ABSTRACT

Tea is one of the highly sought after refreshing drinks in the world and has become a basic part of daily life. India produces around 1350 M kg of tea annually, making it the second largest tea producing country after China. Around 20% of the tea production is exported to other countries. India exported 201 M kg of tea in the financial year 2021-22. Above 1.5 million people are directly or indirectly associated with the tea industry in India. The tea industry contributes immensely to the overall economy of the country. Out of the total tea production in India, about 50% tea is produced in Assam in North-east India.

The fresh tea leaves undergo five primary operations after harvest, namely-withering, maceration, fermentation, drying and grading or sorting before the production of the final product. Drying consumes the highest amount of thermal energy followed by withering. Natural gas, coal and oil are the generally used thermal energy resources in the tea industries. About 30% of the total cost in tea production is constituted by the overall energy costs. For manufacturing one kg of tea, the thermal and electrical energy requirements are respectively within the ranges of (16.02-24.62) MJ and (1.44-2.52) MJ. Around 3252 M kg greenhouse gases have been reported to be emitted by the Indian tea industries running on fossil fuels.

The issues pertaining to the use of conventional fuels in tea processing have been a concerned topic since recent times. There is an essential requirement to employ some alternate sources of energy in this field. To some extent certain experimental studies on utilization of renewable energy in the drying operation has been carried out in different regions along with Assam. Being an energy intensive process, withering also needs attention regarding the usage of non-renewable energy resources. A techno-economically and environmentally sound substitute may be employed to serve the purpose. The alternative of solar thermal energy is a viable option for tackling the problem.

In solar air heating technology, the solar radiation is trapped by an absorber plate and then used for heating air. Out of the many solar thermal technologies, solar air heater is generally known to be the most economic with low complications. However, the technique of using solar air heaters specifically in tea-leaf withering for the local variety of tea in Assam is not yet experimented. The possibilities of implementation of solar thermal energy in tea-leaf withering is taken up as the primary goal of the present research

work keeping in mind the above facts. The factors and conditions are considered strictly abiding to the local variety of green tea leaves of Assam.

As the first objective, an assessment was made on the energy consumption in the various tea processing stages in a black tea processing factory. Following this, the withering characteristics of local tea leaves were determined using a temperature and humidity controlled ambience in an environmental chamber to learn the appropriate conditions of low-temperature drying. Experiments were conducted using a newly developed laboratory set-up of solar thermal based tea withering trough. The performance of the tea-leaf withering trough coupled with a corrugated solar air heater was evaluated along with an economic analysis. A detailed comparative energy and exergy analysis of the tea-leaf withering trough was conducted with the help of two different absorber plates in the SAH- first a corrugated plate and then with a plate having Al-can protrusions. Further, the environmental aspect of the withering trough was analyzed.

To have a brief idea about the energy usage, its consumption pattern was assessed for all the processing stages of black tea manufacture in a local tea factory. The energy depleted in the processing steps of CTC tea manufacturing was evaluated and compared with that of the South-Indian tea industries. Energy management was assessed in terms of the cost of energy per unit volume of production. Thermal energy consumed to wither 100 kg tea leaves was estimated to be 179.10 MJ. Again, 1791.11 MJ of thermal energy was consumed in drying 100 kg of fermented tea leaves. The average thermal energy consumption was found to be around 20% higher than that of the South Indian tea industries from available literature. Possible energy effluent techniques were discussed in order to reduce the energy ingestion.

The withering characteristics of local tea leaves were determined in an environmental chamber under an ambience of controlled temperature and relative humidity. The experiments were conducted by considering air temperatures (25-35) °C and RH of (80-90) % in increments of five units each. Nine different combinations of temperature and RH were set by keeping one variable constant at a time. The withering characteristics were fitted into five drying models thereafter. The total phenolic and flavonoid contents of the withered tea-leaf samples were estimated using standard procedures.

The green tea-leaf withering characteristics obtained from the experiments in the environmental chamber showed that both withering air temperature and relative humidity had good impacts over them. The Page model best fitted the withering characteristics at 30 ℃ air temperature and 90% relative humidity. A moderate withering rate of 0.28 g water/g dry solid-h was obtained at this combination. The total phenolic and flavonoid contents at 30 °C were estimated as (50.6 ± 0.02) mg GAE/g and (22.47 ± 0.01) mg QCE/g respectively.

A laboratory-scaled tea-leaf withering trough was developed with a leaf bed area of 0.18 m^2 according to scoping design estimations. The withering trough was coupled with a solar air heater having a corrugated absorber plate with an exposed area 1.41 m^2. The withering characteristics of fresh tea leaves were obtained by performing experiments in the newly developed solar assisted tea-leaf withering trough. The withering air temperatures and relative humidity were maintained within 32 °C and (75-85) % respectively. The overall thermal efficiency of the arrangement was computed along with the estimation of specific energy consumption and activation energy. Also, the best fit withering model was found out by using seven drying models.

In the solar powered tea-leaf withering trough, the maximum rate of withering at the beginning was 0.93 g water/g dry solid-h at 32 °C. The activation energy was estimated as 104.05 kJ/mol. The total energy input to the tea withering trough was calculated as 0.91 kWh with a specific energy consumption of 1.76 kWh/kg. The overall thermal efficiency of the solar-powered tea-leaf withering trough was computed as 40.98%. The Midilli and Kucuk model gave the best fit results at 27 °C. At 32 °C, the Two-term model gave the best fit for the withering characteristics among the other models.

The energy and exergy analyses were performed for the solar powered tea-leaf withering trough considering two cases. First, the absorber plate was a corrugated one while in the second case, the absorber plate had cylindrical protrusions of waste Al-cans. Mass flow rates of 0.03, 0.04 and 0.05 kg/s were considered for conducting the experiments in both the instances. The thermal as well as exergetic efficiencies were computed for all the cases. The environmental impact was assessed for the better system by estimating the earned carbon credit.

For both the corrugated and Al-can absorber plates, the mass flow rate of 0.04 kg/s proved to be better than the rest. The thermal efficiencies in this particular mass flow rate were obtained as 64.2% and 74.77% respectively for the two plates. The exergetic efficiency of the withering chamber in the corrugated plate SAH varied within (52.11-94.23) % during the day at 0.04 kg/s. In the Al-can arrangement, the exergy efficiency of the trough varied within (69.06-95.63) % at 0.04 kg/s.

The economic payback period of the solar powered tea-leaf withering trough was computed as 0.90 years for a lifespan of 20 years. The environmental analysis of the whole system gave the earned carbon credit of (145.25-581) $ for 20 years. According to these assessments, the arrangement of solar thermal energy in the process of tea-leaf withering seemed to be economically and environmentally viable. The outcomes from the experiments and the analyses prove the solar assisted tea-leaf withering system to be a viable option for implementation in the tea sector. A potential benefit in terms of energy costs is very much likely due to the reduction in use of conventional energy resources.

However, the experiments being done at a laboratory-scaled arrangement brought certain limitations. Assumptions had to be taken since industrial data was unavailable. To implement such an alternative in the local tea processing factories, it has to be ensured that the manpower associated with the industries are motivated to accept the new approach. More geometries may be introduced to the absorber plate of the solar air heater and experimented accordingly to get more applicable results. Different tea varieties may be experimented upon. Moreover, factory-roof integrated solar air heaters may be installed and experimented upon to get more realistic results in future.