ISSN: 2347-467X, Vol. 13, No. (2) 2025, Pg. 667-682

Current Research in Nutrition and Food Science

www.foodandnutritionjournal.org

Drying Kinetics, Statistical and Nutritional Analysis of a Drip Lock Sheet Greenhouse Dryer for *Cucumis sativus* Drying

MADHANKUMAR SEENIVASAN[1,2]*, VELUSAMY KOLANDASAMY[3], SENTHILKUMAR KANDHAMPALAYAM MUTHUKRISHNAN[4], SELVAN THOTTIAPALAYAM ARUMUGAM[2], VISWANATHAN ARUMUTHU[5], RAJESH SURESH[6] and GOTTUMUKKALA SANTHI[7]

[1]Department of Mechanical Engineering, Indian Institute of Technology Guwahati, Assam, India.
[2]Department of Mechatronics Engineering, Sri Krishna College of Engineering and Technology, Coimbatore, India.
[3]Department of Mechanical Engineering, Annai Mathammal Sheela Engineering College, Namakkal, India.
[4]Department of Mechanical Engineering, Kumaraguru College of Technology, Coimbatore, India.
[5]Department of Mathematics, SNS College of Technology, Coimbatore, India.
[6]Department of Mechanical Engineering, R.M.K. Engineering College, Kavaraipettai, India.
[7]Department of Mathematics, SRKR Engineering College, Andhra Pradesh, India.

Abstract

This research focused on drying cucumber (*Cucumis sativus*) through multiple techniques, including Open Sun Drying (OSD) and a Drip Lock Sheet Greenhouse Dryer (DLSGD), functioning in natural and forced airflow modes. The effectiveness of the drying processes was analyzed using drying kinetics, statistical modelling, and nutrient retention studies. Under forced airflow at a flow rate of 1.2 m/s, the DLSGD reduced *Cucumis sativus* moisture levels from 94% to 11.5% within 4.5 days, whereas natural airflow achieved the same result in 5.7 days. In contrast, OSD needed 8 days for equivalent moisture removal. The drying patterns were described using twelve different predictive equations. The Midilli-Kucuk equation was found to be the most accurate for DLSGD in both airflow scenarios, while the Two-term equation best represented OSD. Nutritional evaluation revealed that DLSGD with forced airflow preserved 8.4% and 2.25% more carbohydrates than OSD and DLSGD with natural airflow, respectively. Furthermore, forced airflow resulted in

Article History
Received: 08 January 2025
Accepted: 25 April 2025

Keywords
Cucumis Sativus;
Drying Kinetics;
Greenhouse Dryer;
Nutritional Analysis;
Statistical Modelling.

CONTACT Madhankumar Seenivasan madhankumars@skcet.ac.in Department of Mechanical Engineering, Indian Institute of Technology Guwahati, Assam, India.

Doi: https://dx.doi.org/10.12944/CRNFSJ.13.2.9

higher calcium retention, while natural airflow better preserved Vitamin C content. Ultimately, the research identified forced airflow in DLSGD as the most effective drying method, surpassing others in drying rate and nutrient preservation, making it a viable option for industrial use where performance and product quality are essential.

Abbreviations

χ^2	Chi-square
R2	Coefficient of determination
DLSGD	Drip Lock Sheet Greenhouse Dryer
m	Mass of the sample (kg)
M_R	Moisture ratio
OSD	Open Sun Drying
RMSE	Root Mean Square Error
YU	Uncertainty

Introduction

Cucumis sativus, a prominent horticultural crop, holds significant importance in India's farming sector and everyday cuisine. Extensively cultivated in regions such as Karnataka, Andhra Pradesh, Tamil Nadu, Maharashtra, and Uttar Pradesh, India is among the leading global producers of *Cucumis sativus*. This vegetable flourishes in warm climates with well-aerated soils and reliable irrigation, often grown as a short-cycle crop under open-field conditions or in controlled environments. Its adaptability to varied agricultural methods makes it an essential component of India's vegetable output.[1] Renowned for its exceptional water content (approximately 94%), *Cucumis sativus* is a hydrating and cooling dietary option. With only 15 calories per 100 grams, it is a low-calorie food enriched with nutrients such as vitamins C and K, potassium, magnesium, and antioxidants like flavonoids and beta-carotene. The fiber content aids digestion, while the high water content supports hydration and improves skin vitality. Additionally, silica present in *Cucumis sativus* contributes to enhanced skin firmness and joint flexibility.[2] From a health perspective, *Cucumis sativus* offer notable benefits due to their anti-inflammatory and antioxidant attributes, helping to mitigate oxidative damage and lowering the risks of chronic disorders such as heart illness, diabetes, and cancers. Their mild diuretic action promotes detoxification and assists in regulating blood pressure. Moreover, *Cucumis sativus* derivatives are widely utilized in cosmetic products for their cooling, soothing, and anti-aging properties.[3] As a result, *Cucumis sativus* serve not only as a valuable agricultural product in India but also as a significant element of nutrition and holistic health. Although *Cucumis sativus* offers numerous health advantages, it is highly perishable, with its availability often restricted by seasonal and geographic factors. To overcome these challenges and prolong its usability, preservation techniques like dehydration are vital. Drying not only ensures a consistent supply of *Cucumis sativus* throughout the year but also retains their essential nutrients. The primary objectives of drying are to extend shelf life and minimize post-harvest wastages, which are key to ensuring food security and reducing waste. A key approach to extending the shelf life of a specimen is by reducing its moisture content to below 11% on a wet basis. Reaching this wet threshold is essential to prevent deterioration and preserve the product's quality for a prolonged period. These standards act as important benchmarks for maintaining the ideal moisture levels in dehydrated food items, helping to enhance their durability and preserve their nutritional value.[4]

Preservation methods play a crucial role in maintaining the nutritional integrity of vegetables after harvest.[5] Among these, greenhouse drying has emerged as an eco-friendly and sustainable solution.[6] This technique is particularly effective in reducing the environmental impact of the drying process while ensuring the quality and nutritional value of food products, making it an ideal choice for long-term preservation.[7] A natural-mode greenhouse dryer was first developed for drying vermicelli products of varying sizes, providing a more eco-friendly alternative to the OSD method.[8] Another greenhouse dryer was created for drying ginger and turmeric in natural and forced convection modes, where heat absorption within the dryer caused the ginger and turmeric temperature to exceed that of the surrounding air.[9] The implementation of a mixed-mode greenhouse dryer, which combines both natural and forced convection drying methods, has been shown to accelerate the drying process for red pepper and grape, with forced airflow significantly reducing the overall drying time compared to natural airflow. Optimizing the use of greenhouse dryers can also contribute to reducing carbon dioxide emissions.[10] In a constructed setup, the item undergoing drying is enclosed within a framework encased by a transparent cover that shields it from contaminants. The cover absorbs sunlight, raising the temperature of the internal air in the greenhouse, which facilitates moisture extraction from the item.[11]

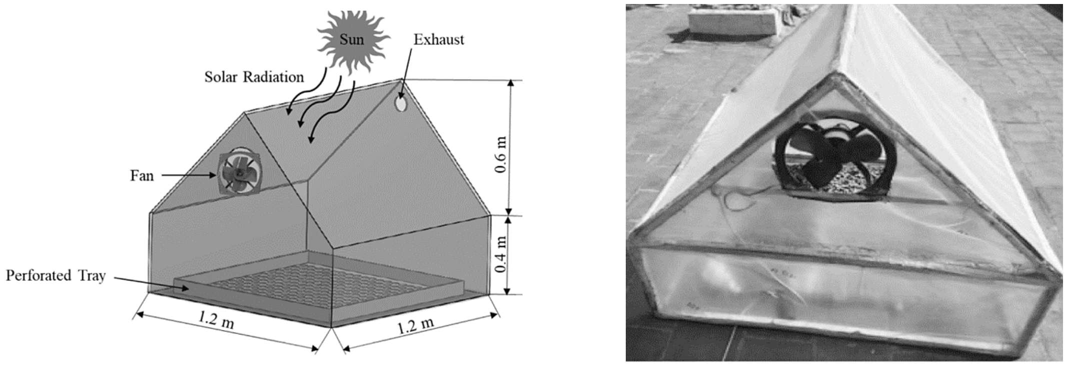
Recent progress in solar-powered drying systems for greenhouses has been investigated by numerous scientists, who have employed various types of covering materials to improve the performance of the drying units. When transparent glass is utilized as the covering in a natural greenhouse dryer, the drying period for pepper is shortened by 30%. Adding a non-transparent northern wall and dark PVC coverings on the ground minimized heat dissipation in both natural and forced greenhouse dryer configurations. Enhanced energy transmission has been noted when ginger has been dried using a forced greenhouse dryer system.[12] To dehydrate bitter melon samples, a natural greenhouse dryer with a roof-shaped plastic cover was designed, featuring a sheet with a depth of 0.0015 meters. In comparison to the OSD method, the forced convection greenhouse dryer demonstrated a higher convective heat transfer coefficient.[13] Cassava chips was dehydrated utilizing a natural convection drying system with a plastic cover, employing transparent glass with a thickness of 0.005 meters as the glazing material, which resulted in a 30% reduction in drying time.[14] The effectiveness of the greenhouse drying technique for dehydrating mint leaves has been evaluated and contrasted with the OSD technique, utilizing ten statistical models to analyze the drying kinetics.[15]Likewise, ten statistical models have been applied to examine and describe the moisture removal operation of handmade papers in greenhouse dryer, with the Midilli-Kucuk model providing the best fit to the empirical results.[16] These models play an important part in understanding the drying behaviour of food products in greenhouse dryer under different time conditions, aiding in the enhancement of drying process predictions. Items dried in greenhouse dryer generally show superior quality compared to those dried through conventional methods.

The literature review highlights a limited understanding of the drying kinetics of *Cucumis sativus*. To address this gap, this study introduces a straightforward DLSGD under both natural and forced convection, aiming to evaluate its effectiveness in moisture removal. The research objectives include developing and enhancing a greenhouse dryer by incorporating a drip lock glazing sheet to optimize the drying process. In this study, *Cucumis sativus* was selected as the plant material. The samples were sourced from a local farm and authenticated based on botanical characteristics. The plant material was assigned the Boucher number Sp. Pl. 1012/1753, serving as a reference for identification and traceability in the study. Additionally, experimental observations will compare the efficiency of OSD and DLSGD under both convection conditions. The study will also examine drying kinetics by measuring moisture content, moisture ratio, and drying rates to achieve the safest moisture level in the shortest possible time. Furthermore, eleven mathematical models will be utilized to identify the most accurate drying model for each technique, using statistical matrices such as R^2, RMSE, and χ^2. Lastly, the research will investigate the nutritional retention of essential components like carbohydrates, vitamin C, and calcium in *Cucumis sativus*, assessing the impact of different drying methods on nutrient preservation and overall drying effectiveness.

Materials and Methods

DLSGD System

A DLSGD, designed with a 1.2 m × 1.2 m floor area and a 1 m height, enclosed with drip lock glazing sheet of 0.001 m thick to capture solar radiation. This setup developed for *Cucumis sativus* drying in both natural and forced convections. In natural convection, the dryer uses natural solar energy and a tactically positioned roof vent to facilitate airflow, enabling drying without mechanical support. In forced convection, a fan working at 1.2 m/s improves air movement inside the dryer. These design features ensure effective air movement and maximize solar energy absorption. Figure 1 presents a schematic of the DLSGD built for this drying operation. The dryer was intentionally oriented in an east–west direction to optimize sunlight exposure. For both OSD and DLSGD processes, 2 kg *Cucumis sativus* samples were placed in trays. *Cucumis sativus* pieces were uniformly sliced to a thickness of 0.005 m for consistency during drying. The drying experiments took place from 08:00 to 17:00 hours in May 2024. To prevent moisture reabsorption overnight, sealed plastic covers have been utilized to store the dried *Cucumis sativus*. The goal was to achieve a safest moisture content suitable for storage, ensuring the dried product's quality and extending its shelf life by efficiently using solar irradiation in the DLSGD system.



(a) (b)

Fig. 1: (a) Schematic representation of designed DLSGD and (b) Developed experimental DLSGD system

The examination utilized the HR83 Halogen moisture analyzer to determine the initial water content of the *Cucumis sativus*. Solar irradiance has been measured with a solarimeter that can gauge values up to 1500 W/m², with a precision of ±5%. Temperature readings were taken using infrared thermocouples, which provide a precision of ±1.5°C and could be measured up to 100°C. Wind velocity in the experimental environment was evaluated with the Benetech anemometer, which has a measurement range from 0 to 30 m/s. These specialized and accurate tools supplied reliable data on important ecological parameters, enabling a complete assessment of the drying conditions for *Cucumis sativus* in both the OSD and DLSGD devices.

Table 1: Uncertainties in the observed and computed variables

Parameters	Uncertainty
Temperature (°C)	2.04%
Solar irradiation (W/m²)	3.98%
Air velocity (m/s)	0.96%
Specimen mass (kg)	0.53%
Moisture content (%)	1.87%
Drying rate (kg/hr)	2.14%
Moisture ratio	1.56%

Uncertainty Analysis

The reliability of the data could be affected by dimensions measured errors during the drying operation like precision, calibration, and interpretation inaccuracies. Temperature, air velocity, mass, and solar irradiation are independent variables in the *Cucumis sativus* dehydrating process, while moisture content and drying rate are dependent variables.[17] Let Y_1, Y_2, Y_3, …, Yn represent the independent parameters, each linked to uncertainties signified by X_1, X_2, X_3, …, Xn. These uncertainties in the independent variables impact the accuracy and precision of the observations in the drying operation. The dependent outcome, Y, is influenced by these independent parameters, and its uncertainty is termed by YU in Equation (1).[18] The uncertainties in both the observed and computed variables are provided in Table 1.

$$Y_U = \pm\sqrt{\left(\frac{\partial U}{\partial X_1}Y_1\right)^2 + \left(\frac{\partial U}{\partial X_2}Y_2\right)^2 + \cdots + \left(\frac{\partial U}{\partial X_n}Y_n\right)^2} \quad ...(1)$$

Drying kinetics

The starting moisture level of the *Cucumis sativus* was measured at 94% employing a Halogen moisture analyzer, regulated to a drying temperature of 120°C. The moisture content of the specimens during the drying process was calculated throughout the day using Equation (2) in % wet basis. This wet basis calculation monitored changes in moisture content over the course of the drying process:[19,20]

Moisture content=$(m_i$-$m_f)$/m×100 ...(2)

where m_i and m_f represent the initial and final masses of the sample during the drying process, respectively in kg, while *m* denotes the total mass of the *Cucumis sativus* sample (2 kg). The drying process is finalized once the *Cucumis sativus* achieves a moisture level close to 11.5%.

The drying rate is a vital parameter for assessing the efficiency of the drying process. It is determined using Equation (3) in kg/hr, which quantitatively measures the speed at which the drying process occurs and the effectiveness of reaching the target moisture content for storage. This metric is crucial for analyzing and relating various drying techniques, providing key insights into the overall effectiveness of the drying system.[21]

Drying rate=$(m_i$-$m_f)$/(Drying duration) ...(3)

The moisture ratio is a critical parameter for assessing and comparing the performance of greenhouse dryers. It is mathematically defined by Equation (4), offering a quantitative representation of the moisture level in relation to the solid mass of the sample.[22] This parameter serves as a key metric for analyzing and benchmarking the effectiveness of various dehydrating techniques and systems in *Cucumis sativus* drying processes:[23]

Moisture ratio,M_R=$(MC_{it}$-$MC_e)$/$(MC_i$-$MC_e)$ ...(4)

Here, MC_{it} represents the instantaneous moisture content, MC_e denotes the equilibrium moisture content, and MCi refers to the initial moisture content in % wet basis.

Table 2: Mathematical models for understanding the drying behaviour of *Cucumis sativus*[26,27]

S. No	Mathematical model names	Model equation
1.	Lewis	$M_R = e^{-bt}$
2.	Modified Page	$M_R = e^{[-(bt)n]}$
3.	Henderson and Pabis	$M_R = Be^{-bt}$
4.	Logarithmic	$M_R = Be^{-bt} + C$
5.	Midilli and Kucuk	$M_R = B_1\ e^{-btn} + B_2\ t$
6.	Two-term	$M_R = B_1\ e^{-b1t} + B_2\ e\ -b_2t$
7.	Modified Henderson and Pabis	$M_R = B_1\ e^{-b1t} + B_2\ e\ -b_2t + B_3\ e\text{-}b_3t$
8.	Wang and Singh	$M_R = 1+B_1\ t+b_2t^2$
9.	Diffusion approach	$M_R = B_1\ e^{-bt} +(1-B_1)e^{-bB2\ t}$
10.	Verma *et al.*	$M_R = B_1\ e^{-bt} +(1-B_1)e^{-b2\ t}$
11.	Weibull	$M_R = B_1\text{-}B_2\ e\text{-}^{btn}$

Statistical Analysis

The constants of the model were determined and the curve-fitting process was executed using the Excel Solver tool to evaluate the mathematical models for *Cucumis sativus* drying. Nonlinear regression analysis was conducted for the eleven models presented in Table 2. Key evaluation parameters, such as the coefficient of determination (R^2), Root Mean Square Error (RMSE), and reduced chi-square (χ^2), were employed to assess the fitting quality of each model.[24] The model that exhibited the maximum R^2 and the minimum RMSE and χ^2

values was identified as the most suitable. Equations (5), (6), and (7) were applied to calculate the R^2, RMSE, and χ^2 values, respectively. These metrics play a crucial part in determining the precision and reliability of the mathematical models describing the drying behavior of *Cucumis sativus* under the specified experimental conditions.[25]

$$R^2 = 1 - \frac{\sum_{i=1}^{n}(M_{Rfi} - M_{Rei})^2}{\sum_{i=1}^{n}(M_{Rfmi} - M_{Rei})^2} \quad ...(5)$$

$$\chi^2 = \frac{\sum_{i=1}^{n}(M_{Rei} - M_{Rfi})^2}{n-m} \quad ...(6)$$

$$RMSE = \frac{1}{n}\sum_{i=1}^{n}\left(M_{Rfi} - M_{Rei}\right)^2 \quad ...(7)$$

Where, n and m represent the number of observations and the constants of the mathematical model, respectively. M_{Re}, M_{Rf} and M_{Rfm} correspond to the empirical, forecasted, and mean forecasted moisture ratios.

Nutritional Analysis

The drying of food products can greatly affect their nutritional value, influenced by variables like pre-treatment techniques, drying temperature, and storage conditions.[28] To reduce nutrient degradation, methods like reducing moisture removal durations, using minimal temperatures, and controlling oxygen exposure during preservation can be applied.[29,30] In this study, these issues were tackled by incorporating drip lock glazing sheet material. The goal was to reduce nutrient loss and decrease drying times for *Cucumis sativus* in both natural and forced convection drying conditions. This method represents a pro-forced approach to improve the quality of the dried samples while preserving the nutritional content of the *Cucumis sativus* by optimizing the drying process. The analytical methods used for measuring the nutritional content of food samples are discussed further. The mineral composition, including calcium and iron, has been analyzed using an atomic absorption spectrophotometer, following modified standard procedures as outlined in the referenced methodology.[31] The Kjeldahl method has been employed for protein measurement.[32] The equations and methodologies used for determining ash content and carbohydrate content were adopted from the references cited in[31] and[34] respectively. The ascorbic acid (vitamin C) concentration in fresh and dehydrated *Cucumis sativus* samples was determined using a modified titration method.[33]

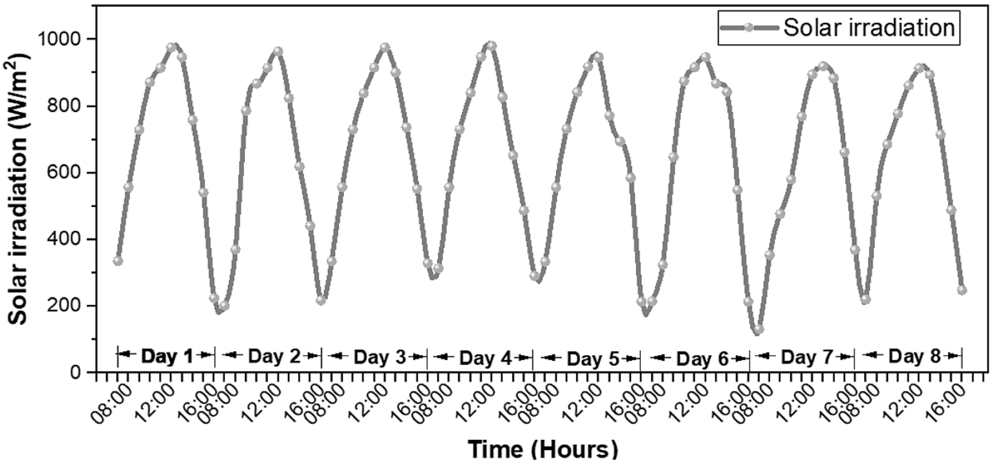


Fig. 2: Variations of solar irradiance with drying hours

Results

Experimental Results

Experimental assessments have been performed to evaluate the performance of DLSGD configurations and OSD in removing moisture from *Cucumis sativus* slices. Observations were carried out under both natural and forced airflow scenarios. A comprehensive error assessment was conducted on the collected parameters, verifying that all equipment readings were within permissible limits, ensuring data accuracy. Figure 2 illustrates the daily fluctuations in solar energy levels over eight consecutive days in May 2024, measured between 08:00 and 17:00 hours. The mean solar energy intensity was approximately 649.2 W/m². Peak solar intensity of 980.6 W/m² was recorded at 13:00 hour on 05 May 2024. To maintain the target moisture level and prevent humidity absorption from the environment, the dehydrated specimens were stored securely in sealed containers at the conclusion of every session. The drying experiments were repeated daily to ensure uniformity and facilitate cross-comparison of outcomes among various sessions. Natural and forced airflow approaches, alongside the OSD technique, were executed concurrently under equivalent environmental parameters. This methodology enabled a detailed evaluation of the drying approaches and supported an in-depth comparison of their performance.

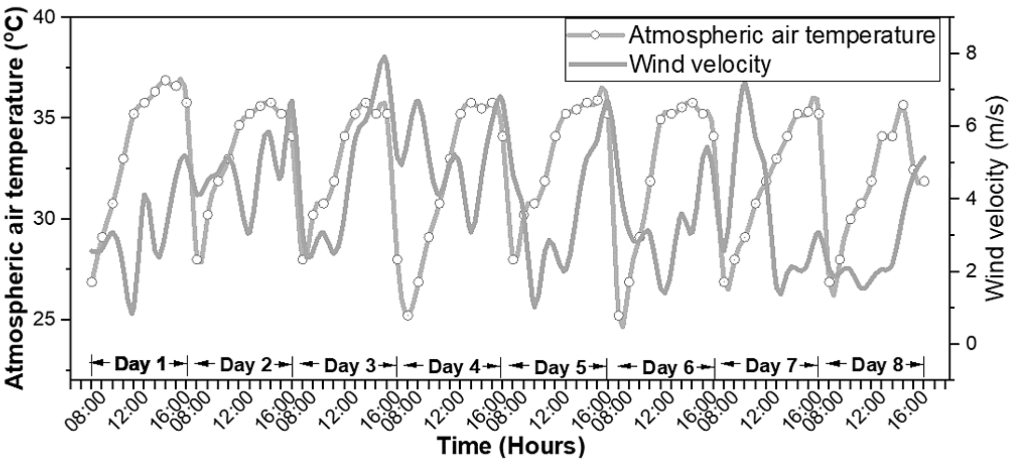


Fig. 3: Variations of atmospheric air temperature and wind velocity with drying hours

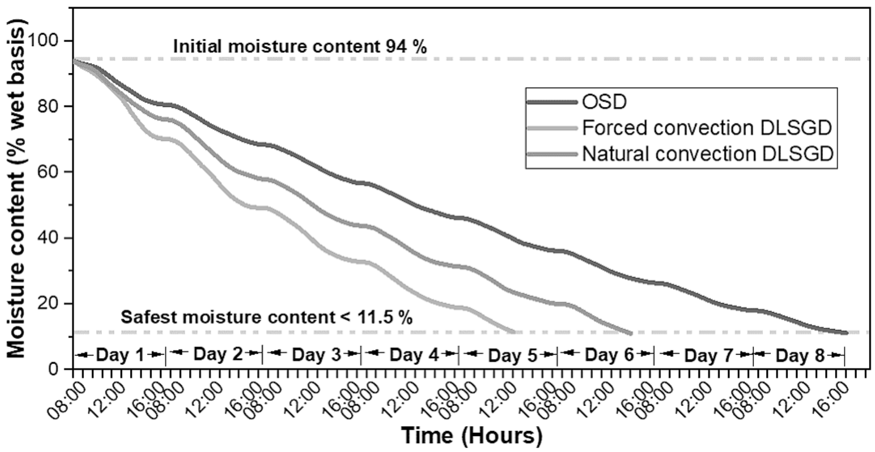


Fig. 4: Moisture content of the *Cucumis sativus* in DLSGD and OSD with drying hours

Figure 3 illustrates the daily patterns of ambient air temperatures and wind speeds recorded between 08:00 and 17:00 hours. On 02 May 2024, the maximum air temperature reached 36.9°C around 14:00 hour. The temperature ranged between 25°C and 37°C, exhibiting a direct correlation with solar radiation rising with increased solar intensity and declining as it decreased. Wind speeds fluctuated between 1.03 m/s and 7.19 m/s, with an average value of 3.91 m/s. For the forced convection experiments, a consistent wind velocity of 1.2 m/s was applied to study the drying behavior of the *Cucumis sativus* slices.

Drying Kinetics

The initial moisture content of *Cucumis sativus*, measured at 94%, was reduced to a preservation target of below 11.5% over varying durations depending on the drying method. The OSD process required 8 days to achieve a moisture content of 11.5%. In comparison, the DLSGD system operating under forced convection achieved a moisture content of 11.4% in 4.5 days, while the natural convection mode of the DLSGD system reached 11.05% in 5.7 days. These findings underscore the superior efficiency of greenhouse drying, particularly in forced convection mode, for rapidly lowering the moisture content of *Cucumis sativus*. The selection of drip-lock glazing material played a crucial role in optimizing the drying process, enhancing the overall efficiency of the system. Forced convection in the DLSGD system accelerated moisture reduction due to improved heat transfer facilitated by enhanced air circulation. This faster drying process not only preserves higher nutritional content by reducing the product's exposure to heat and air but also extends shelf life by minimizing moisture levels more effectively, thereby preventing microbial growth and spoilage.[35,36] Figure 4 provides a graphical representation of the gradual decrease in moisture content over time across various dehydration techniques, including OSD and DLSGD under both natural and forced convection modes.

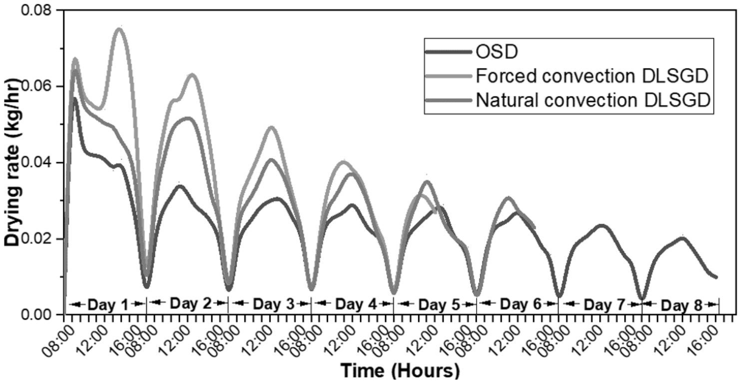


Fig. 5: Drying rate of the *Cucumis sativus* in DLSGD and OSD with drying hours

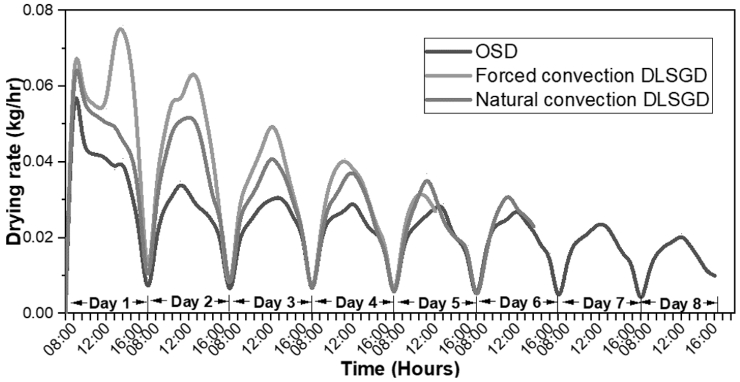


Fig. 5: Drying rate of the *Cucumis sativus* in DLSGD and OSD with drying hours

The choice of glazing material significantly affects both the drying rate and the dryer inside air temperature. Larger heat transfer rates result in faster drying. Figure 5 provides a visual comparison of drying rate variations over several days for DLSGD in both natural and forced convection modes, as well as for OSD. Experimental findings reveal the following average drying rates: 0.0221 kg/hr for OSD, 0.0379 kg/hr for DLSGD under forced convection, and 0.0303 kg/hr for DLSGD under natural convection. Among these, the DLSGD system operating in forced convection mode exhibits the highest drying rate. This can be attributed to the enhanced air movement generated by the fan, which improves heat transfer efficiency, and the glazing material, which effectively increases the internal temperature of the greenhouse dryer. During the initial hours of the first day, the drying rate is notably higher across all methods due to the rapid removal of surface moisture from the sample. However, as drying progresses, the rate steadily decreases, aligning with observations in prior research studies.[37]

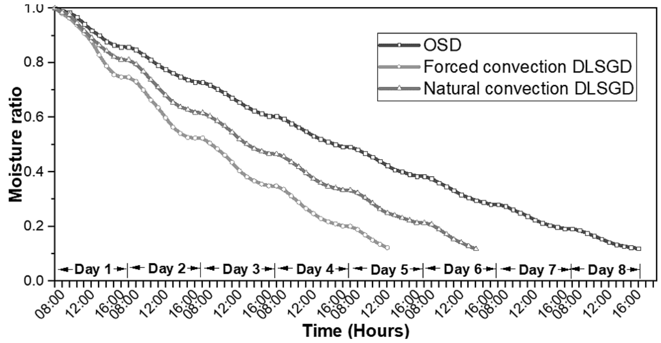


Fig. 6: Moisture ratio of the *Cucumis sativus* in DLSGD and OSD with drying hours

Figure 6 illustrates the temporal variation of moisture content in *Cucumis sativus* samples based on observed results. A final moisture level of roughly 0.12 was attained after 4.5 days using the DLSGD setup with forced airflow, 5.7 days with natural airflow, and 8 days using the OSD approach. These variations highlight the differing effectiveness of the drying techniques in achieving target moisture levels within specified timeframes. In the early stages, surface moisture is quickly eliminated, driven predominantly by evaporation. As drying advances, the moisture removal rate declines, shifting to the internal movement of moisture toward the surface, supported by thermal energy. This leads to a consistent decline in moisture levels throughout the drying period. Of all methods, the OSD process shows the slowest rate of moisture loss, while greenhouse drying methods, particularly those employing forced airflow, demonstrate superior drying effictiveness.

Mathematical Model Analysis

A regression analysis has been conducted on twelve different models, as detailed in Table 2, to identify the most suitable model for describing the thin-layer drying behavior of *Cucumis sativus*. The evaluation criteria focused on selecting the model with the maximum R^2 value and the minimum RMSE and χ^2 values. All models showed a strong correlation with the empirical observations. The findings indicated that the Two-term model provided the best representation of *Cucumis sativus* drying under OSD, with parameters $R^2 = 0.982679$, RMSE = 0.033165, and $\chi^2 = 0.001619$, as outlined in Table 5. For DLSGD, the Midilli and Kucuk model emerged as the most accurate under both natural and forced convection conditions, achieving $R^2 = 0.997452$, RMSE = 0.014567, and $\chi^2 = 0.000263$ for natural convection (Table 3), and $R^2 = 0.997685$, RMSE = 0.013751, and $\chi^2 = 0.000226$ for forced convection (Table 4). To further validate this model, the error analysis of predicted versus actual moisture ratios over drying hours in the DLSGD forced convection was performed. Most error values were near zero, confirming the high accuracy of predictions. Changes in air temperature and initial moisture content of the sample were identified as key factors influencing the observed deviations in moisture ratio during the drying operation. The mathematical equations that best describe the drying behaviour of *Cucumis sativus* slices in the DLSGD system under natural convection, forced convection, and OSD are presented as Equations (8), (9), and (10), respectively. These equations represent the optimal models derived from regression analysis, reflecting the drying kinetics for each drying method.

$$M_R = 0.9742e^{-0.0431t^{1.7125}} + 0.0091t \quad ...(8)$$

$$M_R = 0.9754e^{-0.052t^{1.5874}} + 0.0071t \quad ...(9)$$

$$M_R = 0.8593e^{-0.1602t} + 0.0883e^{-0.2606t} \quad ...(10)$$

Table 3. Results of mathematical models of drying behaviour of the *Cucumis sativus* in DLSGD during natural mode

S. No	Mathematical model names	Coefficients	R^2	χ^2	RMSE
1.	Lewis	b=0.1382	0.966291	0.003655	0.055015
2.	Modified Page	b=0.1384;n= 1.3301	0.989703	0.001047	0.030186
3.	Henderson and Pabis	B=1.0857;b=0.1519	0.976553	0.002727	0.045812
4.	Logarithmic	B=1.1746;b=0.1213;C=-0.1145	0.980413	0.002474	0.041832
5.	**Midilli and Kucuk**	**B_1=0.9742;b=0.0431; n=1.7125;B_2=0.0091**	**0.997452**	**0.000263**	**0.014567**
6.	Two-term	B_1=0.5428;b_1=0.5431; B_2=0.1504;b_2=0.1504	0.976553	0.003288	0.045812
7.	Modified Henderson and Pabis	B_1=0.3622;b_1=0.1486; B_2=0.3622;b_2=0.1486;` B_3=0.3622;b_3=0.1486	0.976553	0.00413	0.045812
8.	Wang and Singh	B_1=-0.1131;B_2=0.0042	0.984436	0.001777	0.037251
9.	Diffusion approach	B_1=1;b=0.1382;B_2=1	0.966291	0.004334	0.055015
10.	Verma *et al.*	B_1=1.4872;b_1=0.1925;b_2=0.5526	0.991718	0.000986	0.027004
11.	Weibull	B_1=0.1239;B_2=-0.8475; b=0.0392;n=1.7976	0.997212	0.000263	0.015291

Table 4. Results of mathematical models of drying behaviour of the *Cucumis sativus* in DLSGD during forced mode

S. No	Mathematical model names	Coefficients	R^2	χ^2	RMSE
1.	Lewis	b=0.1414	0.972773	0.002898	0.049122
2.	Modified Page	b=0.1405;n=1.3067	0.993502	0.000616	0.023703
3.	Henderson and Pabis	B=1.0745;b=0.1525	0.981034	0.002161	0.040927
4.	Logarithmic	B=1.1765;b=0.12;C=-0.1274	0.985749	0.001751	0.035408
5.	**Midilli and Kucuk**	**B_1=0.9754;b=0.052; n=1.5874;B_2=0.0071**	**0.997685**	**0.000226**	**0.013751**
6.	Two-term	B_1=0.5377;b_1=0.5377; B_2=0.1525;b_2=0.1525	0.981034	0.002609	0.040927
7.	Modified Henderson and Pabis	B_1=0.3587;b_1=0.1525; B_2=0.3587;b_2=0.1525; B_3=0.3587;b_3=0.1525	0.981034	0.003281	0.040927
8.	Wang and Singh	B_1=-0.1144;B_2=0.0044	0.990028	0.001088	0.029532
9.	Diffusion approach	B_1=1;b=0.1414;B_2=1	0.972773	0.00344	0.049122
10.	Verma *et al.*	B_1=1.5644;b_1=0.1983; b_2=0.4811	0.994565	0.000604	0.021611
11.	Weibull	B_1=0.1005;B_2=-0.8745; b=0.0498;n=1.6487	0.99752	0.000241	0.014273

Table 5. Results of mathematical models of drying behaviour of the *Cucumis sativus* in OSD

S. No	Mathematical model names	Coefficients	R^2	χ^2	RMSE
1.	Lewis	b=0.0997	0.981462	0.001399	0.034324
2.	Modified Page	b=0.0997;n=0.9669	0.981927	0.001457	0.033886
3.	Henderson and Pabis	B=0.9985;b=0.0995	0.981469	0.001497	0.034318
4.	Logarithmic	B=0.9692;b=0.1087;C=-0.039	0.981909	0.001569	0.033903
5.	Midilli and Kucuk	B_1=1.0203;b=0.1212; n=0.9046;B_2=-0.0017	0.982371	0.00165	0.033462
6.	**Two-term**	**B_1=0.8593;b_1=0.1602; B_2=0.0883;b_2=0.2606**	**0.982679**	**0.001619**	**0.033165**
7.	Modified Henderson and Pabis	B_1=0.4079;b_1=0.0883; B_2=0.1602;b_2=0.2606; B_3=0.4517;b_3=0.0883	0.982679	0.001928	0.033165
8.	Wang and Singh	B_1=-0.0862;B_2=0.0025	0.971559	0.002349	0.042609
9.	Diffusion approach	B_1=1;b=0.0997;B_2=1	0.981462	0.00161	0.034324
10.	Verma *et al.*	B_1=0.866;b_1=0.0894;b_2=0.22	0.982257	0.001537	0.033572
11.	Weibull	B_1=-0.0287;B_2=-1.0469; b=0.1167;n=0.9188	0.98227	0.00166	0.033559

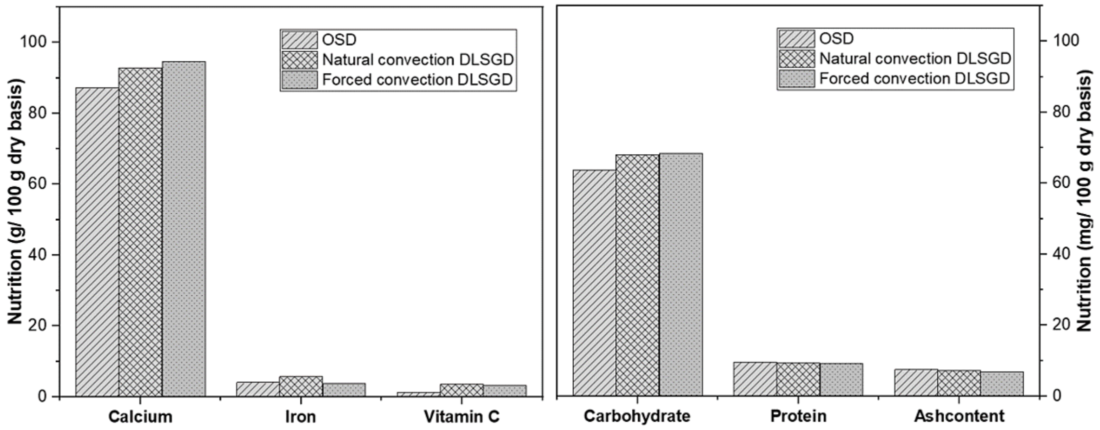


Fig. 7: Variation of nutritional content under OSD and DLSGD scenarios

Nutritional Analysis

A comprehensive assessment of the nutritional composition was performed to examine the nutritional attributes of *Cucumis sativus* subjected to drying under different settings, including OSD and DLSGD with both natural and forced airflow. The key nutritional elements evaluated were carbohydrates, vitamin C, calcium, and other essential nutrients.[38] Each measurement was repeated three times (n = 3) to ensure consistency and reproducibility of the results. The mean values of each parameter are presented in Figure 7. *Cucumis sativus* dried through the DLSGD with forced airflow showed an increased carbohydrate concentration compared to those dried utilizing alternative coating techniques. On the other hand, the protein levels were marginally lower in the forced convection setting than in the natural convection setting, due to the elevated temperatures within the DLSGD affecting protein stability. Vegetables typically contain a considerable amount of calcium, and its preservation was more significant under the DLSGD with forced airflow compared to natural convection and OSD, with calcium playing a role in the firmness of the vegetable tissue. In contrast, iron preservation was superior in the natural convection mode compared to the forced convection mode. Nevertheless, the iron concentration in DLSGD under forced airflow surpassed that in OSD. The reduction in iron levels is attributed to heat and atmospheric exposure. Vitamin C, being sensitive to heat, is better preserved at lower drying temperatures and smaller durations. The retention of vitamin C was superior in DLSGD with forced convection relative to OSD. The mineral content, indicated by ash levels, was higher in DLSGD with natural convection than in other drying techniques. Nutrient variations after drying with OSD and DLSGD under different modes are visually represented in Figure 7.

Discussion

The experimental results from this study indicate that the Drip Lock Sheet Greenhouse Dryer (DLSGD) with forced convection offers significant advantages over traditional Open Sun Drying (OSD) and DLSGD with natural convection for drying *Cucumis sativus*. The forced convection mode demonstrated the shortest drying duration, achieving the target moisture level of 11.5% within 4.5 days, compared to 5.7 days for natural convection and 8 days for OSD. The accelerated drying process observed in forced convection mode can be attributed to the enhanced heat transfer facilitated by the increased airflow. This aligns with previous research indicating that forced convection significantly reduces drying times by improving moisture removal efficiency. From a drying kinetics perspective, the Midilli and Kucuk model emerged as the best fit for DLSGD, while the Two-Term model was most appropriate for OSD. The high R^2 values and low RMSE and χ^2 values confirmed the accuracy of these models in predicting the moisture removal process.[15,16] These findings reinforce the importance of selecting the appropriate mathematical model to describe drying behaviors accurately, as previously suggested by studies on greenhouse drying applications for other agricultural products. The superior fit of the Midilli and Kucuk model for DLSGD suggests that incorporating additional parameters such as moisture diffusivity and non-linear drying behavior improves the model's reliability for greenhouse drying conditions.

Nutritional analysis further demonstrated that drying method selection plays a crucial role in nutrient retention. DLSGD with forced convection preserved higher carbohydrate and calcium levels compared to OSD and DLSGD with natural airflow. However, vitamin C retention was superior in natural convection mode, likely due to the lower drying temperature, which minimizes heat-induced degradation.[39] This trade-off between drying efficiency and nutrient preservation is a critical consideration for optimizing food drying processes. The findings align with prior studies that highlight the impact of drying temperature and duration on nutrient degradation, reinforcing the need for balance between efficiency and product quality. The choice of glazing material also played a significant role in drying efficiency. The drip lock glazing sheet effectively absorbed and retained heat, creating an optimal environment for moisture removal while preventing contamination from external factors. This design feature contributed to the superior performance of the DLSGD system compared to OSD, where exposure to environmental contaminants and fluctuations in solar radiation can lead to inconsistent drying rates and potential microbial growth.

Despite these advantages, certain limitations of the DLSGD system should be acknowledged. The reliance on solar irradiation means that drying efficiency may decrease during rainy or winter months, necessitating the integration of thermal energy storage or hybrid energy solutions for continuous operation.

Conclusion

This study introduced a DLSGD system to enhance the efficiency of food dehydration. Experiments were conducted to dry *Cucumis sativus* using both OSD and DLSGD under natural and forced convection. The findings led to several key conclusions. Firstly, the safest moisture content of under 11.5% was achieved in 4.5 days using DLSGD with forced airflow, compared to 5.7 days with natural convection and 8 days with OSD, demonstrating significant time savings. The drying rates were 0.0221 kg/hr for OSD, 0.0379 kg/hr for DLSGD with forced convection, and 0.0303 kg/hr for DLSGD with natural convection, with the forced convection method achieving the highest drying rate. From a mathematical modeling perspective, the Two-Term model best described the drying behavior in OSD, whereas the Midilli and Kucuk model was optimal for DLSGD under both convection modes, based on the highest R^2 and lowest RMSE and χ^2 values. Nutritional analysis indicated that carbohydrate retention was highest in DLSGD with forced convection, Vitamin C retention was superior in natural convection, and calcium retention was better in forced convection. Overall, DLSGD with forced convection emerged as the most effective drying method, ensuring faster drying, higher moisture removal rates, and improved carbohydrate retention. Additionally, the use of DLSGD provided a hygienic advantage, as the dried *Cucumis sativus* remained free from dust and contamination, enhancing the overall quality of the dehydrated product. The methods proposed here could be beneficial for professionals in food processing and agriculture, as they help in enhancing product quality, reducing drying hours, and lowering energy usage, thus promoting added sustainable food drying approach. A limitation of the proposed system is its reduced operational efficiency on rainy or winter times owing to insufficient solar irradiation for the moisture removal operation. Future research should explore the integration of energy storage solutions, such as thermal or phase change materials, to enhance the efficiency and sustainability of the drying process. These innovations could help maintain consistent drying conditions, reduce energy consumption, and improve overall performance. In future studies, detailed statistical analyses such as two-way or factorial ANOVA can be employed to better understand the interaction effects between drying and nutrient retention. This will allow for more precise identification of critical factors influencing drying performance and nutritional outcomes, ultimately aiding in developing optimized, data-driven drying protocols tailored for specific crops. Additionally, an economic evaluation is recommended to assess the cost-effectiveness of the DLSGD system in comparison to conventional drying methods. This analysis would provide valuable insights into operational expenses, energy savings, and the potential for large-scale implementation, ensuring both technical and financial viability.

Acknowledgement
The author expresses sincere gratitude to the management of Sri Krishna College of Engineering and Technology, Coimbatore, for their continuous support and encouragement throughout this work.

Funding Sources
The author(s) received no financial support for the research, authorship, and/or publication of this article.

Conflict of Interest
The author(s) do not have any conflict of interest.

Data Availability Statement
The manuscript incorporates all datasets produced or examined throughout this research study.

Ethics Statement
This research did not involve human participants, animal subjects, or any material that requires ethical approval.

Informed Consent Statement
This study did not involve human participants, and therefore, informed consent was not required.

Clinical Trial Registration
This research does not involve any clinical trials.

Permission to Reproduce Material from Other Sources
Not Applicable.

Author Contributions
- **Madhankumar Seenivasan:** Conceptualization, Methodology, Writing – Original Draft
- **Velusamy Kolandasamy:** Visualization, Supervision, Project Administration
- **Senthilkumar Kandhampalayam Muthukrishnan:** Analysis, Methodology
- **Selvan Thottiapalayam Arumugam:** Conceptualization, Methodology
- **Viswanathan Arumuthu:** Data Collection, Analysis, Writing – Review & Editing
- **Rajesh Suresh:** Conceptualization, Methodology, Resources, Writing – Original Draft
- **Gottumukkala Santhi:** Writing – Review & Editing

References

1. Das A, Singh S, Islam Z, *et al.* Current progress in genetic and genomics-aided breeding for stress resistance in cucumber (Cucumis sativus L.). *Sci Hortic (Amsterdam).* 2022;300:111059. doi:10.1016/J.SCIENTA.2022.111059
2. Das S, Chatterjee A, Pal TK. Comparative studies on physicochemical and nutritional values of organically and conventionally grown Cucumis sativus stored at different temperatures in different household packaging. Org Agric. 2022;12(4):563-579. doi:10.1007/s13165-022-00409-y
3. Sharma V, Sharma L, Sandhu KS. Cucumber (Cucumis sativus L.) BT - Antioxidants in Vegetables and Nuts - Properties and Health Benefits. In: Nayik GA, Gull A, eds. Springer Singapore; 2020:333-340. doi:10.1007/978-981-15-7470-2_17
4. Duraivel B, Muthuswamy N, Gnanavendan S. Comprehensive analysis of the greenhouse solar tunnel dryer (GSTD) using Tomato, snake Gourd, and Cucumber: Insights into energy Efficiency, exergy Performance, economic Viability, and environmental impact. Sol Energy. 2024;267:112263. doi:10.1016/J.SOLENER.2023.112263
5. Madhankumar S, Viswanathan K, Taipabu MI, Wu W. A review on the latest developments in solar dryer technologies for food drying process. Sustain Energy Technol Assessments. 2023;58:103298. doi:10.1016/J.SETA.2023.103298
6. Román-Roldán NI, López-Ortiz A, Ituna-Yudonago JF, *et al.* A current review: Engineering design of greenhouse solar dryers exploring novel approaches. *Sustain Energy Technol Assessments.* 2025;73:104137. doi:10.1016/J.SETA.2024.104137
7. Amonovich KB, Salimovich MM, A'zamovich SK. A systematic review on greenhouse type solar dryers. Sol Energy. 2024;283:113021. doi:10.1016/J.SOLENER.2024.113021
8. Kumar M, Shimpy, Sahdev RK, Tawfik MA, Elboughdiri N. Natural convective greenhouse vermicelli drying: Thermo-environ-econo-kinetic analyses. Sustain Energy Technol Assessments. 2023;55:103002. doi:10.1016/J.SETA.2022.103002
9. Borkakoti S, Das B, Gupta A. Environmental and economic assessment of single-slope solar greenhouse dryer for ginger and turmeric drying in north-eastern region of India. J Stored Prod Res. 2024;106:102299. doi:10.1016/J.JSPR.2024.102299
10. ELkhadraoui A, Kooli S, Hamdi I, Farhat A. Experimental investigation and economic evaluation of a new mixed-mode solar greenhouse dryer for drying of red pepper and grape. Renew Energy. 2015;77. doi:10.1016/j.renene.2014.11.090
11. Anuma O, Ndukwu MC, Usoh G, et al. Energy and exergy analysis of a natural convection solar greenhouse drier with insulated opaque walls for drying aromatic yellow pepper. *Renew Energy.* 2024;233:121141. doi:10.1016/J.RENENE.2024.121141
12. Ndukwu MC, Akuwueke L, Akpan G, et al. Modification approach of Northern Wall to improve the performance of solar greenhouse dryers: A review. *Green Energy Resour.* 2024;2(4):100104. doi:10.1016/J.GERR.2024.100104
13. Hazra P, Hazra S, Acharya B, et al. Diversity of nutrient and nutraceutical contents in the fruits and its relationship to morphological traits in bitter gourd (Momordica charantia L.). *Sci Hortic (Amsterdam).* 2022;305:111414. doi:10.1016/J.SCIENTA.2022.111414
14. Udomkun P, Romuli S, Schock S, et al. Review of solar dryers for agricultural products in Asia and Africa: An innovation landscape approach. *J Environ Manage*. 2020;268:110730. doi:10.1016/J.JENVMAN.2020.110730
15. Daliran A, Taki M, Marzban A, Rahnama M, Farhadi R. Kinetic analysis, mathematical modeling and quality evaluation of mint drying in greenhouse solar dryer. Therm Sci Eng Prog. 2023;46:102252. doi:10.1016/J.TSEP.2023.102252
16. Morya P, Agarwal M, Das Agarwal G. A medium-size greenhouse solar dryer for drying eco-friendly handmade papers: Performance analysis and drying kinetics.

Sol Energy. 2024;274(May 2024):112609. doi:10.1016/j.solener.2024.112609

17. Patel PM, Rathod VP, Patel VK. Development and enhancement in drying performance of a novel portable greenhouse solar dryer. J Stored Prod Res. 2024;105:102228. doi:10.1016/J.JSPR.2023.102228
18. Madhankumar S, Viswanathan K. Computational and experimental study of a novel corrugated-type absorber plate solar collector with thermal energy storage moisture removal device. Appl Energy. 2022;324:119746. doi:10.1016/J.APENERGY.2022.119746
19. Rajesh S, Sekar S, Madhankumar S. Energy and environmental analysis in an indirect solar dryer with flat coil inserted phase change material. Sustain Energy Technol Assessments. 2024;66:103805. doi:10.1016/J.SETA.2024.103805
20. Elavarasan E, Natarajan SK, Bhanu AS, Anandu A, Senin MH. Experimental Investigation of Drying Cucumber in a Double Slope Solar Dryer Under Natural Convection and Open Sun Drying BT - Innovations in Energy, Power and Thermal Engineering. In: Palanisamy M, Natarajan SK, Jayaraj S, Sivalingam M, eds. Innovations in Energy, Power and Thermal Engineering. Springer Singapore; 2022:41-52.
21. Arunkumar PM, Balaji N, Madhankumar S. Performance analysis of indirect solar dryer with natural heat energy retention substances for drying red chilli. Sustain Energy Technol Assessments. 2024;64(December 2023):103706. doi:10.1016/j.seta.2024.103706
22. Kohli D, Shahi NC, Kumar A. Drying kinetics and activation energy of Asparagus root (Asparagus racemosus Wild.) for different methods of drying. Curr Res Nutr Food Sci. 2018;6(1):191-202. doi:10.12944/CRNFSJ.6.1.22
23. Madhankumar S, Viswanathan K, Wu W. Energy, exergy and environmental impact analysis on the novel indirect solar dryer with fins inserted phase change material. Renew Energy. 2021;176. doi:10.1016/j.renene.2021.05.085
24. Choudhary AK, Hazarika MK. Modelling and thermal analysis of an integrated solar greenhouse dryer for ginger (Zingiber officinale) and product quality. J Stored Prod Res. 2024;106:102313. doi:10.1016/J.JSPR.2024.102313
25. S. M, Ilangovan D, Viswanathan K. Integrating computational models and machine learning for corrugated absorber plate solar collector thermal predictions. Process Saf Environ Prot. 2024;188:336-349. doi:10.1016/J.PSEP.2024.05.069
26. Madhankumar S, Viswanathan K, Wu W, Ikhsan Taipabu M. Analysis of indirect solar dryer with PCM energy storage material: Energy, economic, drying and optimization. Sol Energy. 2023;249:667-683. doi:10.1016/J.SOLENER.2022.12.009
27. EL khadraoui A, Hamdi I, Kooli S, Guizani A. Drying of red pepper slices in a solar greenhouse dryer and under open sun: Experimental and mathematical investigations. Innov Food Sci Emerg Technol. 2019;52:262-270. doi:10.1016/j.ifset.2019.01.001
28. Mohammed HH, Tola YB, Taye AH, Abdisa ZK. Effect of pretreatments and solar tunnel dryer zones on functional properties, proximate composition, and bioactive components of pumpkin (Cucurbita maxima) pulp powder. Heliyon. 2022;8(10):e10747. doi:10.1016/J.HELIYON.2022.E10747
29. Mongi RJ, Ngoma SJ. Effect of Solar Drying Methods on Proximate Composition, Sugar Profile and Organic Acids of Mango Varieties in Tanzania. Appl Food Res. 2022;2(2):100140. doi:10.1016/J.AFRES.2022.100140
30. Igbabul B, Adole D, Sule S. Proximate composition, functional and sensory properties of bambara nut (Voandzeia subterranean), cassava (Manihot esculentus) and soybean (Glycine max) flour blends for "Akpekpa" production. Curr Res Nutr Food Sci. 2013;1(2):147-155. doi:10.12944/CRNFSJ.1.2.06
31. Suborna MN, Hassan J, Rahman MM, et al. Color, antioxidant and nutritional composition of dehydrated country bean (Lablab purpureus) seeds using solar drying techniques and pretreatments in Bangladesh. *Heliyon.* 2024;10(10):e30936. doi:10.1016/J.HELIYON.2024.E30936
32. Goulding DA, Fox PF, O'Mahony JA. Milk

proteins: An overview. *Milk Proteins From Expr to Food.* Published online January 1, 2020:21-98. doi:10.1016/B978-0-12-815251-5.00002-5

33. Akter J, Hassan J, Rahman MM, et al. Colour, nutritional composition and antioxidant properties of dehydrated carrot (Daucus carota var. sativus) using solar drying techniques and pretreatments. *Heliyon*. 2024;10(2):e24165. doi:10.1016/j.heliyon.2024.e24165
34. NEWBURG DS, NEUBAUER SH. CHAPTER 4 - Carbohydrates in Milks: Analysis, Quantities, and Significance. In: Jensen RGBTH of MC, ed. Food Science and Technology. Academic Press; 1995:273-349. doi:https://doi.org/10.1016/B978-012384430-9/50015-9
35. Arunkumar PM, Balaji N, Madhankumar S, Mohanraj T. Prediction of red chilli drying performance in solar dryer with natural energy storage element using machine learning models. J Energy Storage. 2024;101:113825. doi:10.1016/J.EST.2024.113825
36. Valdiviezo-Seminario CS, Sánchez-Chero MJ, Flores-Mendoza LC. Effect of Osmotic Dehydration Pretreatment On Melon (Cucumis Melo) Drying Time. Curr Res Nutr Food Sci. 2024;12(3):1421-1432. doi:10.12944/CRNFSJ.12.3.34
37. Vignesh T, Selvakumar D, Madhankumar S. Drying kinetics, energy, colour and FTIR spectroscopy analysis on indirect solar dryer with paraffin wax and glass pieces as thermal storage material. Sol Energy. 2024;282:112925. doi:10.1016/J.SOLENER.2024.112925
38. Rajesh S, Sekar S, Sekar SD, Madhankumar S. Drying kinetics, energy, statistical, economic, and proximate analysis of a greenhouse dryer using different glazing materials for Coccinia grandis drying. Sol Energy. 2024;284:113047. doi:10.1016/J.SOLENER.2024.113047
39. Deepak CN, Behura AK. Effect on drying kinetics and product quality of cucumber in a mixed mode solar tunnel dryer upon integration of sensible and latent heat thermal energy storage. *Sol Energy*. 2025;285:113113. doi:10.1016/J.SOLENER.2024.113113