Introduction

1.1 Importance of tea

Tea is one of the principal and cheap soft drink in the world. Per capita tea consumption in the world (0.3 kg y\(^{-1}\), in 2009) is steadily increasing with augmentation of production in recent years. India is largest producer of tea manufacturing about 1137 M kg next to China (1761 M kg). India exported about 236 M kg teas for revenue of about $ 480 million in the year 2012. About 20% (of total tea production is exported rest 80% is used for domestic consumption. Indian tea industry is about 200 years old and it has 579350 hectares total tea cropped area. Tea plantation area covered by small grower is about 163326 ha (up to 10.12 ha) and area under big grower is about 416024 ha (above 10.12 ha). Present average productivity of made tea is about 2000 kg ha\(^{-1}\) in India. About 50 % of Indian tea production is from tea estate situated in Assam. Therefore, tea processing is one of the traditional plantation based beverage industries in India providing direct and indirect employment to one million workforces. Tea crops provide the highest employment per unit arable area. It generates largest employment to the men and women of weaker section of the society. Tea industries generate indirect employment for tea- machinery development sector, agricultural chemicals, warehouse facilities, road transport, etc. These are in addition to the direct employment generation in tea production and processing sector. Moreover, tea industry is supporting machinery-manufacturing industries for supply and maintenance of tea processing machines. It also supports fertilizer and manure production chemical industries for tea cultivation practices. Thus, growth and development of tea industry is essential to ensure these economic benefits. Improved tea processing machinery development, adoption of energy efficiency and conservation practices, intervention of renewable energy for tea processing, etc., are the future need for sustainable development of this important agro based industrial sector in India. Tea plays a key role in Indian economy and society [1, 2].

It has been reported that tea productivity has increased by 60 % in last two decades. However, internal consumption of tea has increased 7% annually. To
maintain India’s lead in tea export and upward foreign exchange earnings, stress on tea productivity coupled with stress on better quality and reduced production cost are essential. Employment of improved and innovative tea processing machinery, efficient and economic energy system are some of the key factors to be targeted to achieve such a goal [3]. Since tea manufacturing is highly energy intensive chemical engineering unit operation, therefore a brief description of black tea processing has been discussed below.

1.2 Black tea processing

Black tea processing consists of five unit operations namely withering (partial removal of moisture), rolling (size reduction), fermentation (biochemical reaction in presence of oxygen), drying and sorting (fiber removal and grading). Thermal energy is required in the form of hot air for withering and drying operations. Out of these two energy requirements, drying shares the major fraction of total thermal energy while withering requires very small amount thermal energy (5-10) % for black tea processing [4, 5]. The main sources of thermal energy in Indian tea industries are natural gas, coal, tea drying oil, and fuel wood. Woody biomass is more prominently used in South Indian tea industries. Assam and Northeast India tea industries use other three non-renewable thermal energy sources for black tea manufacturing. Specifically, the Southeast Assam tea industries significantly use natural gas and tea drying oil whereas Northern Assam tea industries use coal for tea drying energy requirement. The principal unit operations with a special reference to thermal energy consumption have been discussed below.

1.2.1 Withering

A standard tea shoot is consisted of two leaves and a terminal bud with (74-77) % moisture (dry surface) and (23-26) % solid matter. About half the solid matter is insoluble in water and it is made up of crude fiber, cellulose, proteins, fat, etc. Fresh tea after plucking is spread in thin layers to dry (withering) it partially for (12-20) hours. During first (4-8) hours, moisture loss is quite rapid and then it slows down for next (10-12) hours until the equilibrium is reached. Green leaf is loaded over the
trough at the rate of (25-30) kg m\(^2\) area up to 20 cm depth. About 2000 tonne of air is required to process one tonne of made tea and 75% of this air is required during withering. It has been reported that dryer exhaust air may be very efficiently used for withering green leaf in very dry weather.

Optimal withering air temperature and humidity are two important factors to determine quality of made tea and thermal energy requirement for this unit operation. Normally best quality tea is obtained for withering air temperature near to 27 °C with a dry bulb and wet bulb temperature difference 3 °C, at withering trough. As the air has passed through the exhaust, the hygrometric temperature difference should not be below 1.6 °C. Thermal energy is wasted rapidly if hygrometric temperature difference is more than 2.2 °C, at exhaust stream. The wet bulb temperature raises approximately 0.55 °C for (1.65 – 2.2) °C increase in dry bulb temperatures [5]. Moisture is usually reduced to (68-60) % particularly in tea factory situated in Assam. Normally, the tea manufacturing peak time ranges from May to November over the year. From May to September, the climate of Assam is hot and humid. Daytime room temperature is well above 27 °C and therefore addition of extra heat to withering air is not recommended for quality purpose. During rainy or winter season, additional thermal energy is required for withering purposes. Separate tea drying oil burners are used in certain tea factories for withering. Therefore, withering thermal energy requirement is met from varied sources as per availability and ease of operation [5].

During physical wither; there is a change in cell permeability by losing moisture. Bio-chemicals changes occur inside leaf during chemical wither. It is achieved by blowing air sporadically or incessantly at low flow rate to keep leaf cool with loss of moisture for 4-18 hours [6]. However, chemical wither is necessary for producing full and round liquors. The duration could be reduced to 6-8 hours by holding leaf at 30 and 37 °C temperature and airflow rate of 0.01 m\(^3\) s\(^{-1}\) [7]. Immediately after plucking, the fresh leaf starts to lose water vapour. The stomata of the lower leaf surface begin to close [8-9]. The maximum initial drying rate is 0.075 kg kg\(^{-1}\) (water per kilogram of green leaf per hour) [10].
1.2.2 Fermentation

During fermentation process, the most important quality property of tea is produced. This process is carried out simply by laying the \( dhool \) \((3.75 - 7.00)\) cm thickness at an average air temperature of 27 °C. On an average, fermentation takes \((2.75 - 3.50)\) hours for completion at a temperature of 26.7 °C. A rapid fermentation at higher temperature suits certain tea; a longer fermentation at a lower temperature might suitable for other variety. By shortening or lengthening the period of fermentation, the degree of colour and quality may be varied. The compounds responsible for tea quality, such as theaflavins (TFs) and thearubigins were found to augment with fermentation time [11].

1.2.3 Drying

The principal objectives of drying are to arrest the fermentation process to have desired properties and to obtain a stable finished product for preservation and marketing. Normally hot air generated by furnace and heat exchanger or flue gas mixed with air is used as a drying medium. Multi-stage tea drying process uses different drying medium temperature range in identified zones of dryer for fuel economy and quality. In general, two types of tea dryer are used in black tea manufacturing. They are endless chain pressure and vibrated fluidized bed types tea dryer. The understanding on the working of tea dryer is essential in relation to the present work. Therefore, both the types of dryers are briefly highlighted below.

**Endless chain pressure type dryer**

Conventional tea dryer is an endless chain pressure (ECP) type. This dryer is normally double firing type and is used traditionally in Northeast India tea factory for better quality. Normal range of drying air temperature is \((82-99)\) °C with an exhaust temperature of \((49-54)\) °C to stop stewing and case hardening of \( dhool \). Exhaust air temperature 52 °C is ideal for both economy and quality of black tea produced. For double firing, initial temperature may be \((93.3 – 104)\) °C whereas a temperature of (77

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*Fermented tea undergoing drying is called \( dhool \)*
– 82.2) °C is suitable for CTC† and (71-77) °C for orthodox (special type of tea) tea in second drying depending on the moisture of first drying per batch drying. Average drying time in endless chain pressure type varies from (30-40) minutes. Though ECP dryer ensures better quality, to achieve better thermal efficiency and associated higher production rate there has been a shift towards vibrated fluidized bed dryer for processing of black tea after 1990 (Fig.1.3).

**Vibrated fluidized bed dryer**

These dryers may have three or five zones in mixed flow or cross flow mode in addition to a cooling section. When a fluid flows upwards through a bed of granular particles, the pressure drop is initially proportional to the rate of flow. At a certain increased air velocity, the frictional drag of the particles become equivalent to the perceptible weight and bed begins to expand. This stage is known as onset of fluidization or incipient fluidization. Further boost in velocity causes the individual particles to separate from one another and float on stream of air. At this stage, the system is said as a fluidized bed. Good thermal contact between the tea particles and drying medium results in improve fuel performance. Particle to particle attrition in a fluidized bed medium is minimized because its own fluid cushion bound each particle. This gives rise to blacker tea with better appearance and bloom as quality parameters. Plug flow fluidization is very much necessary for optimal energy consumption of black tea drying. Particles look like a boiling liquid in plug flow fluidized bed condition. The upper surface of the bed remains horizontal. The solids rapidly mix that lead to near isothermal condition in each zone of the bed.

The fermented leaf is loaded in grid plate of drying chamber. The top of the drying chamber is totally enclosed and two sets of centrifugal fans are provide with cyclones; one for re-firing and other is for dust collection operations. Plenum is situated beneath the bedplate where the air pressure is equalized as per requirements. Damper controls the direction of hot air entering into the bedplate. It has dual purposes namely direction of damper determines the residence time of tea particles as

† Curl tear and crush
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well as evacuates the dryer completely at completion of drying. The fermented leaf enters into the drying chamber with a very high moisture contents. It is reduced rapidly by admitting maximum volume of hot air for swift evaporation of moisture. The rapid loss of moisture causes increase in bulk density of fermented tea. Therefore, the material tends to move away from the feed end because it is displaced by incoming fresh fermented tea containing high moisture.

In addition to the understanding of tea dryers, the major factors influencing the tea drying process need also a brief discussion as below.

Factors affecting tea-drying process

The factors affecting tea drying process are, inlet air temperature, volume of air, fermented tea feeding rate into the dryer, drying time and outlet humid air temperature from dryer. Tea drying is normally carried out at a temperature range of (90 -140) °C depending on various factors to reduce withered tea average moisture from 67 % to (2.5-3) %. Normally, (1.5-2.5) kg moisture is removed against each kilogram of made tea in drying. When the fermented leaf enters into the drying chamber, it has very high moisture content (58-72) %. It is rapidly reduced in the first drying zone of the dryer. In the first drying zone, maximum air volume and high temperature is introduced. As a result, the material density is decreased and it tends to move away from the feed end towards exit of the dryer. Moreover, it is displaced by fresh material containing high moisture contents. As the material is fully dried, it is expelled into a cooling chamber at ambient temperature. Cooling of tea undergoing drying is essential for stopping case hardening as well as over drying. If only quality aspect is considered, then endless-chain pressure type dryer for tea drying is preferable over fluidized bed tea drying.

1.3 Thermal energy utilization for black tea drying

Black tea drying is a highly energy intensive unit operation in tea manufacturing process. Different literature pertaining to tea drying energy consumption, drying efficiency, and energy conservation works are available both
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International and national level. Importance of thermal energy management in tea drying had been highlighted almost all the major tea processing regions including China [12], India [13, 14, 16], Japan [15] and Africa [17]. Coal and biomass are the predominant sources of thermal energy for tea processing in China. The studies indicated the requirement of appropriate management practices including introduction of improved drying machinery, utilization of waste heat, planning of unit operation, etc., for tea processing in order to conserve thermal energy. This would reduce unit cost of production.

Similarly, black tea manufacturing industries situated in Assam (India) had been reported to have variation in specific thermal energy consumption for different types of fuel. The minimum rate of energy consumption was 23.88 MJ kg\(^{-1}\) of made tea in oil-fired burners, 43.72 MJ kg\(^{-1}\) for coal-fired furnace and, 27.49 MJ kg\(^{-1}\) for gas-fired burner [13]. Energy efficiency improvement in air heater of a tea-manufacturing unit revealed that dryers were operating at very low efficiency due age-old design and improper selection of materials. Appropriate excess air control techniques might conserve 38 % of thermal energy in coal or biomass fired furnace with little or no investment. Therefore, optimal selection and discharge control of induced draft and forced draft fan was key factor for consideration. Moreover, furnace cum cast iron air heater (Fig.1.1) might be replaced with steam boiler for hot air generation [14].

Development of a primary drying tea roller with heat recovery devices in order to save energy in the primary drying process in tea manufacturing had been reported in Japan. The energy saving devices adopted were a heat exchanger that recovered heat from the furnace exhaust gas, heat pipes that recovered heat from the dryer exhaust air and a circulation path for the dryer exhaust air. The heat flow and energy saving effect of these devices used singly or in combination were calculated and discussed. A saving of between 12 and 29 % of the fuel consumption in the primary drying process was achieved with this waste-heat recovery device [15].
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Fig. 1.1 Coal fired air heater furnace

Fig. 1.2 A Natural gas fired furnace for black tea manufacturing
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The energy and economic issues related to the drying of tealeaves, with focus on the "zero physical wither system" being implemented in some areas in Africa, specifically in Kenya had been reported [17].

Sri Lanka also produces tea and importance of electrical and thermal energy management in tea drying is realized in that country [18]. Conservation of thermal energy required in tea processing and search for a new and sustainable sources of energy seem to be universal requirements.

It has been observed that almost all tea-manufacturing industries in India have been using tradition fuel (Natural gas, Coal, Tea drying oil, and Wood) for tea drying process. It is evident that except wood, other three thermal energy resources are fossil origin based. Moreover, wood is burnt conventional fixed bed biomass fired furnace to heat air. Studies shows that conventional fixed bed coal fired furnace and air heaters have been operating at a very low overall efficiency in most of the tea factories excluding a prominent part of upper Assam (Eastern part), India for long time. The reasons behind very low efficiency are, age old design of furnace and air heater, inconsistent quality of coal (low calorific value), inherently low heat transfer coefficient from flue gas to air in cast iron shell and tube heat exchanger. Moreover, with increase in coal prices in international market, as well as operation of low energy efficient fixed coal fired furnace (Fig.1.1), the cost of production of black tea is augmented. Secondly, even though a natural gas burner (Fig.1.2) for tea drying is energy efficient, yet natural gas is not available to most of the tea factories in Assam, India. Natural gas being a fossil origin fuel, it is non-renewable in nature. Therefore, for economy and sustainability for tea manufacturing urgently need to use certain amount of green energy like biomass gasification derived producer gas, solar thermal energy for tea drying in place of inefficient fixed bed coal fired furnace and air heater. The details of biomass gasification, solar air heating technology, and the nature of hot fluid used to dry tea and the related drying kinesics will be discussed later.
1.4 Black tea drying performance

The drying experiments were reported at three different inlet air temperatures of 100, 115 and 130 °C and fluidization condition at five vibration intensity levels of 0 (no vibration), 0.063, 0.189, 0.395 and 1.184 respectively. The results showed that bed channeling and de-fluidization problems were declined in vibration condition. The vibration system decreased the requirement of minimum fluidization velocity of tea particles and this velocity reduced by increasing the vibration intensity. In the experiments, the maximum evaporation rate \(13 \times 10^{-3} \text{ kg m}^{-2} \text{ s}^{-1}\) was experimented at the vibration intensity of 1.184 and inlet air temperature of 130 °C. In addition, the minimum specific energy consumption (4955 kJ kg\(^{-1}\)) was observed at 1.184 vibration intensity and inlet air temperature 100 °C. Based on lower minimum fluidization velocity and specific energy consumption, the vibration intensity of 1.184 and inlet air temperature of 100 °C were recommended for drying black tea particles [19].

![A vibrated fluidized bed dryer](image-url)
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The characteristics; performance, availability, and cost analysis of wedge wire as an ideal dryer bedplate material in tea industry has been reported. This material was recommended for its short drying times, found incredibly economical and expected for a very long life. In another study reported factors influencing the effectiveness and efficiency of fluidized bed dryers for tea and gave the optimum design parameters for the three drying stages [20, 21].

Different aspects of black tea drying under Northeast Indian tea factories such as drying medium temperature, types of dryer and drying time have been reported. Six dust collection systems for tea dried in a vibrating fluidized bed dryer and observations regarding their influence on tea quality was reported [22, 23]. Another study observed that the rate of drying of tealeaves during the primary drying process is related to the temperature and humidity of the drying air, the air and tea ratio, the number of revolutions of the main shaft of the dryer and the physical characteristics of the tea. In the initial stage, the tealeaves were dried at a constant rate agreeing with the wet bulb temperature of the air. However, in the later stages, the rate of drying tended to decrease as the surface area of the leaves changed, but overall the rate could be considered constant. A model based on drying at a constant rate agreed well with the experimental results. Experimental results meshed with calculated values for drying rate, the conditions of exhaust air, and drying efficiency. It assumed adiabatic heating and total mixing of air inside the dryer. A study on recirculation of humid exhaust air indicated that this could increase thermal efficiency without greatly affecting the quality of the tea [24]. A tea dryer house in which the roof space was incorporated to form an integrated exhaust system was reported. This offered the advantage of improved dust extraction and negligible discharge of saleable products. The exhaust system had no moving parts, there was no obstruction to the passage of the exhaust to the open air and a chamber formed by the roof of the building, and a platform over the loading end of the dryer allowed all exhaust air to develop gently and mix thoroughly [25]. Fuel burning efficiency in wood-fired furnace and heat losses with respect to improved tea dryer efficiency and performance had been reported [26]. A rotary dryer made from an unserviceable concrete mixer mounted on
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an iron frame over a brick fireplace was proposed. The dryer produced good quality tea more cheaply than that of hand processing one [27]. Another study was observed in Switzerland on a brief report of the work done by three dryers. These dryers were installed by the Department of Agriculture in different parts of Switzerland in 1941. Performance results of these three dryers were considered as exclusively satisfactory. The material dried included grass, cereals, vegetables, and tea. The dried grass was of a good, green colour and high quality as reported [28].

1.5 Tea drying kinetics studies

A study on modelling and simulation of fluidized bed tea drying was reported for both batch and continuous process. It was observed that for thin layer drying of tea, constant rate drying period did not exist. However, a constant rate-drying period may exist for batch fluid bed tea-drying experiments. Constant rate period exist if there is more saturated air per unit mass of tea particles. Therefore, constant rate period is not the property of tea drying, but of saturated air [29]. The heat and mass transfer theory of tea drying had been reported with development of one leaf temperature moisture content model to describe the drying process of rolled tealeaves. The average difference between the predicted and experimental moisture contents of output leaves was 2.43% (w.b.) for rolled tealeaves in the primary drying process under various conditions. Leaf layer thickness: (3-4) cm, hot air temperature: (91-116) °C, rotary speed: (2.0-5.1) rev min⁻¹) respectively had been considered [30]. At constant temperature drying conditions, the moisture diffusion coefficient of tea leaves and stems (Yabukita variety, second cut) had increased from (1.24 x 10⁻⁹ and 2.07 x 10⁻⁸ ) to (1.14×10⁻⁸ and 1.17 x 10⁻⁷ m² h⁻¹). The drying constants increased from (0.288, 0.155) to (2.089, and 1.273 h⁻¹) respectively as drying temperature increased from (30 to 70) °C. Under crude drying conditions, drying time significantly affected the diffusion coefficient and drying constants of stems in particular. Agitation was reported to have no significant effect on diffusion coefficient, but it was clearly at least partly responsible for the drying rate of stems that was greater than leaves drying rate under these conditions [31].
Similarly, quality of black tea that is dried to variable moisture assessed by spreading tealeaves on troughs (25.75 kg m$^{-2}$) and withered by a combination of hot and cold air for 12-18 hours. The withered leaves were macerated in a spiral rotovane followed by a triplex CTC (cutting, tearing, and curling) to achieve fine cuts. The green dhool was fed into trolleys and fermented for (90 ± 2) minutes. The temperatures were controlled by manual forking and air volume adjustment from (30.8 ± 1.4) °C at the start to (23.1 ± 0.8) °C at the end of fermentation. The fermented dhool was dried in a 3-stage fluidized bed dryer with temperatures set at the standard firing regime of (145 ± 2) °C (wet end), (135 ± 2) °C (mid chamber) and (105 ± 2) °C (dry end). The dryer was set to fire teas to three different moisture content levels of (3.1-3.3) percentage (low), (3.4-3.6) percentage (medium), and (3.7-3.9) percentage (high). The results showed that optimum quality of black tea fired in a fluidized bed dryer was achieved at a moisture content of (3.0-3.4) percentage. However, tea fired to high moisture content level of (3.5-3.9) percentage was also found to be of acceptable quality and with a higher throughput. This study demonstrates that the keeping quality of tea fired to high moisture content is similar to the tea fired to low moisture content for a period of up to 2 years [32]. Another study reported drying durations and quality parameters for orthodox and CTC tea in hot air, radio frequency, and hybrid hot air-radio frequency (RF) dryers. Drying duration was the shortest for RF drying at 60 min for orthodox tea whereas for CTC tea it was 90 min. Hybrid drying for CTC tea took total of 55 minutes and the same for orthodox at 20 kW power was 85 minutes. Aroma index of made liquor increased at 16 kW compared to 20 kW RF power applied [33].

1.6 Energy efficiency in processing industries

Different research, development and application based works are available regarding energy conservation, efficiency and renewable energy application in processing industries. Prospect of low-grade energy heat recovery had been reported in United Kingdom food processing industries. An estimated 11.4 TWh of recoverable heat was wasted each year, a quarter of that was from the food and drinks.
processing sectors. The most economical recuperation of the waste heat was by heat exchange/direct re-use to a nearby heat sink. This might be preferably from within the same process; numbers of different heat exchange systems were well developed and economically available for such projects. They observed that increasing energy costs and the drive towards energy efficiency and associated carbon reductions should increase motivation for such projects. Additional government funding towards demonstration of novel waste-heat recovery project highlighting successful cases were major factor in reducing the perceived risk and uncertainty of such projects amongst UK engineers [34]. The authors beautifully represent different type of possible combination of heat exchanger for waste heat recovery and low temperature thermodynamic cycle. However, authors fail to conclude about the most appropriate technology solution for food processing industry with waste-heat recovery. Another studies revealed possible Organic Rankine Cycle to generate power with waste heat in a crisps processing industry with five options. The first two options (A and B) made use of the waste heat from the foul gas and exhaust to stack respectively for power generation using a single ORC system each while the third option (option C) made use of a novel dual heat source single ORC system. Here the low temperature waste heat from the foul gas was used to provide preheating. The high temperature waste from the exhaust to the stack was used to provide the evaporation. Option D also showed a dual heat source ORC system where the high temperature waste heat to the exhaust stack was used to provide the preheating the lower temperature foul gas for the evaporation (reverse of option C in terms of waste heat usage). Option E made use of a reheate cycle where the waste heat from the foul gas was used to provide the reheating of the working fluid exiting the turbine [35]. It is really an appreciable work for waste heat utilization. However, the authors have not highlighted details technical specification and appropriate hardware for such an energy system. Energy requirement in cashew (Anacardium occidentale L.) nut processing operation had been reported and results of application test of the equations showed thermal energy intensity varied from (0.085 to 1.064) MJ kg\(^{-1}\). Cashew nut drying and cashew nut roasting are two energy intensive operations. Both altogether accounted for over 85%
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of the total energy consumption in all the three mill categories. They developed appropriate correlation for different unit operations of cashew nut processing is a commendable work. Diesel fired burner thermal energy represented about 90% of the unit energy cost for cashew nut processing [36]. However, the analysis assumed the data provided by cashew nut processing milling that was not directly measured by the authors and it is only limitation of the work.

It has been seen that conventional thermal energy requirement for black tea drying is non-renewable fossil fuel (Coal, Tea Drying Oil, and Natural Gas) in the tea factories located in Assam, India. The variation of fossil fuels uses range from inefficient indirectly heated old coal fired furnace air heater to improved coal fired steam generator, furnace oil and natural gas fired furnace, etc. However, site specific improved solar air heater and locally available fuel specific gasifier performance study for black tea drying in Assam is necessary for sustainable development. The application of renewable sources of energy and technologies such as biomass gasification, solar thermal air heating have not been explored individually or hybrid mode yet for black tea processing in Assam. It was noticed that knowledge of material characteristics related to tea drying kinetics is essential for understanding and assessing drying performance using the existing theory of drying by incorporation of renewable thermal energy (producer gas combustion products mixed with air) as drying medium. However, there exists knowledge gaps, with reference to biomass gasification and solar air heating technology applied for black tea drying kinetics, for local varieties grown in Assam (India). Innovation in renewable energy resources and technologies based tea drying should be conceptualized and experimented to generate appropriate knowledge for selecting and characterization of appropriate local biomass samples, low cost and energy efficient solar air heater development, hybridization analysis, drying kinetics, conventional energy substitution potential and overall performance of the system. The above discussion is summarized with the following observations.
Tea is an important beverage product manufactured in Assam (India) and drying is a significant processing step that requires (85 to 90) % conventional thermal energy. This necessitates urgent research attention with reference to locally available renewable energy technology intervention for tea drying. The characterization of some locally available biomass as potential gasification feedstock for tea drying is necessary to study suitability for black tea drying. The existing theory of drying implies the requirement of information on fundamental material characteristics pertaining to drying and drying kinetics that are material and system dependent. Such information is not available for local variety of tea with intervention of renewable energy. Therefore, this is important to determine local variety tea drying kinetics through precise experimentation in producer gas fired dryer. Therefore, hybridization studies of biomass gasification technology and solar air heater for partial substitution tea drying thermal energy is necessary for optimal and assured utilization and reliable supply of above mentioned renewable energy sources in local tea industries.

1.7 Objectives of research work

Considering the discussion made in this Chapter, the focus of the present study has been to investigate the prospect of a new tea drying technique based on biomass gasification and solar thermal (Air heater) technology for supplying hot air. Therefore, this research work has been undertaken through a systematic procedure with the following objectives:

- Fuel characterization of some locally available biomass samples through proximate, ultimate analysis and calorific value determination to access potential feedstock for gasification in a downdraft woody biomass gasifier.
- Investigation of the best-fit tea-drying model and activation energy with producer gas fired tea-drying setup.
- To study an improved solar air heater to assist biomass gasification in hybrid energy based tea drying to substitute thermal energy partially in tea drying.
- Economic analysis of solar air heater assisted producer gas fired tea dryer over conventional inefficient coal fired furnace cum air heater.
1.8 Organization of report

- **Chapter 1**
  This chapter discusses importance of tea industry in Assam, different tea drying unit operations, thermal energy consumption pattern, and different type of industrial tea dryer performance, and energy efficiency. The problem statement and objectives of the research work have been defined.

- **Chapter 2**
  This chapter is consisted of literatures pertaining to renewable energy applications for different process industries with its potential for tea drying. Reason for selection biomass gasification cum improved solar air heater technology over other renewable energy system for tea drying, biomass gasification, drying kinetics, solar air heater technologies, and hybridization of biomass and solar energy for drying and a critical review have been presented.

- **Chapter 3**
  This chapter covers methodology adopted for characterization of some locally available biomass samples. The results of gasification studies of a selected biomass sample and gasifier performance have been presented in this chapter.

- **Chapter 4**
  This chapter covers detailed methodology of thin layer tea drying kinetics with producer gas as a fuel. The results of best thin layer drying kinetics model and activation energy from experimental data of tea drying had been presented.

- **Chapter 5**
  This chapter discusses detailed methodology of analysis of improved solar air heater. An analysis of improved low cost air heater and hybrid (solar assisted biomass gasifier performance) had been presented.

- **Chapter 6**
  This chapter enlists the summary of the results obtained to achieve the objectives of the thesis and concluding remarks. It also discusses the limitations and possible future extensions of the present work.