: drying kinetic and specific energy consumption, TIChE International Conference 2011, Hatyai, Songkhla Thailand.

[96] Ranjbaran, M., & Zare, D. A new approach for modeling of hot air-microwave thin layer drying of soybean, *Electronic Journal of Polish Agricultural Universities* **15** (3), 2012.

[97] Wight, W. Tea classification revised. *Curr. Sc.*, **31**, 298-299, 1962.

[98] Ahmed, A., et al. Release of clones from the Estates in North East India under TRA clonal selection scheme, *Two and A Bud* **9** (2), 9-13, 1986.

[99] Greenspan, L. Humidity fixed points of binary saturated aqueous solutions, *Journal of Research of the National Bureau of Standards* **81A**, 89-112, 1977.

[100] Horwitz, W. (ed.), *Official Methods of Analysis of AOAC INTERNATIONAL*, 17th ed., AOAC International Suit 500, USA, 1984.

[101] Iglesias, H.A., & Chirife, J. *Handbook of Food Isotherms*, Academic Press, NewYork, 1982.

[102] Mujumdar, A. S. Principles, Classification, and Selection of Dryers, in *Handbook of Industrial Drying*, A.S. Mujumdar, ed., CRC Press, Boca Raton, Florida, United States, 2006, 4-31.

[103] McLaughlin, C.P., & Magee, T.R.A. The effect of shrinkage during drying of potato spheres and the effect of drying temperature on vitamin C retention, *Trans. Inst. Chem. Eng.* **76**, 138-142, 1998.

[104] Da Silva, M., et al. Desorption and isosteric heat of mango pulp, *Rev. Bras. Eng. Agric. Ambient.* **6** (1), 123-127, 2002.

[105] Gouveia, J., et al. Mathematical models for adjustment of desorption isotherms of Banana variety silver, *Eng. Agric.* **24** (3), 799-806, 2004.

[106] Montes, E., et al. Models of desorption isotherms of yam (Dioscorea rotundata), *Dyna.* **76** (157), 145-152, 2009.

[107] Chen, C. Factors which affect equilibrium relative humidity of agricultural products, *Transactions of the American Society of Agricultural Engineers* **43**, 673-683, 2000.

[108] Rizvi, S. S. H., & Benado, A.L. Thermodynamic analysis of drying foods, *Drying Technology* **2** (4), 471-502, 1984.

[109] Cenkowski, S., et al. Latent heat of vaporization for selected foods and crops, *Canadian Agricultural Engineering* **34** (3), 281-286, 1992.

[110] Billiris, M.A., et al. Estimating the theoretical energy required to dry rice, *Journal of Food Engineering* **107**, 253-261, 2011.

[111] Zuritz, C.A., & Singh, R.P. An equation to compute the heat of evaporation of water for rough rice during drying, *Drying Technology* **3** (3), 421–435, 1985.

[112] Mulet, A., et al. Sorption isosteric heat determination by thermal analysis and sorption isotherms, *Journal of Food Science* **64** (1), 64-68, 1999.

[113] Aviara, N.A., & Ajibola, O.O. Thermodynamics of moisture sorption in Melon seed and cassava, *Journal of Food Engineering* **55** (2), 107-113, 2002.

[114] Temple, S.J., & Van Boxtel, A.J.B. Fluidization of tea, *Journal of Agricultural Engineering Research* **74**, 5-11, 1999.

[115] Joseph, S. (ed.), *ASAE S448*, 45^{th} ed., ASABE, USA, 1998.

[116] Xia, B., & Sun, D.W. Application of computational fluid dynamics (CFD) in the food industry: a review, *Computer and Electronics in Agriculture* **34**, 5-24. 2002.

[117] Mathioulakis, E., et al. Simulation of air movement in a dryer by computational fluid dynamics: application for the drying of fruits, *Journal of Food Engineering* **36**, 182-200, 1998.

[118] Temple, S.J., & Van Boxtel, A.J.B. Thin layer drying of black tea, *Journal of Agriculture Engineering Research* **74**, 167-176, 1999.

[119] Mazza, G., & Le Maguer, M. Dehydration of onion: some theoretical and practical considerations, *Journal of Food Technology* **15**, 181-194, 1980.

[120] Madamba, P.S., et al. The thin-layer drying characteristics of garlic slices, *Journal of Food Engineering* **29** (1), 75-97, 1996.

[121] Lopez, A., et al. Thin layer drying behaviour of vegetable waste from wholesale market, *Drying Technology* **88**, 995-1006, 2000.

[122] Datta, A.K., & Anantheswaran, R.C. *Handbook of Microwave Technology for Food Applications*, Marcel Dekker Inc., NewYork, 2001.

[123] Crank, J. *The mathematics of diffusion*, Claredon Press, Oxford, England, 1975.

[124] Chayjan, R.A. Modeling some drying characteristics of high moisture potato slices in fixed, semi fluidized and fluidized bed conditions, *Journal of Agricultural Science Technology* **14**, 1229-1241, 2012.

[125] Roberts, J.S., et al. Drying kinetics of grape seeds, *Journal of food engineering* **89,** 460-465, 2008.

[126] Doymaz, I. Thin layer drying behavior of mint leaves, *Journal of Food Engineering* **74** (3), 370-375, 2006.

[127] Kaleemullah, S., & Kailappan, R. Modelling of thin layer drying kinetics of red chillies, *Journal of Food Engineering* **76**, 531–537, 2005.

[128] Meisami-asl, E., et al. Mathematical modeling of moisture content of apple slices (var. golab) during drying, *Pakistan Journal of Nutrition* **8** (6), 804-809, 2009.

[129] Prabhanjan, D.G., et al. Microwave-assisted convective air drying of thin layer carrots, *Journal of Food Engineering* **25**, 283-293, 1995.

[130] Mudgett, R.E. *Microwave food processing, Food Technology* **43** (1) 117-126, 1989.

[131] IEA, Energy Prices and Taxes, The International Energy Agency, 1996, http://www.iea.org, accessed on 12/06/2012.

[132] Owusu-Ansah, Y.J. Advances in microwave drying of foods and food ingredients, *J. Inst. Can. Sci. Technol. Aliment* **24** (3), 102-107, 1991.

[133] Akaranuchat, P., et al. Combining radio frequency drying with hot air oven for energy reduction in GABA rice, International Research on Food Security, Natural Resource Management and Rural Development 2012, Georg-August University Gottingen and University of Kassel-Witzenhausen, Tropentag, Gottingen, Germany, 19-21.

[134] Obanda, M., et al. Changes in the chemical and sensory quality parameters of black tea due to variations of fermentation time and temperature, *Food Chemistry* **75**, 395–404, 2001.

[135] Biswas, A.K., et al. Biological and chemical factors affecting the valuations of North-East Indian Plains teas. II.- Statistical evaluation of the biochemical constituents and their effects on briskness, quality and cash valuations of black teas, *Journal of Science and Food Agriculture* **24**, 1457-1477, 1973.

[136] Roberts, E. A. H., & Smith, R. F. The phenolic substances of manufactured tea IX.-the spectrophotometric evaluation of tea liquors, *Journal of Science and Food Agriculture* **14**, 689–700, 1963.

[137] Barua, D.N. Tea Quality, *Two and A Bud* **39** (2), 2-6, 1992.

[138] Pal, M., et al. A statistical approach to study the subjectivity of Tea Tasters' Scores, *Two and A Bud* **44** (2), 15-18, 1997.

[139] Badache, M., et al. A full 3^4 factorial experimental design for efficiency optimization of an unglazed transpired solar collector prototype, *Solar Energy* **86**, 2802-2810, 2102.

[140] SAS Publishing. *Design of Experiments Guide, Release 7*, SAS Institute Inc, Cary, NC, USA, 2007.

[141] Wu, C.F., & Hamada, M. *Experiments: Planning, Analysis and Optimisation,* 2nd ed., Wiley, Hoboken, USA, 2009.

[141] Ricardo, D., et al. Models of sorption isotherms for food: Uses and limitations, *Journal Vitae* **18**(3), 325-334, 2011.

[142] Pancharyia, P.C., et al. Desorption isotherm modeling of black tea using artificial neural networks, *Drying Technology* **20**, 351–362, 2002.

[143] Peng G., et al. Modeling of water sorption isotherm for corn starch, *Journal of Food Engineering* **80**, 562–567, 2007.

[144] Janjai, S., et al. Neural network modeling of sorption isotherms of longan,

Computers and Electronics in Agriculture **66** (2), 209-214, 2009.

[145] Lin, X., et al. Effect of drying technologies on quality of green tea, *International Agricultural Engineering Journal* **19** (3), 30-37, 2010.

[146] Basu, R. P., Drying of Tea, *Two and A Bud* **20**(1), 27-33, 1973.

LIST OF PUBLICATIONS

Hatibaruah, D. et al. Modeling desorption isotherms and thermodynamic properties of Assam CTC manufactured from tea cultivar T3E3, *Journal of Food Processing and Preservation* **35**, 729–738, 2011.

Hatibaruah, D. et al. Microwave drying characteristics of Assam CTC tea (*Camellia assamica*), *Journal of Food Processing and Preservation*, doi:10.1111/j.1745-4549.2011.00656.x

Appendix A1. Details of CTC tea sample used in experiment

Experiments	Variables	Sample collected, g	Date of collection
Thermodynamic characterisation of CTC tea	30 ^{0}C	200	03/4/2009
	40 ^{0}C	200	28/4/2009
	50 ^{0}C	200	19/5/2009
	80 ^{0}C	200	04/5/2012
	90 ^{0}C	200	15/5/2012
	30 ^{0}C	200	29/5/2009
	40 ^{0}C	200	23/6/2009
	50 ^{0}C	200	17/7/2009
	80 ^{0}C	200	22/5/2012
	90 ^{0}C	200	08/6/2012
	30 ^{0}C	200	04/8/2009
	40 ^{0}C	200	25/8/2009
	50 ^{0}C	200	15/8/2009
	80 ^{0}C	200	15/6/2012
	90 ^{0}C	200	26/6/2012
Best fit drying model for conventional hot air drying of CTC tea	80 ^{0}C	200	26/4/2011
	90 ^{0}C	200	28/4/2011
	95 ^{0}C	200	29/4/2011
	80 ^{0}C	200	03/5/2011
	90 ^{0}C	200	06/5/2011
	95 ^{0}C	200	10/5/2011
Best fit drying model for microwave drying of CTC tea	175 W	200	04/5/2010
	350 W	200	07/5/2010
	525 W	200	07/5/2010
	700 W	200	11/5/2010
	875 W	200	11/5/2010
	175 W	200	14/5/2010
	350 W	200	18/5/2010
	525 W	200	18/5/2010
	700 W	200	21/5/2010
	875 W	200	21/5/2010
Microwave assisted hot air drying of CTC tea	80 ^{0}C -175 W	200	24/4/2012
	90 ^{0}C - 175 W	200	27/4/2012
	95 ^{0}C - 175 W	200	08/5/2012
	80 ^{0}C - 350 W	200	11/5/2012
	90 ^{0}C - 350 W	200	18/5/2012
	95 ^{0}C - 350 W	200	25/5/2012
	80 ^{0}C - 525 W	200	29/5/2012
	90 ^{0}C - 525 W	200	05/6/2012
	95 ^{0}C - 525 W	200	12/6/2012

Appendix A2. Water activities of the saturated salt solutions at different temperatures used in the desorption experiments.

	Water activity				
Salt	30^0 C	40^0 C	50^0 C	80^0 C	90^0 C
KOH	0.0735	0.0626	0.0572	----	----
$MgCl_2$	0.3238	0.3159	0.3054	0.2505	0.2412
K_2CO_3	0.4317	0.4230	0.4091	----	----
$NaNO_3$	0.7275	0.7100	0.6904	0.6522	0.6500
KCl	0.8362	0.8332	0.8120	0.7890	0.7850
$BaCl_2$	0.8980	0.8910	0.8823	---	-----
LiBr	0.0616	0.0580	0.0553	0.0520	0.0526
LiCl	0.1128	0.1121	0.1110	0.1051	0.1023
KI	0.6789	0.6609	0.6449	0.6097	0.6021

Appendix A3. Oven dry method for determination of initial moisture content of CTC tea sample

(1) Empty container along with its cover is weighed.

(2) The sample is mixed thoroughly with a small spoon and two small portions of samples are weighed directly into the containers.

(3) After weighing, the cover or lid of the container is removed and the open container is kept in the oven, which has already been heated to the prescribed drying temperature.

(5) At the end of the drying period, container is closed with its cover or lid.

(6) The container is allowed to cool in a desiccator.

(7) The sample is weighed again and the moisture content in dry basis is calculated by the following formula:

$$M = \frac{M2 - M3}{M3 - M1}$$

where,

M = seed moisture content, kg kg^{-1} (d.b.)

$M1$ = weight of the empty container with its cover, g

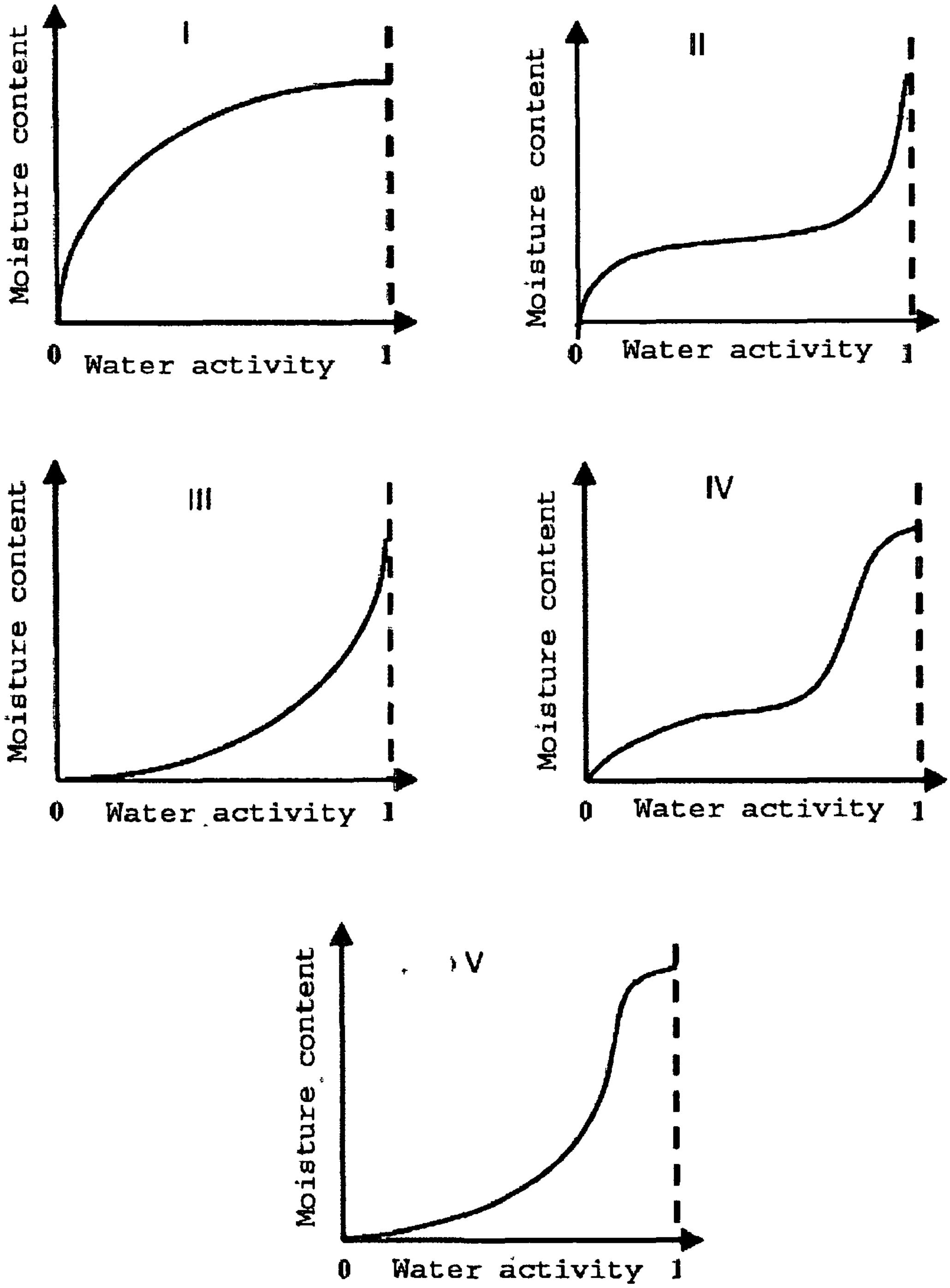
$M2$ = weight of the container with its cover and seeds before drying, g

$M3$ = weight of the container with its cover and seeds after drying, g

Appendix A4: Equilibrium moisture content data of CTC tea

Temperature, ^{0}C	Water Activity, a_w	Equilibrium Moisture Content (d.b.)
30	0.0735	0.0200
	0.3238	0.0518
	0.4317	0.0675
	0.7275	0.1358
	0.8362	0.1890
	0.8980	0.2547
40	0.0626	0.0152
	0.3159	0.0421
	0.4230	0.0616
	0.7100	0.1256
	0.8362	0.1800
	0.8910	0.2423
50	0.0572	0.0128
	0.3054	0.0390
	0.4091	0.0554
	0.6904	0.1120
	0.8120	0.1621
	0.8823	0.2321
80	0.0520	0.0090
	0.1051	0.0200
	0.2605	0.0300
	0.6097	0.0700
	0.7890	0.1200
90	0.0526	0.0060
	0.1023	0.0090
	0.2412	0.0120
	0.6021	0.0540
	0.7850	0.1000

Appendix A5. The five types of BET isotherms



Appendix A6. Measurement of mass flow rate in hot air drying experiment

- Diameter of air flow pipe = 8 cm = 0.08 m
- Cross sectional area of the pipe a_1 = 50.265 cm^2 = 50.265 x 10^{-4} m^2
- Diameter of orifice plate = 3 cm = 0.03 m
- Cross sectional area of orifice a_0 = 7.07 cm^2 = 7.07 x 10^{-4} m^2
- Coefficient of discharge of orifice plate C_d = 0 62
- Sp. Gravity of mercury, S_g = 13.6
- Sp. Gravity of air, S_0 = 1
- Density of air, ρ = 1.16 kg m^{-3}

Manometer Reading, x, m	Differential head, m $h = x(\frac{S_g}{S_0} - 1)$	Volume of air inlet to dryer , m^{3}s^{-1} $V_1 = \frac{C_d\, a_0 a_1 \sqrt{2gh}}{\sqrt{(a_1^2 - a_0^2)}}$	Velocity of air, m s^{-1} $v = \frac{V_1}{a_1}$	Mass flow rate of air, kg s^{-1} $\rho a v$
0.08	1.008	1.969 x 10^{-3}	0.4	2.33 x 10^{-3}

Appendix A7. Power measurement Test Procedure-IMPI 2-Liter Test

The oven is operated at its rated line voltage with a load of 2000 ± 5 g water placed in two 1-litre beakers. The beakers should initially be at room ambient temperature. Initial water temperature should be $20^0C \pm 2^0C$, measured after water is placed in beakers and before placing in the microwave oven. The beakers are placed in the center of the oven, side by side in the width dimension of the cavity, and touching each other. The oven is turned on for 2 minute and 2 s. The beakers are removed from the oven, and the final temperatures are measured and recorded.

The power is calculated from the following formula:

$$P(W) = 70 \times \frac{\Delta T_1 + \Delta T_2}{2}$$

where ΔT_1 and ΔT_2 are the temperature rises (^0C) of the water in the two beakers, calculated by subtracting the initial water temperature from the final temperature.

Experiments		P1		P2		P3		P4		P5	
		T_1	T_2	T_1	T_2	T_1	T_2	T_1	T_2	T_1	T_2
1	T_i ^0C	21.5	21.5	21	21	20	20	21	21	22	22
	T_f ^0C	24	24	26	26	27.5	27.5	31	31	34.5	34.5
	ΔT	2.5	2.5	5	5	7.5	7.5	10	10	12.5	12.5
	P (W)	175		350		525		700		875	
2	T_i ^0C	21	21	21	21	20	20	21	21	21.5	21
	T_f ^0C	23.5	23.5	26	26	27.5	27.5	31	31	34	33.5
	ΔT	2.5	2.5	5	5	7.5	7.5	10	10	12.5	12.5
	P (W)	175		350		525		700		875	
3	T_i ^0C	21	21	20	20	20	20.5	21.5	21	22	22
	T_f ^0C	23.5	23.5	25	25	27.5	28	31.5	31	34.5	34.5
	ΔT	2.5	2.5	5	5	7.5	7.5	10	10	12.5	12.5
	P (W)	175		350		525		700		875	
Power (W)		P1 = 175		P2 = 350		P3 =525		P4= 700		P5= 875	

Appendix A8. Calculation of effective moisture diffusivity of CTC tea in hot air drying

The effective diffusivity can be defined from Fick's second law,

$$\frac{\partial M}{\partial t} = D_{eff}\nabla^2 M$$

where, D_{eff} is the effective moisture diffusivity in m^2s^{-1}; M is the material moisture content in $kgkg^{-1}$ (d.b.) and t is the drying time in second.

The solution of Fick's equation for a slab, with the assumption of moisture migration being by diffusion, negligible shrinkage, constant diffusion coefficients and temperature is given by Crank [123] as:

$$\frac{M_t}{M_0} = \frac{8}{\pi^2}\sum_{n=0}^{\alpha}\frac{1}{(2n+1)^2}\exp\left(-\frac{(2n+1)^2 D_{eff}\,\pi^2}{4L^2}t\right)$$

where, L is the half-thickness of a thin layer sample in m; and n is a positive integer.

For long drying time, only the first term of this series is significant, and then the solution becomes:

$$\mathrm{MR} = \frac{M_t}{M_0} = \frac{8}{\pi^2}\exp\left(-\frac{D_{eff}\,\pi^2}{4L^2}t\right)$$

Where, MR is the moisture ratio and is expressed as $MR = \frac{M_t - M_e}{M_0 - M_e}$

where M_t, M_0, M_e, are the moisture content in $kgkg^{-1}$ (d.b.) at a given time, beginning of the drying, at the equilibrium condition respectively.

The above equation can be further simplified to a straight-line equation as:

$$\ln(MR) = \ln\left(\frac{8}{\pi^2}\right) - \left(\frac{D_{eff}\,\pi^2}{4L^2}t\right)$$

The effective moisture diffusivity is determined by plotting the experimental drying data in terms of ln (*MR*) against drying time (*t*) with a slope of:

$$Slope = \frac{D_{eff} \times \pi^2}{4 \times l^2}$$

Thickness of sample = 6 mm,

l = half thickness of thin layer = 6/2 = 3 mm = 0.003 m

Temp, ^{0}C	Slope of ln (*MR*) vs. *t*	R^2	$D_{eff} = \frac{4 \times Slope \times l^2}{\pi^2}$ m^2s^{-1}
80	-0.0015123	0.954	5.5162×10^{-9}
90	-0.0019621	0.936	7.1569×10^{-9}
95	-0.0021217	0.893	7.7390×10^{-9}

Appendix A9: Specific energy consumption for different food in hot air drying

Food	Drying method	Temp, ^0C	Air velocity, m s^{-1}	*SEC*, MJ kg^{-1}	Reference
CTC tea (T3E3)	Hot air	80	0.4	7.80	
		90	0.4	6.63	
		95	0.4	6.12	
Onion	Electrical dryer	50	0.5	65.45	[85]
		70	0.5	43.34	
		50	2	84.64	
		70	2	70.59	
	Gas dryer	50	0.5	41.22	
		70	0.5	33.56	
		50	2	50.89	
		70	2	42.52	
Potato	Hot air fixed bed	40	1.53	0.074	[124]
		50	1.53	0.11	
		60	1.53	0.15	
		70	1.53	0.17	
	Semi FBD	40	2.96	0.064	
		50	2.96	0.1	
		60	2.96	0.146	
		70	2.96	0.15	
	FBD	40	4.12	0.05	
		50	4.12	0.07	
		60	4.12	0.08	
		70	4.12	0.085	
GABA Rice	Hot air oven drying	50	--	52.56	[133]
		60	--	17.37	

Appendix A10. Energy consumption in tea drying – An Industrial Study

Factory	Name of the tea garden	Dryer Type	Fuel used	Electrical Equipment used
A	Singlijan Tea Estate, Doom Dooma, Assam, India	PCD	Natural gas	Hot air blower Spreader motor Tray motor
B	Mohanbari Tea Estate, Dibrugarh, Assam, India	PCD	Natural gas	Hot air blower Tray motor
C	Jalan Nagar South Tea Estate, Dibrugarh, Assam, India	VFBD	Natural gas	Hot air blower Cold air blower Feed control motor Excitation system Dust collector

Factory	Made tea, kg W_{tea}	Drying time, hours	Natural gas consumption, m_f	Electrical Equipment	Rated power, hp
A	2325	15	1700 m^3	Hot air blower	15
				Spreader motor	1
				Tray motor	5
B	1630	16.3	1200 m^3	Hot air blower	15
				Tray motor	3
C	6600	18.75	4750 m^3	Hot air blower	35
				Cold air blower	5
				Feed control motor	0.5
				Excitation system	10
				Dust collector	15

Sample calculations

a) Total moisture removed for Garden A

Weight of made tea at dryer output = 2325 kg

Initial moisture content of fermented tea at dryer inlet = 70 % (w.b.)

Final moisture content of made tea = 3 % (w.b.)

2325 kg made tea contains = 2325 × 3/100 = 69.75 kg moisture

Weight of bone dry tea = 2325 – 69.75 = 2255.25 kg

Percentage of bone dry tea at inlet = 100 – 70 = 30 %

Total weight of fermented tea at dryer inlet = 2255.5 × 100/30 = 7517.5 kg

So, Total moisture removed in the dryer = 7517.5 – 2325 = 5192.5 kg or 5193 kg

b) Calculation of specific energy consumption in Tea drying

Specific energy consumption due to burning of fuel is calculated from the following equation :

$$\text{Specific thermal energy consumption} = 4.186 \times \frac{w_f \times CV_f}{m_w} \text{ kJ kg}^{-1}$$

where,

w_f = natural gas consumption, m^3

CV_f = calorific value of the natural gas supplied to the garden, kcal m^{-3}

= 5000 kcal m^{-3}

m_w = weight of moisture removed, kg

Calculation of total specific energy consumption, MJ kg^{-1} in the tea garden of Assam

Factory	Moisture removed, kg	Specific thermal energy consumption, MJ kg^{-1}	Specific electrical energy consumption, MJ kg^{-1} (Electrical)	Total specific energy consumption, MJ kg^{-1}
A	5193	6.851	0.163	7.014
B	3540	7.094	0.224	7.318
C	14740	6.744	0.224	6.968

Appendix A11. Mathematical models of sorption isotherms

Aiming to mathematically express the relation between the water activity of food and its moisture content, diverse models have been developed such as nonlinear, linear, regression models etc. In many cases, the model that is suitable for certain food product is not suitable for a different one, what is more, the model only exhibits a suitable predictive ability for certain moisture activity ranges. Several mathematical models have been proposed to describe sorption isotherms. Some of them were developed with a theoretical basis to describe adsorption mechanisms; whereas the others are just empirical or a simplification of more elaborate models.

Name of Model	Model	References
Langmuir	$a_w\left(\frac{1}{M_e}-\frac{1}{M_m}\right)=\frac{1}{CM_m}$	[141]
Smith	$M_e = A + B\,ln\,(1-a_w)$	[141]
Ferro Fontan	$\ln\left(\frac{\gamma}{a_w}\right)=\alpha\,M_e^{-r}$	[19]
Timmerman GAB	$\frac{M_e}{M_m}=\frac{CKa_wHH_0}{(1-Ka_w)[1+(CH-1)Ka_w]}$	[19]
Viollaz GAB	$\frac{M_e}{M_m}=\frac{CKa_w}{(1-Ka_w)[1+(C-1)Ka_w]}+\frac{CKK_2a_w^2}{(1-Ka_w)(1-a_w)}$	[19]

where,

M_e = equilibrium moisture content, kg kg^{-1}(d.b.)

a_w = water activity, (dimensionless)

M_m = monolayer moisture content, kg kg^{-1}(d.b.)

A, B, C, γ, K_2 and K = model coefficients

α, r = constant

H , H_0 = functions containing a fourth dimensionless parameter h.

$$H = 1+\frac{1-K(Ka_w)^h}{K(1-a_w)}$$

$$H_0 = 1+\frac{H-1}{H}\left(\frac{1-Ka_w}{1-a_w}\right)[h+(1-h)a_w]$$

Langmuir proposed a physical adsorption model on the basis of unimolecular layers with identical and independent sorption sites. Langmuir's isotherm is the most crucial equation among the theoretical models, which is based on the forces acting between the product surface and the water condensed from the vapour as a monomolecular layer. In 1947, Smith developed an empirical model to describe the final curved portion of water sorption isotherm of high molecular weight biopolymers. He theorized that there are two fractions of water that are sorbed onto a dry surface; the first fraction exhibits a higher condensation heat than the normal and it would be expected to follow the Langmuir model. Smith based his model on the second fraction, which only can be formed after the first fraction has been sorbed.
He considered that the second fraction consists of multilayers of condensed water molecules, which effectively prevent any possible evaporation of the initial layer.
Iglesias and Chirife compiled sorption data for 156 food items and documented that Ferro-Fontan equation is an accurate tool for the mathematical description of food isotherms. The Ferro-Fontan equation accurately represents the sorption isotherm in the range of water activity 0.1–0.9 with only 2–4% error in the predicted moisture content.

One of the popular models for describing sorption theory is the GAB model. But the GAB model underestimates the water content values at high water activities ($a_w > 0.93$). The discrepancy underlines two facts: (a) this type of model is unsuitable for high humidity range, and (b) the saturated salt solution method does not afford sufficient information to get a complete sorption curve. The GAB model was refined for higher water activities by Timmerman and Chirife and Viollaz and Rovedo. They modified the GAB model by inserting a new parameter to add a third sorption stage without changing the values of the usual parameters defined in the GAB model. Compared to the classical BET isotherm, the GAB isotherm contains a third constant, K, which measures the differences between the standard chemical potential of the molecules in the second sorption stage and in the pure liquid. Some researchers noted that at very high water activities some systems showed a sorption stage larger than the predicted by the GAB model. Timmermann suggested that the second sorption stage introduced by the GAB model may be limited to a certain number of layers and that, thereafter, a third stage becomes available for the sorbate molecules, which has true liquid-like properties, as postulated by the original BET model. Original GAB model was modified by Viollaz and Rovedo in an empirical way by adding a term K_2 as an additional dimensionless parameter. The introduction of the second term in the GAB model allows the necessary flexibility to obtain a good fitting for high a_w values. This term has a very low weight for low values of a_w, so the values of M_m, C, and K are not substantially affected by the addition of this new term.

Sorption isotherms of agricultural and food products are usually sigmoid-shaped curves which are even difficult to draw and manipulate. Several complex mathematical models were developed to describe these curves. Non-linear direct optimization techniques required for estimation of these model parameters, accuracy and shape of the isotherms and also reliability of the predictions over the whole range of the air relative humidity limited by these estimations. Therefore, finding an alternative computational model is necessary to calculate the relationship of isotherms of agricultural and food products to increase accuracy and reliability in predictions. Artificial neural network (ANN) method can be an alternative for this purpose. An ANN consists of processing units, named neurons. They are related with special arrangement. Neurons are in layers and every neural network includes some neurons in input layer, one or more neurons in output layer and neurons in one or more hidden layers. Algorithms and architectures of ANNs are different through variation in neuron model and type of relationship between neurons, and their weights. The learning purpose in ANNs is weight updating, so that desired outputs are obtained with presenting a set of inputs. Many researchers applied the ANN models for sorption isotherm modelling of agricultural and food products, such as black tea [142], maize starch [143], longan [144]. In all of these studies the ANN models were better than mathematical models.

Appendix A12. Mathematical models of fluidized bed drying

Many mathematical models of fluidized bed drying have been proposed in the literature and verified with experimental data. These models have been developed based on different assumptions. Some are discussed below.

Diffusion Model assumes that drying of single particles in a fluidized bed is totally controlled by diffusion of moisture inside the particle. If diffusivity is variable and dependent on the radial distance of drying boundary from the centre of the solids, the following diffusion equation is used

$$\frac{\partial x}{\partial t} = D\left[\left(\frac{\partial^2 x}{\partial r^2}\right) + \frac{2}{r}\left(\frac{\partial x}{\partial r}\right)\right] + \frac{\partial D}{\partial x}\left(\frac{\partial x}{\partial r}\right)^2$$

Where, x is the free moisture content , i.e., that in excess of the equilibrium value, D is the diffusivity (m^2s^{-1}), and r is radial dimension (m). Once the diffusivity is known, numerical analysis is applied to the diffusion equation in order to find moisture content profile inside the solid.

In **Empirical model**, the drying process is divided into different periods where drying mechanisms in each drying period are different. Since the general solution of the diffusion equation is expressed as a series of exponential functions, experimental data obtained from fluidized bed drying can be correlated as an exponential function. Many empirical exponential equations have been proposed.

Kinetic model are developed for fluidized bed drying of solids. For a batch fluidized bed kinetic model, it is assumed that the drying process has both constant and falling rate periods. Drying rate in the falling rate period falls linearly with decreasing moisture content. Feed conditions and total contact area between solids and hot airstream remain the same throughout the whole drying process. In the batch drying operation, there is little interaction between the particles (wet and dry particles) in the system. Thus, data on drying kinetics is sufficient to estimate the residence time of solids in order to achieve the desirable final moisture content.

In a **single-phase model**, the fluidized bed is regarded essentially as a continuum. Heat and mass balances are applied over the fluidized bed. It is assumed that particles in the bed are perfectly mixed.

A simple **two-phase model** of fluidized bed drying treats the fluidized bed to be composed of a bubble phase (dilute phase) and an emulsion phase (dense phase). The bubble phase contains no particles or the particles are widely dispersed. This model assumes that all gas in excess of minimum fluidization velocity flows through the bed as bubbles whereas the emulsion phase stays stagnant at the minimum fluidization conditions.