

Original Research Article

SunSync Innovation: Empowering Traditional Solar Flat Plate Collectors with Autonomous Sun-Tracking for Tea Leaf Drying

ABSTRACT

This research addresses the global challenge of synchronizing food production with seasonal growth patterns, focusing on post-harvest technology for preserving tea leaves. The research introduces an innovative approach by incorporating an autonomous solar tracker into a flat plate solar collector, strategically optimizing its orientation towards the sun. The solar tracker, a low-cost and fully automatic prototype, plays a pivotal role in maximizing incident solar rays, thereby enhancing the overall energy absorption efficiency of the system. The study explores indirect solar drying, particularly the Sun-Tracking Solar Dryer (STSD), as an eco-friendly alternative to traditional methods. Furthermore, the investigation extends to the comparison of traditional drying methods, such as open sun drying to the developed prototype. Quality analysis reveals superior attributes in solar-dried green tea leaves, emphasizing the benefits of the developed solar tracker.

Keywords: Solar tracker, green tea processing, autonomous system, sustainable agriculture

1. INTRODUCTION

The escalating trajectory of global food production, propelled by sophisticated agricultural methodologies, mechanization, and the cultivation of disease-resistant crops, confronts a challenge in synchronizing with the seasonal growth patterns of specific food items(1–3). This incongruence results in a disparity between food supply and demand. In response, post-harvest technology, with a primary focus on food preservation, emerges as a pivotal strategy to mitigate the annual loss of approximately 40% of fruits and vegetables, ensuring a consistent food supply throughout the year (4). Within this context, this research investigates the domain of tea leaf processing, concentrating on *Camellia sinensis*, an evergreen plant predominantly thriving in tropical and subtropical climates. The tea processing industry, deeply rooted in India as one of the oldest industries, positions India as the second-largest global tea producer after China. Tea, distinguished by its diverse processing methods, offers a spectrum of aromatic compounds and antioxidants, contributing to its esteemed status as a health-promoting beverage(5,6). Specifically, this study delves into green tea production, a non-oxidized variant achieved through meticulous drying and steaming of fresh leaves, inhibiting polyphenol oxidase enzymes. The preservation of natural polyphenols in green tea involves immediate steaming or heating post-harvest to arrest enzymatic breakdown, ensuring the tea maintains its characteristic green color during drying (7). The primary objective of the drying process extends beyond moisture removal, encompassing the enhancement of product shelf life, reduction of packaging requirements, and minimization of bulk weight. Traditional drying methods, involving mechanical and open-sun drying, present environmental concerns, high operational costs, and compromised product quality. To address these challenges, the study advocates for the utilization of solar energy, the most abundant non-conventional energy source, as an alternative for drying operations. While traditional open-sun drying is cost-effective, it suffers from quality degradation due to contamination and discoloration. Consequently, researchers have redirected their focus toward solar dryers, categorizing them into direct and indirect systems based on radiation exposure. In direct systems, the product is exposed to solar radiation directly which may have some adverse effects on quality. In an indirect type solar dryer, the black surface heats incoming air which is

passed over the substance and exits through the chimney, taking moisture away. The study specifically explores the use of indirect solar dryers, where the black surface heats incoming air, maintaining product quality as the drying temperature remains below 80°C. Recognizing the dynamic solar position owing to Earth's orbital rotation, the study introduces a solar tracker as an integral component in flat plate solar collectors. This device optimally orients collectors towards the sun, maximizing incident rays for enhanced energy absorption. The research proposes the integration of an autonomous solar tracker in a flat plate solar dryer, aiming to optimize energy efficiency.

In conclusion, this research contributes to the evolution of solar technology for green tea leaf drying by integrating autonomous sun-tracking in flat plate solar collectors. The development of a low-cost fully automatic solar tracker, coupled with an in-depth analysis of the quality and quantity of green tea, positions the study to provide valuable insights for optimizing the drying process in the tea industry.

2. MATERIALS AND METHODS

2.1 Flat plate solar dryer (FPSD)

The experimental apparatus will be devised by integrating a tracking system and air supply mechanism into an existing single-axis flat plate indirect-type solar dryer situated at the Dairy Food and Engineering (DFE) building within the Agricultural and Food Engineering Department at the IIT Kharagpur campus. The extant configuration encompasses a solar collector, drying chamber, and chimney, operating with natural air circulation and lacking an air supply system (Fig.1).

The solar collector in the indirect-type solar dryer assumes a rectangular form with dimensions of 150 cm in length, 40 cm in breadth, and 23 cm in height. It is supported by a frame with a height of 56 cm on the inlet side and 98 cm at the junction with the drying chamber. The solar collector comprises an absorber plate (painted black), a central shaft, and a glass cover positioned above it, accompanied by two mirror reflectors along its longitudinal sides inclined at a 45° angle. The absorber plate, facilitating solar radiation absorption, features six 3.5 cm diameter openings for air intake on the downward side at one rear end. The drying chamber, serving as a containment for the drying process, adopts a cubical structure with dimensions of 35 * 33 * 35 cm, housing three meshed trays with a 10 cm gap between each. Each tray, measuring 30 * 33 cm, permits the passage of hot air. The chimney, a prolonged narrow rectangular section, stands at a height of 190 cm and has a width of 15 cm, culminating in a conical cap at the top with openings on its sides.

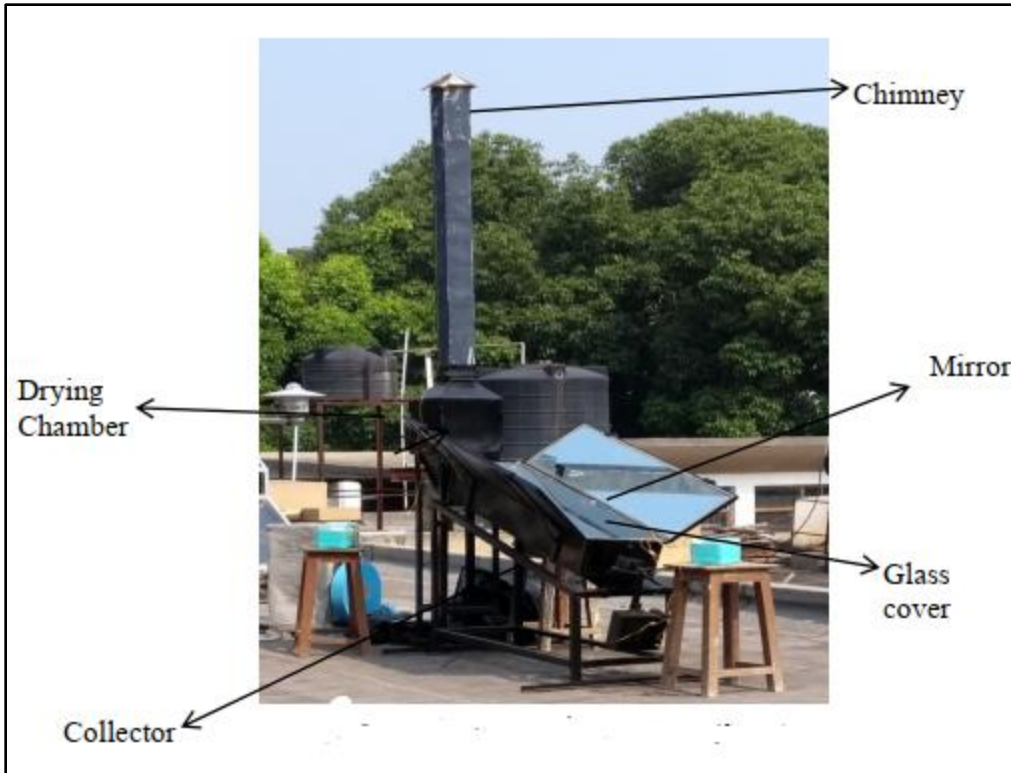


Fig. 1: Existing Flat plate solar dryer

2.2 Developed tracking system

A circuit configuration is devised as illustrated in Fig.2A, featuring two voltage comparators constructed with LM358 Dual Op-Amp. A light-dependent resistor (LDR) is coupled with a series resistor (R3 and R4), where an increase in the intensity of incident light on the LDR leads to a proportional rise in voltage across the corresponding resistor (R3 or R4). The inverting (-) terminals of both comparators are interconnected and linked to a variable resistor (RV1), serving as a reference voltage adjustment. Consequently, the sensitivity of both LDRs can be fine-tuned by manipulating the 10K potentiometer. When light intensity on an LDR increases, the voltage at the non-inverting (+) terminal of the respective comparator rises, causing its output to go high. Motor rotation direction is regulated by an H-Bridge configuration formed by complementary symmetry transistors BC547, BC557, and four MOSFETs (two p-n-p and two n-p-n types). For instance, when the output of the first comparator (U1: A) is high and the output of the second comparator (U1: B) is low, transistors Q1 and Q4 are activated, leading to a current flow that rotates the motor clockwise. Conversely, if the output of the first comparator is low and the output of the second comparator is high, transistors Q2 and Q3 are activated, causing the motor to rotate counterclockwise. In cases where the output of both comparators is low, transistors Q3 and Q4 are activated, but no current flows through the motor. Similarly, if the output of both comparators is high, transistors Q1 and Q2 are activated, but the motor remains devoid of current flow. The developed tracking system is depicted in the accompanying Fig.2B.

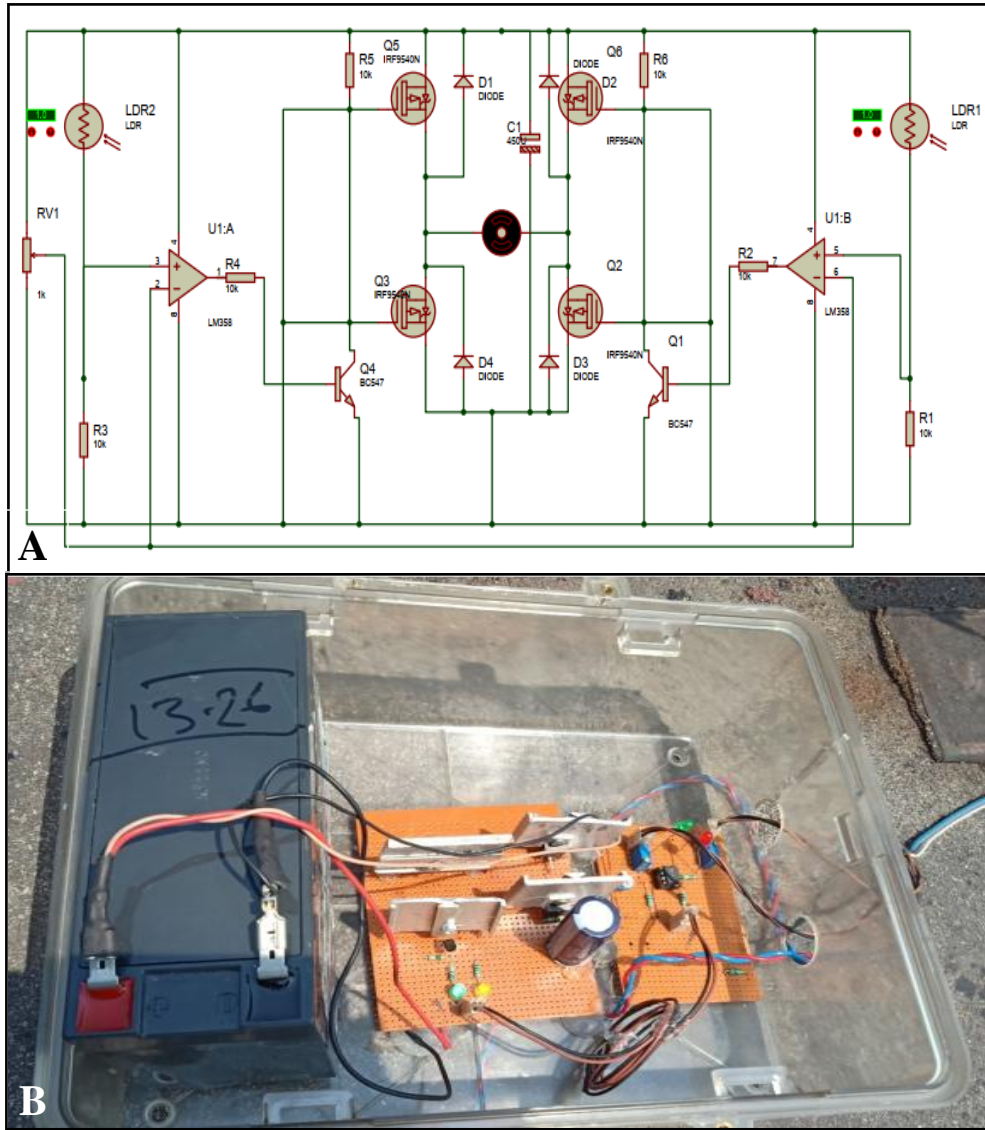


Fig. 2:(A) Schematic circuit diagram of developed tracking system (B) developed circuit

2.3 Developed sun-tracking solar dryer (STSD)

A structural framework supporting the DC wiper motor, worm gearbox, and linkage mechanism was engineered utilizing a mild steel iron angle with a thickness of 1.5 mm. This frame is affixed to the extended section of the weight of the Flat Plate Solar Dryer (FPSD). The frame's dimensions are configured to mirror the height and slope of the FPSD. A 12V DC wiper motor, with a torque rating of 18 Nm, was carefully chosen and linked to the connecting shaft through a worm gearbox featuring a speed ratio of 40:1. The output shaft of the gearbox is connected to a 1 mm MS flat, 30 cm in length, which is pivoted to a 60 cm MS flat. The other end of this 60 cm flat is attached to the dead weight of the FPSD. Consequently, when the motor imparts power to the gearbox, the flat undergoes a to-and-fro rotation in a semicircular trajectory resembling a pendulum motion, thereby inducing the rotation of the FPSD.

The integrated embedded system facilitates signal transmission to the wiper motor, dictating its clockwise and anticlockwise rotations in tandem with the sun's position. The motor rotations are meticulously regulated by the voltage supplied by Light-Dependent Resistor (LDR) sensors.

Importantly, the electrical circuit obviates the need for programming and computer interfacing. Geological data is deemed unnecessary, as LDRs operate differentially based on light intensity variations at both ends of the plate. For effective air circulation (2 m/s), an AC centrifugal blower boasting 0.5 hp and a rotation speed of 1450 rpm was incorporated. The culmination of these components results in the development of a comprehensive system termed a Sun-Tracking Solar Dryer (STSD) (Fig.3).

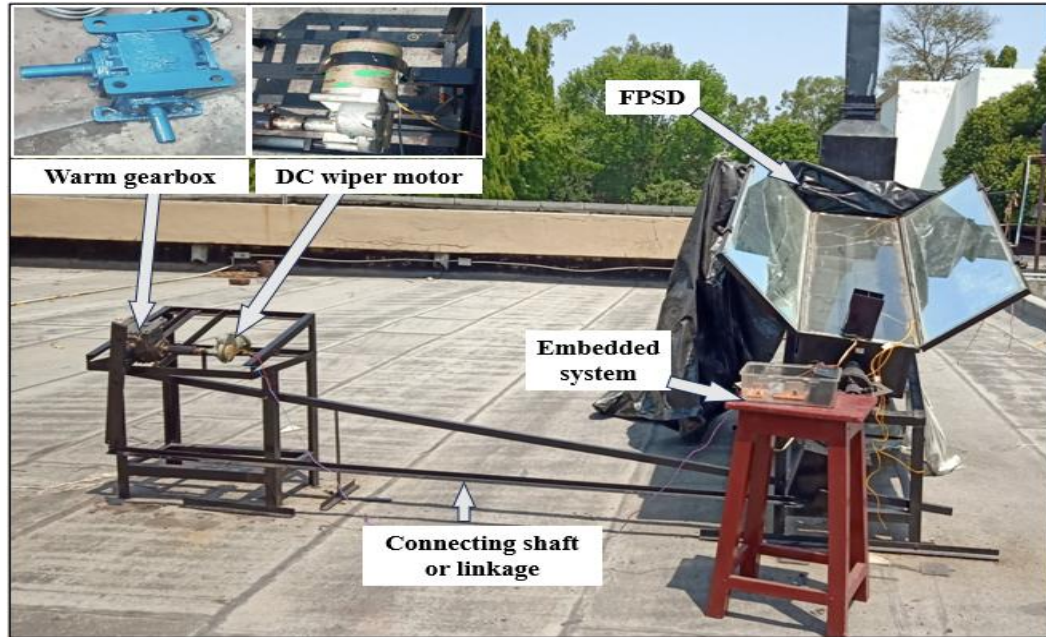


Fig. 3: Developed Sun tracking solar dryer

2.4 Green tea leaves processing

Tea leaves sourced from the Tea Engineering Research Centre, Agricultural and Food Department, IIT Kharagpur, West Bengal, constituted the basis for the study. The processing of green tea involved a sequence of fundamental operations, including plucking, de-enzyming, rolling, and drying, each pivotal in shaping the final product. Plucking, the initial operation, entailed the careful harvesting of young and tender leaves from tea plants, categorized into imperial (bud and one leaf), fine (bud and two leaves), and coarse (bud and more than two leaves) plucking types. The de-enzyming process aimed to heat tea leaves before fermentation, a precursor to the drying phase. In this study, steaming was employed as the de-enzyming method, involving exposure to temperatures of 95-100°C for 10-15 minutes. Rolling, a critical step influencing the visual characteristics of green tea, is typically executed using rolling machines in commercial settings. However, in our study, a manual hand-rolling approach was adopted after allowing the tea leaves to cool at room temperature for approximately 10-15 minutes, applying slight pressure by hand on a tray. Drying deemed the most crucial stage in green tea processing, was executed using the Sun-Tracking Solar Dryer (STSD) in our study. The utilization of STSD contributes to the efficient and controlled drying of tea leaves, thereby playing a central role in determining the quality attributes of the final green tea product.

2.5 Experimental setup

In the Sun-Tracking Solar Dryer (STSD), an array of 11 K-type thermocouples was strategically positioned at various locations, encompassing both the STSD and the drying chamber. These thermocouples served the purpose of measuring critical temperatures, including the inlet air

temperature (T_{ai}), outlet air temperature (T_{ao}), absorber plate temperature (T_{ap}), glass cover temperature (T_g), and the temperature of the product at the top (T_t), bottom (T_b), and the exhaust of the chimney (T_{ext}). Furthermore, two additional thermocouples were situated external to the dryer to capture the ambient air temperature (T_{amb}). The arrangement of green tea leaf samples on each fine mesh tray (30×33 cm) within the solar cabinet was integral to the experiment. Temperature readings were systematically recorded at regular 60-minute intervals, spanning from 9 a.m. to 4 p.m. Data were recorded and compared both with natural air circulation and with blower (forced air circulation).

2.6 Quality analysis of solar-dried green tea leaves

For quality analysis, various parameters, namely color, water activity, total phenolic content (TPC), and antioxidant activity, were measured for green leaves subjected to both open sun drying and drying with STSD. The color analysis involved the use of a colorimeter with CIE standard illuminant D65 at an observer angle of 10° to obtain coordinates in the CIE color spaces, L^* (lightness), a^* (redness/greenness), and b^* (yellowness/blueness). The objective of drying green tea leaves is to reduce moisture content, thereby impeding food spoilage caused by microorganisms and facilitating product storage. Water activity (a_w), measuring the free moisture content of the product, was determined for solar-dried green tea leaves using a water activity meter. The Total Phenolic Content (TPC) of both fresh and solar-dried green tea leaves (via open sun drying and STSD) was analyzed spectrophotometrically utilizing the Folin-Ciocalteu colorimetric method(8). The 2,2-Diphenyl-1-picrylhydrazyl (DPPH) method was employed to assess antioxidant properties, providing a quick, easy, and cost-effective approach to measure the potential of substances to act as hydrogen providers or free-radical scavengers.

3. RESULTS AND DISCUSSION

3.1 Performance evaluation of sun tracking by developed prototype

The evaluation of the solar tracker's performance involved measuring the angle from the vertical. The vertical direction served as the reference point, denoted as the 0° standard, while the east direction was considered positive and the west direction negative. An ideal angle was defined as the manually adjusted angle from the vertical when the incident rays were perpendicular to the surface, measured using a tilt level meter. Concurrently, the angle obtained with the developed tracker was measured (Fig. 4). The deviation from the ideal condition was determined by calculating the difference between these two angles. The graphical representation illustrated in the figure indicated that the angles obtained by the developed tracker closely approximated the ideal position. An average deviation of 3.25° was calculated, with a maximum deviation of 6°. Consequently, the data suggests that the solar tracker was functioning efficiently as designed. A comparative analysis was performed between stationary collectors and sun-tracking collectors with reflectors, revealing that the sun-tracking system produced more heat energy(9).

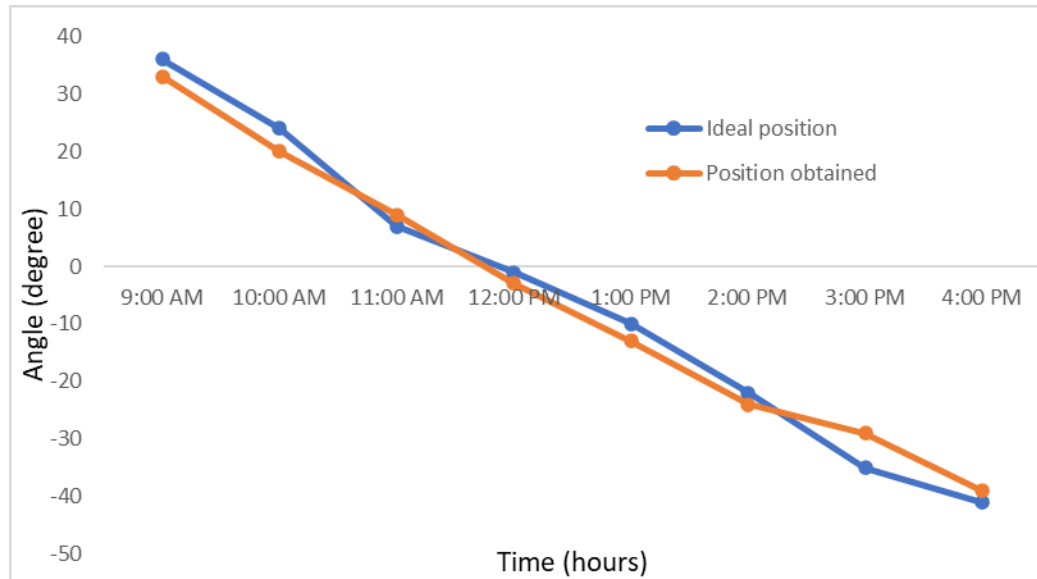


Fig. 4: Comparison of ideal positions and positions obtained by STSD

3.2 Comparison of temperature distribution

The temperature distribution at various points with natural air circulation (Fig. 5A) was juxtaposed with the temperature distribution at the same points with forced air circulation (Fig. 5B) for the Sun-Tracking Solar Dryer (STSD). Analysis of Figures 5A and 5B elucidates that the temperatures at all points experienced an increment from morning to afternoon, followed by a subsequent decrease from noon to evening. Notably, in both cases, the maximum temperature was observed at the absorber plate. The hot air emanating from the absorber plate facilitated moisture extraction from the trays and subsequently exited through the chimney. Comparative analysis revealed that, for both cases, the temperature at each point was higher for the STSD with forced circulation compared to the STSD with natural air circulation. This temperature disparity can be attributed to the elevated air pressure, leading to an increase in temperature and, consequently, enhancing the overall efficiency of the system(10).

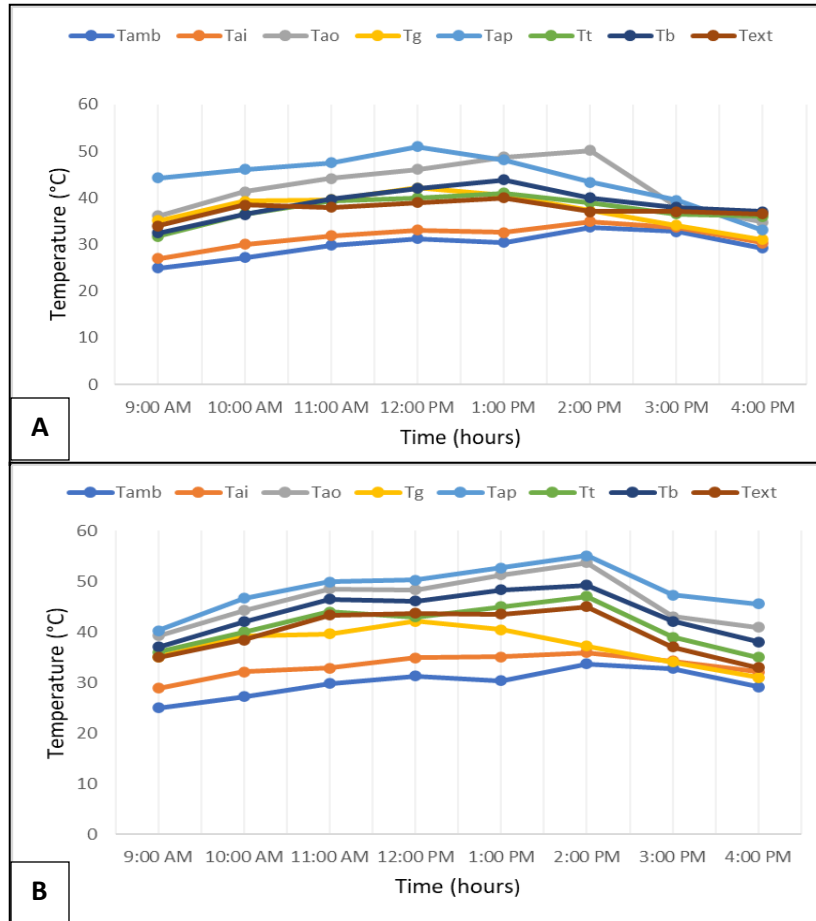


Fig.5: Temperature distribution at various points (A) STSD with natural air circulation (B) STSD with forced air circulation

3.3 Comparison of drying kinetics of green leaves

Steamed green tea leaves, initially possessing a moisture content within the range of 79.12% to 83.64% (dry basis), underwent drying processes until reaching a safe moisture content of 5% (dry basis) through the utilization of both Sun Tracking Solar Dryer (STSD) and open sun drying (OSD). The comparative analysis between open sun drying and forced convection solar dryer drying (STSD) is presented in Figure 6. The graph depicted the moisture content (dry basis) plotted against drying time (minutes). Figure 6 distinctly illustrated a noteworthy reduction in moisture content during solar drying in STSD in comparison to OSD. The graphical representation underscored that the drying process with STSD was approximately 2 hours shorter than that with OSD (11).

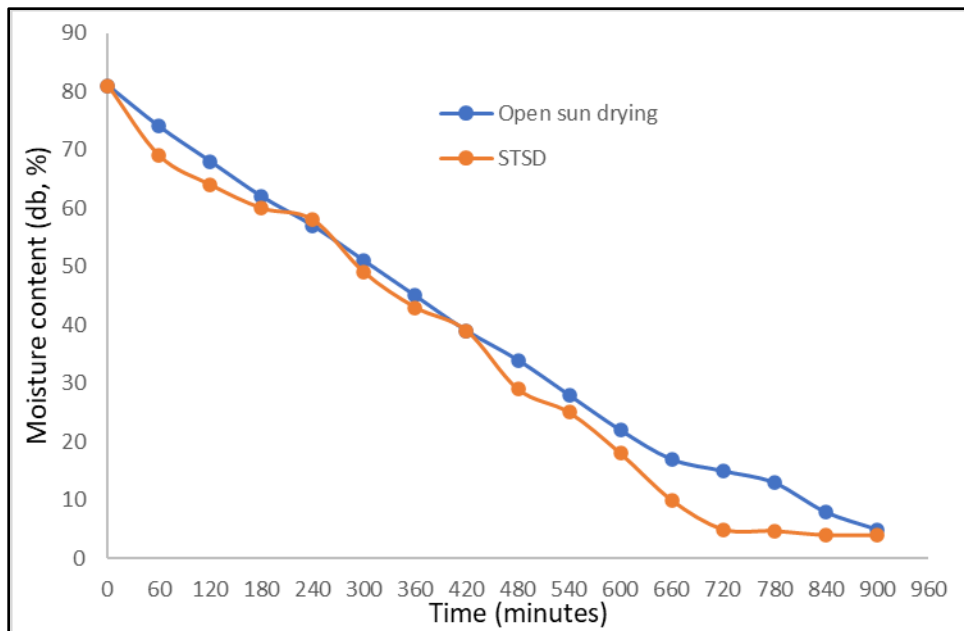


Fig. 6: Moisture content (dry basis) versus drying time curve

3.4 Evaluation of quality parameters of green leaves

Diverse quality attributes of both fresh and solar-dried green tea leaves, subjected to open sun drying (OSD) and solar-tracked solar dryers (STSD), were comprehensively assessed, and the outcomes are elucidated in Table 1. Notably, color, a pivotal quality attribute for both fresh and processed products, was evaluated using the CIELAB color space, recognized for its applicability in various industrial contexts, especially in the food sector (12). Examination of Table 1 revealed no significant disparity in most color parameters, with the exception of a^* . The a^* value exhibited an increase from -14.78 ± 1.32 (Fresh) to -3.04 ± 0.99 (open-dried), indicative of a lighter green tea color post-drying. Specifically, OSD resulted in a lighter shade of green tea leaves compared to STSD, albeit with compromised quality in the former. Water activity, a critical parameter ensuring microbiological safety, exhibited values below 0.6 post-drying, signifying a reduction in water content and microbial activity inhibition. Fresh tea leaves demonstrated a water activity of 0.901, diminishing to 0.531 after solar drying.

The total phenolic content (TPC) in fresh tea leaves registered at 311.6 mg GAE/g dm (dry matter). In OSD and STSD, TPC increased to 357.61 and 398.21 mg GAE/g dm, respectively, indicating a significant enhancement in phenolic content through solar drying. This augmentation in TPC in dried green tea leaves, compared to their fresh counterparts, may be attributed to the fermentation process, while OSD, characterized by more intense heat treatment, exhibited lower TPC, aligning with observations by (13). The DPPH radical scavenging activity exhibited an increasing trend from STSD to OSD. Fresh tea leaves displayed a remarkable $91.32 \pm 1.66\%$ inhibition of DPPH activity. However, solar drying led to a significant reduction in DPPH inhibition, attributed to the degradation of polyphenolic compounds, particularly catechins, under the influence of sunlight and heat during the drying process (14).

Table 1: Quality attributes of solar-dried leaves

Parameters	Fresh leaves	Open sun drying	STSD
------------	--------------	-----------------	------

L*	48.85 ± 5.21	28.05 ± 2.21	30.21 ± 2.1
a*	-14.78 ± 1.32	-3.04 ± 0.99	-5.0 ± 2.01
b*	22.88 ± 2.8	3.49 ± 1.65	0.69 ± 2.54
a _w (decimal)	0.901	0.554	0.531
TPC (mgGAE/gdm)	311.6	357.61	398.21
DPPH radical scavenging activity (%)	91.32 ± 1.66	75.41 ± 1.7	73.53 ± 2.3

4. CONCLUSION

In conclusion, this research presents a pioneering approach to solar technology in green tea leaf drying. The integration of an autonomous solar tracker in a flat plate solar collector enhances energy efficiency. The developed solar tracker demonstrates effective performance, aligning with the ideal solar position. The study emphasizes the advantages of indirect solar drying, showcasing superior quality attributes in green tea leaves. The Sun-Tracking Solar Dryer (STSD) proves to be a sustainable and efficient alternative to traditional drying methods, contributing valuable insights for optimizing tea processing in the industry.

REFERENCES

1. Chowdhury M, Thomas EV, Jha A, Kushwah A, Kurmi R, Khura TK, et al. An automatic pressure control system for precise spray pattern analysis on spray patternator. *Computers and Electronics in Agriculture*. 2023;214:108287.
2. Kushwah A, Sharma PK, Mani I, Kushwaha HL, Sahoo RN, Sarkar SK, et al. Parameter optimization for selective harvesting in cauliflower (*Brassica oleracea*) using response surface methodology. *Indian J Agri Sci*. 2023;93(8):912–8.
3. Yadav R, Sudhishri S, Khanna M, Lal K, Dass A, Kushwaha HL, et al. Temporal characterization of biogas slurry: a pre-requisite for sustainable nutrification in crop production. *Front Sustain Food Syst*. 2023;7:1234472.
4. Anonymous. Study to Determine the Level of Food Processing in India [Internet]. Ministry of Food Processing Industries, Government of India; 2021 Jul. Available from: https://www.mofpi.gov.in/sites/default/files/final_report_of_lop_july_2021.pdf
5. Chacko SM, Thambi PT, Kuttan R, Nishigaki I. Beneficial effects of green tea: A literature review. *Chin Med*. 2010;5(1):13.
6. Banerjee S, Chatterjee J. Efficient extraction strategies of tea (*Camellia sinensis*) biomolecules. *J Food Sci Technol* [Internet]. 2014 Aug 6 [cited 2023 Oct 22]; Available from: <http://link.springer.com/10.1007/s13197-014-1487-3>
7. Roshanak S, Rahimmalek M, Goli SAH. Evaluation of seven different drying treatments in respect to total flavonoid, phenolic, vitamin C content, chlorophyll, antioxidant activity and color of green tea (*Camellia sinensis* or *C. assamica*) leaves. *J Food Sci Technol*. 2016;53(1):721–9.
8. Kopjar M, Tadić M, Piližota V. Phenol content and antioxidant activity of green, yellow and black tea leaves. *Chem Biol Techn Agric*. 2015;2(1):1.

9. Afarulrazi AB, Utomo WM, Liew KL, Zarafi M. Solar Tracker Robot using microcontroller. In: 2011 International Conference on Business, Engineering and Industrial Applications [Internet]. Kuala Lumpur, Malaysia: IEEE; 2011 [cited 2023 Oct 22]. p. 47–50. Available from: <http://ieeexplore.ieee.org/document/5994256/>
10. Hegde VN, Hosur VS, Rathod SK, Harsoor PA, Narayana KB. Design, fabrication and performance evaluation of solar dryer for banana. *Energ Sustain Soc.* 2015;5(1):23.
11. Babar OA, Tarafdar A, Malakar S, Arora VK, Nema PK. Design and performance evaluation of a passive flat plate collector solar dryer for agricultural products. *J Food Process Engineering.* 2020;43(10):e13484.
12. Wu D, Sun DW. Colour measurements by computer vision for food quality control – A review. *Trends in Food Science & Technology.* 2013;29(1):5–20.
13. Chong KL, Lim YY. Effects of drying on the antioxidant properties of herbal tea from selected *vitex* species. *Journal of Food Quality.* 2012;35(1):51–9.
14. Alara OR, Abdurahman NH, Abdul Mudalip SK, Olalere OA. Effect of drying methods on the free radicals scavenging activity of *Vernonia amygdalina* growing in Malaysia. *Journal of King Saud University - Science.* 2019;31(4):495–9.