Chapter 2

Literature Review

This chapter is aimed to provide an extensive literature survey of the various research works done on the wide area of tea withering and drying. Also, it throws light on the studies related to solar drying, thermodynamic analyses as well as on economic and environmental aspects of renewable energy based drying systems.

2.1 Customization in tea withering trough

In tea withering, two types of troughs are normally used- open and closed withering troughs. The tea leaves are spread at a particular thickness and the air blows upwards from beneath the perforated bed in an open trough. Usually it takes (12-14) h for the withering to take place in open troughs. The edges of the withering troughs are raised in enclosed troughs thus keeping the bed in a closed environment. This creates a plenum chamber at the top of the withering trough. The fan blows air in the forward direction only allowing the air to blow either from top to bottom or vice-versa. A damper and a shutter arrangement controls the flow of air at the entry and exit points. The leaf damage is comparatively less in an enclosed trough due to less handling of leaves. The process of enclosed trough withering completes in about 6 h. In the open trough arrangement, the fans require reversal in their direction intermittently to let the leaves in the upper part to wilt. A reversing switch in the casing of the fan motor is provided for the reversal of airflow process. But the efficacy of the fan reduces to nearly 60% and results in more power consumption compared to the normal fan operation. Heat losses occur during reverse blowing of fan while withering the upper layer of tea leaves [88].

Tea withering troughs were modified from their conventional design to enhance the standard of withering. A customized trough was developed to emphasize on the role of the primary aspects that effect the consistency of withering throughout the trough length, time of wilting and energy consumed in the process. A novel two-section open trough was designed and developed with the portable and static parts. The portable section could be elevated, rotated and moved both in the forward and reverse directions. The fan having a speed control element was placed between the two parts which controlled the operation of the trough with different air flow rates. The air temperature, velocity and humidity could be examined in the trough. There were provisions to study the variations in moisture content, proteins, amino acids, polyphenols and chlorophyll in the newly developed tea withering trough [162]. The thickness of the leaves spread over the bed of the withering trough is a necessary factor to ensure proper withering. A depth of around 0.3 m of leaf spread is maintained in the prevailing withering troughs. During the peak season, the trough is forced to be overloaded or the depth needs to be more in order to accommodate the high capacity of tea leaves. To increase the intake capacity of the existing withering troughs, two parameters were used. Modifications in the ratios between the areas of cross-section of upper and lower conduits and between recesses of alternating air flow through the withering trough bed proved to fasten the moisture loss. This increases the leaf intake capacity [42]. Kamau designed a withering trough having more capacity with less ingestion of energy. Fibre re-inforced fans were incorporated in the design with 79.77% efficiency in the motive to consume less energy. The ratio between the ducts and durations between air flow were considered as 2:1 which sped up the tea withering process. The area of the withering sector was increased by 1800 m^2 in order to increase the intake capacity from 44000 kg to 120000 kg of tea leaves [88].

An instrumentation arrangement was made to investigate the tea withering process online by taking relative humidity and temperature into account. Ten sensor nodes were installed at the entry and exit of the path of air-flow to measure these two parameters. The sensors were equally placed above and beneath the tea leaves. The loss of moisture level was measured using gravimetric method by a load-cell based arrangement of weighing. A considerable variation was reported in the temperature and humidity at the entry and exit points of the air-flow path in the withering trough. The moisture loss was predicted using the artificial neural network. The predicted results tallied with the actual results with a maximum inaccuracy of -3.6% [39-41].

2.2 Effect of withering and drying on different types of tea

2.2.1 Impact of withering time

The duration of tea withering has a crucial impact in the moisture level, amino-acids, volatile composites, mineral elements and eventually the quality of made tea. Significant results were obtained after 24 h of black tea withering for the moisture, ash content and elements like sodium, phosphorous, magnesium, zinc, copper, manganese, aluminum, lead and nickel. Sodium and magnesium contents reduced to 162.5 and 803 mg/kg respectively whereas the rest of the components increased with the withering time. The moisture content reached 63.8% from 76.4% at the end of the process. However, amino acids, potassium, iron and cadmium altered insignificantly [82]. The effects of withering duration on the black tea quality were determined according to environmental conditions, sensory evaluation and colorimetric experiments. Air flux of 6.3 m^3/min per kg of tea leaf with a temperature of 27 °C was fixed for the work. Five different levels of withering time were considered. There was an increase in tea water extract during wilting. No significant effect was reported for theaflavins (TF) and the brightness of the liquor. On the contrary, colour of tea and thearubigins (TR) showed substantial changes during the withering process. The highest content of thearubigins as well as the best sensory attributes were recorded after 16 h of tea withering [165]. The levels of theanine in the tea shrubs were determined throughout the process of wilting based on withering time and exposure to sunlight. It was quantified by High Performance Liquid Chromatography (HPLC). There was a considerable decline in the theanine levels as the sunlight intensity increased. However, these showed a significant increase during sun-set and also after 15 h of withering. Standard tea shoots had 1.41% of average theanine levels after 3 h of wither whereas 3.11% was reported for those withered for 15 h. The internodes had more mean levels of theanine as compared to that of the leaves [185]. Owuor et al. reported that caffeine content and flavour index increased if the tea leaves were withered for a prolonged period contrary to theaflavin content and volatile compounds. The thearubigin content did not show significant changes due to longer withering time but the tasters evaluated that it was the highest for 14 h of withering [131]. Again, Owuor and Orchard stated that very less changes occurred in the tea quality parameters by varying the duration of chemical withering to 18 h. The reduction in the Group-I volatile compounds was much more compared to that in Group-II which resulted in higher flavour index. The evaluation of the tasters did not change significantly with such variations in the volatile compounds [132]. Muthumani and Kumar attempted freeze-withering of tea leaves to decrease the time of conventional wilting. The desired flaccidity and permeable cell membrane in the tea leaves were achieved by freeze-withering in a shorter span. The final product obtained was better than the conventionally withered ones. The increased permeability in cell membrane and the fall in chlorophyll content showed that both physical and chemical withers were attained in the leaves by freeze-withering [119].

2.2.2 Bio-chemical changes due to tea withering

Due to withering operation, there occurs various bio-chemical changes in the tea leaves. Tomlins and Mashingaidze reviewed the impact of wilting on the other subsequent tea processing operations and features of black tea. They discussed the effect of plucking standard and handling of fresh leaves on withering as well as the effect of tea wilting on tea storage. It was opined that mechanized system of handling the leaves would be beneficial to the product quality [184]. Soheili-Fard et al. reported the impact of air-flow rate on various parameters of black tea. The appearance of dried tea, colour, aroma, taste, infused tea leaves and the final tea quality showed significant changes at 1% level [164]. The effect of the correlation between tea quality and withering was reported using various light sources. The taste and aroma of black tea improved with red, orange and yellow light wilting which gave a sweet flavour and fresh taste. The sensory levels were reported to be the highest with yellow light followed by orange and red light withering along with the maximum contents of amino-acids, catechins, theaflavins and aroma scores. Strong astringency resulted in black tea due to UV light withering. The taste and aroma were deteriorated under green light whereas there occurred no significant change in hybrid light treatment [7]. The total quantity of volatile compounds was compared for withered and non-withered black tea. It was found that the content of E-2-hexenal was higher in non-withered samples. The quantity of methylsalcylate, Z-3-hexenol ester, linalool and oxides of linalool was reported to be more in the withered tea [175]. There was a decrease in the polyphenol oxidase level of tea leaves after partial drying or withering of the leaves. The rest of the oxidizing action on the remaining substrates in the tea leaves were done by the other processes [186]. The formation of theaflavins and thearubigins were affected by depression in the activity of polyphenol oxidase during the process of withering. The non-withered CTC tea leaves produced higher theaflavins and lower thearubigins compared to the conventionally withered ones. Such proportions resulted in a brisk, bright and thin drink [187]. Bhatia and Deb used a spectrophotometric method to assess the amides and amino-acids of freshly plucked and wilted tea leaves. Around 90% of the entire amino-acids were reported to be recuperated after chromatography. The fresh leaves of *Betjan* and *19/29/13* samples recorded the amount of amino acids present as 2.50% and 0.85% respectively. There was no asparagine spotted in the fresh leaves during the initial period after plucking contrary to other amino acids. However, it started accumulating rapidly after the initial lag and throughout the storage duration which again was in contrast to the others [30]. It was further reported that the contents of glutamic acid, glutamine, serine, asparctic acid and alanine were higher in the tea leaves plucked in the afternoon than that of those harvested in the morning. The protein breakdown during the withering stage was estimated to less than 8% of the total content in tea processing. It was reported that high temperature withering could bring down the flavour indices, theaflavins, brightness and sensory scores in the black tea leaf samples. Lack of briskness occurred in the leaf samples withered above 30 °C though high levels were obtained in thearubigins and colour [133]. The molecular weight and other properties of various types of phenolic oxidase of tea shoots and four different recurrent species were determined. There was observed a difference in substrate activity in the high and low molecular forms of phenol oxidase. The low forms exhibited hydroxylase activity whereas catechol oxidase activity was demonstrated by the high molecular forms. It was reported that only phenol oxidase having high molecular forms were formed during the withering operation of black tea processing [128]. Baruah et al. studied the impacts of temperature and moisture loss amid withering operation on the degradation of catechins, creation of volatile flavoury components (VFC), theaflavins and thearubigins. Fresh and wilted tea leaves of different clones collected from the experimental garden were processed to estimate the catechin content. Environmentally controlled manufacturing was used to prepare the samples for estimation of VFC, TF and TR. Gas liquid chromatography was used to assess the TF, TR and VFC and the catechins were evaluated by using HPLC. It was concluded that the declination of catechins could be prevented by restricting the initial moisture loss in withering process. Brighter quality tea was found to be produced under low temperature withering. The VFCs which add to the bloomy odour like benzylalcohol, geraniol, linalool, methylsalicylate etc. were the highest in low temperature. A lengthier chemical wither would enhance the flavour quality of the liquor produced [25].

Not only in black tea, withering has its effects on other different varieties of tea as well. The collective role of solar withering, indoor wilting with turn-over treatment and mass rolling were described by comparing the aroma constituents of twelve samples of pouchong and Tee-Kwang-Yin tea. An increase in 23 major constituents was observed due to these processes. There was a significant increase in the concentrations of α-farnesene, benzyl cyanide, nerolidol, indole and jasmine lactone whereas the linalool concentration declined [183]. Kobayashi et al. stated that the impact of indoor withering was greater than that of solar wilting on the aroma components when investigated on nine pouchong tea samples. There were prominent rises on the concentrations of aromatic alcohols, oxidized products of linalool, benzyl cyanide, hexenyl esters, *cis*-jasmone, jasmine lactone, phenylacetaldehyde, indole and sesquiterpenes due to turn-over treatment void solar withering. Four such treatments along with 17 minutes of solar withering was effective enough for producing the flowery fragrance of pouchong tea [97]. Takeo discussed the withering effects on the aroma constituents and volatile compounds of oolong tea. The volatile compounds increased in such type of tea when withered around 40 °C. The aroma formation fastened due to warm withering during the initial period followed by soft manual rolling [176]. In Kenyan tea, the effects of low temperature N-plasma withering on the polyphenol content were studied. The required environment was provided with the help of a dielectric barrier discharge compartment. Seven samples were used for the experiment while five other samples were experimented in non-plasma environment. There was a decline observed in all the polyphenols with the rise in duration of wither. The highest percentage was found in epigallocatechin gallate followed by caffeine. Mixed results were obtained for epigallocatechin and epicatechin for different time periods. In the plasma environment, the highest average content of polyphenol was obtained as 78.56 mg/g in contrast to 133.40 mg/g for the non-plasma one. For the samples dried without wilting and fermenting, the polyphenol content was estimated as 101.91 mg/g [101].

A series of studies was carried out on the impact of tea withering on the tea leaf polyphenol oxidase. The summarized form of these works are given in Table-2.1 below-

Table 2.1. Studies on polyphenol oxidase (PPO) in tea leaves [153]

Sl. No.	Topic	Activity of enzymes	References
1.	Solubilization and characteristics of the structurally bound PPO	Activity of enzymes repressed by potassium cyanide and sodium diethyldithiocarbamate.	[170]
2.	Studies on the variations of PPO activity	Enzymatic activity increased during the withering period. Increase in temperature made it faster.	[171]
3.	Localization of PPO in tea-leaf cell	Most of the enzymatic activities appeared in the centrifugal precipitates within 1400×g to 15000×g; the content of polyphenol declined.	[172]
4.	Impact of antibiotics on development of enzymes	Antibiotics repressed PPO initiation. Novel protein having the activity of enzymes developed in the wilted leaves.	[173]
5.	Purification and characteristics of the solubilized PPO	O-diphenol oxidized by A-I; Vicinal-triphenol and O-diphenol oxidized by A-II. A concentration of substrate inhibited their activities.	[174]

2.2.3 Role of drying on tea

Drying is the final operation of tea processing before sorting where the moisture level is eliminated to an anticipated level from the fermented tea leaves. The parameters like drying time and temperature play important roles in many quality aspects of tea. It was reported that good feature of black tea was obtained when rolled for 25 minutes, fermented for 4 h and 5 minutes and dried at 110 °C with a dryer speed of 1.5 rpm [120]. Teshome et al. appraised the effects of tea drying time and temperature on the quality and composition of tea. Three drying time periods and five temperatures were set to conduct the research on a clone 11/4 sample. Results indicated the presence of significant differences among the considered combinations for moisture content, brightness, colour, flavour, aroma, leaf infusion and thearubigins except for theaflavins. The quality and bio-chemical structure decreased when there was an increase in drying temperature with time. The optimum combination for producing good quality black tea was reported to be 100 °C and 25 minutes of drying [181]. Kavish et al. found out the appropriate drying temperature at inlet in endless chain type tea dryers. This was done to appraise the quality parameters of seven grades of orthodox tea processed using three standards of leaves. The leaf standards were selected as 40%, 50% and 60% of finely plucked tea leaves. Drying temperatures considered were 96 °C for control and 110 °C for treatment. The dried leaf samples were divided into seven grades and organoleptically evaluated for the properties like liquor colour, infused leaf colour, strength and appearance. It was reported that the liquor quality was not affected by higher drying temperatures at inlet. Significant difference in the appearance of 40% good leaves was observed at 110 °C for the grades of OPA, PEKOE, FBOPF and FBOP. But no such difference was observed for OP, OP1 and FBOPF1 grades for all the leaf standards [93]. Temple et al. attempted to compute the appropriate temperatures required for the desired alterations in the tea without causing any damage for excess heat exposure. The temperature range of 60 °C to 140 °C was considered for the experiments. Chromatography, HPLC and commercial tasters were used to monitor the effects. It was observed that 80 °C was required for maintaining the quality while temperatures above 110 °C were not preferred. However, drying period of lesser than 1 minute would tolerate a temperature of 120 °C. In higher drying rates, the inlet air temperature might exceed these values. Drying period of lesser than 15 minutes resulted in the absence of stewing phenomenon [180].

A comparison in the volatile compounds content was made for fresh and old oolong tea. It was reported that decomposition of long straight chained alcohols and acids took place during the conversion of tea along with generation of compounds of nitrogen and short chained acids with their amide derivatives. Five varied oolong tea preparations showed basically similar patterns of volatile constituents. However, this was different in case of oolong tea stocked for 10 years or more void of drying or those prepared under low temperatures and shorter baking period. Four vital aroma nitrogen containing compounds were reported to be consistently present in the evaluated oolong teas [104]. The impacts of different drying techniques were analyzed on the total phenolic (TPC) and anthocyanin contents and antioxidant properties of *Vitex negundo* tea. Thermal, sun and microwave drying methods were conducted on the tea samples in triplicate. The extracts of tea were prepared by hot water extraction method. The TPC was assessed using the Folin-Ciocalteu reagent following standard procedures. The pH differential technique was used to determine the anthocyanin content. In sun drying, there was loss of the TPC and antioxidant properties. No significant changes were observed in the TPC and antioxidant properties due to microwave drying even for longer drying durations. But hot-air oven drying resulted in decline of these properties when the temperature rose from 45 °C to 95 °C. The total anthocyanin content was obtained maximum for microwave drying [140]. Investigations were done on the antioxidant activity and physicochemical characteristics of Thai green tea while drying in microwave vacuum mode. Nine drying conditions were used by combining powers of 3200 W, 3600 W and 4000 W with radiation duration of 20, 25 and 30 minutes. The free radical scavenging activity and TPC were determined using the 1-Diphenyl-2-picrylhydrazyl and Folin-Ciocalteu assays respectively. The catechins were measured by HPLC. The physical properties like water activity, moisture level and colour of the samples were also examined. The catechin content and the antioxidant activity were reported to be significantly affected by the considered microwave parameters. The moisture content and water activity were also highly influenced by the drying conditions. On the other hand, the TPC and colour of the tea samples did not get affected by such drying. The recommended conditions for commercial microwave drying of Thai green tea leaves were 3600 W for 30 minutes [78]. The biological characteristics and chemical compositions of tea processed by freeze, vacuum, spray and microwave-vacuum drying were examined comparatively. The four polysaccharides obtained in the processes showed similarity in molecular weight distribution and infrared and ultraviolet absorptions. Significant differences were found in the crude polysaccharides yield as well as the polyphenol and protein contents. The surface of the polysaccharide obtained from freeze drying was rough and permeable in contrast to that obtained from spray drying. The rest of the polysaccharides showed similar surface as that of bricks when analyzed under scanning electron microscope. It was reported that the metal chelating capacity and superoxide radicals searching assays were better in case of freeze dried samples than the other methods. The polysaccharides from vacuum drying showed a finer ability on α-amylase and α-glycosidase inhibition tests than the rest. The inhibitory percentages were 92.80% and 82.75% respectively [195]. The TPC, total flavonoid content (TFC), antioxidant activity, colour and vitamin-C in green tea were evaluated by using seven drying techniques namely, oven drying with three temperatures, sun, shade, freeze and microwave drying. Except vitamin-C, the rest of the parameters increased with the drying treatment in general. The maximum TPC and radical scavenging activity were estimated in oven drying at 60 °C as 209.17 mg GAE/gdw and oven drying at 100 °C gave the highest TFC as 38.18 mg QE/gdw. The utmost radical scavenging activity was shown in oven drying at 60 °C while the lowest amount was given by microwave drying. Similar was the trend in the reducing power test. Freeze drying revealed the highest amounts of vitamin-C and chlorophyll as 16.36 mg/100 gDM and 17.35 mg/l respectively. It was concluded from the colour of the tea leaves that the most and least desirable drying methods were respectively freeze and sun drying [144].

2.3 Drying mechanism

The drying mechanism in general pertains to the transformation of a wet or moisture-laden substance into a dry, solid state through the extraction of moisture. This procedure finds extensive application across multiple sectors such as food processing, pharmaceuticals, chemicals, and more. The drying process comprises multiple stages and is subject to various influencing factors. An elaborate discussion of the fundamental drying mechanism is given below [116]-

i) Moisture migration: The drying initiates with the transfer of moisture from the inner part of the substance to its surface. This transfer is instigated by various mechanisms like capillary action, liquid diffusion, and vapour diffusion. The pace of moisture transfer relies on the physical characteristics of the material, such as its porosity, permeability, and distribution of pore sizes.

ii) Surface evaporation: When moisture reaches the material's surface, it evaporates, transitioning from liquid to vapour. The speed of this process depends on factors like temperature, relative humidity and air flow. Warmer temperatures and lower relative humidity levels encourage quicker evaporation.

iii) Heat and mass transfer: The drying process operates based on heat and mass transfer principles. Heat is necessary to supply the energy needed for the phase change of moisture from liquid to vapour, known as latent heat of vapourization. Simultaneously, mass transfer takes place as the vapour formed on the material's surface is transported away by the surrounding air or any other medium used for drying.

iv) Constant and falling rate periods: The drying process can be split into two main stages- constant rate and falling rate. In the constant rate phase, the drying rate remains steady, and the material's surface is fully saturated with moisture. During the falling rate phase, the drying rate gradually decreases as the material becomes drier. At this point, moisture migration from the interior to the surface becomes the limiting factor in the drying process.

v) Equilibrium moisture content: As the drying process progresses, the material reaches a balance with the surrounding air, known as the equilibrium moisture content. At this stage, the rate of drying becomes very slow, and removing more moisture becomes difficult or impossible without altering the drying conditions.

2.4 Drying models

The moisture is removed from the core of the already fermented tea leaves by hot drying air by the process of diffusion. The colour of the dried leaves change to black from coppery red. The moisture content after the drying operation is expected to come down to 3% (w.b.) for maintaining the quality of the resultant product. An extensive variation was observed in the critical moisture level of black tea [31]. The revival of hydrolytic enzymes due to such variation could enhance biochemical reactions. Again, catechins get deactivated during the fermentation process which makes the drying process a complex one.

The thin-layer drying models illustrate the drying procedure of various biohygroscopic materials. Three categories of such models are basically dealt with- theoretical, semi-theoretical and empirical models. The theoretical ones consider only the core resistance to the transferal of moisture whereas external resistance is also taken into account by the other two models [77,198]. The resistance offered to transfer is assumed to get evenly distributed throughout the indoors of the fermented tea which is homogeneous in nature. The diffusion coefficient (*D*) does not depend on the indigenous moisture level. The shrinkage of volume is considered as insignificant. Thus, the second law of Fick may be given as-

$$\frac{\partial M}{\partial t} = D\frac{\partial^2 M}{\partial t^2} \tag{2.1}$$

The analytical result of Eq. (2.1) was obtained for different regular shaped bodies like sphere, rectangular, cylinder etc. [37]. The Fick's law was used to define the drying attributes of various agricultural products [38,47,58]. The simplification of the general solution of Fick's 2nd law gives the various semi-theoretical drying models. The validity of such models remains restricted within specific temperature, air flow velocity, humidity and moisture level arrays. The geometry, conductivity and mass diffusivity assumptions for a particular product are not necessary here. The time required by these models is lesser in comparison to the theoretical ones. The Henderson-Pabis, Two-term, Page and Modified Page are some of the commonly used semi-theoretical drying models [76,139,151].

The Two-term drying model comprises of the first two terms of the general solution of the second law of Fick and is given by Eq. (2.2). The drying rate of shelled corn was predicted using this model [151].

$$MR = \frac{M - M_e}{M_0 - M_e} = Ae^{-k_1 t} + Be^{-k_2 t} \tag{2.2}$$

where, MR = moisture ratio, M, M_0, and M_e are the moisture levels of the product at an instant, the initial moisture level and equilibrium moisture level respectively. A, B, k_1 and k_2 are the empirical coefficients. M_e being relatively smaller than the other two moisture contents, it is generally neglected while computing the moisture ratio.

The Henderson-Pabis model is nothing but the first term of the general solution of Fick's 2nd law and is given by [76]-

$$MR = \frac{M - M_e}{M_0 - M_e} = Ae^{-kt} \tag{2.3}$$

The drying characteristics of wheat, corn and peanut were predicted by the Henderson-Pabis model [76,115,196]. The coefficient *k*, which is also the slope, is related to the effective diffusivity throughout the falling rate duration of a drying course. It is regulated by the liquid diffusion process [113]. When the intercept of this model becomes equal to unity, it is termed as the Lewis drying model [108]. The drying characteristics of barley were aptly predicted with the Lewis model [34]. The occurrence of heat flow from a submerged body in a cold fluid is found to be analogous to the transfer of moisture in the agricultural products. It is therefore concluded that the rate of drying is directly proportionate to the variance between moisture level of the material at an instant and the equilibrium moisture level. This is thus equivalent to Newton's law of cooling and is given by Eq. (2.4)-

$$\frac{dM}{dt} = k(M - M_e) \tag{2.4}$$

The Page drying model is a modified version of the Lewis and it was used to illustrate the drying features of rice, short grain rice and white bean [5,80,194]. This is given by Eq. (2.5).

$$MR = \frac{M - M_e}{M_0 - M_e} = e^{\left(-kt^N\right)} \tag{2.5}$$

Again, the Page model was revised as Modified Page to predict the drying behaviour of soybean [130] as shown in Eq. (2.6).

$$MR = \frac{M - M_e}{M_0 - M_e} = e^{(-kt)^N} \tag{2.6}$$

Neglecting the basics of a drying process, the empirical models give directly a correlation between drying time and average moisture content. It becomes consequently difficult to describe the important processes going on during drying. The drying of shelled corn [130] was described by the Thompson drying model as given in Eq. (2.7) and the drying behaviour of rough rice was studied using Eq. (2.8) [94].

$$T = a \times \ln(MR) + b \times (\ln(MR))^2 \tag{2.7}$$

$$MR = 1 + at + bt^2 \tag{2.8}$$

From the literature, it is clear that the drying models have extensively been used to predict the drying performance of various agricultural yields. The use of such models in the withering and drying operations of tea will be discussed in the next sections to follow. An elaborate discussion will be provided on the usage of these models in the solar drying of various products in a later part of the chapter.

Table 2.2. Thin layer drying models

Sl. No.	Model	Equation	Reference
1.	Newton	$MR = e^{-kt}$	[74]

2.	Henderson and Pabis	$MR = Ae^{-kt}$	[76]
3.	Modified Henderson and Pabis	$MR = Ae^{-kt} + Be^{-gt} + Ce^{-ht}$	[17]
4.	Page	$MR = e^{-kt^N}$	[5]
5.	Modified Page	$MR = e^{(-kt)^N}$	[130]
6.	Logarithmic	$MR = Ae^{-kt} + B$	[35]
7.	Two-term	$MR = Ae^{-k_1 t} + Be^{-k_2 t}$	[151]
8.	Two-term Exponential	$MR = Ae^{-kt} + (1-A)e^{kAt}$	[204]
9.	Wang and Singh	$MR = 1 + At + Bt^2$	[205]
10.	Diffusion approximation	$MR = Ae^{-kt} + (1-A)e^{kBt}$	[206]
11.	Midilli and Kucuk	$MR = Ae^{-kt^N} + Bt$	[207]
12.	Thompson	$MR = 1 + at + bt^2$	[94]

2.5 Modeling studies on tea-leaf withering operation

The tea-leaf withering operation has adequate room for simulation model development. Some research works done on the modeling of tea withering operation are discussed below-

In order to replicate the moisture level of tea leaves amid the wilting operation, Botheju et al. developed a 1-D mathematical model of heat and mass transfer. The finite difference method was used for the same with suitable boundary conditions. The real time moisture content was computed using a computer program in QBASIC. Other psychometric parameters were also examined with this program. The assumptions for time and space increments were taken by minimizing the estimation error. To check the validity of the developed model, they conducted four experiments of tea withering in a commercial withering trough. The withering process was carried on for 12 h. The tea leaf samples were collected from the top, mid and bottom layers of the leaf spread bed after each hour of the experiment to estimate the moisture loss. The results obtained from the experimental run tallied with those of the simulated ones with standard error ranges of (0.2940-1.2872) %, (0.7148-1.1025) % and (0.7106-4.5478) % for the top, middle and bottom layers respectively on wet basis [32].

Botheju et al. measured the transfer level of moisture during the process of tea-leaf withering by conducting drying tests of freshly plucked tea leaves. The temperature and relative humidity ranges considered were respectively (20-35) °C and (40-90) % at an airflow rate of (1.2 ± 0.3) m/s. The fresh leaves were dried in a constant climatic chamber and the drying behaviour was analyzed using five different drying models. The Two-term model gave more satisfactory results in comparison to the other models used. It was reported that the desorption process of the tea shoots occurred in the falling rate period. The range of effective diffusivity was obtained as $(3.3409\text{-}5.4669) \times 10^{-10}$ m^2/s and the activation energy value was 1477.75 kJ/kg. An Arrhenius relationship described the dependence of temperature on diffusivity coefficient [33].

Ghodake et al. investigated the wilting behaviour of tea shoots for a temperature array of (20-45) °C with 1.1 m/s airflow rate. The temperatures were incremented with five units for the withering operation. The results obtained from the experiments showed the presence of only falling rate period in the withering process. The drying rates had increased with rise in temperatures and consequently it reduced the drying time. The models of Henderson-Pabis and Page were analyzed by considering *RMSE*, mean bias error, chi-square and the correlation coefficient (R^2). The Henderson-Pabis drying model illustrated satisfactorily the withering behaviour of the tea shoots for the first four temperatures up to 35 °C. For the higher temperatures, the Page model fitted the withering characteristics more suitably. The values of R^2 for both the models obtained were above 0.90 in all the temperatures [66].

Ghodake et al. determined the moisture sorption isotherms of green, black and withered tea for the temperature array of (20-40) °C with an increment of ten units. The standard gravimetric static technique was used for the process considering a relative humidity range of (10-90) %. Fitting of the sorption curves were done using Modified Henderson, Modified Oswin, Modified Chung-Pfost, Modified Smith, Modified Halsey and GAB models. The Modified Halsey model depicted the sorption isotherms of all the three types of tea suitably. The gross isosteric sorption heat of the green, black and withered tea leaves changed within (34.8-20.7) kJ/mol, (25.5-26.8) kJ/mol and (30.8-29.5) kJ/mol respectively. For the withered tea, the moisture levels fluctuated between (8-9) % (d.b.) whereas it was between (6-8) % (d.b.) for green and black samples [67].

Gupta et al. simulated the tea withering process to forecast the withering standard with a desired level of wither needed to harvest green leaves of high quality at the expense of minimum energy. Fuzzy nonlinear methods were used for the simulation. The moisture content of the leaves, thickness of leaf spread, plucking standard, withering duration and capacity of drying of the air were considered as the withering standards. The fuzzy rules were formulated based on expert human verdict for correlation of various fuzzy inputs and outputs. Fuzzy set operations were used to compute the considered withering standards. The withering standard was adjudged to be in the 'good' category of fuzzy operations when the developed model was implemented in the Rosekandi tea factory located in Silchar, Assam. The crisp value obtained was 70.55 [71].

Jayasundara suggested a withering control methodology based on fuzzy logic was for optimum consumption of electrical energy with maintenance of the product quality. To get the air flow rate input to the control system, an average flow grid was proposed. Fuzzification was done for the input air flow, relative humidity, chamber pressure, chamber temperature, fan speed, hot air damper angle by defining the membership functions accordingly. The fuzzy inference system was developed in Matlab and evaluated using 'evalfis' function of tool box. The damper angle was varied by keeping the frequency of the motor constant during the process. It was concluded that the proposed fuzzy logic based tea withering system would solve the issue of energy wastage due to high air flow rates and improper operation of the fans [83].

Sabhapondit et al. studied the effect of various moisture contents of withered tea leaves on polyphenoloxidase (PPO) and peroxidase (PO) enzymes as well as on the formation of TRs and TFs. Processing of six cultivars were done under four moisture content levels of 65%, 68%, 70% and 72%. The withering duration and temperature were kept consistent for all the samples. Huge reduction was observed in the chemicals as the moisture content declined in the wilted leaves. The lowest content was found in the T.3E/3 cultivar. The TFs and TRs were estimated to be the lowest at moisture content of (65 ± 1) % with quantities of (0.83-5.4) mg/g and (23-107) mg/g respectively. The cultivars TV1, TV9 and TV23 showed better product quality at moisture content of (70 ± 1) %. For the cultivars TV7 and TV26, the moisture level of (68 ± 1) % gave better results. It was thus concluded that the optimum level of moisture was cultivar specific and maintaining the desired moisture levels would enhance the final product quality [146].

Sarac developed a model for the energy and exergy investigation of the tea wilting operation in a tea factory in Turkey. The mass flow rates varied within 6218.75 and 6281.25 kg/h. The flow rate of air was taken as 18000 m^3/h at a temperature of 32 °C. The mean values were considered for humidity and dry bulb temperatures with an error of ±0.5 °C between wet and dry bulb temperatures. The boiler heating load and the power of the fan were respectively 1395 and 300 kW. It was reported that the exergy efficiency came down with the rise in specific exergy and temperature of air while it increased with the rise in mass flux of green tea for the intake temperature of air. Again, the exergy efficiency linearly increased with the mass of the product indicating the inverse relationship with the mass flux of process air. Moreover, the efficacy varied linearly with the humidity ratio and it showed a sharp decline with an increase in the humidity ratio of intake air [149].

To foretell the temperature and humidity patterns of the drying air in a tea-leaf withering trough, Gupta et al. created a 3-D model using Fluent 6.2 programme. The dimensions like length, thickness and width of leaf bed, meshes, input blowers and wooden structures were considered the same as in the real withering trough. The input conditions were considered the same as the experiments as the simulation model was expected to give real time performance. Extensive deviation was reported in the aforesaid distributions along the length of the trough which was responsible for non-uniformity in the withering operation. The model was authenticated using data gathered from the Rosekandi tea factory within the allowable bounds of ±1.43% [72].

Weerawardena et al. developed a control system to optimize the consumption of electrical energy during tea withering operation while keeping the made tea quality intact. The air delivered into the withering trough and the speed of the fan were controlled to save the energy. The fan speed was controlled with the help of a variable speed drive and it was estimated according to the theoretically calculated mass flow rate from the model. Raspberry pi 3 model B which was a computer with a single board was utilized as the controller to run the mathematical model and the software controlling the speed drive (variable). The consumption of electrical energy along with the quality characteristics were computed by conducting experiments and these were compared with the wilting process with or void the control system. With and devoid of the control system, the specific energy expended was calculated to be between 0.17 and 0.18 kWh/kg and 0.27 and 0.35 kWh/kg of total made tea respectively. The electrical energy ranged within (36-39) kWh while using the control system whereas it ranged between (55-67) kWh when estimated without the control system. It was thus reported that a saving of around 39% of the electrical energy could be made using the control system in the tea-leaf withering process [197].

Liang et al. established a constructive testing procedure to measure the moisture level of Congou black tea shoots undergoing withering. Detectable light images of the leaf surfaces were first collected using computer visual system. The colour and roughness characteristics were extracted through spatial variations of colours. Non-linear provisioned vector mechanism and partial least squares were used to develop quantitative prediction models to detect moisture of wilted leaves. The correlation coefficients obtained between water content and lightness factor mean value, green factor mean value and homogeneity were above 0.8. This indicated that good capability of the extracted characteristics to predict the water content. The values of predicted set correlation coefficient, *RMSE* and standard deviation (relative) of the predicted model were obtained as 93.14×10^{-2}, 4.11×10^{-2} and 180.04×10^{-2} respectively. The analytical relations between the water content and image could be better illustrated by the non-linear modeling method [109].

2.6 Experimentations on tea drying operation

Drying is the process of extracting moisture from fermented tea leaves through evaporation. The enzyme activities cease during this step while the moisture level drops to about 2-3%. The operation of tea drying has been the subject of numerous studies.

Temple and Boxtel determined the thin-layer drying attributes of black tea. A novel thin layer drying device consisting of a bedplate and a plenum assembly was developed to quantify the high initial rates of drying. The experiment was carried on for 172 runs. The excessive noise led to discarding of occasional runs. Many methods were applied for analysis of the data. Among these, fitting the data directly into the Lewis equation was the most logical one to compute the value of 'k'. A weight of sample graph was plotted against time for each run to find the value of 'k' at every sampling interval. The goodness of fit obtained from the Lewis model for the experimental records confirmed the validity of the model for the tea drying experiment. Drying rate factor was dependent on temperature and airflow rate. No constant rate drying period was reported [179].

Panchariya et al. conducted a similar experiment of thin-layer drying attributes of black tea in a newly developed dryer. Heated ambient air was used for the experiments in the temperature and air velocity ranges of (80-120) ℃ and (0.25-0.65) m/s respectively. The semi-theoretical models like Lewis, Henderson-Pabis, Page, Modified Page and Two-term were selected to fit the experimental statistics obtained from the experiments. For this too, the Lewis model gave the best results for the drying characteristics. The value for activation energy was reported as 406.02 kJ/mol with the range of effective diffusivity as $(1.14\text{-}2.98) \times 10^{-11}$ m^2/s. The temperature dependency on the diffusion coefficient was illustrated by an Arrhenius relationship. Again, the air velocity and temperature dependency on constant of drying was illustrated by Arrhenius-Power relationships. Both the relationships gave the R^2 greater than 0.996. Further, the suitable *MR*s for experimental conditions of drying were predicted by Arrhenius type relationship along with the impact of drying variables on the drying constant. Again, no constant rate drying was reported in this study [137].

Koneswaramoorthy et al. conducted a feasibility study for supplementing solar energy in the tea drying process. To pre-heat the air for drying, a solar thermal arena comprising of two hundred flat plate type solar collectors was fixed with a furnace. The air flow was considered as 24 L/s for the experiments. The average solar radiation during the tests was greater than 630 W/m^2. The fuel consumed by the heater varied between (21.6-27) L/h with the presence of solar field while it was greater than 40 L/h without the solar field. About 32.5% savings was estimated for the fuel consumption by using this alternative. The system was also preferable for re-firing grade teas void auxiliary source [98].

Ethmane Kane et al. conducted experiments on solar drying Mexican tea leaves in single layer in an indirectly operated solar dryer having forced convection. The ranges of ambient and drying air temperature, RH, air flux and solar irradiation used were respectively (21-35) ℃, (45-60) ℃, (29-53) %, (0.0277-0.0556) m^3/s and (150-920) W/m^2. The best fit was shown by the Wang-Singh model for the curves of solar drying among the fourteen empirical models used for fitting the drying data. Temperature controlled the drying rate primarily. The presence of only falling rate was reported. The diffusion coefficient was obtained between (1.0209-10.440) × 10^{-9} m^2/s and the activation energy was 89.1486 kJ/mol [63].

Yahya et al. used a solar based drying arrangement with a solar collector having V-groove to dry herbal tea. Air was circulated with the help of two fans. The temperature in the drying compartment was maintained at 50 ℃. An auxiliary heat source of 10 kW was kept ready to provide the heat if the temperature dropped below the specified one. The air flow rate was considered as 15.1 m^3/min. The ambient temperature was between (27-34) ℃ with a mean solar irradiation of 567.4 W/m^2. The initial weight of 10.03 kg reduced to 2.63 kg by the time drying ceased. In other words, the moisture level of the tea leaves was reduced to 54% from 87% (both wet basis) within 12 h. This drying was done in order to store the tea leaves for future extraction of active components from them keeping the green colour intact. About 56% of the total energy was contributed by the solar energy [201].

Akhtaruzzaman et al. studied the principles of fluidized bed drying in a Kilburn vibro-fluidized bed tea dryer. The inlet and outlet drying temperatures were recorded as 130 and 90 ℃ respectively in the dryer. Tea samples for taken from different positions of the drying bed of 4.88 m length to measure the moisture level. The ultimate moisture level of 2.8% from 69.1% was attained in just 20 minutes of drying. The constant of drying was reported as 31.05 h^{-1} while the equilibrium levels of moisture ranged from (18.3-2) % [10].

Hatibaruah et al. investigated drying behaviour of Assam CTC tea in a microwave oven. Five powers of microwave (180, 360, 540, 720, 900) W were used. A domestic microwave oven having maximum power level of 900 W at frequency 2450 MHz was used for the purpose. The impact of the different power levels on the moisture level and the drying rate of 50 g of the tea sample were studied. The power level of the microwave would determine the time needed to decrease the moisture content to a required level. The time for drying the tea sample at 900 W was lessened by around 77% as compared to that at 180 W. The drying rate ranged from 0.1 kg/kg min to 0.7 kg/kg min at an average for the powers used. In the falling rate duration, the drying rate ranged from 0.42 kg/kg min to 0.03 kg/kg min (d.b.). Out of the four drying models used for fitting the drying data, the Page model displayed the best drying characteristics. The R^2 values for all the different models used were above 0.99 thus showing good tally between predicted and experimental data [74].

Jindarat et al. used a combination of asymmetrical microwave with double feed and vacuum arrangement to examine the energy usage while drying tea leaves. Microwave powers of 800 W and 1600 W were used at 2450 MHz frequency with vacuum pressures of 535 torr and 385 torr for the experiments. The tea leaves underwent drying till the moisture content reached 7% (d.b.). The energy efficiency was evaluated on a model which was based on the 1st law of thermodynamics. Both the energy efficiency and consumption were found highly reliant on power of microwave and vacuum pressure. The energy efficiency was reported to be low in all the cases due to the small load used. Continuous microwave drying resulted in the best colour values of the dried tea samples but with a low specific energy consumption [85].

Dutta and Baruah investigated the thin-layer drying attributes of black tea by means of a tea dryer fired by producer gas which was produced from a woody biomass gasifier. The drying air temperatures used were in the range of (80-110) °C with a difference of ten units for air velocities of (0.50, 0.65, 0.75) m/s. A total of 27 runs were conducted. On fitting the drying data into several semi-theoretical drying models, the Modified Page model gave the finest prediction followed by Lewis. The effective diffusivities varied in the range of $(3.644\text{-}7.287) \times 10^{-11}$ m^2/s. Linear regression analysis gave the activation energy and diffusivity constant values as 52.104 kJ/mol and 0.746×10^{-3} m^2/s respectively. Depending on the producer gas' calorific value, the energy consumption of made tea with moisture content of 3% (w.b.) was estimated as 19.01 MJ/kg. The dryer used about 6.274 MJ/kg of energy per kg of water evaporated according to the calculations [51].

Langat et al. performed experiments to evaluate the drying procedure of tea leaves in a newly developed model. A perforated rotating drum was added in the apparatus to speed up the drying process. Different air flow rates, temperatures and drum rotation rates were used for the experiments. It was reported that the rate of drying was higher with the rise in air flux. A speed of 120 rpm was recommended for proper agitation of the leaves. The specific energy consumption rate was observed to vary significantly with the flow. Though the drying rates were faster in higher flows, the energy efficiency was obtained low. The moisture removal rates were aptly matched with the help of a two parameter predictive model for a variety of flows. The model could also be used to extrapolate certain results for those cases not considered in the experiments. Moreover, the aroma of the green leaves would be preserved better in the rotating type dryer [107].

Aydin et al. conducted freeze drying experiments on brewed black tea extract. The dynamic behaviour of the different stages of drying was explained using a case study on this tea extract. A pilot scale freeze dryer was used for the purpose. The temperature of the heating plates was adjustable from -40 °C to 60 °C. The condenser temperature could be set to -70 °C. The capacity of the four trays was 25 liters. The heating plates were set at -35 °C for 4 h for complete freezing of the solution. The pressure in the drying chamber was fixed to 10 Pa after the freezing was over. Jacobian polynomial approximation based method of orthogonal collocation was used to solve the heat and mass transfer equations. The physical properties and transport parameters were evaluated using the Levenberg-Marquardt algorithm to fit the data from experiments. Experimental results tallied well with the theoretical predictions for the study [19].

Ozturk and Dincer studied the performance of a vibro-fluidized bed three stage tea drying unit by carrying out the energy-exergy studies. With the increase in made tea capacity from 0.2 to 0.5 kg/s, the energy efficacy increased from 7 to 8.8% and the exergy efficiency rose from 42 to 42.3%. But the increase in air flux and air specific exergy reduced the exergy efficiency. As the temperature increased from 10 to 35 °C, the exergy destruction and efficiency changed from 1771 to 2066 kW and 22 to 10% respectively. The overall energy-exergy efficiencies were evaluated as 42% and 7.2% for the system respectively with a sustainability index of 1.08 [134].

Shomali and Souraki investigated the drying characteristics of tea shoots using a cabinet dryer having multiple trays. The moisture level and temperature of the leaves along with the temperature and RH of the drying air in the trays were predicted using heat and mass transfer models. A finite difference technique and trial and errors were used to divide the leaf bed into sequence of thin layers. Each tray was assumed to be a fixed bed. In the experiments, the temperature of the drying air was kept between 30 to 80 ℃ using a temperature controller. The predicted model data were comparable with those of the experimental ones. The Modified Smith drying model could satisfactorily describe the equilibrium moisture level as a function of humidity and temperature with an R^2 value of 0.984. An Arrhenius correlation could describe temperature dependency of diffusivities. Moreover, the drying level was reported to surge with rise in temperature and air velocity but with a reduced amount of tea leaves [158].

Tamuly et al. explored the drying features of Assam CTC tea in a bubbling conical type fluidized bed tea dryer. Among the many parameters studied, the drying temperature as well as the superficial air velocity were observed as the main factors affecting the extraction rate of moisture from tea. This rate went up with the surge in drying air temperature. A decline in the quality of the product was observed once a certain temperature limit was reached. Moreover, at a cone angle of 10°, the moisture extraction rate was reported to be the maximum for a 15 cm heighted static inventory bed [177].

2.7 Solar dryers

A solar dryer is an apparatus that harnesses solar energy to remove moisture from substances, commonly food items. This method of drying is both energy-efficient and eco-friendly, offering a sustainable alternative to traditional drying techniques that depend on electricity or fossil fuels.

2.7.1 Types of solar dryers

Various types of solar dryers have been designed for drying food and agricultural products. These dryers are generally categorized into two main types based on how air circulates within them [208]-

- Passive solar dryers
- Active solar dryers

Further, these can be classified as [209]-

- Indirect type
- Direct type
- Mixed mode type
- Hybrid type

i) *Passive solar dryers:*

Passive solar dryers, also termed natural circulation or natural convection solar dryers, operate solely on density-driven airflow, requiring no electricity and relying solely on renewable energy sources. They are simple to build using local materials, making them ideal for off-grid areas. However, they have limitations: insufficient airflow for large crop masses, no airflow at night or in adverse weather, and a slow drying rate due to poor moisture removal.

- Indirect type Passive Solar Dryer (IPSD):

Solar dryers are categorized into direct-type and indirect-type based on whether the products are exposed to solar radiation. In an indirect passive solar dryer (IPSD), products are dried by hot air without direct exposure to solar radiation. A basic IPSD includes a solar air heater and a drying chamber. The solar air heater warms ambient air, which then moves into the drying chamber and rises through the crop bed due to buoyancy forces from the temperature difference. The drying chamber typically has perforated trays or mats for the products, with hot air supplied from beneath the trays.

- Direct type Passive Solar Dryer (DPSD):

The direct passive solar dryer (DPSD) lacks a distinct drying chamber. Instead, the product is placed within the air heating unit, where it absorbs solar radiation passing through a transparent sheet. Various types of direct solar dryers include box or cabinet types, tent types, and greenhouse types.

- Mixed Mode Type Passive Solar Dryer (MMPSD):

The structural characteristics of the mixed-mode passive solar dryer (MMPSD) are similar to those of the indirect passive solar dryer. It features a drying chamber with transparent walls. The solar air heater generates hot air by capturing solar radiation, which then naturally flows into the drying chamber. The product is heated both by the solar radiation passing through the transparent walls and by the hot air produced by the solar air heater. This type of dryer achieves a high airflow rate and drying rate due to the elevated air temperature within the drying chamber.

- Hybrid Type Passive Solar Dryer (HPSD):

The hybrid passive solar dryer (HPSD) is equipped with either a thermal energy storage unit or an auxiliary heating device. This storage unit retains excess heat collected during the day as either sensible or latent heat, which can then be utilized during periods without sunlight or on cloudy days. Common storage materials in these solar dryers include rock, pebbles, paraffin wax and water.

ii) Active Solar Dryers:

Active solar dryers, also referred to as forced circulation or forced convection solar dryers, use an external device such as a fan to supply the hot air needed for drying. The fan or blower is powered by electricity from either the grid or a solar photovoltaic module. Active dryers offer advantages over passive dryers, including reduced drying time due to enhanced heat transfer. Additionally, the airflow rate and temperature in these dryers can be controlled.

- Indirect - type active solar dryer (IASD):

The indirect active solar dryer (IASD) primarily includes a solar air heater, a drying unit, a fan for air circulation, and air ducts. The fan is crucial for regulating the airflow rate, a key factor that influences the drying rate.

- Direct - type active solar dryer (IASD):

The design of the direct active solar dryer (DASD) is similar to that of the direct passive solar dryer. It includes an exhaust fan to speed up the removal of moist, saturated air from the combined drying chamber and air heater. This exhaust fan is powered by electricity from the grid or a solar photovoltaic module.

- Mixed Mode Type Active Solar Dryer (MMASD):

The active mixed-mode solar dryer (MMASD) typically includes a solar air heater, a blower or fan, and a drying chamber with transparent walls. It operates similarly to the passive mixed-mode dryer, where solar radiation on the air heater and product surfaces generates the required heat for drying. However, the active mixed-mode dryer uses an external device to circulate the drying air.

- Hybrid - type active solar dryer (HASD):

The hybrid active solar dryer (HASD) features auxiliary heating systems such as an electric heater, LPG or HSD burner, and a biomass backup heater, allowing for single or combined mode operation. It includes thermal energy storage, enhancing reliability by providing hot air during non-sunny hours or cloudy weather and maintaining a constant temperature. This enables the HASD to function regardless of weather conditions and extend drying operations beyond daylight hours. However, it has high capital costs and a complex structure.

2.7.2 Solar drying of food, agricultural and leafy products

Owing to the gradually decreasing conventional energy resources, it is observed that alternatives are implied to minimize their uses. There have been various studies related to usage of solar energy in drying food, agricultural and leafy products and also in certain industrial level [129]. Some of such recent works are discussed below-

Dejchanchaiwong et al. investigated the drying performances of 30 natural rubber sheets under indirect and mixed-mode drying systems. For mixed-mode, the moisture content reduced to 2.0% from 32.3% while it fell from 29.4% to 8.0% (all w.b.) in the indirect drying mode in four days. The thermal efficacy of the mixed-mode system was 15.4% as compared to 13.3% of an indirect solar dryer. An amalgamation of Page and Two-term models namely, Hii et al. drying model was obtained as the finest fitting model for the drying data. The R^2 values for mixed and indirect modes were respectively 0.998 and 0.996 [46]. In another work of drying rubber sheets, Page was the better model with R^2 value of 0.9825-0.9841. The average drying temperature was 54 ℃ with an RH of 18% during the final stage of drying [84].

Slices of bitter gourd were dried in an indirect solar dryer included with a porous medium of sensible storage of heat. The absorber plate used in the solar collector was a corrugated plate. The moisture level of the slices reduced from 92 to 9% in 9 h of drying in the dryer in contrast to 10 h under direct sun. At 0.0636 kg/s mass flux, the highest specific rate of moisture extraction was 0.215 kg/kWh along with an SEC of 4.44 kW/kg. The collector and dryer efficiencies were 22% and 19% respectively with a specific energy ingestion of 4.44 kWh/kg. The drying data fitted well in the Midilli and Kucuk model statistically for both approaches of drying. The slices dried in the solar dryer showed superior quality than those under direct sunlight [189]. The thin layer drying attributes of curry leaves in the same dryer were determined and the Modified Henderson-Pabis and Wang-Singh drying models best suited the same. The pick-up efficiency while drying curry leaves in the dryer varied between 4.9% and 23.02% [190].

Kareem et al. discussed the thermal enactment of solar drying process of Roselle. The experimentation was conducted in a multiple pass solar collector with forced convection where granite served as a sensible storage of energy. The daily solar irradiation, RH, temperature of the ambience and wind velocity were considered respectively as 635.49 W/m^2, 64%, 32.24 ℃ and 0.81 m/s. The mean rate of drying, efficiencies of collector, drying, moisture pick-up and system optical were respectively 33.57 g/kgm^{2}h, 64.08%, 36.22%, 66.95% and 70.53%. The dryer retained the colour of the dried product and proved to be 21 h quicker than the conventional method [89].

Alara et al. examined the drying characteristics of *V. amygdalina* shoots under direct sunlight and shade. Among the eight drying models used to fit the drying behaviour, the Midilli-Kucuk model finely fitted the data in both the modes. The R^2, *RMSE* and reduced chi-square values were obtained as 0.99951, 0.00243 and 0.000511 for open sun dried and 0.99981, 0.00253 and 0.000428 for shade dried *V. amygdalina* leaves. The respective effective diffusivities for both the drying modes were computed as 26.58×10^{-10} and 52.77

$\times 10^{-11}$ m^2/s. It was reported that stark deformity of the morphology of the leaf occurred during open sun drying. Thus, shade drying was recommended for preservation of the nutrients [11].

Eltawil et al. attempted to create a moveable and hybrid solar tunnel dryer to dry peppermint and improve its performance with the use of flat plate solar collector and solar photovoltaic system. The dryer worked in mixed mode and an axial mode direct current fan was operated by the photovoltaic system. A black thermal screen was provided in the dryer to avoid direct sunlight. The time taken to dry peppermint in the dryer varied from (210-360) minutes whereas under the open sun it took (270-420) minutes. The drying took place without the presence of constant rate period. The Two-term model perfectly fitted the drying data. The dryer efficiency, daily average photovoltaic efficiency and the overall efficiency were estimated as 30.71%, 9.38% and 16.32% respectively. Also, the product quality along with the colour index were better when peppermint was dried in the novel dryer [61].

The effectiveness of a mixed type solar dryer with forced convection having paraffin wax thermal storage was studied to dry black turmeric. The thin-layer drying attributes of the samples dried in the dryer was related with that of open sun mode. The samples took 18.5 h to dry from moisture content 73.4% to 8.5% in the solar dryer in comparison to 46.5 h under direct sunlight. The Two-term model fitted the drying data of turmeric dried in the dryer whereas it was the Page model that suited the open sun drying behaviour the best. The overall SAH and solar dryer efficiencies obtained were respectively 25.6% and 12.0%. The square roots of the deviation summation in colour indices were found to be 6.02 and 10.47 for solar dried and open sun dried turmeric samples respectively. The antioxidant activity for the solar dried samples was 28.33 μ mol TE/g which was better than that of the open sun dried ones. Moreover, the TFC estimated for the mixed mode dried samples was 7.59 mg QE/g [105]. Lakshmi et al. obtained the dryer efficacy was obtained as 33.5% while drying leaves of stevia plant in the same dryer. Ambient temperature of 30 °C with mean solar irradiation of 567 W/m^2 was considered at 0.049 kg/s rate of mass flow. The preferred moisture level of 0.053% (d.b.) was attained in 330 minutes and 870 minutes for mixed-mode and direct sun drying respectively. The antioxidant activity, TFC, sensory and colour indices were again found better in the solar dried sample [106].

Bahammou et al. dried the medicinal Moroccan horehound leaves in a solar dryer with forced convection and studied its thermos-kinetics to investigate the appropriate drying and storing conditions. Two mass flow rates of 150 and 300 m^3/h and drying air temperatures of (50-80) °C with increment of 10 units were considered for the experiments. The relative humidity and ambient temperature ranged between (11-37) % and (26-37) °C respectively. The moisture level of the leaves declined on a dry basis from 6.941% to 0.014% while the drying time dropped significantly from 4 h to 0.34 h with the rise in temperature. The Midilli-Kucuk fitted the drying data suitably. The average activation energy estimated was 2938.46 kJ/kg. The overall energy consumption increased with the surge in air flux while showed a decreasing trend with rising temperature. The opposite effect was reported for the energy efficiency evidently. The leaves dried at 80 °C and 300 m^3/h contained the maximum amount of total phenols [20].

Djebli et al. presented the drying kinetics and thermodynamic properties of a mixed solar dryer while drying tomatoes. The tomatoes were cut into slices and wedges and dried separately. The moisture content reduced to (18-25) % from the initial (92.5-93.6) % after drying. The drying duration for the tomato slices was (5-21.25) h while it was (8.5-28.5) h in case of the wedges. The activation energy obtained was within the ranges of (0.223-1.21) × 10^5 J/mol and (3.83-7.97) × 10^4 J/mol for the slices and wedges respectively. Similarly, the values of effective diffusivity varied between (0.329-2.3) × 10^{-9} m^2/s and (0.348-2.95) × 10^{-9} m^2/s for the samples. Higher entropy and enthalpy values were obtained from a literature model in comparison to this novel approach. The spontaneity of the solar drying process was shown by the negative Gibbs free energy values [48].

Djebli et al. used an indirect and mixed type solar dryer with forced convection to assess the drying attributes of potatoes. Although the trays in the mixed type dryer had higher temperature, it showed a slower drying time of 4.45 h whereas it was 3.40 h for the indirect dryer. The diffusivity equation was solved with the help of Laplace transforms and Fourier series. The relative accuracy of seven theoretical drying models was validated with the data obtained from the experiments. The two newly suggested models were obtained as the best fitted models for drying potatoes in the two dryers [49].

Murali et al. developed a solar dryer and evaluated the drying performance of shrimps. The thermal storage and heat transfer medium was water in the dryer. LPG was used as an assisting heat source during lesser sunlight hours. Water showed the capability to capture maximum heat energy during sunlight hours. The highest temperature obtained at the outlet of the collector was 73.5 °C. The solar system provided 73.93% of the total heat energy while the rest was supplied by LPG water heater during lower radiation. The moisture level of 15.38% from 76.71% was attained in 6 h duration. The highest collector efficiency was 42.37% and the drying efficacy was reported as 37.09% for solar-LPG drying of shrimps [117].

Lingayat et al. dried slices of watermelon and apple in an indirect type solar dryer and analyzed the performance. The temperature within the drying chamber kept on varying due to the fluctuating solar radiation. The average collector efficiencies for drying the slices were recorded as 56.3% and 54.5% respectively. The corresponding dryer efficiencies were 28.76% and 25.39%. The moisture levels came down to 0.799 from 6.16 kg/kg (d.b.) in drying the apple slices while it was 10.76 to 0.496 kg/kg for the watermelon drying. The effective moisture diffusivities were computed as 4.28×10^{-9} m^3/s and 4.01×10^{-9} m^3/s for apple slices and watermelon slices respectively. The ranges of mass transfer coefficients obtained were accordingly $(0.1584\text{-}3.158) \times 10^{-3}$ m/s and $(0.517\text{-}4.98) \times 10^{-3}$ m/s. The respective activation energies for apple slices and watermelon slices were 17.34 kJ/mol and 18.71 kJ/mol [110].

Ekka et al. dried black ginger in a horizontal mixed type solar dryer with forced convection. A fixed rate of mass flux of 0.062 kg/s was used as the first case and two succeeding rates of 0.018 and 0.062 kg/s were used amid the initial and falling drying rate periods as the second case. The dryer’s performance was analyzed based on duration of drying and efficiency, *SEC* and diffusivity of moisture. The experimental specific energy consumptions for both the cases were respectively 1.07 kW/kg and 0.56 kW/kg. The drying time for the first was 11 h while it reduced to 7 h in the second case. The dryer efficiencies were computed as 6.4% and 10.8% accordingly. Further, elevated antioxidant activity and phenolics were obtained in the dried product along with the preservation of colour and texture [60].

Kouhila et al. evaluated the thin-layer drying attributes of solar drying of mediterranean mussel. The focus was given on the temperature as required for storage seafood. A solar dryer with forced convection was used to evaluate the hygroscopic behaviour and kinetics of the product. The air temperatures considered were 50, 60, 70 °C and the air fluxes were 300 and 150 m^3/h. The ranges of ambient temperature, ambient humidity and solar irradiation were respectively (36-42) ± 1 °C, (8.92-18.86) ± 2% and (422-988) W/m^2. The characteristic drying curve was plotted from the data obtained from the experiments. The Logarithmic model among the nine models used gave the finest fit for the drying data. The value of the effective diffusion coefficient varied within $(1.14\text{-}3.61) \times 10^{-9}$ m^3/s [99].

Dutta et al. studied the drying behaviour of *garcinia pedunculata* in a corrugated type solar dryer with free convection and under open sun in two batches. In the dryer, the moisture level decreased from 88% to 7.22% and 7.1% in 28 h while 55 h was taken in direct sunlight to bring down the moisture to 10.18% and 10.08% for the first and second batches respectively (all w.b.). The Midilli-Kucuk and Two-term model suited the drying characteristics obtained from solar dryer and direct sunlight respectively. The thermal efficiencies of the SAH obtained for the batches were 33.29% and 33.45%. The specific energy consumed and thermal efficiencies of the dryer were accordingly estimated as 68 kWh/kg and 10.69% for the first batch while these were 65.54 kWh/kg and 10.77% for the second one [54].

In addition to these, similar studies on solar thermal energy utilization for heating water [27,55,69], improved SAH [28,29,50,52,53,154,156,157], parabolic collectors [64,75], numerical techniques [56,57,138,200] etc., have been reported.

2.8 Exergy analysis of solar air heaters and solar drying

Among the many non-conventional energy resources, solar energy is an extensively used option for drying. Solar drying of different agriculture related products has been found from literature. In most of the studies made in this field, both energy-exergy assessments of the drying practices are looked upon. The quantity of energy required is known from the energy analysis. However, the causes for irreversibility can only be achieved from the exergy analysis.

Mokhtarian et al. used a solar dryer with (case-1) and without (case-2) air re-circulation to dry pistachio and performed a thermal analysis on the systems. The moisture level of pistachio was reduced from 40 to 5% (w.b.) during the course of drying. The thermal efficacy of the dryer having air re-circulation was 40% more than that without the provision of re-cycling. The maximum exergy loss of the former method was higher than that of the latter. The energy utilization ratio of case-1 was 30% and 20% more than case-2 and direct sunlight drying respectively. However, the exergy efficiencies for both the methods were around 95%. It was finally reported that drying pistachio in the solar dryer with air recycling was more efficient compared to other methods and also produced better quality products [114].

The energy and exergy evaluations of a solar dryer incorporated with a thermal storage of $Na_2SO_4.10H_2O$ and NaCl were assessed and compared with control-experiment conditions. Red chili was dried in this dryer. The moisture level of the product decreased from 72.27% to 7.6, 10.1 and 10.3% for the three cases respectively. In the process, the overall drying and exergy efficiencies ranged from 10.61% to 18.79% and 66.79% to 96.09% respectively with energy consumption of (7.54-12.98) MJ. The waste energy ratio, improvement potential and sustainability index of the system ranged within (0.166-0.174), (1.285-1.295) W and (3.01-8.15) respectively [124].

Rabha and Muthukumar used a solar dryer having forced convection and incorporated with two SAHs and a latent heat storage arrangement of paraffin wax to dry red chili. The temperature for drying 20 kg red chili was within (36-60) ℃. The moisture level was reduced from 73.5 to 9.7% in 4 days when operating the dryer for 10 h daily. The average energy efficiencies for the first and second SAH were respectively 32.4% and 14.1% while the exergy efficiencies obtained were 0.9% and 0.8%. The ranges of energy and exergetic efficiencies computed for the latent heat storage element were 43.6 to 49.8% and 18.3 to 20.5% respectively. The mean exergetic efficacy of the solar dryer was 52.2%. The *SEC* was estimated as 6.8 kWh/kg and the total efficiency of the dryer was 10.8% [141]. Rabha et al. again dried ghost chili pepper and ginger in the same system with temperature ranges within (42-61) ℃ for 42 h and (37-57) ℃ for 33 h respectively. In these cases, the average thermal efficiencies of the SAHs varied between 22.95% and 23.30%. The mean exergetic efficiencies for drying ginger and ghost chilli pepper were obtained as 47% and 63% respectively. The specific energy consumed in both the cases were accordingly 18.72 and 8.82 kWh/kg [142]. In a similar dryer with mixed mode, Lakshmi et al. reported the average exergy efficiency for drying stevia leaves as 59.1% [106].

Yahya et al. designed and developed a hybrid mode fluidized drying arrangement of solar and biomass energy. The drying kinetics and the exergetic performance of drying paddy in the dryer was evaluated in the study. The drying temperatures for the experiments were 61 ℃ and 78 ℃ along with an air flux of 0.125 kg/s. The average amount of solar energy used for 61 ℃ was 1.63 kW and 1.40 kW for 78 ℃ whereas the energy from biomass used were respectively 2.06 and 3.95 kW in average. The moisture level of paddy declined from 20% to 14% (w.b.) in 1281 s and 796 s respectively for the two temperatures with average 0.16 and 0.24 kg/s drying rates. The mean thermal and exergy efficiencies computed for drying paddy at 61 °C were 13.45 and 16.28% whereas at 78 °C these were respectively 47.6 and 49.5%. The specific energy consumptions were accordingly 4.76 and 4 kWh/kg [202].

Karthikeyan and Natarajan dried orange peels in a mixed type solar tunnel dryer with forced convection and compared its performance to that under direct sun drying. The temperatures at inlet and outlet of the dryer were recorded within (37-60) ℃ and (31.2-49.1) ℃ respectively. The initial moisture level of 0.802 kg/kg came down to 0.046 kg/kg in 8 h in the dryer while it took 14 h under direct sunlight. The Midilli-Kucuk was the best fitting model for the drying characteristics obtained. The energy utilization ratio of the dryer was between (7.03-36.31) %. The mean exergetic efficiency was reported to be 42.01% [91]. Karthikeyan and Murugavelh used the same dryer to dry turmeric. The drying temperatures ranges were within (42.2-82.8) ℃ in the tunnel inlet and (40-71.8) ℃ at the outlet. In this case the moisture level reduced to 0.070 kg/kg from 0.779 kg/kg in 12 h of drying. The energy utilization ratio and mean exergy efficiency for drying turmeric were around (9.75-33.98) % and 49.12% respectively [90].

Amjad et al. used a solar hybrid dryer with an inline airflow to dry green chilies at 60 °C. The heat sources used were gas, solar and dual. The drying temperature was set at 60 ℃. The energy utilization ratios were obtained within (0-60) % for gas, (0-47.8) % for solar and (0-56.8) % for dual modes. The exergy losses were within (2.45-5.56) kJ/kg, (1.48-4.00) kJ/kg and (2.26-5.41) kJ/kg for the three sources while the exergy efficiencies were estimated within (24-73.58) %, (17-69) % and (33.95-74.11) % accordingly. Exergetic factor of 54.37 and rate of improvement potential of 2.016 were obtained for the heating element consisting of heat exchanger and evacuated tube collector [13].

Lingayat et al. carried out energy and exergetic efficiencies during drying banana in a solar dryer with indirect natural convection. A solar collector with flat plate is used in the dryer to heat the air. The solar radiation and drying temperature ranged from (335-1210) W/m^2 and (38-82) ℃ respectively. The maximum useful heat gained was obtained as 885.6 W. The mean collector energy and exergy efficiencies were respectively 33.14% and 25.64%. An average amount of 724 W heat loss occurred from the collector. The exergy losses in the dryer were estimated within (3.36-25.21) kJ/kg with the exergy efficiency varying between (7.40-45.32) % [111].

Vijayan et al. dried slices of bitter gourd in a solar dryer with indirect forced convection having a sensible heat storage medium of porous bed. The mass flow rates considered were in between 0.0141 to 0.0872 kg/s. After 7 h of drying, the weight of the slices reduced to 723 g from 4000 g. The mean exergy efficiency values varied between (28.74-40.67) % while the pickup efficiency was observed to vary between (54.29-17.18) %. The range of effective diffusivity was obtained within (8.6293-12.9585) × 10^{-10} m^2/s. On drying the slices under open sun, the effective diffusivity was reported to be the lowest with a value of 0.9568 × 10^{-10} m^2/s [191].

Tagnamas et al. performed energy-exergy analyses for drying carob pulp in a solar based dryer along with determination of kinetics of drying. The drying temperatures used were within (50-80) °C with steps of 10 units and the air velocities were 0.09 and 0.18 m/s. The range of diffusivity coefficient obtained was (1.56-6.98) × 10^{-9} with activation energy of 93.18 kJ/mol. The specific energy consumption was noted as 0.15 kWh/kg. The energy efficiency varied within 4.23% to 7.25% for the solar based dryer. The variation of exergy for the drying procedure and the chamber were respectively (21.35-53.26) % and (30.12-80.5) %. These values showed extensive exergy loss in the drying process [169].

Sileshi et al. dried *injera* in a newly designed mixed type solar dryer with natural convection. The overall rate of drying was 3.69 × 10^{-5} kg/s along with a drying efficiency of 17.7%. It took 4 h for the moisture level of the *injera* to drop from 65.5 to 12% (w.b.). The Midilli and Verma drying models suited the finest for the drying kinetics. Only falling rate drying occurred during the course of drying. The maximum drying temperature was 50 °C [160].

Studies have been made on the energy-exergy assessments of various types of SAHs and collectors.

Velmurugan and Kalaivanan assessed the energy-exergy performances on SAHs with different geometries at various solar radiations and mass flow rates. The analytical solutions were performed using Matlab 8.1 and compared with the experimental results. The solar insolation and mass flux varied respectively within (0.01-0.04) kg/s and (500-600) W/m^2. The peak rise in temperature was recorded as 25.2 °C in the wire mesh SAH with double pass at 0.01 kg/s. It gave better analytical and experimental results as compared to flat plate with single pass, roughened and finned plate SAHs. The experimental energy efficiency for the wire mesh SAH was obtained as 76.46% at 0.04 kg/s. The pressure drop of the wire mess SAH was greater than the rest. The analytical exergy efficiency was 22.84% and experimental was 21.03% at 0.01 kg/s mass flux [188].

Kalaiarasi et al. performed energy-exergy analysis experimentally on a newly developed flat plate SAH along with a sensible heat storage medium. The absorber plate was made of Cu-strips in longitudinal position to one another. A high grade oil named Therminol-55 was put in the Cu-tubes for serving as the storage medium. Two mass fluxes of 0.018 and 0.026 kg/s were used for the experiments. The results obtained proved the novel design as the better one when compared with a conventional air heater. At 0.018 kg/s, the peak energy efficiencies were obtained as 20% and 54.28% for the conventional and new air heater respectively. The maximum energy efficiency values at 0.026 kg/s were accordingly 32.07% and 59.02%. The average exergy efficiency values for the conventional and novel air heaters were computed as 8.3% and 15.51% for 0.018 kg/s and 15.03% and 31.02% for 0.026 kg/s respectively. The lowest exergy loss range of (0.059-0.217) % was obtained for the new one at 0.026 kg/s [86].

Zhu et al. acted upon a comparative assessment based on the exergy performances on two types of flat plate solar collectors with micro heat pipe array. The thermal performances were also investigated. The non-slotted collector showed the highest irreversibility at 0.027 kg/s. The pressure drop observed in the V-shaped slotted fins collector was 7.1 Pa while in the rectangular non-slotted fins it was 6.8 Pa. The collector having V-shaped slotted fins showed better thermal and exergetic efficiency than the second one at high mass flow rates. However, the reverse was held true for lower mass flow rates. The ratios of performance evaluation criteria obtained for 240, 160 and 80 m^3/h were respectively 1.5433, 1.2104 and 0.8668 indicating the better performance of the slotted type than the non-slotted type for mass flow rates higher than 80 m^3/h. The results revealed that the critical parameters like Reynolds number, length of air duct and fin shape were effective in selecting proper solar collectors [203].

Gunjo et al. developed a CFD model for a solar collector for predicting the operation of a single-bent riser tube which was coupled to the flat absorber plate. This model was authenticated with experimental results. A maximum error of 9% was obtained while predicting the temperature at outlet, temperature of absorber plate, energy efficacy and the total coefficient of heat loss. A thermal efficiency of 71% was obtained for the bent tube collector with an outlet temperature of 60 °C. The exergy efficiency increased from 1 to 4% and the energy efficacy decreased from 82% to 40% on rising the loss factor of the collector from 0.001 to 0.1 m^2K/W by keeping the mass flux constant. The energy-exergy efficiencies were obtained the highest and lowest on using the working fluid as $C_2H_6O_2$ and water respectively. Also, the exergy efficiency decreased from 6 to 1% when the ambient temperature rose from 300 to 320 K. But it increased from 4 to 6.5% with the increase in solar radiation from 110 to 1060 W/m^2 [70].

Abuska examined the thermal enactment of a conical surface absorber plate in a single pass SAH and compared it with that of a flat plate. The thermal and exergetic efficiencies for the conical plate were respectively (63.2%, 19.3%) at 0.04 kg/s mass flux, (71.5%, 15.1%) at 0.08 kg/s and (74.6%, 12.5%) at 0.10 kg/s. The values for the flat plate SAH were obtained accordingly as (57.2%, 16.1%) at 0.04 kg/s, (61.7%, 11.5%) at 0.08 kg/s, and (64.0%, 9.2%) at 0.10 kg/s flow rate. On an average, the percentage upsurge in the thermal efficacies for the conical plate were 6.0%, 9.8% and 10.6% respectively for the three mass flow rates [4].

Debnath et al. matched the performances of a corrugated plate solar collector with those of a flat one emphasizing on various parameters. The factors considered were tilt angles, mass flux and glazing. The energy-exergy results obtained were better for the absorber plate with double glazing due to decline in the top losses. Increase in the number of glazing and mass flow rate improved the energy efficiency by about (10.35-17.42) %. The energy efficiency increased by 14% while using the corrugated plate due to more heat transfer area along with increased turbulence. At 0.0118 kg/s, the collector with double glazing showed the highest enhancement of 6.867% in the exergy efficiency [44]. Debnath et al. (2020) investigated the performance of the same collector was during different seasons for tilt angles 30° and 45° for the mass fluxes between 0.0039 to 0.0118 kg/s. The corrugated plate absorber turned out about 9% more effective than the flat one. The enhancement in thermal efficacy of the double glazed collector was (2-4) %. The exergy efficiency was within (0.44-17.3) %. The tilt angle of 45° showed better performances by around 5%, especially in the summer season [45].

Raam Dheep and Sreekumar modified the absorber and type of air flow in the duct of an SAH to improve the convective heat transfer. The energy-exergy analyses were performed on the SAH incorporated with an absorber of longitudinal circular type fins. The thickness of the duct was 100 mm. The considered mass flow rates were within (30-90) kg/h m^2 with steps of 15 units. The irreversibility reduced from 0.12 kW to 0.09 kW while the dimensionless exergy losses came down from 18.58% to 11.65% with the rise in mass flux. The energy and exergetic efficiencies varied from (44.13-56.98) % and (24.98-36.62) % respectively when the mass flux was increased from 30 to 90 kg/h m^2. Further, the highest temperature difference for the two extreme mass flow rates were recorded as 43.2 ℃ and 26.7 ℃ accordingly [143].

Hassan et al. assessed the performances of a flat plate double-pass SAH with V-corrugated and corrugated-perforated absorber plates and matched with those of a flat absorber plate. Four levels of air-mass flow ratios were taken for the experiments (single pass, 1/3 of double pass, 2/3 of double pass and double pass). The corrugated-perforated plate resulted in the highest efficiencies of 67.67, 69.70, 71.85 and 70.8% respectively for the conditions. The average exergy efficiencies of 0.78, 0.89, 0.97 and 0.92% were obtained for the perforated plate for the four air-mass flow ratios. The percentage growth in the exergy efficacy for the perforated plate was by 47, 55, 76 and 54% than the flat plate

[73]. Similarly, a V-shaped absorber plate SAH with transverse fins showed better energy and exergetic performances when compared with those of an absorber having longitudinal fins [2].

Kumar et al. performed a thermodynamic assessment of an SAH by fastening Cu-tubes in the absorber plate and compared it with that void Cu-tubes. Under natural convection, the energy efficacy of the SAH with and void the Cu-tubes was respectively on an average 18.26 and 16.29%. The exergy efficacy was reported as 1.69 and 1.41% accordingly, thus showing that the provision for attaching copper tubes was fruitful. Under forced convection, the highest values of energy efficacy for the Cu-tube attached SAH was 62.8% and exergy efficacy was computed 5.848% for the mass flux 0.05 kg/s. The sustainability index for the air heater with Cu-tubes was within the range of 1.0012-1.00193 [103].

2.9 Economics and environmental assessment in solar applications

For any novel system to be commercially stable, it is necessary to analyze its economic viability for sustainability. There have been literature regarding the economic analyses of the newly developed solar assisted drying systems and solar collectors. Sreekumar carried out a techno-economic analysis to dry veggies and fruits in a roof integrated system of solar drying. The methods of annualized cost, present value of yearly and collective savings were used to analyze the dryer performance. The annualized capital cost of the dryer was calculated as ₹55990. The savings per day was ₹4773 with a cumulative present value of around ₹17 million for an investment of ₹550,000. For an assumed lifetime of 20 years, the system showed a much lesser payback value of 0.54 year [167]. In another thermodynamic analysis of drying roselle in a multi pass SAH with granite as sensible energy storage matrix, Kareem et al. (2017) carried out the commercial viability of the new system. The total cost of the arrangement was evaluated by summarizing the expenses of manufacture, repairs and running. The cash inflow was determined from the drying cost. The payback period for the drying system was estimated as 2.14 years [89]. An experiment of laboratory scale was piloted in the Sonitpur district of Assam, India using a hybrid system of SAH and biomass gasifier to assist the drying operation. This hybrid system of renewable energy reduced the use of fossil fuels and emission of CO_2 to the atmosphere. The producer gas was generated from timbers, shade tree branches and tea plant wastes. The return on investment for the arrangement was estimated to be 1.5 years [178]. Vijayan et al. evaluated the economic feasibility of a solar dryer with indirect forced convection while investigating the thin-layer drying properties of curry leaves. The repayment period for the dryer was computed as 0.8 years against a lifespan of 15 years. The net profit per annum was estimated to be ₹59,500 for a capital cost of ₹40,000 making it viable for rural areas [190]. Lakshmi et al. did the economic breakdown of a mixed type solar dryer to dry stevia shoots. The dryer cost was approximately ₹55,000 with the savings of ₹91,671 annually. The repayment period of the novel solar dryer was estimated to be 0.65 year. This was quite less as compared to the lifetime of 10 years for the dryer thus making it feasible to use [106]. Ozturk and Dincer analyzed a solar-based tea drying system using an exergoeconomic approach. The system consisted of a batch type tea dryer along with photovoltaics. The analysis was carried out using the EXCEM method. The exergy efficiency of the system was obtained as 74% with exergy destruction of 201.6 GJ. The total capital cost of the arrangement was estimated as 11023$. The cost got reduced by 820$ when the direct normal irradiance increased from 300 to 600 W/m^2. Similarly, the cost reduced by 162$ as the reference temperature rose from 15 to 35 °C. The amount of generated capital was calculated as 5953$ with a capital productivity of 1.54 [134]. Naemsai et al. obtained a payback period of 1.9 years for a solar dryer with heat pump used for drying chili peppers. The dryer had a provision of heat recovery in it [121]. Dutta et al. found the payback period for a corrugated solar dryer with free convection as 0.6 year while drying *garcinia pedunculata*. The lifespan of the dryer was 10 years. For a capital cost of 93.34$, the annual savings was estimated to be 252.99$ [54]. Sileshi et al. reported that the per day savings of the solar dryer for drying *injera* was 111.48 ETB. The payback period obtained was 104 days with the cumulative saving of 154,459 ETB [161]. The minimum energy cost at 0.05 kg/s mass flux was reported as 0.0248$/kWh for a double pass tubular SAH [3]. Bahammou et al. found it economically viable to dry Moroccan horehound leaves in a convective mode solar dryer [21].

Like the economic feasibility, it also becomes essential for a system to be environmentally sound. Thus, an environmental assessment is necessary to be done. Shrivastava and Kumar evaluated the environmental impact for drying fenugreek leaves in an indirect type solar dryer. The embodied energy of the structure was calculated as 1081.83 kWh. The energy repayment time for the drying component was 4.36 years with a thermal efficacy of 31.42%. The carbon dioxide (CO_2) emitted per year was obtained as 85.46 kg. The CO_2 mitigation for the system per year was estimated to be 391.52 kg. The carbon credit earned for a lifespan of 15 years was reported to vary between ₹46982 to ₹187931 [159]. Zhu et al. reported that the use of flat plate solar collectors with micro-heat plate array with V-slotted fins in the rural areas could save the burning of 0.65 kg of coal per day. This would lead to the reduction of CO_2 emissions by 1.7 kg daily along with the decrease in SO_2 and NOx by 0.00553 kg and 0.00481 kg respectively [203]. For drying coconut in a solar greenhouse natural convection dryer, Ayyappan calculated the embodied energy of the drying system as 18,302 kWh. The total CO_2 emitted by the system was 1518 kg/annum. The overall carbon credit earned for mitigation of 678 t CO_2 was 18,645$ [18]. Eltawil et al. calculated an energy payback period of 3.63, 3.01 and 2.06 years for drying peppermint in a hybrid solar tunnel dryer using three layers of different densities. The embodied energy for the arrangement was 1361.83 kWh. The CO_2 mitigation was estimated to be 17.48, 21.40 and 31.80 t for the peppermint layers [61]. Chauhan et al. evaluated the energy payback periods for drying flakes of bitter gourd in a greenhouse dryer with north wall insulation as 1.68 and 2.35 years for natural mode and forced mode respectively. The total embodied energies for the natural and forced modes were 554.65 and 750.41 kWh. The CO_2 emissions were computed for the two modes as 15.53 kg and 21.01 kg per year while the net CO_2 mitigations were 33.04 and 36.34 t respectively for a lifespan of 35 years. For the natural convection, the earned carbon credit varied between ₹11,068 to ₹44,273 while it was within ₹12,173 to ₹48,695 for the forced one [35]. Vijayan et al. reported that the energy payback time for drying slices of bitter gourd in an indirect type solar dryer was 2.21 years. The embodied energy was 1109.307 kWh for the whole unit. The CO_2 mitigation in this case was 33.52 t with the variation of earned carbon credit between ₹10,894 and ₹43,576 for a lifetime of 35 years [191]. Ndukwu et al. assessed the environmental impact of solar drying of aromatic and medicinal plants by conducting case studies in African countries. Around (40702.38-407023.8) kg and (2308.5-23085) kg CO_2 was estimated to be saved per annum while drying grape and chili in Egypt and Nigeria respectively [125].

2.10 Renewable energy in tea processing industries

As discussed in the previous chapter, energy is a vital part of tea processing. It is an energy intensive process both in thermal as well as electrical energy. In a bid to minimalize the use of conventional energy, the switching over to renewable sources has become very essential. There have been attempts to implement sources of renewable energy in tea industries across the globe to a certain extent. Some of such works are discussed in this part as follows-

A solar PV plant of 100 kW was installed at the tea estate of Attareekhat, India. The plant comprised of a total of 400 solar panels of 250 W per module capacity, Neo Watt Sunbird 3000 inverter arrangement and 240 Pb acid batteries with an output of 480 V. The demand for electrical energy was attempted to be fulfilled by this arrangement [102]. A solar plant was set up at Madurai, Tamil Nadu with capacity 3 MW for electricity generation in a local tea estate. The power plant consisted of 9332 solar photovoltaic modules over a large area of 26 acres. Power of around 4.5 million units got produced in the power plant annually. The excess electricity from the power plant got linked to the grid. A wind farm of 2.3 MW was also built across 32 acres area. In past 20 years, about 95 GWh of power was estimated to be generated in the farm which was provided in the tea estate [102]. The concept of using heat exchangers based on heat pipes for withering and drying operations were developed in Indonesia. A total of 182 fins (aluminum) were attached to the heat exchanger having 42 pipes (copper). The heat coming from a geothermal source was utilized by using water as the heat transfer source. Major portion of the heat was used in withering. The system effectiveness varied between (66-79.59) %. The thermal energy ranged from (0.15-0.45) kW for producing 1 kg of tea leaves [68]. In Kenya, small hydropower facilities of 31 MW were set up. The Kenyan authority of tea development and the tea farms owned 11% of these plants to compensate the requirements of electrical energy in the tea industries. On fruitful execution of this alternate source of energy, the Kenyan authority of tea development planned to further mount such plants with capacity 21 MW in the region [96]. In China, a solar PV plant with capacity 51 MW was built in a tea garden. Provisions were made to make the use of land effectively by mounting the solar panels above the tea shrubs without affecting their growth. The solar plant comprised of 197,800 dual solar PV modules of glass and produced about 80,000 MWh power annually. Further, CO_2 mitigation of 80,000 t was estimated from the plant [166].

A survey was conducted on the potential and bioenergy utilization in the North-east Indian tea industries. It was reported that around 1771.18$ could be saved annually if bamboo could be used as material for feed in the gasification procedure. Moreover, use of paddy straw could save 14431.90$ by direct firing system. Also, the use of diesel would get reduced by 20% thus saving 196.78$ in the process [147]. Sharma et al. calculated the energy consumed by the various tea processing steps in tea industries in Assam. For 100 kg, the thermal energy required in the wilting and drying stages were estimated to be 49.75 and 497.53 kWh respectively. The electrical energy required for wilting, maceration, drying and sorting operations was computed as 5.54, 8.63, 6.23 and 3.95 kWh respectively [155]. Kalita et al. performed a viability assessment on the installation of a grid connected solar PV power plant of MW level in North-east India. According to the climatic data, a solar PV power plant of 2 MW was designed. Such plants would definitely serve the purpose of supplying the energy needed in the tea industries of the region [87]. Due to the soaring oil prices, the Kenyan industry depended on the use of firewood to fulfill the demand of thermal energy. Almost 50 lakhs of firewood are utilized for production of 432.4 million kg tea in Kenya. However, gradually the Kenyan tea industry switched over to the use of briquetting techniques for enhancing the combustion efficiency. The raw materials used to make briquettes had a moisture content of less than 15%. There would be 50% savings in the cost of production if the firewood got replaced by briquetted woods completely [126].

2.11 Summarization of the literature

The chapter presented a vast literature on the aspects of tea withering and drying. It is clearly observed that a considerable amount of work has been done on both the major operations (withering and drying) of tea processing. Extensive studies have been made on the effects of tea withering and drying on the various aspects of tea. The impacts of tea withering and drying on other stages and the overall quality of made tea are broadly studied. The various biochemical changes occurring in the tea leaves due to wilting are elaborated by many researchers. Efforts have been made to modify the withering trough in terms of design. For the tea drying operation, many studies have already been carried out to find the drying characteristics under different types of drying systems. The thin-layer drying attributes and analyses of various types of tea drying processes are found in the literature. But comparably the tea withering stage has been less touched upon, especially for the Assam tea variety. Since tea withering is nothing but a low temperature drying process, there is a scope to analyze the withering characteristics of tea leaves and to obtain the kinetics from it. Under a controlled environment of temperature and relative humidity, an attempt is thus made in the present work to study the tea withering characteristics for the locally available tea leaves. From the energy point of view, it is proven that the tea production is an energy exhaustive process. Studies are carried out to find substitutes to the conventional energy sources in the tea processing industries. Out of all the renewable energy sources, solar energy is vastly used as the alternative.

2.12 Research gap and motivation

There have been lots of research on the solar drying of various agricultural and food products including drying of tea leaf. Tea withering, also being an energy intensive operation, may be experimented to be carried out with the aid of solar thermal energy.

However, no such literature is found pertaining to solar withering of tea leaves which may be an interesting area to work upon. Again, the economic and environmental analyses can be seen on many novel units except tea withering. This is again a new area to work upon for the local variety of tea. Hence, the present research work focuses on the prospects of using a solar based tea withering system giving emphasis on the critical parameters adhering to the local tea of Assam. Also, use of corrugated plates and waste Al-cans as solar absorbers would add more newness to the study undertaken. Moreover, the energy, exergetic, economic and environmental assessments of the system are attempted to be carried out in the study.

2.13 Objectives of the work

Based on the discussion done above, the task of experimenting the green tea-leaf withering process in a laboratory scaled set-up with the involvement of solar thermal energy is considered. The factors and conditions are considered strictly adhering to the local variety of green tea leaves of Assam. Following are the objectives to be undertaken during the study-

Objective-1: To assess the energy consumption pattern in a local tea processing factory of Assam

Objective-2: To experimentally determine and model the withering characteristics of tea leaves of Assam in an environmental chamber

Objective-3: To design, develop and evaluate the performance of a laboratory scaled solar thermal energy based tea withering trough

Objective-4: To perform thermodynamic analysis of the solar thermal energy based tea withering process

2.14 Structure of the thesis

The thesis has been divided into seven distinct chapters keeping in mind the objectives and literature pertaining to the research work. The organization of the chapters are given below-

- **Chapter-1**

This chapter illustrates the origin and significance of tea with respect to Assam. The different steps leading to the production of tea are discussed in detail. The energy utilization pattern, environmental impact and a brief detail on solar air heaters are also included. The chapter ends with the background of the present study undertaken.

- **Chapter-2**

The literature associated with tea withering and drying operations are reviewed in this chapter. Moreover, the various works done on energy, exergy, economic and environmental analyses of solar drying processes are included here. The research gap and the objectives of the study are mentioned in this chapter.

- **Chapter-3**

This chapter illustrates the energy consumption and management in the various tea processing operations pertaining to a local tea factory of Assam.

- **Chapter-4**

The detailed methodology of experimental determination and modeling the tea withering characteristics in an environmental chamber is presented in this chapter. The thin layer withering characteristics have been discussed from the results along with a quality analysis.

- **Chapter-5**

In this chapter, the details of the design and development of the laboratory scaled solar thermal based tea withering trough have been discussed. The performance analysis of the system has been illustrated giving emphasis to the best drying or withering model, activation energy and specific energy consumption. An economic analysis of the withering trough is discussed.

- **Chapter-6**

This chapter presents the results of a detailed energy and exergy analyses of the solar thermal based tea-leaf withering process with two different absorber plates. A comparative analysis is made for the two types of solar air heaters with different absorber plates. An environmental assessment of the arrangement is done and discussed in detail.

- **Chapter-7**

This is the final chapter which summarizes the objectives of the research work with concluding statements. The restrictions and future possibilities of extending the work are also discussed.