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 loses (desorb) or gains (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

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

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 models and gives a reasonable fit for a variety of food products 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 products [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]

\[
\frac{\partial M}{\partial t} = D_{\text{eff}} \nabla^2 M \quad \ldots \ldots \ldots (1.1)
\]
where, \( D_{eff} \) is the effective moisture diffusivity, \( m^2 \text{ s}^{-1} \), which represents the conductive term of all moisture transfer mechanism; \( M \) is the material moisture content at a specific time, \( \text{kg kg}^{-1} \) (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.

\[
\text{Slope} = \frac{D_{eff} \pi^2}{4l^2} \quad \cdots \cdots \cdots \quad (1.2)
\]

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].

\[
D_{eff} = D_0 \times e^{-\frac{E_a}{RT_k}} \quad \cdots \cdots \cdots \quad (1.3)
\]

where,

\( D_0 = \) Arrhenius factor, \( m^2 \text{ s}^{-1} \)

\( E_a = \) activation energy for diffusion, \( \text{kJ mol}^{-1} \)

\( R = \) universal gas constant, \( \text{kJ mol}^{-1} \text{ Kelvin}^{-1} \)

\( T_k = \) 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].
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

<table>
<thead>
<tr>
<th>Model name</th>
<th>Model description</th>
<th>Parameters estimated from model</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Two Term</td>
<td>( MR = a \times e^{(-k \times t_1)} + b \times e^{(-k_1 \times t_1)} )</td>
<td>( a, b, k ) and ( k_1 )</td>
<td>[47]</td>
</tr>
<tr>
<td>Henderson and Pabis</td>
<td>( MR = a \times e^{(-k \times t_1)} )</td>
<td>( a, k )</td>
<td>[48]</td>
</tr>
<tr>
<td>Lewis</td>
<td>( MR = e^{(-k \times t_1)} )</td>
<td>( k )</td>
<td>[49]</td>
</tr>
<tr>
<td>Page</td>
<td>( MR = e^{(-k \times t_1^n)} )</td>
<td>( k, n )</td>
<td>[50]</td>
</tr>
<tr>
<td>Logarithmic</td>
<td>( MR = a \times e^{(-k \times t_1)} + c )</td>
<td>( a, k ) and ( c )</td>
<td>[51]</td>
</tr>
<tr>
<td>Midilli et al.</td>
<td>( MR = a \times e^{(-k \times t_1^n)} + b \times t_1 )</td>
<td>( a, b, k ) and ( n )</td>
<td>[44]</td>
</tr>
</tbody>
</table>
where,

\[ MR = \text{moisture ratio (dimensionless)} \]
\[ k \text{ and } k_1 = \text{drying coefficient, minute}^{-1} \]
\[ n = \text{exponent (dimensionless)} \]
\[ t_1 = \text{time, minute} \]
\[ a \text{ and } b = \text{model coefficients (dimensionless)} \]

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 indispensable. 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](image-url)
**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.

![Schematic diagram of Fluidised Bed Dryer](image)

**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.

![Schematic diagram of Vibro Fluidised Bed Dryer](image)

**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.