# Scientific and technological aspects of tea drying and withering: a review

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**Abstract:** Withering is the preliminary stage of tea processing where tea leaves undergo physical and chemical transformation for the next phases. In tea processing, the moisture content in the tea leaves matters a great deal. Withering is a partial drying process for removing superficial and core moisture of tea leaves. Drying removes moisture by evaporation from the fermented leaf. The withering trough is an indispensable organ in tea withering and research has been done to enhance and modify the design of the trough. During withering various biochemical changes take place. Like drying, withering is also an energy intensive process. However, less concentration has been given to the energy aspect of withering. It is required to make readiness among tea producers about utilizing sustainable power source for better financial returns. This paper gives a wide survey on the different scientific and technological aspects of tea withering and drying.

**Keywords:** tea, withering, trough, theaflavins, thearubigins, theanine

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## 1 Introduction

Tea is a standout amongst most of the popular drinks. Moisture estimation plays a vital part in tea processing. The durability and excellence of produced tea is exceedingly reliant upon the best possible level of moisture in the preparing steps required in the manufacturing of tea. The quality of intermediate processing depends not just on the moisture level of the present procedure, additionally on the moisture levels of past. There are many reasons for withering newly culled leaves. The majority of these manage the equipment and systems required for the whole process. Withering is imperative since it makes the leaves flabby and diminishes moisture content. These two qualities aid the rolling and drying process. This at that point permits more consistent preparing, and shields the leaves from throwing out up the machinery. The physical changes that happen amid withering are called as physical withering. Chemical withering is the biochemical changes taking place in the leaf (Deb and Jolvis, 2016). Generally, for best outcomes dry and wet bulb temperature difference is maintained at 4°C. Tea leaf withering trough is a rectangular channel. An axial fan blows air into the trough. The evading air carries moisture and heat of respiration in the leaf away (Jayasundara, 2008).

Drying refers to the elimination of moisture by evaporation from leaf undergoing fermentation. During drying, fermented leaf turns black or blackish brownish from coppery red and loses its moisture to about 3% (w.b.) finally. The removal of moisture from the leaf particle yields a stable product with superior keeping quality. Drying is a thermal energy dominant processing step and it is mostly crucial for quality and energy perspective (Hatibaruah, 2013). The principal objectives of drying are to arrest the method of fermentation to have desired properties, thereby, obtaining a stable end product for preservation and marketing. Multi-stage tea drying process uses different drying medium temperature range in recognized zones of dryer for fuel economy and quality (Dutta, 2014).

In this paper, efforts have been made to toss light on

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the reviews and research done on the different scientific and technological aspects of tea withering and drying. Endeavours have been made to highlight the works done on the design of modified withering trough. A few specialists have made ventures to demonstrate the heat transfer part of withering and furthermore to optimize the process parameters. The impact of withering and drying on various parameters and the biochemical changes in tea leaves are discussed here. The experimentations done by researchers on tea drying have been touched upon. Further, the energy aspects of tea withering and drying have been focussed. There is ample scope for implementation of renewable energy in tea withering to minimize the fossil fuel utilization.

## 2 Trough design in tea withering

Withering process causes certain variations either chemically or physically in the tea leaf. Depending on leaf type and moisture content the total withering time may vary from 12 to 14 hours. Withering requires a considerable amount of electrical power to complete the process out of the total energy consumption in tea processing. The main operating parameters in a withering process are thickness of leaf over bed, humidity of ambient air, air temperature and air velocity. Figure 1 shows a tea withering trough used in a tea processing industry.

Figure 1 Withering trough

### 2.1 Problem statements of withering trough

The existing withering troughs generally have a leaf spread capacity of around 0.3 m depth. This constraint becomes critical during the peak season. The only option that remains is to overload the troughs or to spread the leaves to a greater depth. This results in degraded quality of withering (Das, 2006). Both electrical and thermal energy are consumed in the withering process. Human labour becomes intensive in loading and unloading the leaves. During reverse mode of operation, the fan efficiency reduces to around 60% resulting in consumption of more power. Moreover, heating the air in ventilated space rises the temperature of the atmosphere. In other words, there is a considerable amount of heat loss into the atmosphere (Kamau, 2013).

### 2.2 Types of artificial withering

In mechanical or artificial withering, four systems are generally used which are described below (Wallis-Tayler, 1900)-

- ***Dry warm air system***: Warm air heated in a furnace is drawn by a fan over the leaf in this system of withering. Two or more floors of trays may be placed one above the other. A tubular steam heater, a close exhaust pressure fan, an air distributing pipe and a winding gear are the parts of a patented artificial withering system. The trays are around 7 feet in length and 5 feet in width.
- ***Moist warm air system***: Green leaf is subjected to warming with an influence of moisture laden air. The trays are superposed as in the dry air system. Perforated plates are fitted at the inlet and outlet ends of the withering chamber. Conduit pipes are connected with the inlet and outlet ports for conveying the exhaust air of the withering chamber to and from an air heating apparatus. It is again fitted with a fan which draws the exhaust air from the chamber passing it through the heating apparatus and back to the chamber.
- ***Vacuum system***: The leaf is subjected to the action of a vacuum in this type. The leaves are placed on a series of galvanised iron trays. The trays are supported on brackets in an air tight chamber fitted with a hinged door. The chamber communicates through a pipe with a valve box, which is again connected with an air pump. The pump helps to regulate the vacuum.
- ***Withering by waste heat***: The waste heat is used by two methods- in one, exhaust fans draw the waste warm air through the withering room and in the other, blast fans are used for the same. The proper height of the ceiling cloth depends on the size of the fans used. The number of fans, however, depends on the length of the withering

room. The power required to drive the fans depends on the velocity at which it which it is running.

In the North-East region of India, the moist air system of withering is generally used because of the weather conditions prevailing here.

### 2.3 Design parameters of a withering trough

In withering, the role of the fan is very vital. If the area of the withering trough is known, then the relevant factors required for the process are possible to determine.

Let the area of the trough be 'A' square metres. If the fan diameter is considered to be 'd' feet, then the other parameters could be estimated as follows (Hudson, 2000):

- Volume flow rate of air per unit area through the trough = $q_a$ (m$^3$ minute$^{-1}$)
- Volume flow rate of air through the trough = $Q_a$ (m$^3$ minute$^{-1}$)
- Actual cubic feet per minute (ACFM) = $Q$ (feet$^3$ minute$^{-1}$)
- Actual static pressure (ASP) = $P$ (inches wg)
- Air temperature at fan = $T$ (°C)
- Elevation above mean sea level = $z$ (feet)
- Air density = $\rho$ (lb feet$^{-3}$)
- RPM or tip speed = $s$ (feet minute$^{-1}$)
- Density Ratio = DR
- Density correction factor = (1/$DR$)
- Net section area of the fan = NFA (feet$^2$)
- Velocity of air through fan = $V$ (feet minute$^{-1}$) = $Q$/NFA
- Velocity pressure = $VP_{std} = (V/4005)^2$ (inches wg)

For standard conditions, DR=1. Hence,

- Total pressure (TP) = Total standard pressure ($TP_{std}$) = $P \times (1/DR) + VP_{std}$

By estimating the Speed Factor (SF) from the Hudson fan curve, the Brake Horse Power of the fan is given by-

$$BHP_{act} = (BHP_{std}) / (1/DR) \times SF^3$$

$BHP_{std}$ depends upon the diameter of the fan and the value could be extrapolated from standard table. Accordingly, the speed and the air flow rate of the fan could be determined.

A typical fan curve is shown in Figure 2 below-

The total efficiency of the fan is given by-

$$Eff_{total} = (TP \times Q)/6356 \times BHP_{std}$$

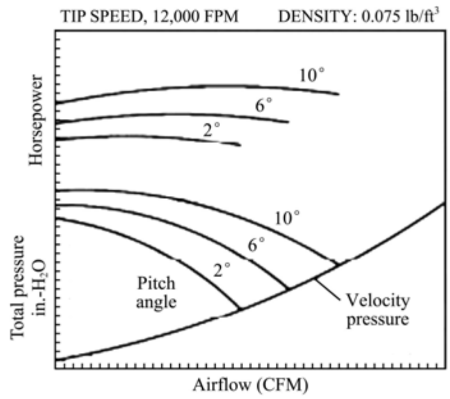


Figure 2 A typical fan curve (Hudson, 2000)

### 2.4 Design of modified withering trough

In a customized open withering trough concentration was given on the impact of withering parameters on equity of withering over the length of the trough, total withering time and total energy consumption. Changes in moisture content, polyphenol oxidase and peroxidase specific activity, protein, amino acid, and chlorophyll content amid withering were considered in the altered trough and natural withering (Singh et al., 2012). Das, (2006) tried two unconventional parameters to address the constrained limit of tea leaf withering troughs. The specific levels of the modifications of the ratio between cross sectional areas of both the ducts and ratio between time intervals of alternate air flow through the bed of the trough could generously expand the moisture loss rate and consequently increment the withering trough limit. In the quest to design an improved withering trough, Kamau (2013) developed a trough with increased capacity and reduced energy consumption. The capacity of the trough could be increased from 44000 to 120000 kg per day with the same number of troughs. Fibre Reinforced Fans were used in the new design. Further, a swing damper was introduced to control the direction of air for uniform withering.

### 2.5 Instrumentation in withering trough

In an improved instrumentation setup for the investigation of tea withering process online, the parameters considered were relative humidity and temperature at two unique places of the withering trough. The perception demonstrated an extensive change in the distinction in variety of relative humidity and temperature at both the vents of airflow path in the trough. The design considerations of a scaled down prototype of a withering trough and the related signal conditioning of the sensors were also reported (Das et al., 2015, 2017). In an attempt to predict the moisture loss in withering process by artificial neural network technique, the maximum mean error was reported to be -3.6% (Das et al., 2018). Manual treatment of tea leaf additionally damaged fresh tea leaf and degraded quality of processed tea. To motorize the leaf managing actions, a theoretical useful outline of an automated framework was estimated and a working replica was produced (Das and Tiwari, 2006).

In tea withering, the trough design plays an important role. The capacity of the troughs may be increased beyond the usual dimensions so that the usage of additional parameters can be reduced. Moreover, the review on trough design throws light on the energy aspect involved in tea withering process. A more sophisticated withering trough may be capable of making the whole process energy efficient. In an enclosed trough, a constant pressure should be maintained inside the plenum chamber all over the length to have an even air flow rate.

## 3 Modelling in tea withering

Tea withering is a process having sufficient scope for development of simulation models. A one-dimensional heat and mass transfer mathematical model was developed to simulate moisture content of tea leaves during trough withering. Experimental and simulated moisture data were in close settlement for top, centre and base layers of the withering trough with standard errors in the scope of 0.2940-1.2872, 0.7148-1.1025 and 0.7106-4.5478, individually on percent wet basis (Botheju et al., 2006). Ghodake et al. (2006) inspected the withering qualities of tea leaves for a temperature range of $20^oC$-$45^oC$ with a consistent air velocity of 1.1 m $s^{-1}$. The Henderson and Pabis model was a superior model for portraying the withering attributes of tea leaves for each of the temperatures of $20^oC$, $25^oC$, $30^oC$ and $35^oC$. The values acquired from Page model were observed to be more sensible for temperatures of $40^oC$ and $45^oC$ than others. The modified Halsey model was found to depict the sorption isotherms of withered leaves, black and green tea agreeably. The net isosteric heat of sorption of withered leaves changed in the vicinity of 30.8 and 29.5 kJ $mol^{-1}$ at moisture levels fluctuating in the vicinity of 8% and 9% (d.b.) (Ghodake et al., 2007). Simulation of the tea withering procedures was done to foresee the standard of withering with the coveted level of wither using fuzzy nonlinear simulation methods (Gupta et al., 2012). A fuzzy logic based withering control methodology was proposed by Jayasundara (2008) which optimized the electrical energy consumption. Huge lessening in polyphenoloxidase (PPO) and peroxidase (PO) chemicals, theaflavins (TFs), thearubigins (TRs) and theaflavin digallate equivalent with the abatement in moisture content of withered leaf was reported by Sabhapondit et al. (2014). The energy and exergy analysis of the wither process showed that exergetic efficiency decreased with increase in ambient air temperature in agreement with the decreasing heat exergy (Sarac, 2015). Wide deviation was observed in the velocity and temperature distributions of drying air along the length of the trough in a 3D model using Fluent 6.2 computational fluid dynamics package (Gupta et al., 2014). Moreover, Suyanto et al. (2010) designed a geothermal energy dryer for tea withering and drying.

However, not much work has been done on the direct modelling of the tea withering process. In an open withering system, air is released having high moisture content to the environment. The fan sucks in this air and the released air through withering bed which gets mixed with dry air becomes high in moisture content. Evidently, the withering process gets slow and energy inefficient. During different weather conditions, the humidity levels vary to a great extent. An improvisation may be done to control the humidity in such cases.

## 4 Impacts of withering and drying on tea

### 4.1 Role of withering in black tea

The withering duration plays a vital role in moisture content, minerals, amino-acids, volatile compounds and tea quality. The most elevated moisture content of 76.4% was inspected in new leaves. Total free amino acids showed a gradual increase up to 23 hours. Ash, phosphorus (P), copper (Cu), zinc (Zn) and manganese (Mn) contents demonstrated an increasing pattern. Lower amounts of sodium (Na) (162.5 mg $kg^{-1}$) and magnesium (Mg) (803 mg $kg^{-1}$) were recorded in tealeaves following 24 hours withering. Aluminium (Al), nickel (Ni) and lead

(Pb) contents expanded over withering time (Jabeen et al., 2015). Withering time had no huge impact on theaflavin contents and tea liquor brightness. Thearubigin contents and tea liquor colour changed altogether. Withering the tea leaves in 16 hours gave best sensory quality attributes in final product (Soheili-Fard et al., 2015b). Mean theanine levels of 1.41% and 3.11% were obtained for three leaves and a bud withered for 3 and 15 hours respectively (Too et al., 2015). Variation of chemical withering time by up to 18 hours in the manufacture of black tea caused insignificant changes in plain tea quality factors (Owuor and Orchard, 1992). Caffeine contents continuously incremented with delayed withering while theaflavins diminished. No huge changes occurred in thearubigin levels (Owuor et al., 1990).

Withering has its effects on various aspects like colour, aroma, polyphenol oxidase levels, volatile compounds of tea and so on. Effect of the air flow rate on dry tea appearance, taste, aroma, liquor colour, infused leaves and final product quality was significant at the 1% level (Soheili-Fard et al., 2015a). Black tea withered with UV light showed a solid astringency. The green light irradiation harmed the smell and taste of the tea. Yellow, orange and red light withering enhanced the smell and taste (Ai et al., 2017). Quantities of Z-3-hexenol ester, linalool, its oxides and methylsalycylate were higher in withered compared to non-withered. Reverse was in case of E-2-hexenal content (Takeo, 1984a). The impact of plucking standards on withering and the impact of withering on the storage of tea were reviewed by Tomlins and Mashingaidze (1997). Level of polyphenol oxidase diminished on fractional drying of the leaf amid withering (Ullah and Roy, 1982). Despondency in polyphenol oxidase action amid withering influenced the oxidative condensation of tea flavanols in shaping theaflavins and thearubigins (Ullah et al., 1984). Expanded cell layer porousness and abatements in the levels of chlorophyll were reported due to freeze withering of black tea (Muthumani and Kumar, 2007). Owuor and Obanda (1996) mentioned that a decrease of theaflavins, brightness, flavour index and sensory evaluation scores occurred with high leaf temperatures during withering of black tea. Withering temperature above 30°C resulted in high thearubigins and total colour levels void of briskness.

Physical withering is the deduction of moisture from tea leaf. The moisture content of the leaves reduces to 60%-70% (Jabeen et al., 2015). The cell permeability of the leaf changes due to physical withering. Thereby, the turgid leaf converts to flaccid during this process and makes it amiable to the subsequent processes. The stomata of the lower leaf surface start to close with the progress of withering (Tomlins and Mashingaidze, 1997).

### 4.2 Impact of withering in other types of tea

The effects of withering are prominent in many other types of tea. The joint effects of solar and indoor withering and mass-rolling processes showed a boost in the concentrations of 23 main components in pouchong type semi-fermented tea (Tokitomo et al., 1984). Increase in the concentrations of hexenyl esters, aromatic alcohols, oxidised products of linalool, phenylacetaldehyde, sesquiterpenes, cis-jasmone, jasmine lactone, benzyl cyanide and indole by turn over treatment was seen without solar-withering in pouching tea. Seventeen minutes solar-withering and four turn over treatments was the most efficient to produce the elegant floral aroma (Kobayashi et al., 1985). The quantity of volatile compounds in oolong tea increased in warm-withering leaves around 40$^{o}$C as compared with normal withered leaves at room temperature. The creation of aroma compounds hastened by soft hand rolling every 30 minutes (Takeo, 1984b).

### 4.3 Effects of drying

Like withering, drying of tea also has its impacts on different facets of tea. Teshome et al. (2013) reported that biochemical composition and quality of tea decreased as the drying temperature increased with duration. A combination of 100°C and 25 minutes was identified as the optimum combination. Drying of tea at 110°C with a dryer speed of 15 r minute$^{-1}$ produced good quality black tea (Naheed et al., 2007). Higher inlet drying temperature against dryer temperature 96°C did not affect the overall quality of tea. Better appearance could be attained with high inlet temperature when there are only 40% good leaves (Kavish et al., 2016). For quality development, tea constituent temperatures of up to 120°C might be accepted for periods less than 1 minute. With drying periods of lower than 15 minutes, the stewing phenomenon could not be found (Temple et al., 2001).

Out of many drying methods, microwave drying was found to be a good method to maintain the total phenolic content, anthocyanin content and ascorbic acid equivalent antioxidant activity of Vitex negundo Linn. tea (Rabeta and Vithyia, 2013). The degradation of ascorbic acid could occur during drying in Indian gooseberry tea. The hot water was recommended to keep low during its preparation (Kongsoontornkijkul et al., 2006). Total polyphenol content and colour factors were not much affected while using a commercial microwave vacuum dryer. Drying conditions at 3600 W for 30 minutes were suggested to obtain optimal physicochemical properties of Thai green tea (Hirun et al., 2014).

### 4.4 Biochemical changes in tea due to withering

As tea leaves contain a lot of chemical compounds, it is evident that certain biochemical changes would occur while the leaf undergoes some process. Apparently, withering results in such changes. While determining the molecular weight and some properties of phenol oxidase from tea leaves and four other perpetual plants, it was observed that withering was accompanied by the development of only phenol oxidase with high molecular varieties having catechol oxidase activity essential for attaining oxidative reactions and product quality (Omiadze et al., 2014). By restricted moisture loss during initial stage of withering, quality could be enhanced irrespective of cultivars (Baruah et al., 2012). Kuloba et al. (2014) studied the impact on the polyphenol quantity by withering green tea leaf by low-temperature nitrogen plasma. In one hour, polyphenol content of 78.56 mg $g^{-1}$ in made tea was obtained and it was the highest. Again, for a sample withered anaerobically in nitrogen gas at room temperature and atmospheric pressure for 18 hours, the highest polyphenol content was attained as 133.4 mg $g^{-1}$ in made tea. A polyphenol content of 101.91 mg $g^{-1}$ was attained in the sample which was straight away macerated and dried devoid of withering and fermenting. Wang et al. (2013) obtained four tea polysaccharides (TPSs), namely, TPS-V, TPS-F, TPS-S and TPS-M from tea leaves by vacuum-drying, freeze-drying, spray-drying and microwave-vacuum drying respectively. Results demonstrated that they possessed similarity in UV, IR absorption and molecular weight allocation. Differences in amounts of crude polysaccharides and protein and total polyphenols content were observed. Further, their surface varied in size and shape when inspected by Scanning Electron Micrographs. A spectrophotometric technique was used to estimate the amino-acids and amides of new and withered tea shoots (Bhatia and Deb, 1965). Drying increased antioxidant activity, flavonoid, phenolic and chlorophyll contents, but vitamin C decreased. The highest radical scavenging movement was shown by oven drying at 60°C and microwave drying showed the lowest. Alike was the trend in dropping power assay. Highest contents of vitamin C and chlorophyll of 16.36 mg per 100g DM and 17.35 mg $l^{-1}$ were obtained in freeze drying. With regard to the ultimate colour of leaves, sun and freeze drying methods were the least and the most desirable drying methods respectively (Roshanak et al., 2016). Kuo et al. (2010) made a comparison of the volatile compounds in new and old oolong teas. Basically identical overall outlines of volatile compounds were seen in five diverse processing of old oolong teas. However, this pattern varied from that which was either stocked up for more than 10 years without drying or processed at comparatively low temperatures and short baking time.

During tea withering, a lot of biochemical changes take place. The changes comprise of enzyme activity, volatile compounds' movement and variations in organic

**Table 1 Studies on Tea Leaf Polyphenol Oxidase**

| Sl. No. | Topic | Enzyme activity | References |
|---|---|---|---|
| 1. | Solubilization and properties of the structurally bound polyphenol oxidase in tea leaves | Enzyme activity inhibited by potassium cyanide and sodium diethyldithiocarbamate. | Takeo, 1965 |
| 2. | Purification and properties of the solubilized polyphenol oxidase in tea leaves | A-I oxidized o-diphenol whereas A-II oxidized both vicinal-triphenol and o-diphenol. Their activities were inhibited by a concentration of substrate. | Takeo and Uritani, 1966 |
| 3. | Studies on the changes of polyphenol oxidase activity | Enzyme activity increased in the withering period. It became faster with rise in temperature. | Takeo, 1966a |
| 4. | Localization of polyphenol oxidase in tea leaf cell | Major part of the enzyme activity appeared in the centrifugal precipitates in the range of 1400×g to 15000×g, and polyphenol content decreased. | Takeo, 1966b |
| 5. | Effect of antibiotics on enzyme formation | Antibiotics inhibited polyphenol oxidase activation. New protein containing the enzyme activity developed in the withered leaves. | Takeo, 1966c |

acids and sugars. Increase of caffeine content and a decrease in chlorophyll, lipids, fatty acids and carotenoids is observed in addition to breakdown of amino acids and proteins. Furthermore, complex compounds are seen to break into their corresponding simpler compounds. Some studies were conducted on the tea leaf polyphenol oxidase and the respective results are shown in Table 1.

## 5 Experimentations and modelling in tea drying

Drying refers to the removal of moisture by evaporation from fermented leaf. It is the process in which the enzyme activities cease and the moisture content comes down to around 2%-3%. Many researches have been carried in tea drying process.

To determine kinetics of tea drying, a new thin layer drying apparatus was designed and built to measure the high rates of drying with the Lewis equation satisfying the results. Drying rate constant was a linear function of temperature and air flow rate (Temple and Boxtel, 1999). In another similar experiment, variation of effective diffusivity was from $1.14\times10^{-11}$ to $2.98\times10^{-11}$ $m^2$ $s^{-1}$ over the temperature range of $80^oC$-$120^oC$. The Lewis model gave better results for the drying characteristics. Activation energy was 406.02 kJ $mol^{-1}$ (Panchariya et al., 2002). Again, diffusivity constant and activation energy were $0.746\times10^{-3}$ $m^2$ $s^{-1}$ and 52.104 kJ $mol^{-1}$ respectively when a producer gas fired tea dryer was used. The energy consumption of made tea (3% w.b.) was recorded as 19.01 MJ $kg^{-1}$. The specific energy consumption of the dryer was reported to be approximately equal to 6.274 MJ $kg^{-1}$ of water removed. The Modified Page model gave better predictions in this case (Dutta and Baruah, 2014). In single-layer solar drying experiments for Mexican tea leaves, diffusion coefficient varied between $1.0209\times10^{-9}$ and $1.0440\times10^{-8}$ $m^2$ $s^{-1}$. Activation energy was 89.1486 kJ $mol^{-1}$. The best fit among fourteen empirical models was the Wang and Singh model for solar drying curves (Ethmane Kane et al., 2008). Hatibaruah et al. (2013) determined microwave drying characteristics of Assam CTC tea at five different powers of 180, 360, 540, 720 and 900 W. Page model gave better drying characteristics. Both energy consumption and energy efficiency were reported to be strongly dependent on vacuum pressure and microwave power in an energy analysis of drying of tea leaves (Jindarat et al., 2013). Experimental results complied with theoretical predictions when freeze drying was carried out by Aydin et al. (2017). Experiments were performed to assess the drying process of green tea leaves in a prototype. Drying rate increased with increase in air flow rate. The efficiency of energy use quantified by Specific energy Consumption rate varied significantly with flow (Langat et al., 2015). A computer program was calibrated by using experimental data from fabricated gasifier design. A small throat angle could increase the conversion efficiency. Gasification zone was required to be around 0.33 m (Jayah et al., 2003). The various models used for determination of moisture ratio (MR) in drying are illustrated in Table 2. The drying time is given by $t$. The different drying constants are denoted as $a$, $b$, $c$, $k$, $k_0$, $k_1$. $L$ is the half-thickness of dried leaves.

**Table 2 Mathematical models applied in drying (Ethmane Kane et al., 2008)**

| Sl. No. | Model name | Model equation |
|---|---|---|
| 1 | Newton (Lewis) | $MR = \exp(-kt)$ |
| 2 | Page | $MR = \exp(-kt^n)$ |
| 3 | Modified Page 1 | $MR = \exp((-kt)^n)$ |
| 4 | Modified page 2 | $MR = \exp(-(kt)^n)$ |
| 5 | Henderson and Pabis | $MR = a\exp(-kt)$ |
| 6 | Logarithmic | $MR = a\exp(-kt) + c$ |
| 7 | Two term | $MR = a\exp(-k_0t) + b\exp(-k_1t)$ |
| 8 | Two term exponential | $MR = a\exp(-kt) + (1-a)\exp(-kat)$ |
| 9 | Wang and Singh | $MR = 1 + at + bt^2$ |
| 10 | Diffusion approach | $MR = a\exp(-kt) + (1-a)\exp(-kbt)$ |
| 11 | Modified Henderson and Pabis | $MR = a\exp(-kt) + b\exp(-gt) + c\exp(-ht)$ |
| 12 | Verma et al. | $MR = a\exp(-kt) + (1-a)\exp(-gt)$ |
| 13 | Midilli-Kucuk | $MR = a\exp(-kt^n) + bt$ |
| 14 | Simplified Fick's diffusion | $MR = a\exp[-b(t L^{-2})]$ |

Tea drying is an energy exhaustive process. The prospects of implementation of renewable energy have been a recent topic of research in various fields. Renewable energy has been used for domestic, commercial and industrial applications (Panwar et al., 2013). Even in small countries like Nepal, energy sources like biogas, solar thermal and geothermal are being deployed (Gewali and Bhandari, 2005). Moreover, a vast amount of energy is expected to be saved with the utilization of tea wastes in a proper manner (Kumar and Jolvis, 2016). As tea drying consumes a major part of the energy utilized in tea manufacturing, the prospects of the application of non-conventional energy sources have been studied upon. However, similar kind of implementation in tea withering can be done which is yet not touched upon much by the researchers. The range for the consumption of total specific energy varies from 14.5-66.24 MJ $kg^{-1}$ made tea. These disclose that the north Indian, Sri Lankan and Vietnamese tea factories consume more energy as compared to that of the south Indian factories. The total specific thermal energy consumption ranges between 16.02-24.62 MJ $kg^{-1}$ made tea in Sri Lanka and India. Whereas, it is around 36 MJ $kg^{-1}$ made tea in Vietnam (Baruah et al., 2012). Figure 2 provides a graphical representation for the total specific energy consumption in tea manufacturing. The specific thermal energy consumption in withering is shown in Figure 3.

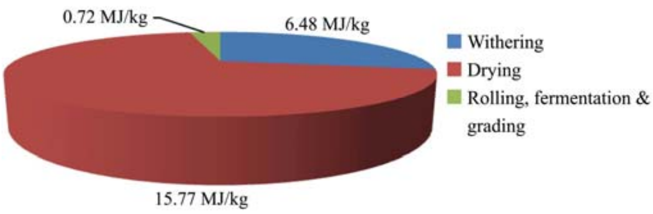


Figure 3 Total specific energy consumption in tea manufacturing

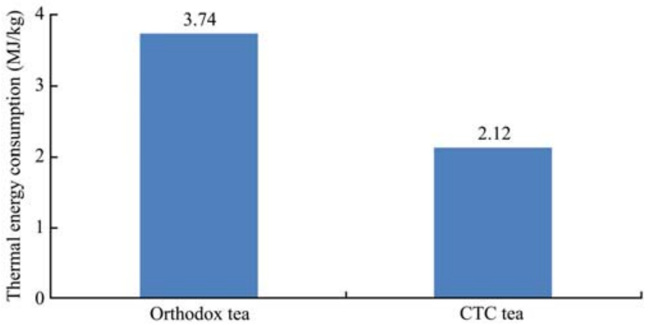


Figure 4 Specific thermal energy consumption in withering

## 6 Conclusions

The tea production in India in the financial year 2015-16 was a record 1,233 million kg (M kg) and exports crossed 230 M kg after 35 years. There has been an increase in the tea production in India by 250% since 1947. The land utilized for the production has increased by 40%. The withering process in tea manufacturing involves moisture reduction of the green leaf under controlled conditions of temperature and relative humidity of the leaf delivered from the actual value which is usually between 74%-83% to a moisture content of about 66%. It has been observed that certain biochemical changes occur in the tea leaves during the withering stage itself. Withering trough is a rectangular duct with one opening for the air to go in and the leaf bed acts as an outlet. Comparatively, less focus has been given on the modelling of withering process in tea manufacturing. It is proved well enough that withering is one of the energy consuming processes in tea manufacturing. Energy costs constitute 30% of the total tea processing cost. It has been estimated that the total specific energy consumption in withering is on an average 6.48 MJ $kg^{-1}$ made tea.

The following conclusions are noted down from the study:

- The dimensions of the withering trough are crucial to achieve good quality withering of tea. The trough design can be further customized in order to optimize the withering parameters like length of leaf spread, humidity and so on. The release of high moisture content air from the withering trough bed in open withering system poses threat to the environment and makes the process energy inefficient. Taking this aspect into account, the withering trough design may be modified.
- At the end of the tea manufacturing process, quality of the finished product is a crucial aspect. The withering temperature, humidity and air flow rate are vital parameters to be controlled during the process. Evidently, to maintain the quality, an improved mechanism to control these factors during various weather conditions may be developed.
- It is observed that modelling and experimentations have been done to a considerable extent in tea drying. However, less research has been done on the modelling aspect of withering. There is ample scope to develop mathematical models based on the different parameters of tea withering which may be a future approach.
- Withering, as partial drying is an energy consuming process. One of the approaches to tackle the energy and environmental concerns is to implement energy efficient and environmentally active production processes. Low temperature solar thermal energy may be useful to solve these issues because it is renewable and therefore it reduces overall greenhouse emission comparing to fossil fuel utilization. Another alternative may be the use of biomass in an efficient burner for tea industries. However, it is also equally crucial to motivate the tea growers to implement the same.

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