



# A review of drying technology in tea sector of industrial, non-conventional and renewable energy based drying systems

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## ABSTRACT

Drying is an important process in the tea processing industry. Drying arrests enzymatic reactions to produce a stable product with increased shelf life. Development of the quality attributes such as taste, fragrance, color, etc. in tea is initiated during processing steps prior to drying, which undergoes the final stage of development during drying to produce the characteristic features of the final product as made tea. In this article, investigations on the drying of tea leaves using industrial/commercially successful driers, such as, endless chain pressure drier, fluidized bed drier and vibro-fluidized bed drier have been discussed. Additionally, investigations on the driers under research stage, such as microwave drier, superheated steam drier and radio frequency drier have also been explored.

Drying is an energy intensive process in the tea factory. It consumes 3.5–6 kWh of thermal energy per kg of made tea. Fossil fuels are primarily utilized in the tea factories to meet the thermal energy demand of drying. The specific carbon dioxide emission of tea factories is found in the range of 2.15 to 2.86 kg per kg of made tea. Several attempts have been made to develop the renewable energy based drying system to meet the energy requirements in the tea factories and to minimize the greenhouse emissions. This study also reports past works on renewable-energy-assisted tea drying. Apart from this, study proposes solar energy-based tea drying system along with thermal energy storage and/or integrated with fossil fuel-based furnace.

## 1. Introduction

Tea is one of the most popular aromatic, non-alcoholic drinks. It is also the second most popular among all drinks. Tea is produced from the apical shoot of the plant *Camellia sinensis* consisting of one bud and two or three leaves [1–4]. As per the data published by the Tea Board India (Annual Bulletin of Statistics, 2020), the total world's tea production is 6012.81 million kg and chronologically, the six top producers are China, India, Kenya, Sri Lanka, Vietnam and Indonesia (Fig. 1). The six top exporters are chronologically Kenya, China, Sri Lanka, India, Vietnam and Indonesia (Fig. 2) [5].

All types of tea are produced from the shoots of the same tea plant. However, the processing steps involved in tea production determine the type of tea to be produced viz., black tea, oolong tea, green tea etc. Fig. 3

shows the various processing steps covered during production of different tea. Processing of the tea leaves is energy intensive. It consumes electrical as well as thermal energy in the ratio of 15:85. In tea factories thermal energy requirement is 3.5–6 kWh per kg of tea produced, and electrical energy requirement is 0.21–0.5 kWh per kg of tea produced [4,6]. In addition, more than 80 % of the total energy consumption is thermal energy, which is consumed in drying and withering operations in tea factories in removing the moisture from leaves. Electrical and thermal energy consumptions per 100 kg of made tea in major processes of tea factory in Assam, India are given in Table 1. The electrical energy is utilized to operate machineries such as fan/blower in withering, CTC machine, rolling machine, rotovane machine for maceration, blower/fan and excitation system for drying, shorting machine for grading the tea, etc. [7].

The purpose of the present study is to explore various drying

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**Nomenclature:****Abbreviations:**

|        |                                                                |
|--------|----------------------------------------------------------------|
| AD     | Air drying                                                     |
| ANN    | Artificial neural network                                      |
| CTC    | Crush tear curl or crushing tearing curling                    |
| CUMV   | Combined unsymmetrical double-feed microwave and vacuum system |
| ECP    | Endless chain pressure drier                                   |
| EES    | Engineering Equation Solver                                    |
| FBD    | Fluidized bed drier                                            |
| FBOF   | Flowery broken orange pekoe                                    |
| FBOPF  | Flowery broken orange pekoe fanning's                          |
| FBOPF1 | Flowery broken orange pekoe fanning's one                      |
| FCC    | Federal Communications Commission                              |
| GHG    | Greenhouse gas                                                 |
| GA     | Genetic algorithm                                              |
| HP     | Horsepower                                                     |
| IMD    | Indirect mode drying                                           |
| MRE    | Mean relative error                                            |
| MBE    | Mean bias error                                                |
| MR     | Moisture ratio                                                 |
| MXC    | Mixing chamber                                                 |
| MMD    | Mixed mode drying                                              |
| MAD    | Microwave assisted drying                                      |
| OP     | Orange pekoe                                                   |
| OP1    | Orange pekoe one                                               |
| OPA    | Orange pekoe 'A'                                               |
| OSD    | Open sun drying                                                |
| PVT    | Photovoltaic thermal collector                                 |
| RMSE   | Root mean square error                                         |
| SD     | Shade drying                                                   |
| SHAG   | Solar hot air generator                                        |
| SEK    | Swedish Krona                                                  |
| SWG    | Standard Wire Gauge                                            |
| TCD    | Total color difference                                         |
| TPC    | Total phenolic content                                         |
| VFBD   | Vibro-fluidized bed drier or vibrating fluidized bed drier     |

**Symbols:**

|           |                                         |
|-----------|-----------------------------------------|
| $A$       | Amplitude of vibration (m)              |
| $Ar$      | Archimedes number                       |
| $C_{pa}$  | Specific heat of air (kJ/kg-°C)         |
| $C_{pv}$  | Specific heat of water vapor (kJ/kg-°C) |
| $d_p$     | Mean particle diameter (m)              |
| $D$       | Diffusion coefficient                   |
| $ER$      | Evaporation rate (kg/m <sup>2</sup> -s) |
| $\dot{E}$ | Total energy involved (kW)              |

|                     |                                                            |
|---------------------|------------------------------------------------------------|
| $\dot{E}x$          | Total exergy involved (kW)                                 |
| $f$                 | Frequency of vibration (Hz)                                |
| $g$                 | Gravitational acceleration (g/m <sup>2</sup> )             |
| $H_a$               | Absolute humidity of air (kg of water vapor/kg of dry air) |
| $k, k_o, k_I, g, h$ | Model coefficients                                         |
| $a, b, c, n$        | Model constants                                            |
| $MC$                | Moisture content                                           |
| $m$                 | Mass of the drying material (kg)                           |
| $M_v$               | Mass of evaporated moisture (kg)                           |
| $N$                 | No. of observations                                        |
| $n$                 | No. of constants                                           |
| $Re$                | Reynold's number                                           |
| $R^2$               | Coefficient of determination                               |
| $SEC$               | Specific energy consumption (kJ/kg)                        |
| $t$                 | Drying time (s)                                            |
| $T$                 | Temperature of air (°C)                                    |
| $V_h$               | Specific volume of air (m <sup>3</sup> /kg)                |
| $\dot{V}$           | Speed of air flow (m/s)                                    |
| $u$                 | Velocity of air (m/s)                                      |

**Greek letter:**

|           |                                    |
|-----------|------------------------------------|
| $\chi^2$  | Chi-square                         |
| $\Delta$  | Difference in values               |
| $\rho$    | Density (kg/m <sup>3</sup> )       |
| $\eta$    | Efficiency                         |
| $\mu$     | Dynamic viscosity (kg/m-s)         |
| $\Lambda$ | Vibrational intensity              |
| $\omega$  | Angular speed of vibration (rad/s) |

**Subscripts:**

|         |                                            |
|---------|--------------------------------------------|
| $d.b.$  | Dry basis                                  |
| $d$     | Dried or final product                     |
| $e$     | Equilibrium                                |
| $eff$   | Effective                                  |
| $en$    | Energy                                     |
| $ex$    | Exergy                                     |
| $exp,i$ | Experimental value of $i^{th}$ observation |
| $exit$  | Exit                                       |
| $g$     | Fluid                                      |
| $i$     | Initial                                    |
| $in$    | Inlet                                      |
| $mf$    | Minimum fluidization                       |
| $o$     | Initial                                    |
| $p$     | Particle                                   |
| $pre,i$ | $i^{th}$ predicted value                   |
| $t$     | Time                                       |
| $used$  | Quantity utilized                          |
| $w.b.$  | Wet basis                                  |

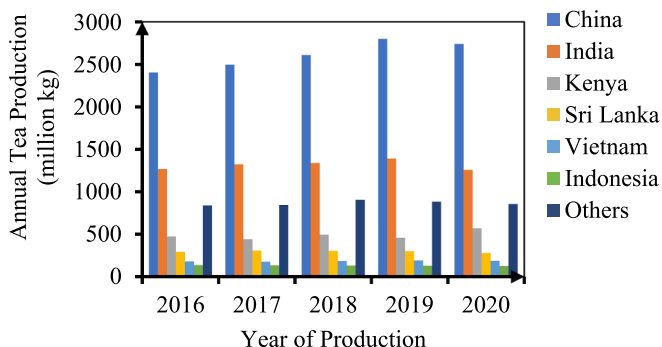


Fig. 1. Annual tea production across the world [5].

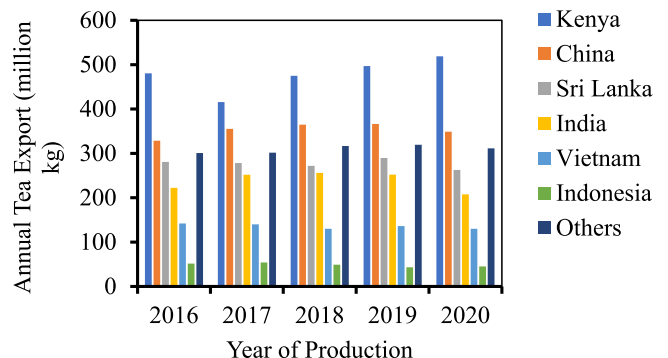


Fig. 2. Annual tea export across the world [5].

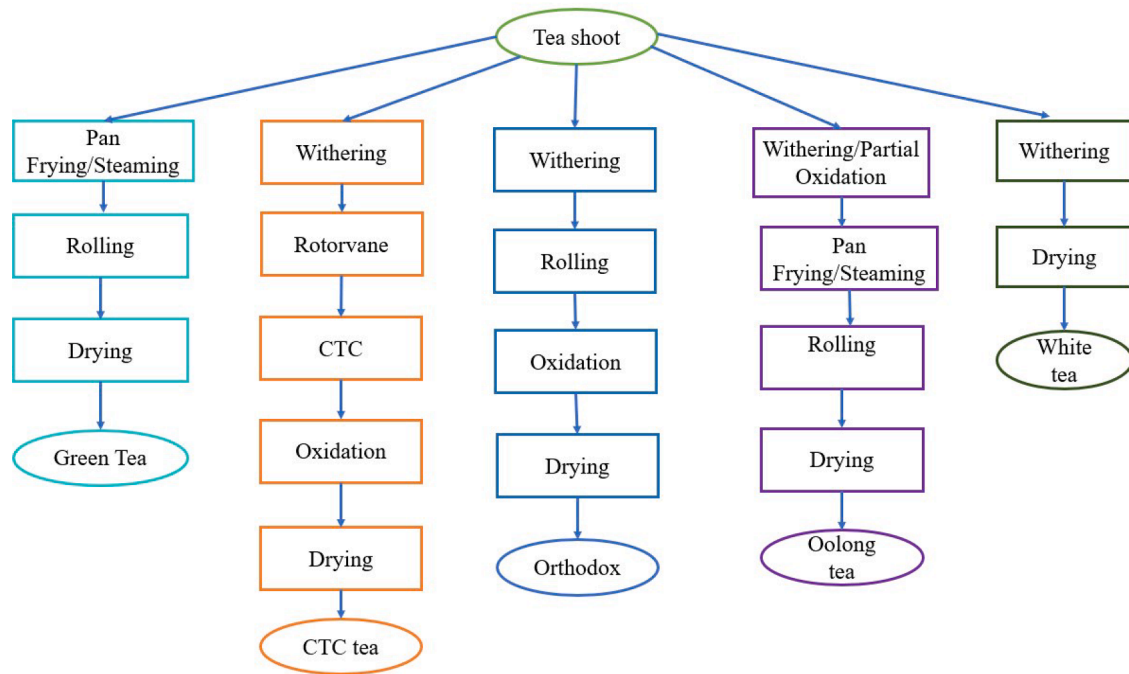


Fig. 3. Processing steps involved in the production of the various varieties of tea [14].

Table 1

Energy requirement in various processes of black tea production per 100 kg of made tea [7].

| Process    | Thermal energy requirement (kWh <sub>th</sub> ) | Electrical energy requirement (kWh <sub>e</sub> ) |
|------------|-------------------------------------------------|---------------------------------------------------|
| Withering  | 49.75                                           | 5.54                                              |
| Maceration | 0                                               | 8.63                                              |
| Drying     | 497.53                                          | 6.23                                              |
| Grading    | 0                                               | 3.95                                              |

technologies existing in the tea factories. In addition, the working principle and novelties associated with the various technologies on commercially successful/industrial driers, and the driers under research stage are described. Later in this study, various investigations on renewable energy assisted drying of tea leaves, and challenges associated with the designing of the tea drying system and their possible solution ideas are incorporated. Additionally, an integrated solar energy-based tea drying system has been proposed for tea factories to

minimize the consumption of fossil fuels.

## 2. Tea processing steps

Production of all types of tea starts with the process of harvesting, commonly referred as plucking and is performed manually or mechanically. Since manual plucking involves selective plucking, it helps to produce good quality of tea as compared to machine plucking. Selective plucking is important as levels of concentration of chemical constituents (such as polyphenols and caffeine contents) are responsible for better quality. The concentration of chemical constituents is maximum in the bud and decreases as coarseness of the leaves increases, as shown in the Fig. 4. Table 2 shows the chemical constituents details of the tea leaves [8]. However, manual plucking results in lower productivity, or in other words, highly labour intensive. Hence, a gradual shift from manual to machine plucking is currently prevailing in the factory to minimise the production cost.

The subsequent steps in processing of black tea, the most preferred

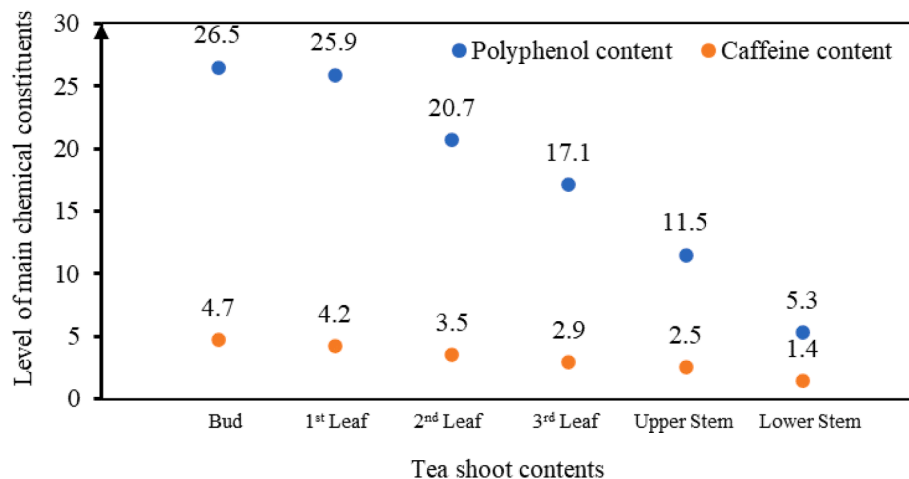


Fig. 4. Level of main chemical constituents with tea shoot contents [3,13].

**Table 2**  
Chemical constituents of tea leaves [8].

| Chemical Constituents | Quantity (%)    |
|-----------------------|-----------------|
| Polyphenols           | 36.0 %          |
| Carbohydrates         | 25.0 %          |
| Proteins              | 15 %            |
| Methylxanthines       | 3.5 %           |
| Lignin                | 6.5 %           |
| Amino acids           | 4.0 %           |
| Lipids                | 2.0 %           |
| Organic acids         | 1.5 %           |
| Volatiles             | less than 0.1 % |
| Chlorophyll           | 0.5 %           |
| Carotenoids           | less than 0.1 % |
| Ash                   | 5 %             |

type of tea worldwide, include withering, maceration/rolling, oxidation, drying, sorting and grading, and packaging. Withering involves temporary storage of the harvested shoots where catabolic reactions are allowed to continue for a certain period concomitant to partial removal of moisture. This process brings about a change in the texture of the harvested shoots, turning the leaves flaccid. The chemical changes during withering are precursors to flavour, aroma, colour and taste of the tea. Maceration imparts definite shape and size to the withered leaves to make the final product acceptable to the consumer as per the market trend. This process also ruptures the cells in the tea shoots to expose the chemicals within. Based on the methods of maceration, black tea may be classified into two types; Orthodox and CTC. While, orthodox tea is treated by rolling of the shoots to give it twisted form, CTC (Crush, Tear and Curl) tea is macerated by chopping the leaves into uniform granulated particles. Oxidation commonly referred as fermentation by mistake, is typical to black tea processing. It involves enzymatic oxidation of the catechins (natural polyphenolic phytochemicals) within the tea shoots to form thearubigin (TR) and theaflavin (TF). During this process, tea turns from green to coppery red and also formation of typical characteristics of tea takes place. TF is accountable for the brightness and briskness, and TR is accountable for the body and strength of the liquors. Catechins responsible for these characteristics are epicatechin (EC), epigallocatechin (EGC), epicatechin gallate (ECG), epigallocatechin gallate (EGCG), and galliccatechin (GC) [3,9–13]. On the basis of extent of oxidation, tea is classified as green, white, oolong and black. Green and white tea are non-fermented tea. Oolong tea is semi-fermented tea and black tea is fully fermented tea. The next process of drying is performed to reduce the moisture content to a required level. Drying also halts the enzymatic reactions and gives chemical stability to the tea. Thus, effective inactivation of the enzymes under the influence of hot air applied during drying allows to handle the product for subsequent activities till it is consumed within its shelf life. Thereafter, dried tea undergoes sorting where fibre and stalky materials are removed and the tea is graded based on the sizes of particles by sieving it. Processing of tea is then ended with packaging which is required to protect the tea from the moisture and other contaminants. The dried tea is recommended to store in cool (at room temperature), dark and dry place to avoid the quality loss with the passage of time [4,12–23].

### 3. Drying: An important step in tea processing

Drying is an ancient way of preserving food materials for longer times. Before storing the food material for longer time, it is essential to minimize the moisture of the materials to a level such that growth of bacteria can be avoided. Presence of excess moisture provides neutral favorable environment for bacterial growth and helps in metabolic process for energy generation required for bacterial growth. This technique of preservation helps in prolonging the utility of the food product depending upon its usage pattern. During drying of the materials, it is extremely important to ensure that there should be no unwanted biochemical reactions, and all the nutrients, fragrance, color etc. should

be retained in the products after drying [24].

Moisture content of above 5 % is detrimental to tea quality, since at this level bacterial growth takes place at a very fast rate. Tea being hygroscopic in nature, production units prefer to maintain a moisture level within 2.8 to 3 % after drying, leaving a narrow allowance for the final stages of blending and packaging. Moisture level below 2.8 % results in scorching of the product and is often referred as “over firing”. Thus, a longer shelf life of tea is ensured, making it easier for handling and transportation [4,25,26]. In addition, drying of leaves is also performed to arrest the oxidation of tea leaves. Drying conditions such as moisture content, drying temperature and rate of evaporation of the moisture are controlled appropriately so that the tea produced would be of good quality and at the same time there would be less energy consumption during the drying process. Additionally, if drying temperature is too high, drying of tea becomes very fast, and because of this case hardening of the leaves occurs; in this case surface of the leaf becomes dried rapidly as compared to the core of the leaf. Hence, it increases the chances of presence of moisture in inner core of the leaves, and thus quality of the tea is affected. Furthermore, if the drying temperature is too low, oxidation process does not stop and it remains unabated, it deteriorates the quality of tea. This condition is termed as stewing; if the drying of tea is fast enough in the beginning, stewing can be minimized [3,27]. Thermal energy demand in hot air-based drying is fulfilled using fossil fuels such as natural gas, high speed diesel, coal and tea drying oil. Controlling the drying conditions and utilizing waste heat are also important concerns to minimize the fuel consumption in the factories [3,4,28,29].

Mechanism of drying operation is intricate because it involves the heat and mass transfer simultaneously. When heated air is brought in contact with leaf particles' surface, it provides latent heat to the moisture and vaporization takes place. Vapors are expelled with the hot air, thus creating a low water vapor pressure zone on the surface of particle. This results a water vapor pressure gradient between the surface and interior of the particle. Thus, the water vapor pressure gradient formed works as the driving force for removing the moisture from the interior of the leaf particle to its surface. Therefore, moisture removal involves two phenomena; one is associated with the moisture removal from the surface and other is from the interior of leaf [3,24]. Moisture removal from the surface in the initial stage of drying does not depend on the moisture content present in the tea leaves; this stage is called “Constant Rate Period”. However, with the removal of the freely available moisture from the leaves' surface, rate of evaporation slows down. This stage is called “Falling Rate Period”. This stage consumes significant amount of energy and time, but quantity of moisture removal is less [1,30].

Many researchers have suggested mathematical models to predict the kinetics of drying of tea. These models can predict the moisture content at any instant during drying. Kinetics of drying are predicted using thin layer drying models under three categories: 1) theoretical, 2) semi-theoretical and 3) empirical. The theoretical models consider only internal resistance to moisture transfer. However, semi-theoretical and empirical models account only external resistance to moisture transfer. Fick's second law may be written in simple form (Eq. (1)) on considering following assumptions:

- The moist tea is homogeneous and isotropic in nature.
- The resistance to moisture transfer is uniform throughout the moist tea.
- Negligible shrinkage in volume during drying
- Independency of effective diffusion coefficient  $D_{eff}$  on local moisture content.

$$\frac{\partial(MR)}{\partial t} = D_{eff} \nabla^2(MR) \quad (1)$$

where,  $t$  is time and  $MR$  is moisture ratio. Effective diffusivity indicates that the rate of water movement inside the material from higher

**Table 3**

Thin layer drying models explored for drying of leaves of various plants.

| Model                        | Equation                                           | Reference  |
|------------------------------|----------------------------------------------------|------------|
| Lewis                        | $MR = \exp(-kt)$                                   | [43,44]    |
| Henderson and Pabis          | $MR = a \cdot \exp(-kt)$                           | [40,45]    |
| Page                         | $MR = \exp(-kt^n)$                                 | [40,46]    |
| Modified Page                | $MR = \exp[-(kt)^n]$                               | [40,45–48] |
| Logarithmic                  | $MR = a \cdot \exp(-kt) + c$                       | [40,44,47] |
| Two term                     | $MR = a \cdot \exp(-k_0 t) + b \cdot \exp(-k_1 t)$ | [40,47]    |
| Verma et al.                 | $MR = a \exp(-kt) + (1-a) \exp(-gt)$               | [40,45,49] |
| Wang and Singh               | $MR = 1 + at + bt^2$                               | [40,44,45] |
| Midilli and Kucuk            | $MR = a \exp(-kt^n) + bt$                          | [45,47,50] |
| Three-parameter              | $MR = a \exp(-(kt)^n)$                             | [51]       |
| Inverse quadratic Dave       | $MR = a + (b \times t) - (c \times t^2)$           | [52]       |
| Two term exponential         | $MR = a \exp(-kt) + (1-a) \exp(-kat)$              | [53]       |
| Modified Henderson and Pabis | $MR = a \exp(-kt) + b \exp(-gt) + c \exp(-ht)$     | [54]       |
| Diffusion approach           | $MR = a \exp(-kt) + (1-a) \exp(-kbt)$              | [55]       |
| Gupta et al.                 | $MR = a \exp(-kt^n) + b \exp(-gt^n) + ct$          | [42]       |

concentration to lower concentration and moisture ratio is the ratio of moisture content at any time to initial moisture content. Analytical solution of the Fick's 2nd law was presented by Crank [31] for different shape of bodies viz. cylindrical, rectangular and spherical [32–36].

Table 3 shows the equations representing drying kinetics of various leaves from different plants and agricultural product. Researchers have utilized thin layer drying models such as Lewis model, Logarithmic model, Page model, Henderson and Pabis model, Two term model, Gupta et al. model etc. for predicting the kinetics of drying of the tea leaves [24,37–42].

Thin layer drying models presented in Table 3 have coefficients and constants such as  $k$ ,  $k_0$ ,  $k_1$ ,  $g$ ,  $h$ ,  $a$ ,  $b$ ,  $c$ ,  $n$ . These parameters are evaluated during the assessment of the model for better prediction the drying experimental outputs. The goodness of fit of drying models with experimental outputs are evaluated using root mean square error (RMSE; Eq. (2)), mean bias error (MBE; Eq. (3)), coefficient of determination ( $R^2$ ; Eq. (4)) and Chi-square ( $\chi^2$ ; Eq. (5)) values. The model exhibiting lesser values of RSME, MBE and  $\chi^2$ , and higher values of  $R^2$  is considered as best model predicting the drying characteristics [42,53,54,56].

$$RMSE = \sqrt{\frac{1}{N} \left[ \sum_{i=1}^N (MR_{pre,i} - MR_{exp,i})^2 \right]} \quad (2)$$

$$MBE = \frac{1}{N} \left[ \sum_{i=1}^N (MR_{pre,i} - MR_{exp,i}) \right] \quad (3)$$

$$R^2 = \left[ \frac{\left[ \sum_{i=1}^N (MR_{pre,i} \cdot MR_{exp,i}) \right] - \left[ \sum_{i=1}^N MR_{pre,i} \cdot \sum_{i=1}^N MR_{exp,i} \right]}{\left[ \sum_{i=1}^N MR_{pre,i}^2 - \left[ \sum_{i=1}^N MR_{pre,i} \right]^2 \right] \left[ \sum_{i=1}^N MR_{exp,i}^2 - \left[ \sum_{i=1}^N MR_{exp,i} \right]^2 \right]} \right]^2 \quad (4)$$

$$\chi^2 = \frac{\left[ \sum_{i=1}^N (MR_{exp,i} - MR_{pre,i})^2 \right]}{N - n} \quad (5)$$

where,  $MR_{exp,i}$  is the experimental moisture ratio of  $i^{th}$  observation,  $MR_{pre,i}$  is the  $i^{th}$  predicted moisture ratio [42,53,54,56]. Eq. (6) and Eq. (7) are utilized to calculate initial moisture contents in dry basis ( $MC_{(d.b.)}$ ) and wet basis ( $MC_{(w.b.)}$ ), respectively.

$$MC_{(d.b.)} = \frac{m_i - m_d}{m_d} \quad (6)$$

$$MC_{(w.b.)} = \frac{m_i - m_d}{m_i} \quad (7)$$

Considering thin layer drying,  $MR$  of drying material at particular drying time is calculated using Eq. (8) and Eq. (9), respectively for the cases of constant relative humidity and continuously fluctuating relative humidity of air during drying process.

$$MR = \frac{MC_t - MC_e}{MC_o - MC_e} \quad (8)$$

$$MR = \frac{MC_t}{MC_o} \quad (9)$$

$MC_t$  is calculated considering mass of drying material at particular time  $t$  in place of initial mass in Eq. (6) [42,53,54,56].

#### 4. Tea drier

Tea drier is the machine which allows tea leaves to dry to a proper level of moisture content and confers required quality attributes of desired levels. A typical tea drier has inlet doors for supplying hot air and wet tea Dhool, outlet door for dried tea and exhaust opening for used air. Hot air is supplied by the air heater. The majority of air heaters used in tea factories use fossil fuels to heat the ambient air. Coal and natural gas are the most common fuels used in tea factories, though tea factories are also known to use firewood.

##### 4.1. Industrial drier

Depending upon the mode of operation, tea driers may be classified as Fluidized bed or Vibro-fluidized bed drier (FBD/VFBD) and Endless chain pressure (ECP) drier. These are hot air based convective driers. Details pertaining to these driers are covered in subsequent sections.

##### 4.1.1. Fluidized bed drier (FBD)

The characteristics and working principle of a single stage fluidized bed drier was explained by Temple and Bostel [13,57]. It was reported that to diminish the moisture content from 70 % to 3 % (w.b.) for black tea, single stage FBD could be used with uniform flow rate and inlet temperature of air throughout the bed of drier. At each position on the drier bed, total mass of the tea was kept constant. As the moisture evaporated from the tea, dry mass of tea started slowing down its movement on the bed. Uniform mixing and drying of tea granules were ensured through fluidization process. The hot air worked as a carrier of the tea granules through the drier and provided forward motion to the leaves until the dried leaves were released at the discharge end. A weir was attached with the drier at the exit of the drier to control the

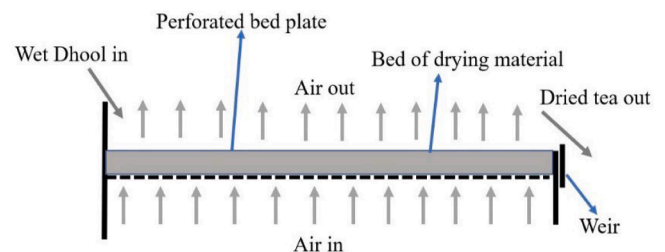


Fig. 5. Single stage fluidized bed drier [57].

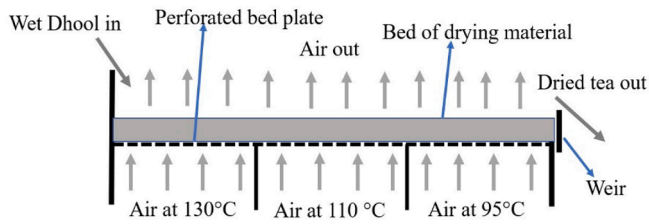


Fig. 6. Multi-stage fluidized bed drier [58].

residence time of dried tea on the bed by adjusting the height of it as shown in Fig. 5. FBD/VFBD drier is more suited for CTC black tea production.

The working of continuous multi-stage fluidized bed drier was explained by Temple et al. and the schematic is shown in Fig. 6 [58]. It was illustrated that there were generally three zones in FBD drier with different flow rates and temperatures of air. These were to handle varying moisture contents during drying of the black tea. The first zone was supplied with the air at temperature of 120–140 °C with higher mass flow rate of air than other zones. The air at exit became almost saturated because of high drying rate in the first zone. In the same sequence middle zone and dry end zone had air of 100–120 °C and 90–100 °C, respectively to make the drying at its maximum. One weir was attached to the drier exit end (or may be multiple weirs between the stages). The height of weir was manually adjusted to control the chances of back mixing and also to control the residence time of dried tea on the bed.

General assembly of Vibro-Fluid Bed Dryer is shown in Fig. 7. It has air heater to generate hot air and blower to feed the hot air into the drier for fluidization of tea material. The feed conveyor is used for feeding the fermented tea into drier. The cyclone separator is used to remove stalks and fibers. The dust extractor is used to remove dust and fibers. An excitation mechanism is attached to provide vibration to the bed to facilitate fluidization. The drier bed is divided into different zones (not

shown in Fig. 7) to avoid overheating of tea [59,60]. Various investigation on FBD/VFBD are reported in the subsequent paragraphs.

The performance of drying and aerodynamic behaviour of black tea using vibro-fluidized bed drier was studied by Sadeghi and Khoshtaghazha [61]. Drying experiments had been conducted for three different inlet temperature conditions of air (100, 115 and 130 °C) at five different levels of intensities of vibration such as 0 (vibration less), 0.063, 0.189, 0.395 and 1.184. Intensity of vibration may be defined as the ratio of vibrational acceleration to gravitational acceleration (shown in Eq. (10)).

$$\Lambda = \frac{A\omega^2}{g} = \frac{A(2\pi f)^2}{g} \quad (10)$$

It was observed that the vibration effect had reduced the necessity of minimum velocity for fluidization and overcome the problems of de-fluidization and bed channeling. Furthermore, based on the specific energy consumption and less minimum fluidization velocity, 100 °C temperature of inlet air and vibration intensity of 1.184 were recommended for drying in vibro-fluidized bed drier. The experiments were conducted at Bangladesh Tea Research Institute to determine the drying time, drying rate constant, dynamic equilibrium moisture content and drying curve by Akhtaruzzaman et al. [59]. Kilburn Vibro-Fluid Bed Drier was used to perform the experiments. It took 20 min in drying of tea from the initial moisture content of 69.1 % to 2.8 % (as shown in Fig. 8a.). Temperatures at outlet and inlet of the drier were 90 °C and 130 °C, respectively. The drying rate constant was calculated using Eq. (11) for thin layer drying conditions, considering moisture contents at two suitable times during drying of tea.

$$MR = \frac{MC_t - MC_e}{MC_o - MC_e} = e^{-kt} \quad (11)$$

The drying rate constant ( $k$ ) from the experimentations was calculated as  $31.05 \text{ h}^{-1}$ . Fig. 8(b) shows the variation in drying rate with time. C to D, B to C, A to B show second falling rate period, first falling rate period and constant drying rate period in drying, respectively. Dynamic

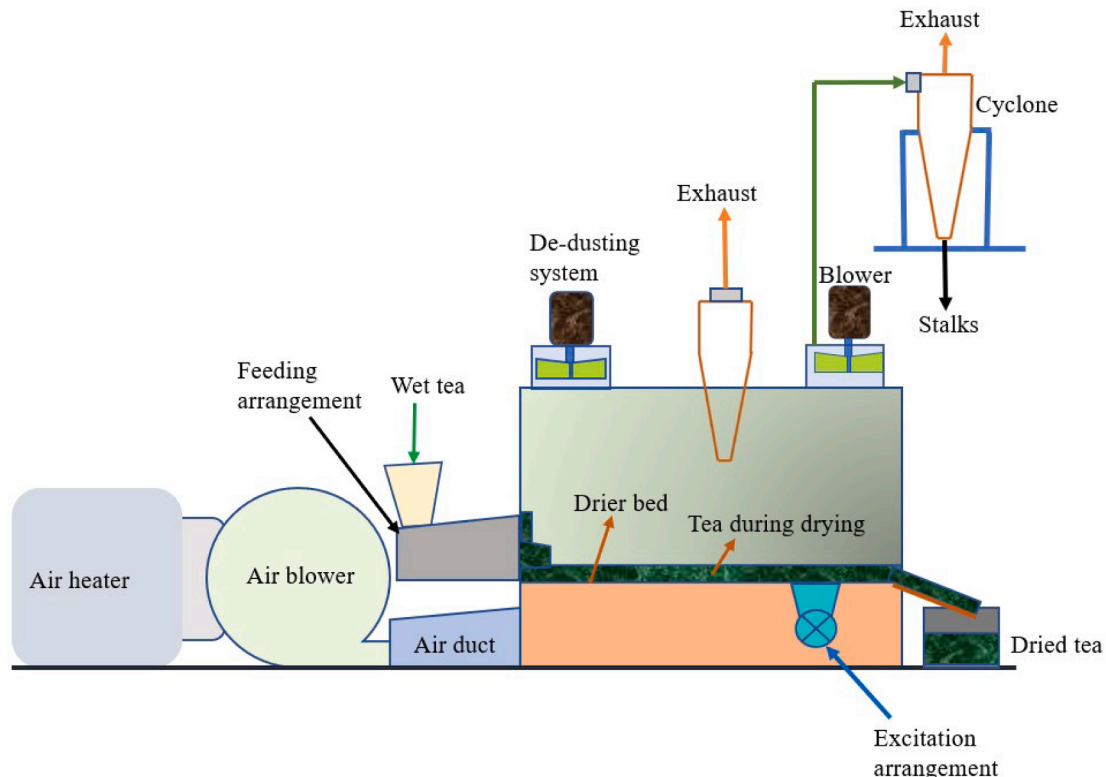


Fig. 7. General assembly of Vibro-Fluid Bed Dryer [59,60].

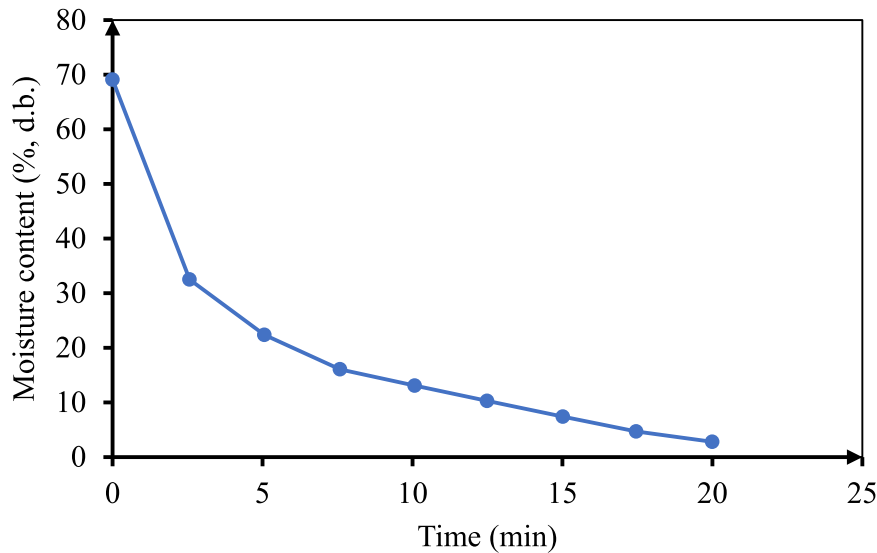


Fig. 8a. Reduction of moisture content with time in drying [59].

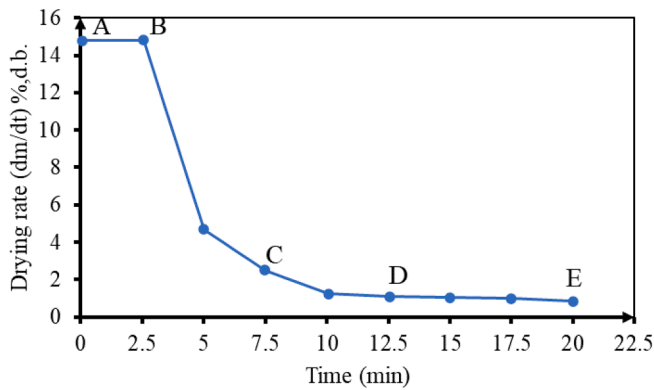


Fig. 8b. Variation in drying rate with time [59].

equilibrium moisture contents were reported between 18.3 % and 2.0 %. For the calculation of dynamic equilibrium moisture content further extension of Eq. (11) i.e. Eq. (12) was used.

$$MC_e = MC_1 + \Delta MC / (1 - e^{-k\Delta t}) \quad (12)$$

The FBD system for tea drying was experimented by Handayani et al. [62]. The drying system had zeolite material-based adsorption dehumidifier for reducing the humidity in the air before entering it into the drying chamber. The study had been performed with air flow rates of 0.44 m/s, 0.46 m/s, and 0.50 m/s at 50 °C and 70 °C considering zeolite to tea ratios of 75:25 and 25:75. It was concluded that high zeolite to tea ratio (75:25) could offer less drying time than less zeolite to tea ratio (25:75). Additionally, in case of zeolite to tea ratio of 25:75, the fastest decreasing in the drying time was achieved when air was supplying at 70 °C with flow rate (speed) of 0.46 m/s. It was also observed that drying time was higher in case of hot air at 50 °C than 70 °C. Schematic of experimental setup for zeolite adsorption based fluidized based drying is shown in the Fig. 9. Zeolite box was attached between blower and exhaust from the drier unit. Prior to the drying, zeolite was activated to ensure the adsorption of the humidity in the air. The activation of zeolite was accomplished by heating it into the furnace at 400 °C for 4 h to evaporate the moisture present in the zeolite. Sodium hydroxide based chemical washing was performed to remove the impurities present on the surface of the pores of the zeolite.

The energy efficient multi-pass vibro-fluidized bed drier having three fixed vertically zigzag arranged oppositely sloped decks was analysed by

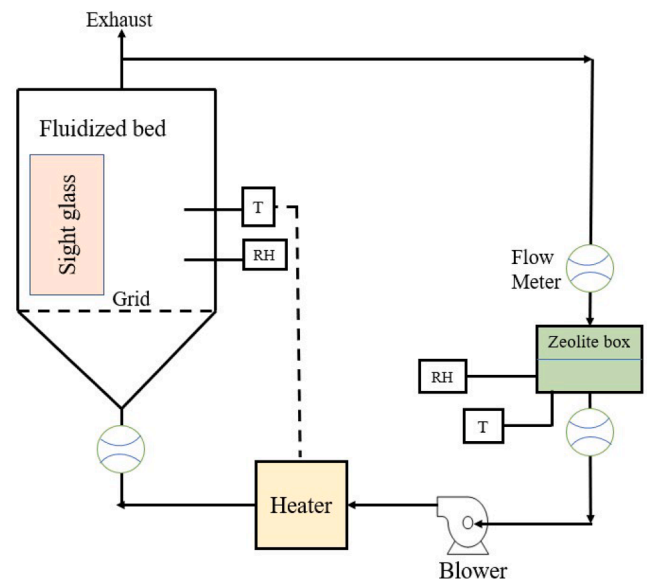


Fig. 9. Zeolite adsorption based fluidized bed drier [62].

Bandara et al. [63]. Decks of dimensions 3.6 m × 0.78 m were having perforated sheets with 13 holes of 1.5 mm diameter in per cm<sup>2</sup> area of sheet. The experiments were performed to optimise the slope and vibrational frequency of the decks for different moisture conditions of orthodox rolled tea dhools. Results had shown that optimum slopes were 3 %, 4 % and 5 % for moisture contents of 10 %, 30 % and 55 %, respectively with air flow rate of 2.83 m<sup>3</sup>/s at 38 Hz of vibrational frequency of decks.

The performance evaluation study on drying of green tea using continuous vibrating fluidized bed drier was presented by Handayani et al. as shown in Fig. 7 [60]. The experimentations were performed for inlet air temperatures of 50, 60 and 70 °C with air flow velocities of 0.71 m/s, 0.94 m/s and 1.09 m/s (Fig. 10). For shortest drying time of green tea, the air velocity of 1.09 m/s and air temperature of 70 °C were recommended. Apart from this, study had also shown that moisture content was reducing more rapidly with the increasing in the flow rate and temperature of inlet air.

The comprehensive thermodynamic study to analyze performance parameters such as exergy and energy efficiencies of three stage vibro-

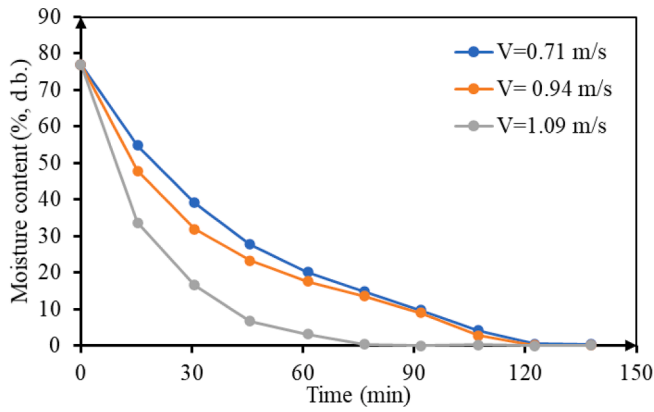


Fig. 10. Moisture content variation with time under different air flow velocity condition [60].

fluidized bed drier system was performed by Ozturk and Dincer as shown in Fig. 11 [64]. The complete system contained 12 subunits such as the three-stage drier, two cold and one hot gas blowers, air heater, cyclone blower, two mixing chambers (MXC), cyclone separator, air recirculation flap. Following equations, Eq. (13) and Eq. (14) were utilized to determine the energy and exergy efficiencies:

$$\eta_{en} = \frac{E_{used}}{E_{in}} \quad (13)$$

$$\eta_{ex} = \frac{\dot{E}x_{used}}{\dot{E}x_{in}} \quad (14)$$

All the variables included in the equations were calculated using energy, mass, and exergy balances across all the components of system. It was found that over all energy efficiency and exergy efficiency were 42 % and 7.2 %, respectively. Main component for exergy destruction was the drier, in which 58 % of overall exergy destruction took place.

The effect of the shrinkage on the physical quality of orthodox tea due to drying was studied by Raveendran et al. [65]. The work was conducted on fluidized bed drier. The correlation between the Archimedes number ( $Ar$ ) and dimensionless moisture ratio (Eq. (15)) was used for this study [65].

$$\ln Ar = 7.5110 + 4.1734(MR) \quad (15)$$

Archimedes number ( $Ar$ ) in the Eq. (15) is given as Eq. (16) [66];

$$Ar = \frac{\rho_g d_p^3 (\rho_p - \rho_g) g}{\mu^2} \quad (16)$$

Archimedes number is the function of the physical attributes of the fluidizing material, which varies with the density of the particles and size of the particles. Further, another correlation was established

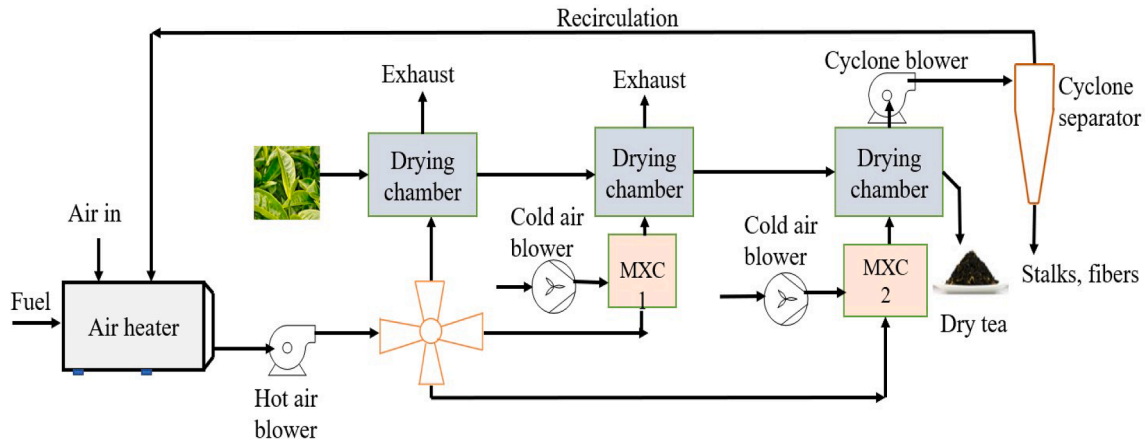


Fig. 11. Schematic of three stages vibro-fluidized bed drier system [64].

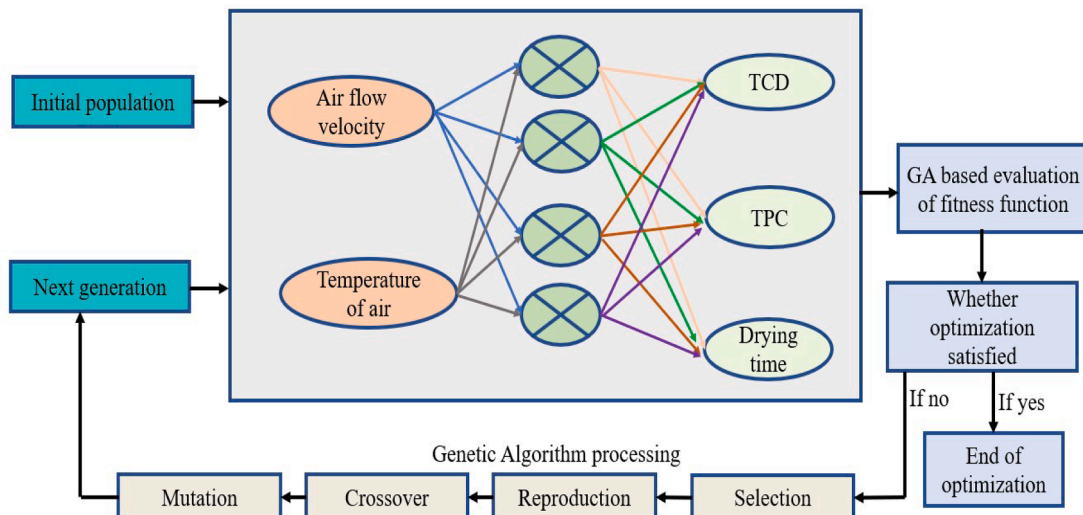


Fig. 12. Optimization process of ANN using GA technique for drying of tea leave [67].

between the Reynold's no. at minimum fluidization ( $Re_{mf}$ ) and Archimedes number ( $Ar$ ) as given in Eq. (17) [65]:

$$Re_{mf} = 0.6792 Ar^{0.3909} \quad (17)$$

where,  $Re_{mf} = (\rho_g u_{mf} d_p) / \mu$ . These two correlations, Eq. (15) and Eq. (17), had been utilized to predict the minimum fluidization velocity  $u_{mf}$  for a particular moisture content. Results from the model were validated with the experimental results from drying of orthodox broken tea on fluidized bed drier at 124 °C considering loading between 44.5–50.5 kg/m<sup>2</sup>. There was good agreement of predicted fluidization velocity with the experimental velocity and the difference was less than 10 %.

The optimum process parameters for fluidized bed drying of green tea leaves by utilizing integration of artificial neural network (ANN) technique with genetic algorithm (GA) was predicted by Kalathingal

et al. [67]. Optimization process of ANN using GA is shown in the Fig. 12. Air flow speed between 7 and 9.5 m/s and temperature between 50 and 80 °C were selected as input parameters for ANN. Total color difference (TCD), drying time and total phenolic content (TPC) were considered as output parameters for ANN. Inputs for genetic algorithm were the bias and weights values from the trained ANN. GA evaluated the fitness function, which had minimized the TCD and drying time, and maximized the TPC. Optimum conditions predicted by the hybrid ANN/GA technique were air temperature of 80 °C and air flow speed of 9 m/s. Further, predicted output values of TPC, TCD and drying time at optimum input conditions were validated with the experimentations conducted on same optimum conditions i.e. air temperature of 80 °C and air flow speed of 9 m/s.

#### 4.1.2. Endless chain pressure drier

Endless chain pressure drier is also called conventional drier. This drier is fed up with hot air in temperature range of 82–99 °C for satisfactory results of drying in tea factory. Exhaust temperature between 49 and 54 °C is advocated for arresting the oxidation of fermented tea leaves. Generally, residence time of tea leaves in the drier is kept from 21 to 24 min. This drier is suited for orthodox, CTC, and green tea (from India) production [13]. Temple and Van Boxtel [57] mentioned endless chain pressure (ECP) drier as the conveyor type of drier having popularity at second place after fluidized bed drier. This drier solved the problem of mixing of tea leaves by falling leaves from one conveyor to the next one below it. In addition to this, the velocity requirement of air for this drier was in the range of half of that required in the case of fluidized bed drier. The feed rate of tea was kept constant on the conveyors (chains). The hot air was being passed from the bottom (chain) to the upper section and so on for the other stages to utilize the thermal energy of hot air efficiently (Fig. 13). The endless chain pressure drier had been considered hybrid between the cross and countercurrent flow. Commercially available ECP drier had usually-four or six stages. Researchers further explained the issues with the ECP drier. It was mentioned that drying rate in the topmost stage was too low because air was almost saturated and it was only heating the tea leaves without performing drying, thus the quality of tea got affected. To address this issue, the concept of “hot feed” was added before the feeding of the tea in the ECP drier (Fig. 14). In hot feed section, same flow rate and temperature of air was supplied as in the case of ECP drier. As a corollary to that, initial drying of tea leaves became very fast without destroying much efficiency, because exhausts from hot feed as well as from ECP drier were saturated or close to the saturation. Addition of hot feed had increased the initial drying of tea in ECP drier and also improved the

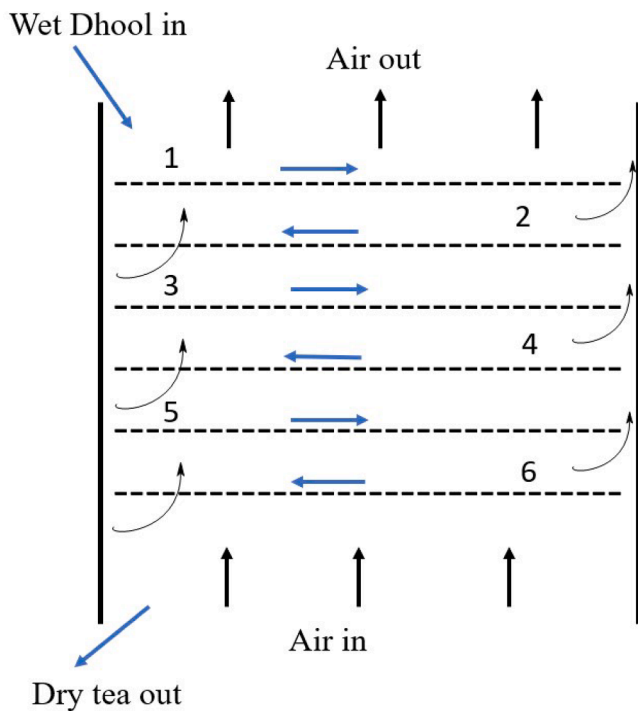


Fig. 13. Schematic of endless chain pressure drier [57].

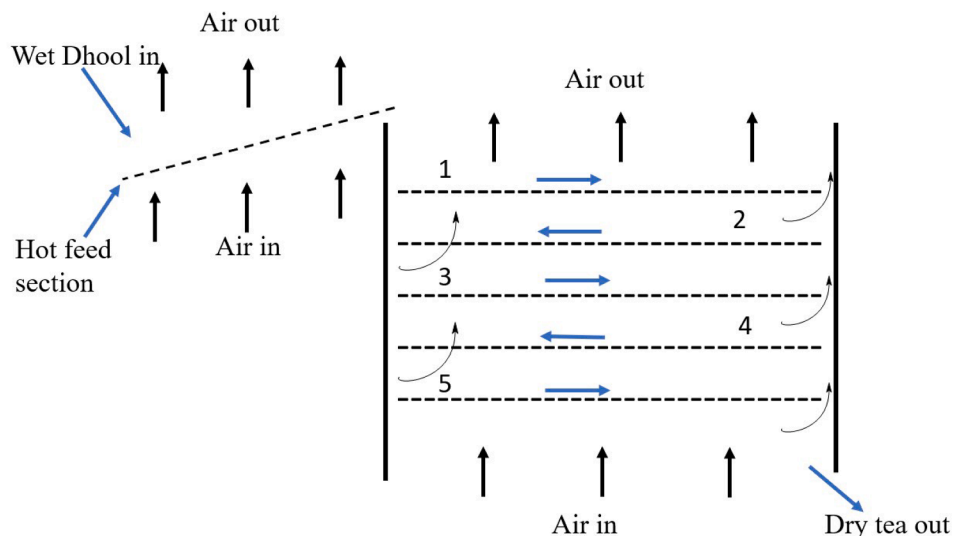


Fig. 14. Schematic of endless chain pressure drier with hot feed arrangement [57].

**Table 4**

Design data/technical specification of industrial fluidized bed and endless chain pressure drier [13].

| FBD/<br>VFBD | Power requirement                               |                   | <ul style="list-style-type: none"> <li>Drying system (38.5–45.0 HP)</li> <li>Dust collection (10–22.5 HP)</li> </ul>                                                                                                       |
|--------------|-------------------------------------------------|-------------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
|              | Specific fuel consumption                       |                   | <ul style="list-style-type: none"> <li>Coal: 0.39–0.7 kg per kg of tea produced</li> <li>Oil: 0.17–0.20 L per kg of tea produced</li> </ul>                                                                                |
| ECP          | Trays width                                     |                   | 4.25 in. (in which 2.875 in. is perforated)                                                                                                                                                                                |
|              | Speed ratio of three tray circuits of ECP drier |                   | 10:14:18                                                                                                                                                                                                                   |
|              | Size of perforation of trays                    |                   | CTC: <ul style="list-style-type: none"> <li>Top circuit (13/72; i.e. 72 holes per inch<sup>2</sup> and each hole has 13 SWG)</li> <li>Middle circuit (13/72 or 14/72)</li> <li>Bottom circuit (14/72 or 15/90)</li> </ul>  |
|              | Temperature range of operation                  |                   | <ul style="list-style-type: none"> <li>Inlet temperature (82–99 °C)</li> <li>For Darjeeling manufacture (115 °C)</li> <li>Exhaust temperature (49–54 °C)</li> </ul>                                                        |
|              | Length of tray (6 ft)                           | Power requirement | <ul style="list-style-type: none"> <li>Chamber drive (2 HP)</li> <li>Fan (12.5–15 HP)</li> </ul>                                                                                                                           |
|              | Length of tray (4 ft)                           |                   | <ul style="list-style-type: none"> <li>Chamber drive (2 HP)</li> <li>Fan (10–12.5 HP)</li> </ul>                                                                                                                           |
|              | Specific fuel consumption                       |                   | <ul style="list-style-type: none"> <li>Coal: 1–1.1 kg per kg of tea produced</li> <li>Oil: direct fired heater (0.3–0.4 L per kg of tea produced) and indirect fired heater (0.5–0.6 L per kg of tea produced).</li> </ul> |

efficiency of drier [24,57,59].

An experimental study was conducted to determine the optimal inlet drying temperature in ECP drier to enhance the quality characteristics of orthodox tea by Kavish et al. [68]. The tea produced of seven grades (OP, FBOPF, PEKOE, OP1, FBOPF1, FBOP and OPA) from three leaf standards were analyzed. Three leaf standards were 40 %, 50 %, and 60 % of good tea leaves (one bud and two tea leaves). Studies were performed considering two inlet temperatures 96 °C and 110 °C for all the leaf standards. All the seven grades of dried tea were organoleptically tested

to evaluate the liquoring properties viz. liquor color and strength, infused leaf color, appearance and quality of graded tea. Experimental results presented that there were no significant dissimilarities in the liquoring properties of tea for all the leaf standards at both the inlet temperatures of air. However, two important trends were observed from experimentations that for leaf standard of 60 %, low temperature of 96 °C was more suitable than higher temperature of 110 °C for better quality of tea. In addition, for leaf standard of 40 %, higher temperature of 110 °C was suitable for better liquoring properties of tea for grades of

**Table 5**

Comparison of studies on industrial tea driers.

| Authors                            | Type of tea | Drying duration                                                                             | Specific energy consumption                                                                          | Drying conditions                                                                                                                                                  | Type of technology                               | Drier type                                                                          |
|------------------------------------|-------------|---------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------|--------------------------------------------------|-------------------------------------------------------------------------------------|
| Temple & Bostel (2000) [57]        | Black tea   | ECP: 900 s                                                                                  | FBD:2800 kJ/kg,<br>Multi-stage FBD: 2840 kJ/kg,<br>ECP: 2110 kJ/kg,<br>ECP with hot feed: 2180 kJ/kg | FBD:41.9 m <sup>3</sup> /kg,<br>Multi-stage FBD: 37.2 m <sup>3</sup> /kg,<br>ECP: 31.7 m <sup>3</sup> /kg,<br>ECP with hot feed: 32.6 m <sup>3</sup> /kg at 100 °C | Hot air-based drying                             | FBD, Multi-stage FBD, ECP, ECP with hot feed                                        |
| Sadeghi & Khoshnaghaza (2012) [61] | Black tea   | 1585 s                                                                                      | 4953.785 kJ/kg                                                                                       | Recommended drying temperature: 100 °C, and vibrational intensity: 1.184                                                                                           | Hot air-based drying                             | VFBD                                                                                |
| Akhtaruzzaman et al. (2014) [59]   | Black tea   | 1200 s                                                                                      | –                                                                                                    | Temperature: 130 °C                                                                                                                                                | Hot air-based drying                             | Kilburn VFBD                                                                        |
| Handayani et al. (2015) [62]       | Green tea   | Drying time is less at zeolite-tea leave ratio of 75:25 than zeolite-tea leave ratio 25:75. | –                                                                                                    | Temperature: 50 °C, 70 °C.<br>Flow rates: 0.5 m/s, 0.44 m/s, 0.46 m/s.<br>Zeolite to tea leaves ratio: 25:75, 75:25                                                | Zeolite adsorption enhanced Hot air-based drying | FBD                                                                                 |
| Bandara et al. (2016) [63]         | Black tea   | –                                                                                           | –                                                                                                    | Recommended air flow rate: 2.83 m <sup>3</sup> /s, vibration frequency of deck: 38 Hz                                                                              | Hot air-based drying                             | Multi-pass VFBD with three fixed vertically zigzag arranged oppositely sloped decks |
| Handayani et al. (2017) [60]       | Green tea   | 2700 s                                                                                      | –                                                                                                    | Recommended temperature: 70 °C, air velocity: 1.09 m/s                                                                                                             | Hot air-based drying                             | Continuous VFBD                                                                     |
| Ozturk and Dincer (2019) [64]      | Black tea   | –                                                                                           | –                                                                                                    | Air velocity: 0.24 m/s, 0.5 m/s, 0.75 m/s, 1 m/s                                                                                                                   | Hot air-based drying                             | Three stage VFBD                                                                    |
| Raveendran et al. (2019) [65]      | Black tea   | –                                                                                           | –                                                                                                    | Temperature: 124 °C, Loading range: 44.5 to 50.5 kg/m <sup>2</sup>                                                                                                 | Hot air-based drying                             | FBD                                                                                 |
| Kavish et al. (2016) [68]          | Black tea   | 1260 s                                                                                      | –                                                                                                    | Inlet temperature: 96 °C, 110 °C.<br>Exhaust temperature: 57 °C                                                                                                    | Hot air-based drying                             | ECP drier                                                                           |

OPA, PEKOE, FBOP and FBOPF. However, there was no considerable difference in properties of FBOPF1, OP1 and OP grades were observed at higher temperature (110 °C) for all the leaf standards.

The stated industrial tea driers are predominantly found in tea estates. The design data of industrial fluidized bed drier and endless chain pressure drier are given in Table 4 in Indian context [13]. Brief description of comparison of various studies on industrial tea drier is included in Table 5.

#### 4.2. Driers under research and development

The driers discussed in the previous sections were hot air-based convective driers. Further researchers have developed driers utilizing non-conventional technologies such as concept of microwave heating, radio frequency drying, superheated steam drying etc. The investigation on these tea driers were covered in the successive sections.

##### 4.2.1. Microwave drier

Microwave drying is well known for having its low drying time of food materials because of having high drying rate. Microwave heating takes place because of conversion of alternating electro-magnetic field into the heat by influencing the polar molecules of the food materials. Water and fat molecules present in the food materials work as the electric dipoles. These electric dipoles rotate when they attempt to align with alternating electric field caused by the microwave radiation. The rapid motion of bipolar molecules generate friction, that causes heat generation in the material. This heat energy is produced throughout the food material, inducing high drying rate as compared to the hot air-based drying. In hot air-based drying, thermal energy is usually transferred to the interior from the surface of the food material. Microwave heating is performed efficiently on water as compared to the fats and sugar which are having lesser molecular dipole moments. Microwave radiation covers the frequency range between 300 and 3000 MHz and recommended frequencies for scientific, medical and industrial applications are 915 (896 MHz is recommended in Europe) and 2450 MHz. Magnetrons are used to generate microwave radiation in the microwave driers [1,69–72].

The study on drying of the Assam CTC tea utilizing the microwave drier was performed by Hatibaruah et al. [1]. Analysis of drying characteristics of CTC tea considering different microwave powers (180, 360, 540, 720 and 900 W) was performed. Sample of 50 g of CTC tea was considered for investigating the consequences of the variable microwave powers on the moisture content and drying rate of tea. It was reported that 900 W in place of 180 W could reduce the drying time by 77 % (Fig. 15) and average drying rate for constant rate drying period was observed between 0.1 and 0.7 (kg of water/kg of dry material -min).

Further, four mathematical drying models (Lewis, logarithmic, Page, Henderson and Pabis models) were utilized to fit the data from experimentations. The empirical parameters were calculated and sum of square errors (SSEs) from the nonlinear regression analysis for all the selected models were calculated. It was concluded that Page model had shown better suitability for depicting the experimental drying characteristics of Assam CTC tea.

Jindarat et al. [73] performed an energy analysis for drying of the tea leaves using a combined unsymmetrical double-feed microwave and vacuum system (CUMV) to optimize the quality of tea and operating conditions of the drying process. The effects of various drying parameters such as microwave operation modes, microwave power and vacuum pressure on the energy consumption had been analyzed. Additionally, it was depicted that energy consumption and energy efficiency (based on 1st Law of Thermodynamics) were firmly dependent on these parameters. The experiments were conducted at 800 W and 1600 W of microwave powers having frequency of 2,450 MHz. The vacuum pressures of 535 torr and 385 torr were considered to explore the effects of the drying parameters under continuous and pulsed microwave operation modes. The experimental results exhibited that drying of tea could be performed more rapidly in case of continuous operation mode than pulsed operation mode. In addition to this, specific energy consumption (SEC) in case of continuous operation mode was found relatively lesser than pulsed operation mode. Reason for this result was the continuity in the supply of microwave energy which caused more absorption of energy and thus more evaporation of moisture occurred from the bulk of tea particles. However, pulsed operation mode provided better physical appearance of tea than in case of continuous operation mode [73–75].

The experimental study (experimental setup is shown in Fig. 16) to evaluate the effects of the drying conditions on the physiochemical attributes and antioxidants activity of the Thai green tea leaves (*Camellia sinensis* var. *sinensis*) was performed by Hirun et al. [2]. The experimental setup consisted of 360° rotating load basket with three magnetrons, vacuum pump to control the pressure inside the drier and air conditioner to control the temperature inside the vacuum pump. Experimental studies at nine distinct drying conditions (microwave powers of 3200, 3600 and 4000 W vs radiation times of 20, 25 and 30 min) were performed. The results showed that individual major catechin content, total major catechin content, antioxidant activity and moisture content of green tea were significantly influenced. However, total polyphenols and color of green tea were not influenced significantly. Based on the experimental results, drying conditions of 3600 W for 30 min of radiation time were recommended for producing the dried tea having low moisture content, high antioxidant attributes and minimum loss of the catechin content. Shi et al. [76] performed experimental study on drying of tea flowers of *Camellia sinensis* cv. Longjing 43 bush

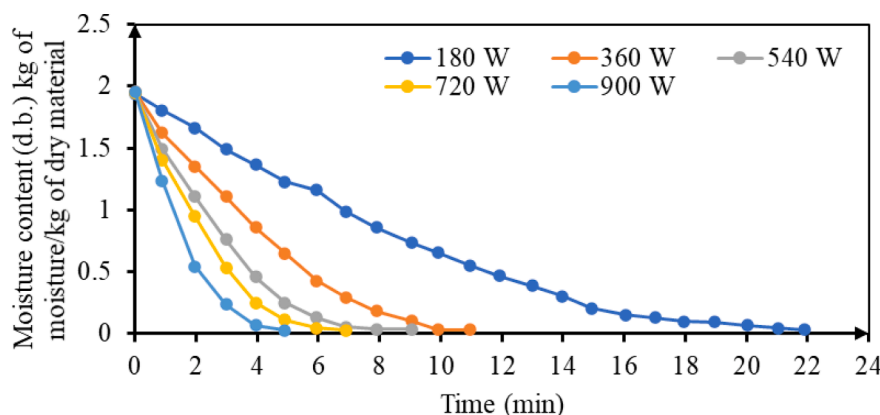


Fig. 15. Moisture variation with time under different microwave powers [1].

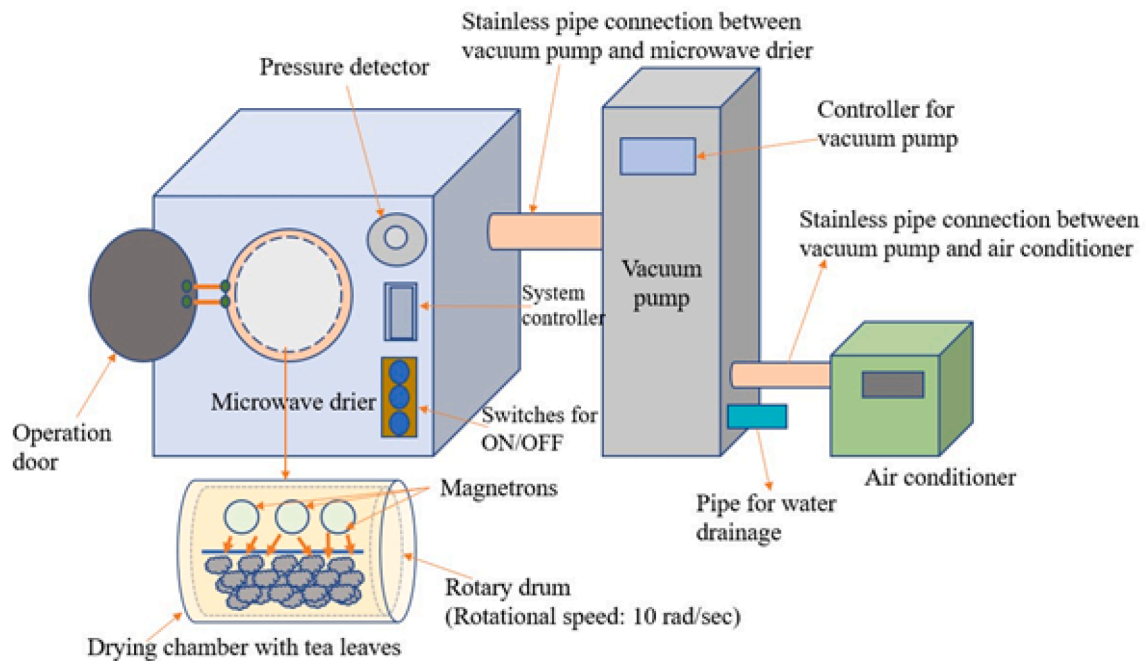


Fig. 16. Schematic of the microwave vacuum drier [2].

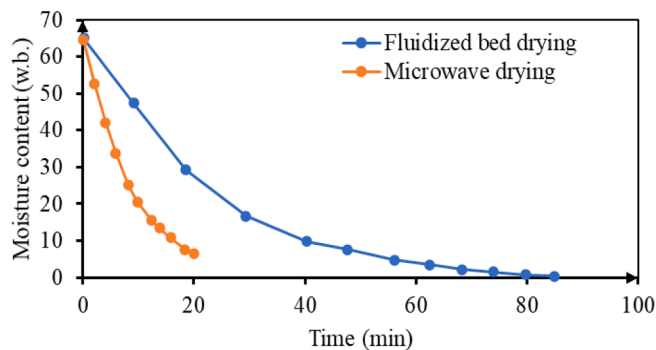


Fig. 17. Moisture content variation with time in case of microwave drying and vibro-fluidized bed drying [77].

using combined microwave-assisted drying and air drying (MAD-AD). It was shown that MAD-AD gave more quantity of important compounds such as flavonol glycosides, catechins and triterpenoid saponins and having higher amount of antioxidant activities as compared to the air drying and freeze drying. This drying improved color of tea flower and preserved a bit more floral fragrance.

A comparative study between vibrating fluidized bed drier (VFBD) and microwave drier was presented by Handayani et al. [77]. It was recommended that for reduced energy consumption and drying time, and improved drying rate, microwave drier should be used in place of VFBD. VFBD and microwave drier took 85 min and 24 min, respectively in drying of 500 g of tea leaves (Fig. 17). Maximum drying rates in case of VFBD and microwave drier were observed as 0.08 and 0.14 kg of water / (kg of dried tea – min), respectively. During the experimentation, air was supplied at 80 °C of air temperature and flow velocity of 1.08 m/s in case of VFBD, however, the temperature inside the microwave drier was kept at 80 °C. Falling rate period took approximately 75 % of the total drying time in case of VFBD drying and rest 25 % in constant rate period. However, in case of microwave drier, it took 50 %

of drying time in constant rate period, and rest in falling rate and critical rate periods.

#### 4.2.2. Radio frequency drier

Radio frequencies are considered between 10 and 300 MHz. However, only specific frequencies such as  $13.56 \text{ MHz} \pm 6.68 \text{ kHz}$ ,  $27.12 \text{ MHz} \pm 160 \text{ kHz}$  and  $40.68 \text{ MHz} \pm 20 \text{ kHz}$  are prescribed for industrial applications by the US Federal Communications Commission (FCC) to avoid the intervention with communication system. Radio frequency can penetrate more deeper into the materials than microwave, because of having its longer wavelengths as compared to the microwave. In case of radio frequency drier, wet fermented tea is put between the electrodes which are facing alternating electric field produced by radio frequency generator. Heat is produced in the wet fermented tea because of the interaction of electromagnetic field with water present in the wet fermented tea. Since, water molecules are bipolar in nature, therefore these molecules alternate their orientation with the alternating electric field. Continuous changing of orientations of water molecules creates friction inside the tea leaves and this causes thermal energy generation which evaporates the water from the inside of tea leaves, thus drying of tea is performed with radio frequency drier (as shown in Fig. 18) [24,70,78–81]. An experimental study was conducted to assess the drying time and quality parameters of the tea using hot air drier, radio frequency drier, and hybrid hot air – radio frequency drier by Shinde et al. [46]. Findings from this study showed that drying durations in case of radio frequency drier were 60 min and 90 min for CTC and orthodox tea, respectively. However, in case of hybrid hot air – radio frequency drier, drying durations were 85 min and 55 min for CTC and orthodox tea, respectively at 20 kW power of radio frequency. Additionally, aroma index (total quantity of positive flavor relative to total quantity of negative flavor) at 16 kW of radio frequency was assessed more as compared to 20 kW for both kinds of tea. It was also reported that RF drier had consumed only 81 % of the energy requirement in case of hot air drier (with 75 % recirculation). However, it was only 53 % of energy consumption in case of hot air drier (without circulation). Moreover, hybrid hot air – radio frequency and radio frequency driers were less energy consuming driers than hot air drier. Hybrid hot air – radio

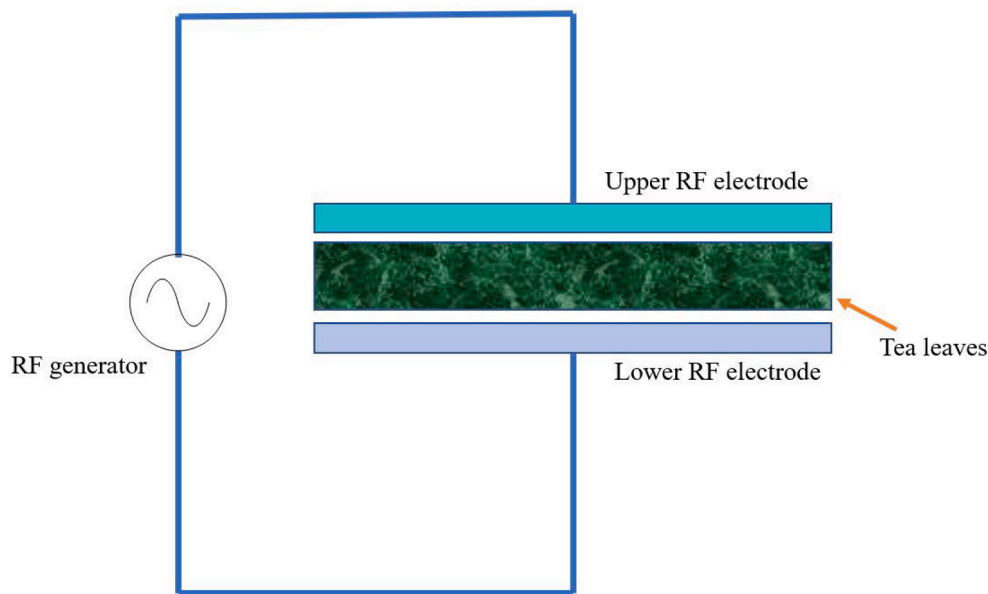


Fig. 18. Concept of radio frequency drying [78].

frequency drier needed only 40 % of the energy consumption in hot air drier (with recirculation).

#### 4.2.3. Superheated steam tea drier

Superheated steam drier is better in terms of energy efficiency, product quality, drying rate and safety than hot air-based drier. Moreover, this drier provides no oxidative reactions between material and steam, and no hazardous gas, dirt, and dust emission into environment. It majorly consists of steam generator, heater, fan and drying chamber as shown in Fig. 19. Steam comes out from the generator is superheated into the heater and is supplied to the drying chamber. The fan disperses the steam in all direction in the drying chamber. To avoid condensation of the steam in the beginning of drying process an electric heater is attached to control the temperature of steam in the drying chamber. Steam performs two tasks; first is to provide heat of drying to the material and second is act as carrier medium for water evaporated during

drying [82,83]. An experimental study was performed to investigate the effect on the quality of the tea under drying temperatures between 120 and 200 °C using superheated steam drier by Rumaisa et al. [84]. It was investigated that increment in drying temperature had reduced the drying time of the tea. Superheated steam drier based dried tea showed better color attributes and phenolic contents than commercial hot air-dried tea. In addition to that emphasis had been given for further study to optimize the drying conditions for the upscaling of the superheated steam drier for tea. Table 6 illustrates the summary of research works conducted on microwave and radio frequency tea driers.

The major limitation of microwave and radio frequency tea driers is that these consume electrical energy. The higher cost of the equipment associated with these driers is a challenge in acceptance for tea drying. Research works on these driers are limited and conducted only for lab scale or small-scale tea drying. In addition, partial loss of aroma and negative sensory changes are possible in these driers. However, studies

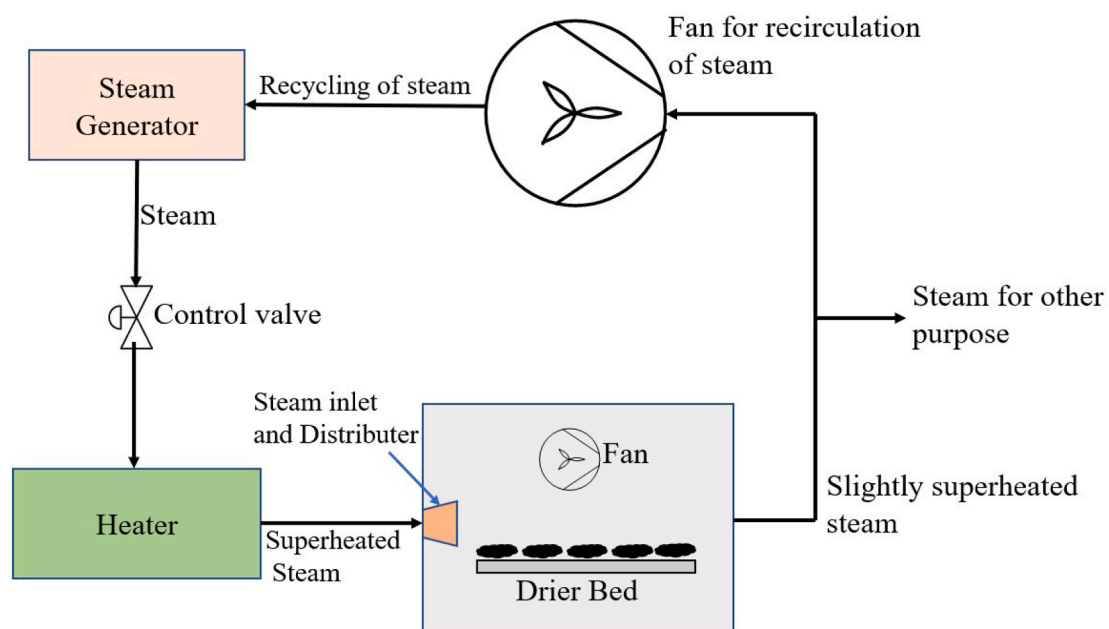


Fig. 19. Schematic of superheated steam drying system [82,83].

**Table 6**

Brief description of the studies on microwave and radio frequency tea driers.

| Type of drier                                                            | Technology used                                                                           | Major findings                                                                                                                                                                                                                                                        | References |
|--------------------------------------------------------------------------|-------------------------------------------------------------------------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------------|
| Microwave drier                                                          | Microwave radiation-based drying                                                          | Drying study conditions: 180, 360, 540, 720 and 900 W.<br>Results:<br>• 77 % drying time reduction at 900 W than 180 W<br>• Range of constant drying rates: 0.1 to 0.7 (kg of water/kg of dry material -min)                                                          | [1]        |
| Microwave vacuum drier                                                   | Combined unsymmetrical double-feed microwave and vacuum system (CUMV)                     | • Performed an energy analysis of drying using a double feed CUMV to optimize the quality of tea and operating conditions of the drying process.<br>• Drying of the tea was slow in case of pulsed microwave operation mode than continuous microwave operation mode. | [73]       |
| Microwave vacuum drier                                                   | Combined microwave vacuum technology                                                      | • Performed experimental study to evaluate the effects of the drying conditions on the physiochemical attributes and antioxidants activity of the Thai green tea leaves.                                                                                              | [2]        |
| Drier with microwave-assisted drying and air drying (MAD-AD)             | Microwave-assisted combined with freeze drying and air drying                             | • Recommended conditions: Microwave power of 3600 W for 30 min<br>Concluded that MAD-AD system gave better quality of tea than freeze drying and air drying.                                                                                                          | [76]       |
| VFBD, Microwave Drier                                                    | • Hot air-based drying for VFBD<br>• Microwave radiation-based drying for microwave drier | • Comparative study between VFBD and microwave drier based drying of green tea.<br>• Microwave drier could be used in place of VFBD for reduced energy consumption and drying time, and better drying rate.                                                           | [77]       |
| Hot air drier (ECP), Radio Frequency drier, Hybrid radio frequency drier | Hot air-based drying, radio frequency based drying technology                             | • Comparative study for drying among hot air drier, radio frequency drier and hybrid hot air - radio frequency drier.<br>• Hybrid hot air - radio frequency drier needed only 40 % of the energy consumption in hot air drier.                                        | [46]       |

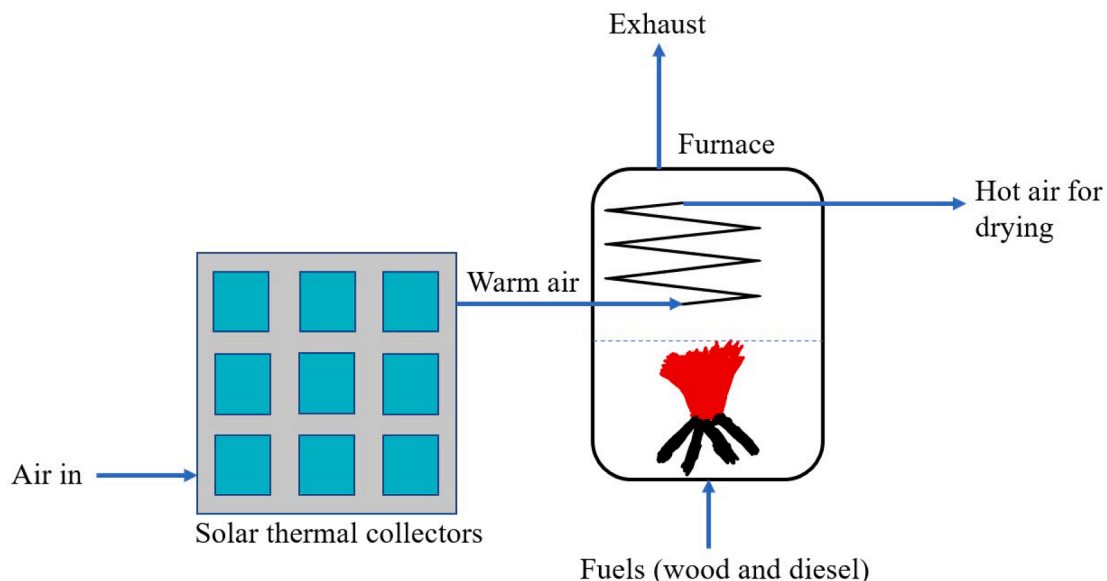
are being conducted to enhance the performance of driers to make them suitable for industry scale. Previous investigation on superheated steam drier for tea drying are limited in number and explored only to lab scale. At present, tea drying community is not much aware of this kind of drier.

## 5. Renewable energy based tea driers

As discussed, majorly tea factories are utilizing the fossil fuels for fulfilling the heat demand of drying of tea and this is the primary reason for the production of greenhouse gases [85,86]. The carbon dioxide emission from Indian, Sri Lankan, and Vietnamese tea factories are 2.15, 2.49, and 2.86 kg per kg of tea produced, respectively [87]. This necessitates the use of the renewable energy resources. Kumar et al. (2021) performed feasibility assessment of potential of renewable energy resources in the tea estates and depicted that various parts of India have possibilities for adopting the renewable energy based drying [4]. Some of the renewable energy-based tea drying units are described in the subsequent sections.

### 5.1. Solar energy assisted tea driers

Multiple solar energy based drying technologies such as direct solar drying, indirect solar drying, mixed-mode solar drying, greenhouse drying, hybrid solar drying, etc. have been investigated. These technologies are suggested for drying of various food and agricultural products, and for industrial applications [88–91]. Further, particularly in tea sector, Palaniappan and Subramanian performed the economic analysis on the roof installed solar air heating system having collector area of 212 m<sup>2</sup> [92]. It was estimated that the payback period of solar flat-plate collector assisted tea drier (which had been in operation for 2.75 years) was in the range of 2 to 4 years. It was also concluded that specific fuel consumption got reduced from 0.932 to 0.71 kg/kg of dried tea. This saved approximately 25 % of the total fuel consumption. A feasibility study was performed on solar energy penetration in tea drying by Koneswaramoorthy et al. [93]. 200 numbers of solar thermal collectors had been used for preheating of the air before entering it into the furnace cum heat exchanger (as shown in Fig. 20). Preheated air was further

**Fig. 20.** Schematic of solar assisted furnace for tea drier [93].

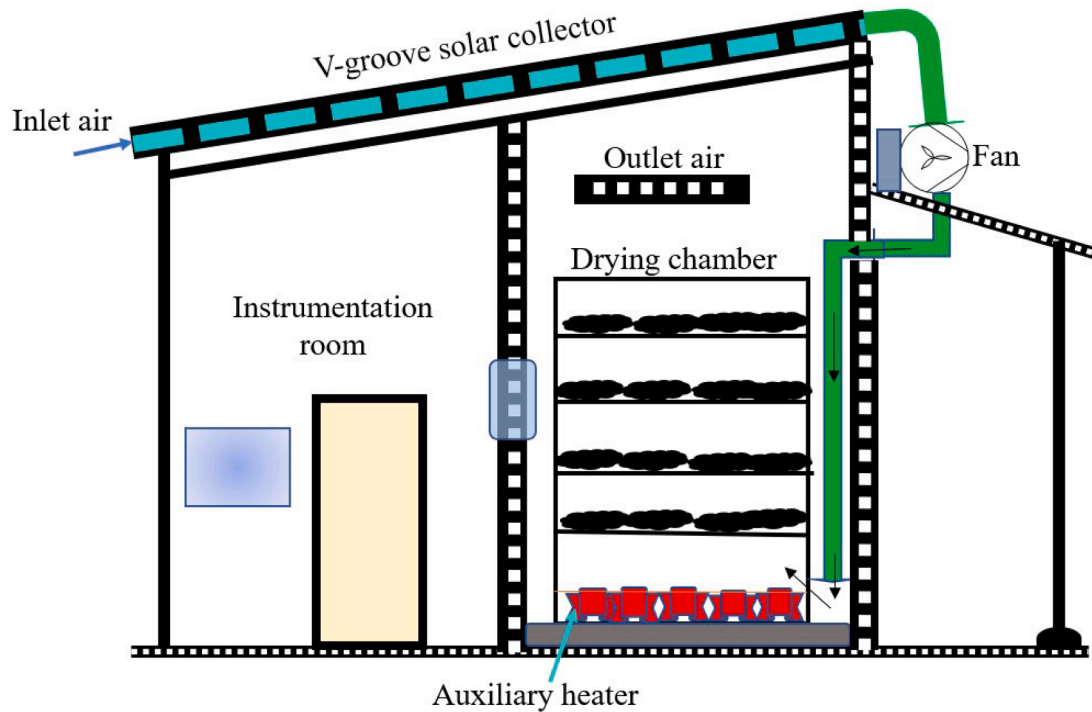


Fig. 21. V-groove solar collector based solar tea drier [94,95].

heated using the fuels (firewood and diesel) in the furnace. From this experimental study, it was concluded that fuel saving was in the range of 25–34 %.

Drying experimental studies was performed on the herbal tea by Sopian et al. [94]. Experimental setup consisted of an array of V-groove-type solar collector of 20 m<sup>2</sup> area, and an auxiliary heater of 10 kW to supply heat when drying chamber temperature went down less than 50 °C (as shown in Fig. 21). Temperature of drying chamber was reached to 55 °C under solar radiation of 600–700 W/m<sup>2</sup> and ambient temperature of 27–30 °C. The air was supplied at constant flow rate of 15.1 m<sup>3</sup>/min. The fresh tea leaves were first soaked in the warm water for 5 min. Further, water was drained out from leaves and leaves were dried in the

solar based drying system. It was observed that moisture content present in the tea leaves was reduced to 54 % from 87 % in 12 h and solar energy contributed 54 % of the total energy requirements of drying [94,95].

The solar air heater based drier was developed for drying the green tea leaves as shown in Fig. 22 by Vijayan et al. [96]. Firstly, fresh green tea leaves were soaked in warm water for few minutes and then water was drained out. Thereafter, tea leaves were dried utilizing the solar based drying system, which was consisted of drying chamber maintained at a temperature of 60 °C. During drying, the weight of green tea leaves was reduced to 38 g from 100 g (62 g of moisture loss) in an hour under clear sky condition and ambient temperature of 30–34 °C as shown in Fig. 23.

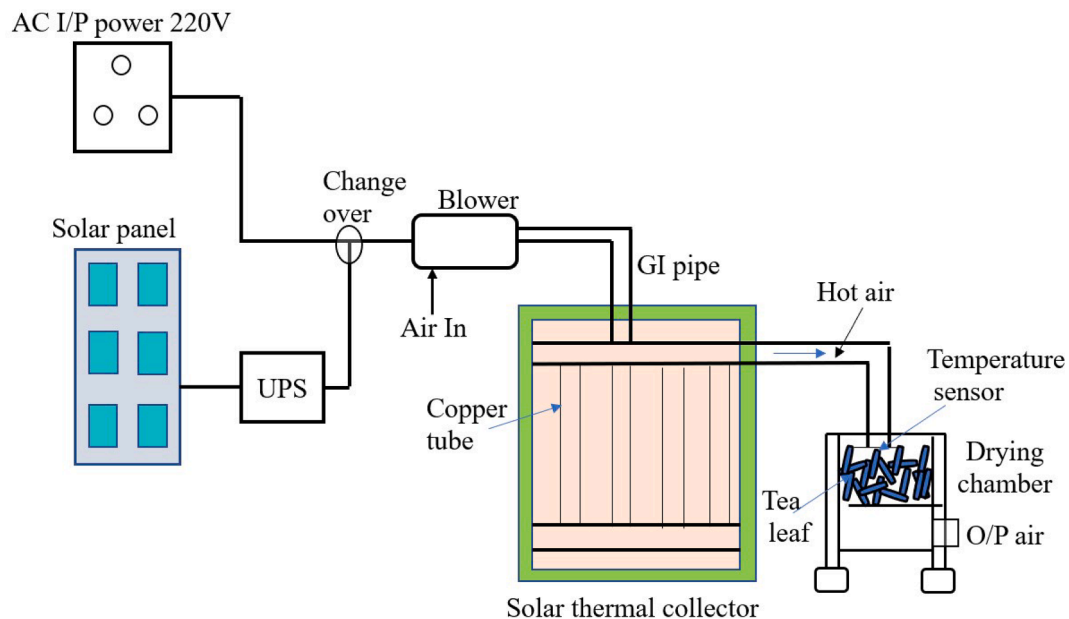


Fig. 22. Solar assisted tea drying system [96].

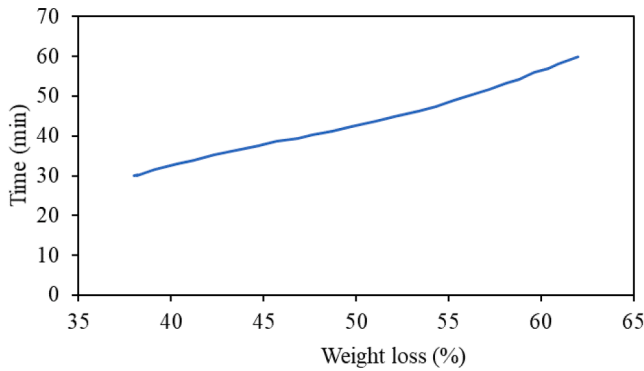


Fig. 23. Rate of weight loss of tea leaves in solar drying system [96].

Three types of solar hot air generator (SHAG) viz SHAG type I, SHAG Type II and SHAG Type III, were developed and performed experimental studies to estimate the performance and physical characteristics of the driers by Baruah [97]. SHAG type I had absorber plate with fins to increase heat transfer, double glazing and double pass provisions, but it was facing the disadvantages of bulkiness and heaviness. SHAG type I was able to provide temperatures of air to 92 °C and 80 °C (nearly) at 0.01 kg/s and 0.04 kg/s mass flow rates of air, respectively. In case of SHAG type II, cross duct for collecting the hot air was incorporated to avoid the pressure drop and enhance the performance, and black painted aluminum based porous material was utilized as absorber plate. The frame of the system was made of aluminum to reduce the weight of the system. The cover plate was made of polycarbonate sheet to avoid the fragile and heaviness nature of glass cover plate as used in the previous SHAG type I. SHAG type II was able to provide instantaneous thermal efficiency variation between 61 % and 98 % (corresponding to air temperatures of 50 °C and 73 °C, respectively). This system was facing the difficulty in terms of cost, safety and durability of the porous material of absorber. SHAG type III was made of black industrial grade painted aluminum foil absorber, GI pipe-based headers, aluminum material-based frame, ceramic blanket of insulation and two layers of polycarbonate cover sheets. Maximum temperature of 93 °C at 0.04 kg/s of mass flow rate of air was attained in case of SHAG type III. SHAG type

III was selected because of being less costly, light in weight and easy in manufacturing. From the study, it was concluded that a coal fired furnace based tea drying unit (with thermal load of 400 kW), could save 20 % of its total fuel consumption using 33 modular units (area of 2 m<sup>2</sup>/unit) of SHAG type III.

Recently, some of the works on drying of the agricultural products have been conducted utilizing hybrid photovoltaic-thermal collector (PVT). Results from these works clearly demonstrate that PVT based drying is efficient and provide dried products of better quality than open sun drying [98–100]. An integrated experimental setup was developed consisting of PVT unit and batch type tea drier as shown in Fig. 24 by Ozturk and Dincer [101]. Electricity produced from the PVT was used for operating blowers. The heat generated from the PVT was utilized for producing the hot air for drying of the tea leaves. The exergoeconomic analysis was performed to evaluate the performance of the system using EXCEM method (exergy-based cost analysis method) and equations were solved using engineering equation solver (EES). The effect of varying parameters on the performance of system was analyzed. The parameters such as mass flow rate, air reference temperature and relative humidity were studied. The exergetic and energetic loss ratios (losses per unit capital cost) were estimated as 72.63 MJ/\$ and 76.45 MJ/\$, respectively. The exergy destruction and exergy efficiency for the whole system were found to be 201.6 GJ and 74 %, respectively.

The PVT collector based experimental test facility was developed (as shown in Fig. 25) by Gupta et al. [42]. The attached DC fan was powered through PVT collector-based battery. The hot air produced from PVT collector was utilized for drying operation. The experimentations were conducted for three cases viz. case I (natural convection), case II and case III (forced convection with air velocities of 0.096 m/s and 0.0144 m/s, respectively) under sunny and cloudy days in north-eastern part of India. It was concluded from the preliminary experimentations that PVT collectors performed better for all the three cases under sunny days than cloudy days. Drying studies were conducted for the green tea leaves under indirect mode drying (IMD) and mixed mode drying (MMD) for all these three cases under sunny days, and compared the performance with shade drying (SD) and open sun drying (OSD). It was observed that mixed mode drying had performed better than indirect mode of drying for all the three cases. In case II of mixed mode drying, minimum drying time of 255 min was observed in reducing the moisture content of 4 kg of tea leaves (approx.) from 2.95 (d.b.) to 0.14 (d.b.) as compared to open

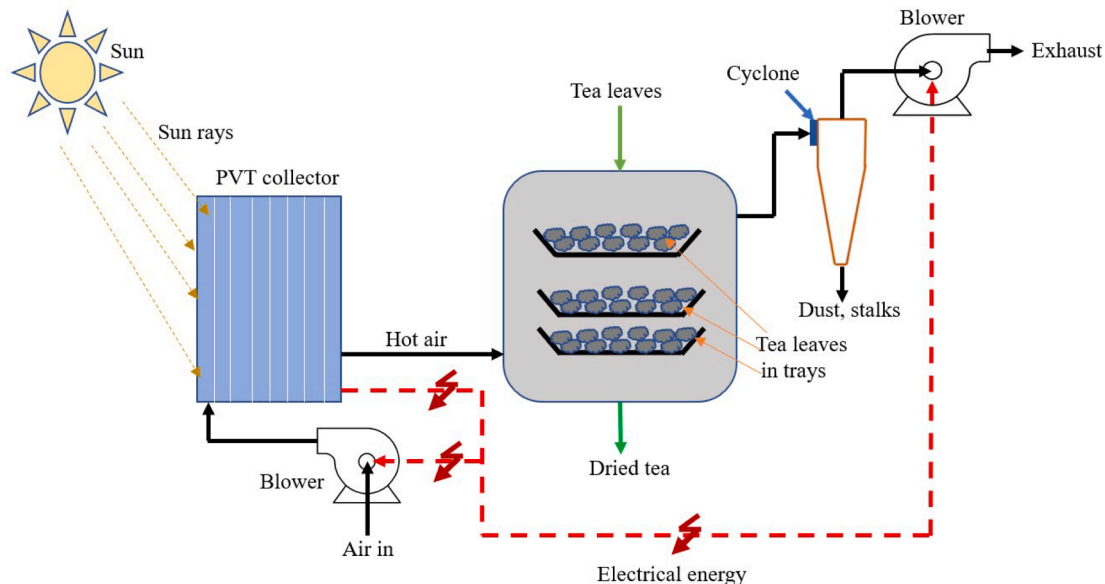


Fig. 24. Schematic view of the solar PVT based tea drying system [101].

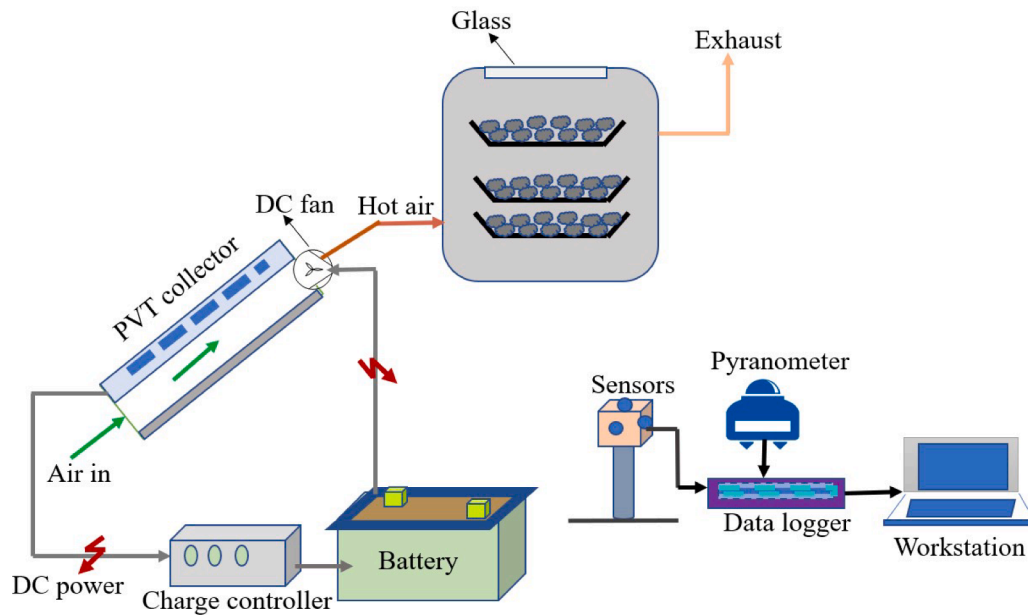


Fig. 25. PVT collector based tea drying system [42].

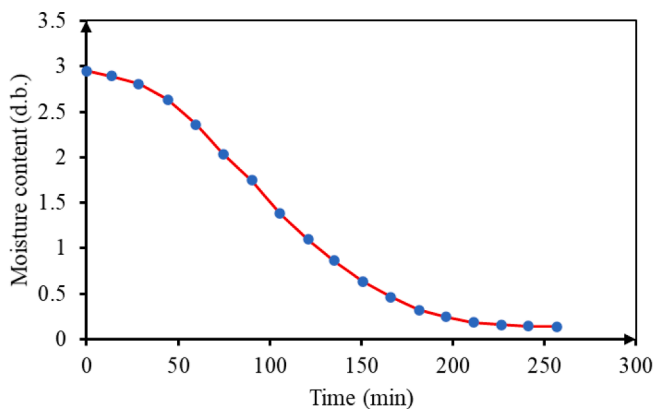


Fig. 26. Reduction of moisture in leaves with time in PVT based drier unit for case II (MMD) [42].

sun drying time (690 min) and shade drying time (930 min) as shown in Fig. 26. All the experimental results for all the cases were fitted in newly proposed model (Gupta et al. model) (included in Table 3) with good amount of agreement.

### 5.2. Bioenergy assisted tea driers

Energy generation from the tea wastes can be an option for meeting part of energy demand of the tea factory. Wastes from the tea estates can be categorized into two parts: one is processing waste and other is garden waste. Processing wastes come from the tea factories in various stages of the processing of tea leaves. Garden wastes are tea bush wastes (leaves and branches) and shade tree wastes (leaves and branches). These wastes can be utilized to produce biofuels. The biofuel production techniques are pyrolysis, gasification, liquefaction, combustion, etc. The

biofuels are utilized to meet the thermal energy and electrical energy demand in drying, and also to replace the fossil fuel consumptions [102]. The calorific values of tea factory waste, tea bush waste and shade tree waste were observed to be 5.012 kWh/kg, 4.302 kWh/kg, and 4.555 kWh/kg, respectively using bomb calorimeter [29]. The locally fabricated downdraft gasifier was utilized for gaseous fuel generation for drying of tea leaves in Sri Lanka by Jayah et al. [103]. This gasifier offered a possibility of reducing fuelwood consumption of about 12 % (0.17 kg of fuelwood per kg of tea) in drying process for the conventional fuelwood consumption-based tea factory. In addition to that, life cycle cost associated with the energy production in the case of the gasifier-based tea factory was 8 % less than the conventional fuelwood tea factory. Further, study on this gasifier was performed to analyze the effect of the design features and operating parameters to enhance the performance of gasifier for drying operation [104].

The producer gas (mixture of hydrogen gas, carbon dioxide, and nitrogen gas) was produced by gasifying dried and chopped uprooted tea shrubs having moisture content less than 20 % (w.b.) using downdraft gasifier by Dutta and Baruah [105]. The generated producer gas had been utilized to produce heated air for drying fermented tea leaves. The experimental setup is shown in Fig. 27. This study concluded if a medium-scale tea factory (having a capacity of 990 tonnes of made tea per year) fulfilled its 28 % thermal energy demand using thus generated producer gas, the factory could save an amount of 21,067 \$ and reduce equivalent carbon dioxide emission of 1299.5 tonnes.

Further, the drying modelling and experimental studies for different air velocities of 0.50, 0.65 and 0.75 m/s and air temperatures of 80, 90, 100 and 110 °C conditions utilizing producer gas furnace-based tea drier was performed by Dutta and Baruah [40]. The decrement in moisture ratio with drying time for different temperatures and flow velocities are shown in Fig. 28 and Fig. 29, respectively. The drying output results were fitted with semi-theoretical models such as Henderson and Pabis, Page, Lewis, Two Term and Modified Page to find the best suited model. The Modified page model had predicted the results better than other models. The specific energy consumption was found 19.01 MJ/kg of made tea in drying of tea leaves to 3 % (w.b.) of moisture content.

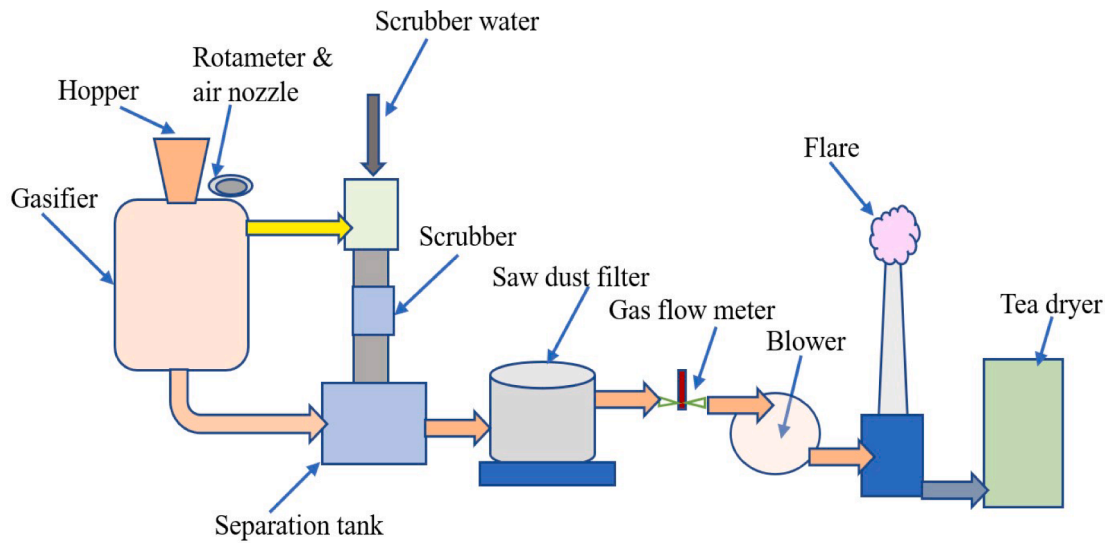


Fig. 27. Experimental setup for generating producer gas for tea drying from uprooted tea shrubs [105].

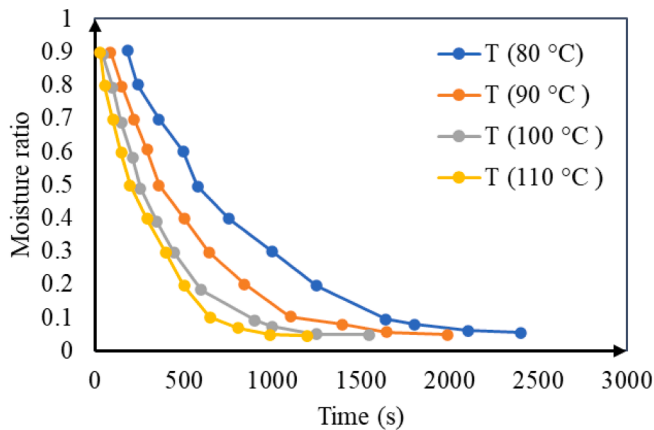


Fig. 28. Decrement in the moisture ratio with drying time at different temperatures of air [40].

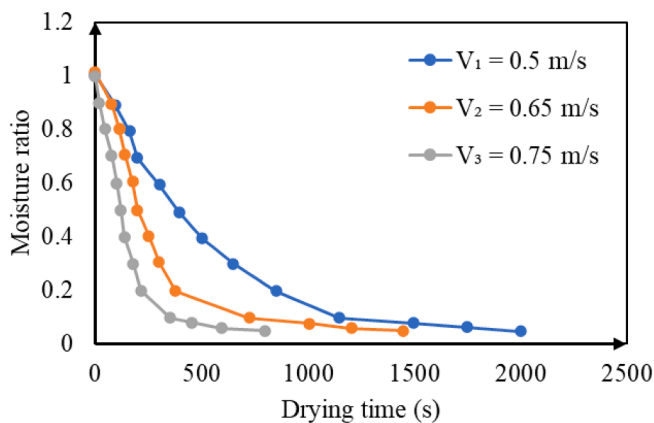


Fig. 29. Decrement in moisture ratio with drying time at different flow velocities of air [40].

### 5.3. Geothermal energy assisted tea driers

The countries with geothermal resources have great potential to utilize the thermal energy of geothermal resources to dry tea leaves. The study on the withering and drying operations was conducted in Malabar tea factory, Indonesia by Surana et al. [106]. Geothermal energy in the

form of brine solution had been utilized to harness thermal energy for withering and drying operations. The heat exchangers (evaporators) were used to extract heat from brine solution and to provide heat to the working fluid (water in this case). The steam generated in the evaporator was used to heat the incoming fresh air. This hot air was brought to the withering trough and drying chamber as shown in Fig. 30. In the present study, an engineering design was presented to replace the Industrial Diesel Oil demand of 1.25 million liters per year with brine generated from geothermal fields. Table 7 shows the short description of various works on renewable energy based drying technology.

### 6. Other investigations on tea driers

An automated controlled batch tea drier was proposed for drying of tea leaves of various genres by Javanmard et al. [107]. The electrical heater was used for hot air generation. A programmable controller had been utilized to control the temperature of the drying chamber and moisture contents present in the tea leaves. The data logger unit was used to record the data from the experiments. In batch tea drier having 6 to 8 trays, the temperature above the trays were controlled between 50 and 100 °C. Moreover, moisture content was reduced from 68 % to 3 % (w.b.) and temperature of the tea leaves was increased from 30 to 80 °C. Drying of the tea leaves took time between 15 and 25 min depending upon the quantity, thickness and type of tea leaves. Apart from this, the results concluded that system could be scaled up for industrial layouts.

Langat et al. [108] performed an experimental study to dry green tea using a prototype drier having a meshed cylindrical agitated barrel. Stainless steel made barrel having mesh openings of size 1 mm, had diameter and length of 300 mm and 500 mm, respectively. The barrel was attached with shaft driven by electric motor as shown in Fig. 31 to provide the agitation to the tea leaves during drying. Before drying, green tea leaves had been gone through steaming at 100 °C and then cooling at 21 °C for 300 s to avoid the loss the aroma and color, and to stabilize the temperature of the leaves. Further, physical withering for 15 min was performed at least at 60 °C to a required level of moisture content (68–72 %) for further maceration operation. Drying operation was performed after the completion of maceration in the meshed barrel at various input conditions such as volume flow rate and temperature of air, angular speed of rotation of barrel (agitation rate) and drying time. Specific energy consumption (SEC) and evaporation rate (ER) have been calculated using Eq. (18) and Eq. (19), respectively.

$$SEC = \frac{t \times \rho \times \dot{V} \times (C_{pa} + H_a C_{pv})(T_{in} - T_{exit})}{V_h \times M_v} \quad (18)$$

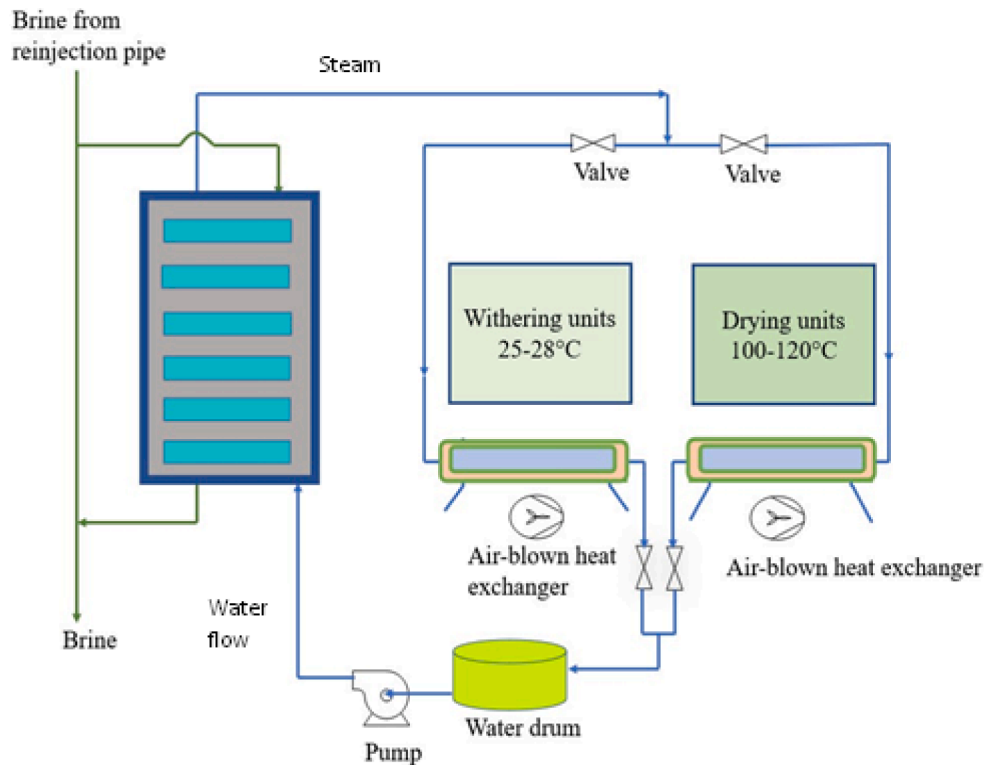


Fig. 30. Schematic of geothermal energy-based tea drying system [106].

$$ER = \frac{\text{Mass of evaporated moisture}}{\text{Area of drying chamber} \times \text{drying time}} \quad (19)$$

SECs from experimentations on drying using prototype drier were 1441.7, 1268.7, and 1153.3 kJ/kg of moisture evaporated, respectively for 80 °C, 100 °C and 120 °C. While, SECs in case of the fluidized bed drier were 2755.5 kJ/kg, 2966.5 kJ/kg and 1648.0 kJ/kg of moisture evaporated, respectively. The reduced specific energy consumption in case of prototype drier was due to requirement of less fluidization velocity than in case of fluidized bed drier. Additionally, it was also observed that evaporation and drying time are less in case of prototype drier than fluidized bed drier because of having high contact ratio between air and tea particles in prototype drier.

An experimental and theoretical analysis was performed to analyze the drying behavior of green tea leaves using multi-tray cabinet tea drier by Shomali and Souraki [109]. Mathematical model for predicting the temperature and moisture content variations of the drying air as well as of green tea leaves was developed considering each tray of drier as a fixed bed of green tea leaves. This model was solved utilizing finite difference method, and trial and error technique. The predictions from this model had shown a good agreement (MRE less than 5 %) with the experimental results. The experimental results were obtained from the domestic three-tray based drier for drying of green tea leaves at 60 °C and 70 °C. Moreover, results showed that first tray of the cabinet drier faced higher drying rate as compared to the other trays. At the same time increasing in the temperature and velocity of air, and decreasing number of tea leaves in each tray had shown increasing trend of the drying rate.

The exergoeconomic performance of gas type drying system for black tea was studied by Zeng et al. [110]. The capacity of drier was 100 kg/h. The schematic of drying setup is shown in the Fig. 32. Inlet air was supplied by blower/induce draft fan into the natural gas furnace-based combustion chamber. Produced hot air was sent to the drying chamber for drying of tea. The drying chamber was consisted of drying plates/conveyor chain networks for putting the tea in movement. The exergy destructions and cost of exergy destructions were analyzed for various parts of the drying system in two stages: 1. Initial drying period, 2.

Redrying period. In initial drying period, hot air at 120 °C was supplied for drying time of 12 min and then tea was flattened and cooled. Further, in redrying period, tea was made in contact with hot air at 100 °C for drying time of 20 min by adjusting the drying plate speed. Total time for initial drying period and redrying period were 60 min and 90 min, respectively for drying of fermented tea of 180 kg to 45 kg of dried tea. During initial drying, the exergy destruction in combustion chamber and drying chamber were 20.42 kW and 74.92 kW, respectively, whereas during redrying, these were 21.15 kW and 51.83 kW, respectively. The corresponding exergy destruction costs were 5.041 \$/h and 18.497 \$/h during initial drying, and 5.222 \$/h and 12.796 \$/h during redrying, respectively. The results of exergy destruction and cost of exergy destruction offered the mandatory requirement of improving the energy and economy by minimizing the exergy destruction and its associated cost. Further, one detailed study [111] of energetic, exergetic and techno-economic analysis on the system shown in Fig. 32 was conducted. It was shown that exhaust air from the drier was the main contributor in exergy and heat loss. The exergy efficiencies were found in the range of 38.08 % to 65.09 % and 24.76 % to 26.97 % for initial drying period and redrying period, respectively. In addition, results from techno-economic study showed the net present value and payback period as 179,442.03 \$ and 5.3 years, respectively.

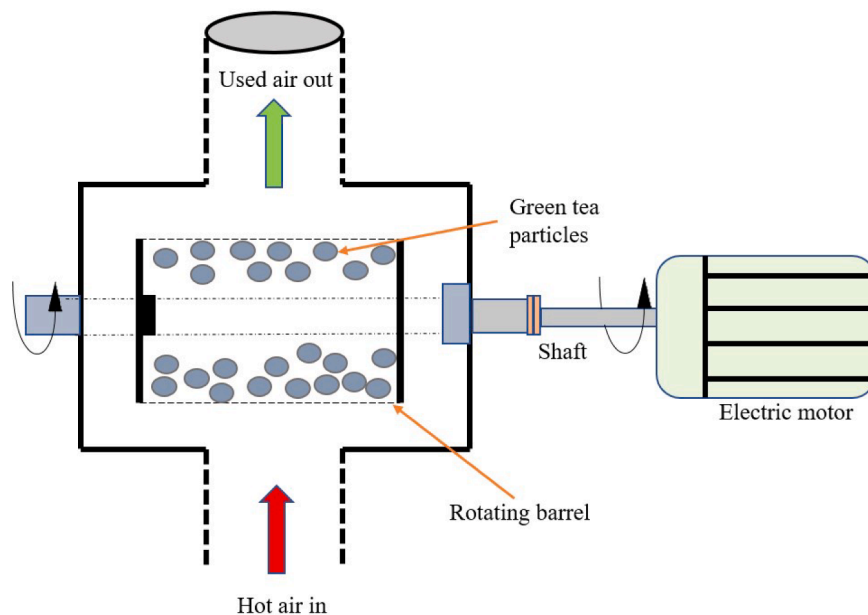
## 7. Techno-economic Appraisal of Industrial Black Tea Drying.

Kumar et al. [4] presented the economic analysis of conventional and renewable energy-based systems for tea plantation and processing. This analysis was presented considering electrical energy requirement in various processes only. Further, techno-economic analysis of drying technologies is required to open the options of improvement and optimization of the drying process. Table 8 shows the techno-economic studies on black tea drying considering renewable energy as a supplement for the drying energy requirement, and addition of heat recovery system. In addition, Table 9 shows monetary benefits analysis of black tea drying process if whole drying energy requirement is fulfilled through solar energy. Total number of hours of plant operation are

**Table 7**

Brief description of the works on renewable energy-based tea driers.

| Technology used                                                                                                        | Major Outcomes                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                             | References |
|------------------------------------------------------------------------------------------------------------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------------|
| Solar flat-plate collector system (collector area: 212 m <sup>2</sup> )                                                | <ul style="list-style-type: none"> <li>Economic analysis showed the payback period of system in the range of 2 to 4 years.</li> </ul>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                      | [92]       |
| Solar flat-plate collector system                                                                                      | <ul style="list-style-type: none"> <li>Reduction in total fuel consumption was reported approximately 25 %.</li> <li>Preheating of the air using solar flat-plate collector before final heating of air in furnace.</li> </ul>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                             | [93]       |
| V-groove solar collector and auxiliary electric heater<br>(Collector area: 20 m <sup>2</sup> , heater capacity: 10 kW) | <ul style="list-style-type: none"> <li>Fuel saving of 25–34 % was reported from the study.</li> <li>Drying chamber temperature of 55 °C was achieved at 600–700 W/m<sup>2</sup>.</li> <li>Moisture content present in the tea leaves was reduced to 54 % from 87 % in 12 h.</li> </ul>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                     | [94,95]    |
| Solar air heater based drier                                                                                           | <ul style="list-style-type: none"> <li>Contribution of solar energy was reported as 54 % of the total energy requirements of drying.</li> <li>Temperature of drying chamber was maintained at 60 °C.</li> <li>Drying reduced the weight of green tea leaves to 38 g from 100 g in an hour under clear sky condition and ambient temperature of 30–34 °C.</li> </ul>                                                                                                                                                                                                                                                                                                                                                                                                                                                                        | [96]       |
| Solar hot air generator (SHAG)                                                                                         | <ul style="list-style-type: none"> <li>Three types of SHAGs with various constructional differences had been studied.</li> <li>SHAG type I consisted of absorber plate, double glazing and double pass provisions.</li> <li>SHAG type II incorporated cross duct, black painted based porous material as absorber plate, frame and polycarbonate sheet cover plate.</li> <li>SHAG type III contained black industrial grade painted foil absorber, GI pipe-based headers, frame, ceramic insulation and two layers of polycarbonate cover sheets.</li> <li>SHAG type III was found better than type I and type II because of its less cost, light weight and ease of manufacturing.</li> <li>Fuel saving of 20 % of total fuel consumption was reported using 33 modular units (area of 2 m<sup>2</sup>/unit) of SHAG type III.</li> </ul> | [97]       |
| PVT collector with batch type drier                                                                                    | <ul style="list-style-type: none"> <li>Electricity produced from the PVT was used for operating blowers and heat generated from the PVT was utilized for producing the hot air for drying of the tea leaves.</li> <li>The exergy destruction and exergy efficiency for the whole system were found to be 201.6 GJ and 74 %, respectively.</li> </ul>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                       | [101]      |
| PVT collector                                                                                                          | <ul style="list-style-type: none"> <li>Studies conducted to evaluate the performance of the collector during sunny and cloudy days.</li> <li>Drying system operation during natural and forced convection cases were also evaluated for indirect and mixed mode drying.</li> <li>Performance of PVT collector was found better during sunny days as compared to cloudy days.</li> <li>Mixed mode drying performed well as compared to the indirect mode drying for all the cases.</li> </ul>                                                                                                                                                                                                                                                                                                                                               | [42]       |
| Downdraft gasifier based drier                                                                                         | <ul style="list-style-type: none"> <li>Downdraft gasifier was used for gaseous fuel generation for drying of tea leaves.</li> <li>Gasifier offered 12 % reduction in fuelwood consumption.</li> </ul>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                      | [103]      |
| Downdraft gasifier based drier                                                                                         | <ul style="list-style-type: none"> <li>Uprooted tea shrubs were utilized to generate producer gas for drying of tea leaves.</li> <li>It was concluded that medium scale tea factory could reduce equivalent carbon dioxide emission of 1299.5 tonnes if factory utilized gasifier for 28 % thermal energy demand.</li> </ul>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                               | [105]      |
| Producer gas furnace-based tea drier                                                                                   | <ul style="list-style-type: none"> <li>Drying modelling and experimental studies had been conducted for various air velocities and temperatures.</li> </ul>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                | [40]       |
| Geothermal technology based drying unit                                                                                | <ul style="list-style-type: none"> <li>Specific energy consumption was found 19.01 MJ/kg of dried tea.</li> <li>Steam was generated using heat of the brine solution extracted from geothermal resources.</li> <li>Withering and drying were performed using hot air generated from utilizing heat of steam.</li> <li>Engineering design was presented to replace Industrial Diesel Oil demand of 1.25 million liters per year with brine solution generated from geothermal resources.</li> </ul>                                                                                                                                                                                                                                                                                                                                         | [106]      |

**Fig. 31.** Schematic of rotating meshed barrel drier [108].

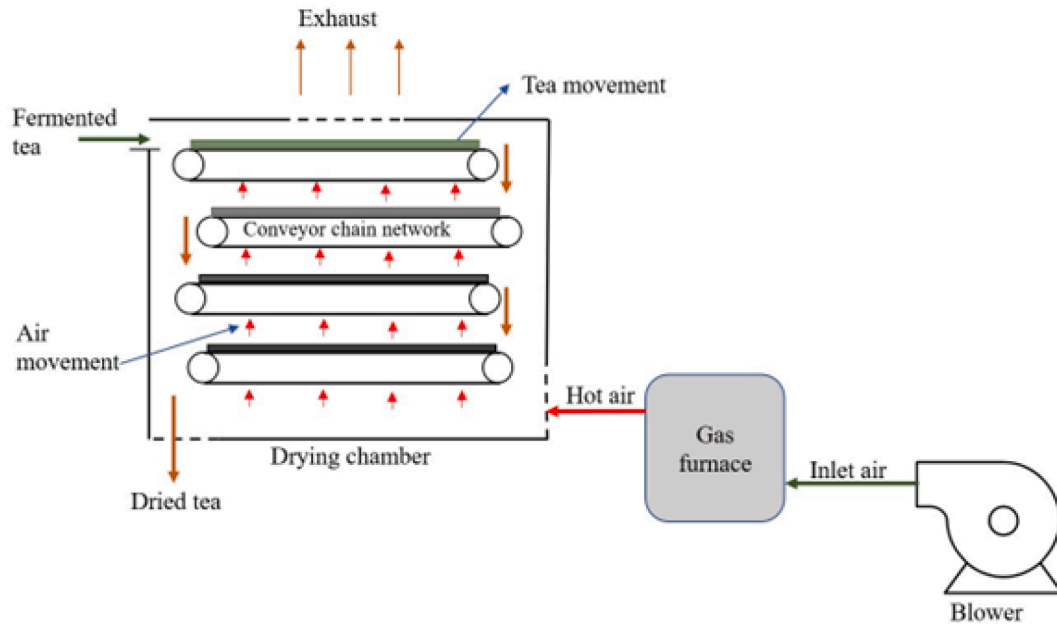


Fig. 32. Schematic of gas type drying system [110,111].

considered as 8 h (sunshine hours). The drying thermal energy requirement is taken as 497.53 kWh per 100 kg of made tea [7]. The annual monetary savings by replacing high speed diesel, coal and natural gas with solar energy for small, medium and large tea growers are presented in the Table 9. The formulation used for calculating the annual benefit is given in Eq. (20).

consumed in drying one kg of tea from 71 % (w.b.) of moisture content to 3 % (w.b.) using six different driers through their simulation studies considering thin layer drying model was reported by Temple and Boxtel (Table 10) [57]. It was shown that energy consumptions in endless chain pressure drier and endless chain pressure drier with hot feed are less as compared to the other driers.

$$\text{Annual benefits} = \frac{\text{Cost of fuel} \times \text{Energy required in drying per unit mass} \times \text{Drier capacity per unit time} \times \text{Plant operation time per day} \times \text{No. of days for plant operation per year}}{\text{Calorific value of fuel}} \quad (20)$$

## 8. Challenges and future research direction in tea drying system

The thermal energy requirement in tea factories is between 4.45 and 6.84 kWh per kg of tea produced (Kumar et al., [4]). The energy

Based on Table 10, energy consumption associated with fluidized bed drier could be reduced by adding the recirculation of air in the system. In place of improvements in the existing driers, it is also worth to innovate new kind of designs of drier for lowering energy consumptions

**Table 8**  
Techno-economic studies on tea drying.

| Technology used                                              | System details                                                                                            | Key points                                                                                                                                                              | References |
|--------------------------------------------------------------|-----------------------------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------------|
| Solar air preheating                                         | Solar collector area: 212 m <sup>2</sup><br>(Location: South India)                                       | Payback period: 2–4 years,<br>Reduction in specific fuel consumption: 0.222 kg/kg of made tea (from 0.932 to 0.71 kg/kg of made tea),<br>Annual total fuel saving: 25 % | [92]       |
| Heat recovery from exhaust of drier and preheating fresh air | Ecoterm heat exchanger for heat recovery<br>(Location: East-African country of Burundi)                   | Annual saving and income: 301,650 SEK,<br>Reduction in thermal energy use: 33 %,<br>Payback period: 1.6 years                                                           | [112]      |
| Solar air preheating                                         | Solar flat plate collector (quantity: 200)<br>Aperture area: 1.7 m <sup>2</sup><br>(Location: Sri Lanka)  | 25–34 % of fuel savings                                                                                                                                                 | [93]       |
| Solar air preheating                                         | Solar hot air generator (SHAG), 33 modular units<br>(area of 2 m <sup>2</sup> /unit)<br>(Location: Assam) | Fuel saving: 20 % of total coal consumption<br>(for drier with thermal load of 400 kW)                                                                                  | [97]       |
| Air heating using gaseous fuel                               | Downdraft gasifier (Location: Sri Lanka)                                                                  | Reduction in fuel wood consumption: 12 %, Life cycle cost of energy production: 8 % less than firewood based tea factory                                                | [103]      |
| Air heating using producer gas as gaseous fuel               | Downdraft gasifier<br>(Location: India)                                                                   | Thermal energy demand fulfillment: 28 % (for medium scale tea factory)<br>Cost savings: 21,067 \$                                                                       | [105]      |

**Table 9**

Monetary benefits analysis using solar energy for drying.

| Parameters                                                                                         | Small tea growers                                           | Medium tea growers                                            | Large tea growers                                              |
|----------------------------------------------------------------------------------------------------|-------------------------------------------------------------|---------------------------------------------------------------|----------------------------------------------------------------|
| Average production capacity of tea growers (kg of made tea/h)                                      | 22.5                                                        | 65                                                            | 270                                                            |
| Type of fuel replaced by solar energy                                                              | High Speed Diesel (HSD), coal, natural gas                  |                                                               |                                                                |
| Annual monetary savings (considering 8 h of thermal energy demand fulfilling through solar energy) | HSD (57824 \$)<br>Coal (10390 \$)<br>Natural gas (50346 \$) | HSD (167047 \$)<br>Coal (30017 \$)<br>Natural gas (190016 \$) | HSD (693888 \$)<br>Coal (124685 \$)<br>Natural gas (789298 \$) |

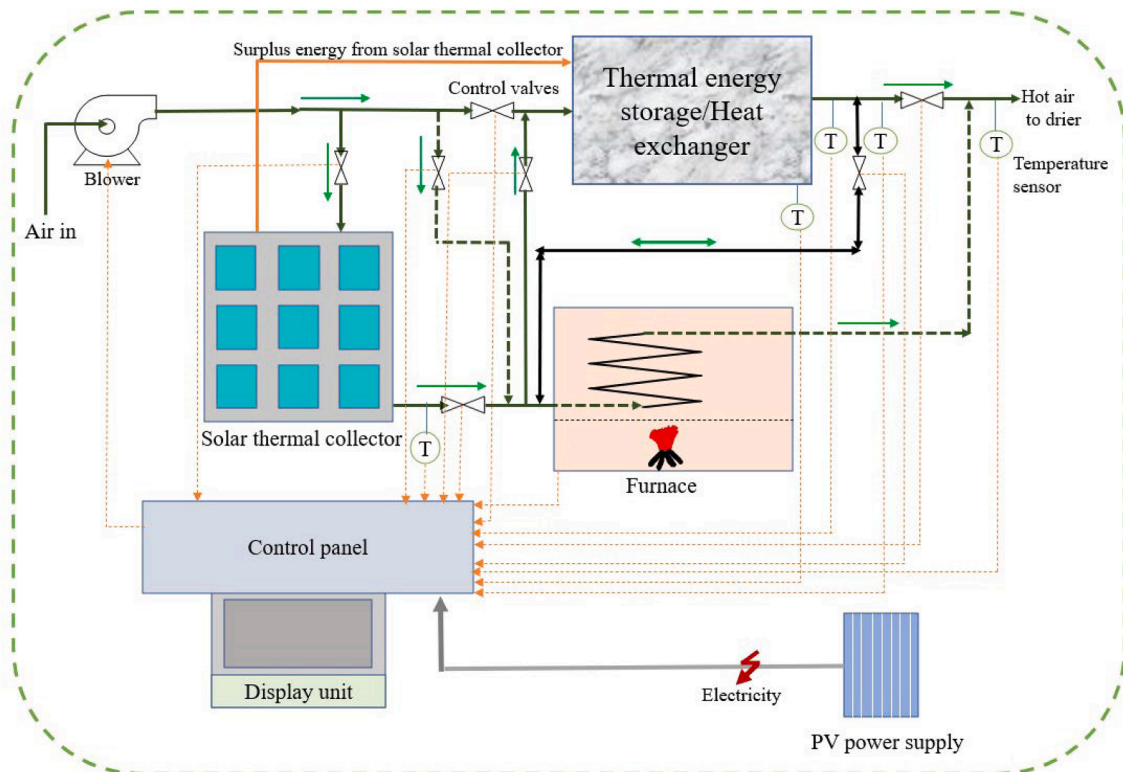
**Table 10**

Energy consumption in drying of tea using six different driers [57].

| Type of drier                              | Energy consumption (MJ/kg) | Energy consumption in percentage relative to FBD |
|--------------------------------------------|----------------------------|--------------------------------------------------|
| Fluidized bed drier (FBD)                  | 2.80                       | 100                                              |
| Three stage fluidized bed drier            | 2.84                       | 102                                              |
| Fluidized bed drier with recirculation     | 2.30                       | 82                                               |
| Endless chain pressure drier               | 2.11                       | 75                                               |
| Cross flow drier                           | 2.95                       | 105                                              |
| Endless chain pressure drier with hot feed | 2.18                       | 78                                               |

and reducing size of the drier. The second factor in designing of drier is capability to render end product of better quality. The color, aroma, appearances and taste should be within the range of acceptance. In addition, to develop drier as per the production capacity of tea growers is one of the challenges in the tea estates [113]. Drying temperature, flow rate of air, drying rate, thickness of bed of tea leaves, drying duration and final moisture content should be put within proper range and monitored to avoid inferiority in the quality of tea [3]. The partial implementation of renewable energy in tea factories may face the issues of operational difficulties in controlling the quantity of fuel supply and burning time requirement. Thus, a dedicated control system is required to manage these issues. In case of solar energy assisted tea drier, it is pertinent that there should be no deterioration in the quality because of intermittency and occasional insufficiency of solar radiation. There are a few literature available that indicate to resolve these kinds of issues

[93,97]. Fig. 33 shows an idea of integrated drying system for tea factories to resolve the issues in drying of the tea using solar energy. This system can work alone with solar thermal collector system or with thermal energy storage or with fossil fuel based furnace. However, in case of any energy insufficiency from solar thermal collector or thermal energy storage, furnace will fulfill the requirement. During sunshine hours, solar thermal collector system will supply the energy for drying and it will deliver excess energy to the thermal energy storage. If temperature of air is not as sufficient as required for drying, furnace will supply additional energy to achieve the requirement. During off-sunshine hours, thermal energy storage will work and in case any energy deficiency from storage side, furnace will work simultaneously or it will supply energy alone to the air in case of completely discharged state of storage. An agile control system will monitor the control valves for controlling the operation of flow lines or operation of equipment. The

**Fig. 33.** Integrated tea drying system.

proposed system will cut down the production of greenhouse gas emissions and will save operating cost of the tea production. The main challenge of this proposed drying system will be integration of the equipment for uninterrupted supply of required heat.

## 9. Summary

Drying operation in the tea processing is crucial to terminate the enzymatic reactions to achieve the desired taste and color in the made tea. In addition, drying is also important to reduce the final moisture content in the tea leaves to 2.8 to 3 % to avoid growth of bacteria and to increase the shelf life of the tea. Drying is done in industrial/commercial hot air-based driers, such as fluidized bed drier, vibro-fluidized bed drier, and endless chain pressure drier. These driers consume large amount of energy. Several attempts have been made in the past by researchers to enhance the performance of these driers. Further, researchers have introduced a few other forms of driers, such as, microwave drier, radio frequency drier, superheated steam based drier etc. These driers are under research and development stage to optimize the drying behavior and retain the quality standard of dried tea. Since, driers are energy intensive, and majorly tea factories are using fossil fuels to meet day to day thermal energy demand of the drying operation, this causes greenhouse gas emission and makes the process costly. Therefore, it is preferable that tea driers should consume less energy without having any adverse effect on the quality. This requirement can be met by introducing energy efficient driers. In addition, renewable energy-based driers would not only address the issue of fossil fuel requirement but also contribute towards sustainability of the environment. However, this area requires more research and development to integrate renewable energy resources with the driers to utilize them efficiently. The present study suggests a solar energy, thermal energy storage and furnace based integrated drying system for tea factories.. Following are the main findings from the present work in a nutshell:

- The driers are energy intensive and more than 80 % of energy consumption in tea factories is thermal energy.
- Majorly fossil fuels are consumed to meet the thermal energy demand of the drying of tea in tea factories.
- Conventional drying methods in tea factories are based on drying in endless chain pressure drier and fluidized bed drier.
- FBD/VFBD suits for CTC black tea production, whereas ECP drier suits for orthodox, CTC and green tea (from India) production.
- Non-conventional drying techniques such as microwave, radio frequency, and superheated steam-based drying are non-air based.
- Renewable energy-based drying systems are required to replace industrial driers to reduce fossil fuel consumption and greenhouse gas emissions.

The study has reported the research works from published literatures or project report only. However, there may be few other information about tea drying technology at small scale industries which is not available in the public domain. This may be one of the limitations of the present study.

## Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## Data availability

No data was used for the research described in the article.

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