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Experimental Investigation and Performance Evaluation of a Solar-Powered Forced-Convection Leafy Vegetable Dehydrator

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Abstract

Post-harvest losses of agricultural perishables, particularly leafy green vegetables, pose severe economic and nutritional challenges in developing regions due to inefficient preservation techniques and unreliable grid power. Open sun drying and traditional shadow drying suffer from prolonged drying times, insect infestation, airborne contamination, and loss of nutritional or sensory quality. This study presents the development, fabrication, and experimental validation of an off-grid, low-cost, forced-convection indirect solar dehydrator optimized for leafy green vegetables. The system incorporates a flat-plate solar thermal collector integrated with an insulated wooden drying chamber, an automated forced air distribution unit powered by a direct current (DC) axial fan, and a dedicated photovoltaic (PV) panel. Comparative experimental evaluations were conducted across three drying operational modes—Open Sun Drying (OSD), Shadow Drying (under fan airflow), and Solar Dehydrator Drying—utilizing equal 100 g samples of spinach (Spinacia oleracea), coriander (Coriandrum sativum), and fenugreek (Trigonella foenum-graecum). Results indicate that the indirect solar dehydrator reduced moisture content to 0% within 11 hours for spinach, 9 hours for coriander, and 9 hours for fenugreek, achieving maximum drying rates of 0.92, 0.85, and 0.88, respectively. In comparison, traditional sun and shadow drying required multiple days while yielding inferior color, aroma, and structural integrity. Total fabrication cost was evaluated at ₹14,400. The developed indirect solar dehydrator proves to be an efficient, affordable, and sustainable technology for small-scale rural and domestic food preservation applications.

Keywords: Indirect Solar Dryer; Forced Convection; Solar Thermal Collector; Leafy Vegetable Dehydration; Post-Harvest Preservation.

How to Cite This Article

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Introduction & Background

Drying is a fundamental method used to preserve agricultural commodities by lowering water activity, thereby inhibiting microbial growth, enzymatic degradation, and chemical spoilage. Leafy green vegetables such as spinach, coriander, and fenugreek possess high initial moisture contents exceeding 80–90% wet basis, giving them extremely short shelf lives under ambient storage conditions.

In rural regions, post-harvest processing overwhelmingly relies on Open Sun Drying (OSD) due to zero capital expenditure. However, OSD is constrained by severe limitations:

- Exposure to ambient dust, dirt, and airborne contaminants.
- Infestation by insects, rodents, and birds.
- Degradation of sensitive heat-susceptible nutrients, vitamins, and chlorophyll from direct ultraviolet (UV) exposure.
- Extended drying durations dependent on weather fluctuations and high land requirements.

Alternative commercial drying machines using electricity or fossil fuels incur substantial operating expenses and remain unfeasible in off-grid rural communities. Solar thermal air heating systems provide an environmentally friendly, non-polluting alternative for crop drying at low-to-moderate operating temperatures below 80°C. To overcome the challenges of direct radiation exposure, this investigation focuses on an indirect forced-convection solar dehydrator that uses solar thermal energy to heat incoming air, which is subsequently driven through a multi-tray drying cabinet using a solar PV-powered DC axial fan.

Literature Review & Objectives

Solar drying technologies have evolved into specialized configurations categorized by operational mechanisms. Rabha et al. (2017) investigated a forced-convection solar dryer integrated with a shell-and-tube latent heat storage unit utilizing paraffin wax, demonstrating a 122.8% reduction in drying time for red chili compared to open sun drying. Salve et al. (2016) developed a portable forced-convection solar dryer incorporating Phase Change Materials (PCM) capable of drying 15 kg of chili over 17 hours, compared to 27 hours required for open sun drying. Shalaby and Bek et al. (2014) evaluated an indirect solar dryer utilizing a PCM thermal storage unit operated at mass flow rates between 0.0664 kg/s and 0.2182 kg/s , sustaining drying temperatures 2.5 – 7.5 0C above ambient post-sunset. Palaniappan et al. (2013) studied a packed-bed thermal storage unit, finding that higher mass flow rates yielded superior collector efficiencies. Tunde et al. (2011) evaluated the drying kinetics of chili pepper, demonstrating that the Page thin-layer drying model best described the falling-rate drying regime.

Research Gap & Objectives

While extensive research addresses solar drying of high-density crops (such as chilies, grains, and fruit slices), minimal empirical data exists regarding dedicated indirect forced-convection solar drying systems for delicate leafy green vegetables. Leafy green crops present unique challenges due to high surface-area-to-mass ratios, extreme moisture sensitivity, and vulnerability to heat-induced chlorophyll destruction.

The primary objectives of this study are:

1. To design and construct a low-cost, durable indirect solar leaf vegetable dehydrator using locally accessible materials.
2. To experimentally investigate the thin-layer drying performance of coriander, fenugreek, and spinach under three comparative modes: Direct Open Sun Drying (OSD), Indoor Shadow Drying under fan ventilation, and Indirect Forced-Convection Solar Dehydrator Drying.
3. To determine drying rate curves, moisture removal kinetics, and thermal performance characteristics of the developed dehydrator.
4. To perform a detailed economic cost analysis of the fabricated prototype system.

Materials, Design, and Experimental Setup

System Components & Working Principle

The system was constructed using structural and thermal materials selected for optimal insulation, mechanical stability, and thermal absorption:

- Structural Frame & Enclosure: Mild Steel (MS) square tubes providing mechanical rigidity, and high-durability Shuttering Plywood offering low thermal conductivity to minimize radiative and conductive envelope heat losses.
- Collector Unit: Mild Steel absorber sheet coated with heat-resistant matte black paint (\alpha \approx 0.95) covered by a high-transmissivity clear window glass sheet to trap longwave infrared radiation.
- Air Circulation & Power: 12 V DC axial flow exhaust fan powered directly by an off-grid Photovoltaic (PV) solar panel.
- Instrumentation: Calibrated digital RTD/thermistor temperature sensors (\pm 0.1 0C accuracy) and digital mass balance scales.

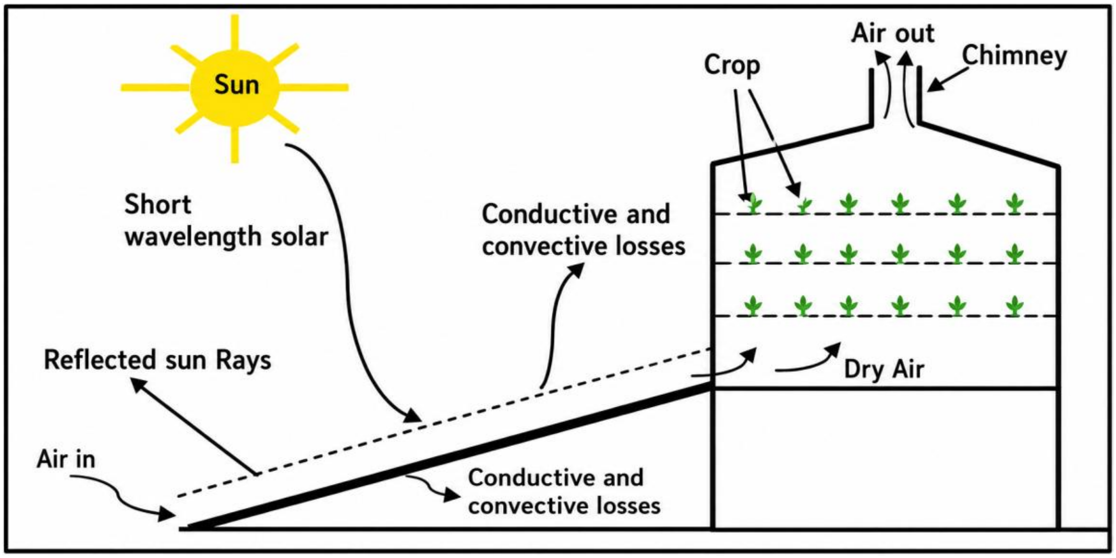
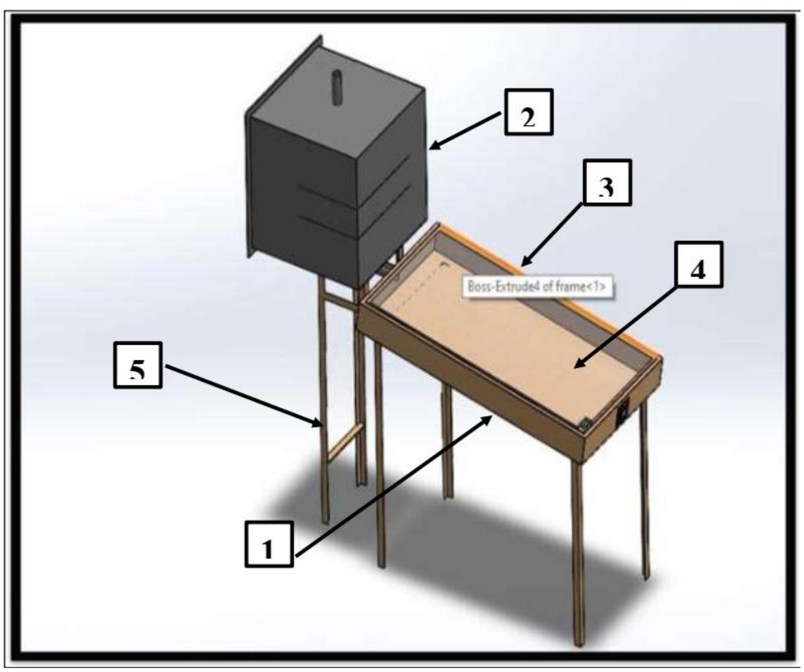


Fig. 1. *Schematic layout and working methodology flow of the indirect forced-convection solar drying system*

Solar energy penetrates the glass cover plate of the tilted collector box and strikes the black MS absorber sheet. The absorbed heat elevates the absorber temperature, transferring thermal energy via convection to the air column within the channel. The 12 V DC fan forces ambient air through the inlet port across the heated plate into the base of the adjacent vertical drying cabinet. As hot air flows through the perforated multi-tier wire mesh trays carrying the leafy crops, it evaporates internal moisture, which is subsequently exhausted out through top ventilation openings.

Design CAD Model

The structural geometry and spatial arrangements were designed using SolidWorks 2022 software. The overall assembly and primary orthographic dimensions are presented in Fig. 2 and Fig. 3.



1. Cabinet Box 1 for Heat trapping. 2. Cabinet Box 2 for Leaf Vegetable drying. 3. Glass for resisting heat to exit from box. 4. Metal Sheet for absorbing heat from the sun. 5. Stand for holding box cabinets (both)

Fig. 2. *Computer-Aided Design (CAD) 3D assembly model of the forced-convection solar dehydrator.*

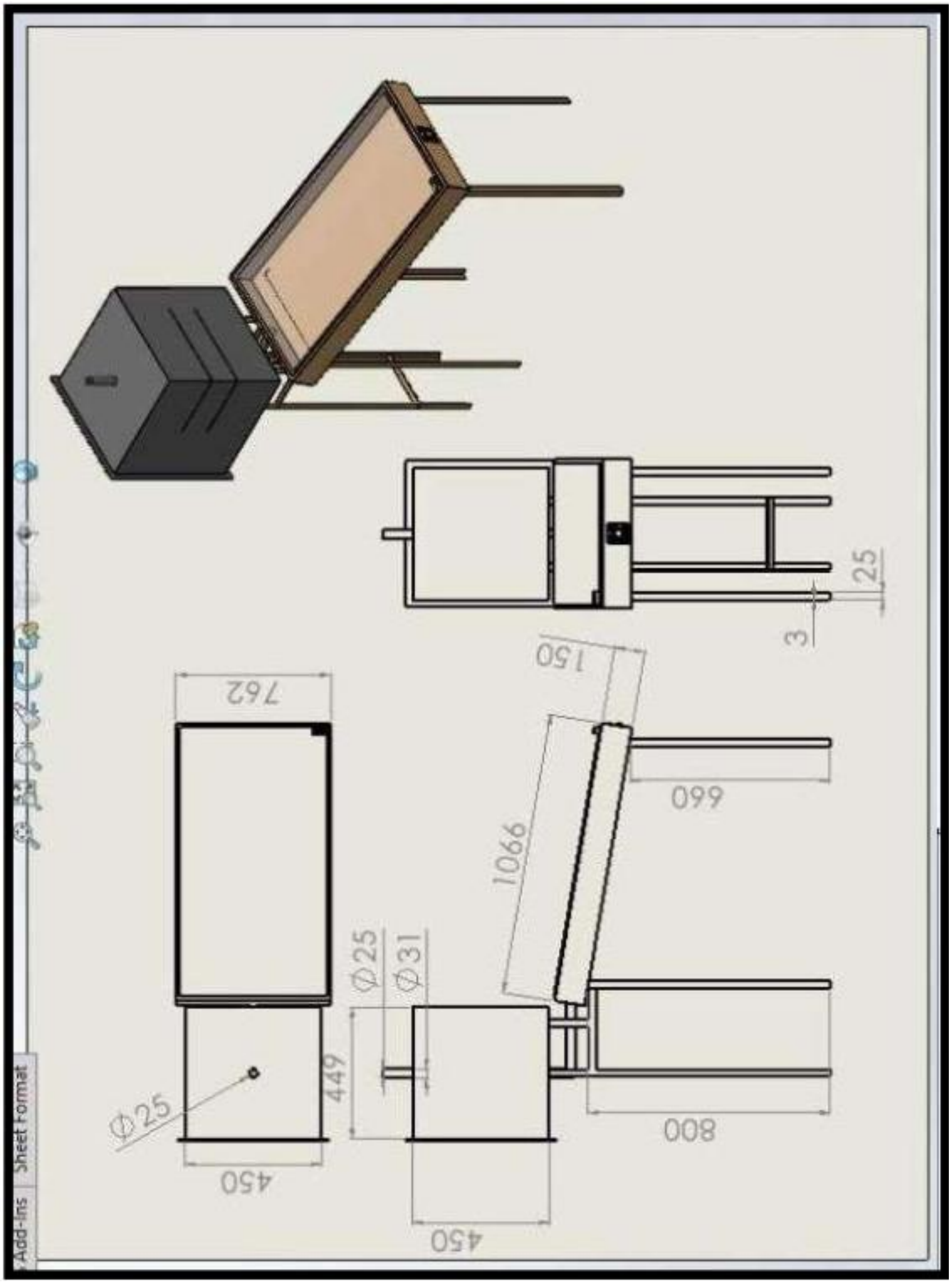


Fig. 3. Detailed CAD projection drawing showing critical orthographic dimensions (in mm) of the physical prototype.

Experimental Procedure

Fresh samples of spinach (Spinacia oleracea), coriander (Coriandrum sativum), and fenugreek (Trigonella foenum-graecum) were washed, blotted, trimmed, and cut into uniform sizes. 100 g samples of each vegetable species were evaluated across three concurrent testing regimes under identical ambient conditions:

- Mode A: Direct Open Sun Drying (OSD): 100 g samples spread in thin layers over paper sheets placed in direct unshaded sunlight. Mass loss was recorded at 24-hour daily intervals following sunset.
- Mode B: Shadow Drying (Indoor Fan Ventilation): 100 g samples placed indoors under continuous forced airflow generated by a standard ceiling fan. Mass loss was recorded at 24-hour intervals.

- Mode C: Indirect Solar Dehydrator Drying: 100 g samples spread evenly over butter-paper-lined perforated trays inside the dehydrator cabinet. Trays were inserted into multi-tier slots (Tray 1: Top, Tray 2: Middle, Tray 3: Bottom). The 12 V DC exhaust fan was energized via the PV panel, and mass loss per tray alongside internal cabinet temperatures were logged hourly.

Mathematical Modelling

The thermal performance of the solar flat-plate air collector is governed by the energy balance equation, where collector efficiency η_c is calculated as:

$$\eta_c = \frac{\dot{m}_a C_P (T_o - T_i)}{A_C I} \quad (1)$$

Where $\dot{m}_a$ is the mass flow rate of air (kg/s), C_p is the specific heat capacity of air (J/kg.°C), T_o is collector outlet air temperature (°C), T_i is inlet ambient air temperature (°C), A_c is collector surface area (m^2), and I is incident global solar radiation (W/m^2).

The total drying energy Q_d required to vaporize water from biomass is calculated using:

$$Q_d = \dot{m}_a C_P (T_{co} - T_f) + m_w L_w \quad (2)$$

where T_{co} is air temperature entering the chamber (°C), T_f is air temperature exiting the drying chamber (°C), m_w is mass of removed water (kg), and L_w is latent heat of vaporization of water (J/kg).

The total mass of water m_w removed from the product during drying is given by:

$$m_w = m_i \left(\frac{MC_i - MC_f}{100 - MC_f} \right) \quad (3)$$

where m_i is initial product mass (kg), MC_i is initial wet-basis moisture content (%), and MC_f is final moisture content (%).

Drying rate (DR) and Moisture Content (MC, % wet basis) at any time increment are calculated via:

$$DR = \frac{W_o - W_t}{W_o} \quad (4)$$

$$DR = \frac{W_t - W_d}{W_o} x100 \quad (5)$$

where W_0 is initial biomass mass (g), W_t is mass at time t (g), and W_d is dry bone mass (g).

Results & Discussion

Baseline Comparisons (Modes A and B)

The mass decay trajectories for spinach, coriander, and fenugreek exposed to Open Sun Drying (Mode A) and Shadow Drying (Mode B) are summarized in TABLE I.

Table 1. *Daily Mass Loss (g) Trajectories for Modes A and B (Initial Mass = 100 g)*

Operational Mode	Crop Type	Day 1	Day 2	Day 3	Day 4	Day 5
Mode A (Open Sun Drying)	Spinach	51	33	17	11	10
	Coriander	49	28	18	17	-
	Fenugreek	48	28	18	17	-

Mode B (Shadow Drying)	Spinach	70	20	12	10	-
	Coriander	76	44	27	23	-
	Fenugreek	57	17	11	11	-

Observations: Sun-dried samples exhibited severe discolouration due to UV degradation of chlorophyll, structural bleaching, and dust contamination. Shadow-dried samples retained moderate green color but exhibited slow moisture removal rates, retaining residual bound moisture and developing off-odors due to prolonged high humidity exposure during early drying stages.

Forced-Convection Solar Dehydrator Performance (Mode C)

Hourly logging of drying cabinet temperatures and tray mass loss for spinach, coriander, and fenugreek inside the solar dehydrator are documented in TABLE II.

Table 2. *Hourly Experimental Drying Mass (g) and Temperature Logs (Mode C)*

Time Elapsed	Temp (∘C)	Spinach Avg. Mass (g)	Temp (∘C)	Coriander Avg. Mass (g)	Temp (∘C)	Fenugreek Avg. Mass (g)
1st Hour	58.1	100	68.6	100	42.7	100
2nd Hour	73.7	76	62.6	78	59.5	70
3rd Hour	76.1	58	62.4	62	68.4	50
4th Hour	73.7	50	38.1	58	69	40
5th Hour	68.8	36	61.6	44	70.1	28
6th Hour	65	28	65.8	33	64.7	20
7th Hour	31	22	38.3	23	56.4	17
8th Hour	63.1	20	53.6	18	70.4	13
9th Hour	66.1	16	66	15	71.2	12
10th Hour	65	12	-	-	-	-
11th Hour	52.2	8	-	-	-	-

Applying (4) and (5) to the experimental datasets yields the computed kinetic parameters presented in TABLE III.

Table 3. *Computed Kinetic Parameters (DR and MC) in Solar Dehydrator*

Time Elapsed	Spinach DR	Spinach MC (%)	Coriander DR	Coriander MC (%)	Fenugreek DR	Fenugreek MC (%)
1st Hour	0	92	0	85	0	88
2nd Hour	0.24	88	0.22	82	0.3	87
3rd Hour	0.42	84	0.38	77	0.5	83
4th Hour	0.5	80	0.42	67	0.6	80
5th Hour	0.64	78	0.56	56	0.72	72
6th Hour	0.72	72	0.67	42	0.8	60
7th Hour	0.78	64	0.77	38	0.83	50
8th Hour	0.8	50	0.82	22	0.87	30
9th Hour	0.84	42	0.85	0	0.88	0
10th Hour	0.88	24	-	-	-	-
11th Hour	0.92	0	-	-	-	-

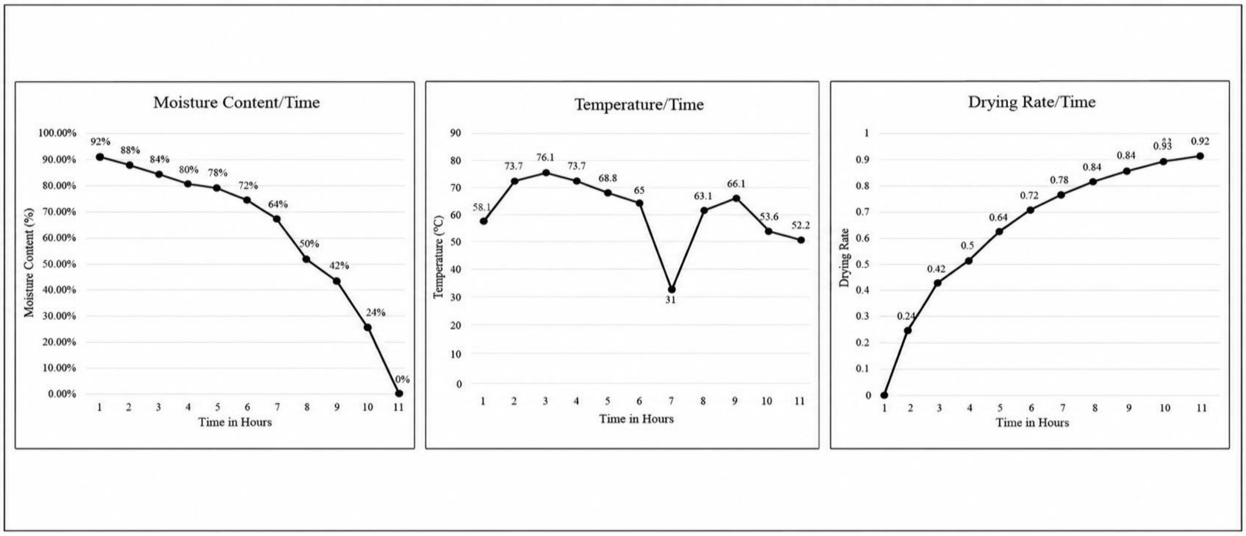


Fig. 4. *Performance and kinetic evaluation curves for Spinach in the indirect solar dehydrator.*

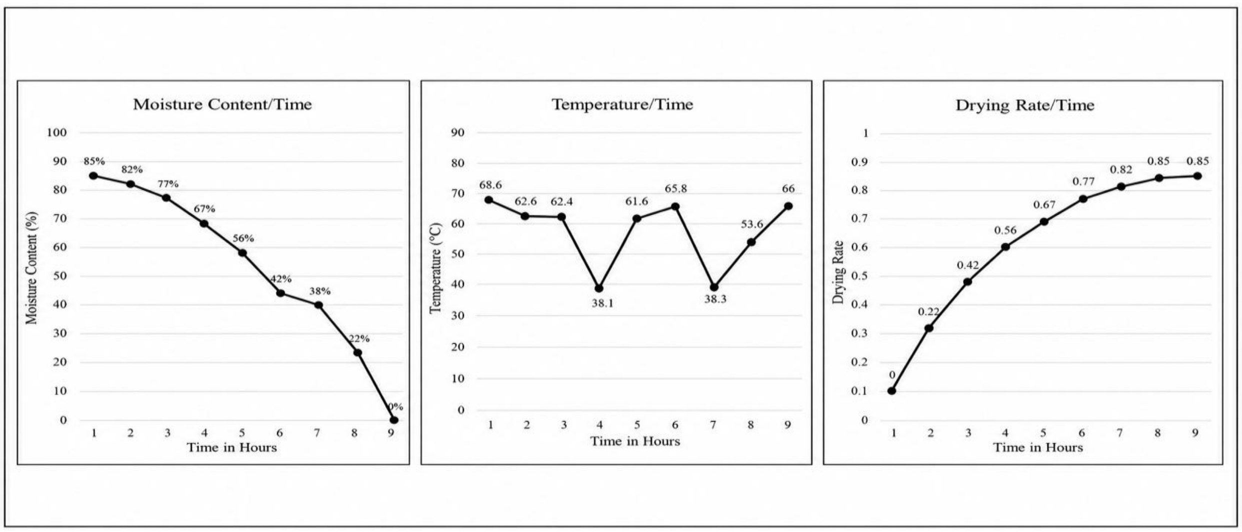


Fig. 5. *Performance and kinetic evaluation curves for Coriander in the indirect solar dehydrator.*

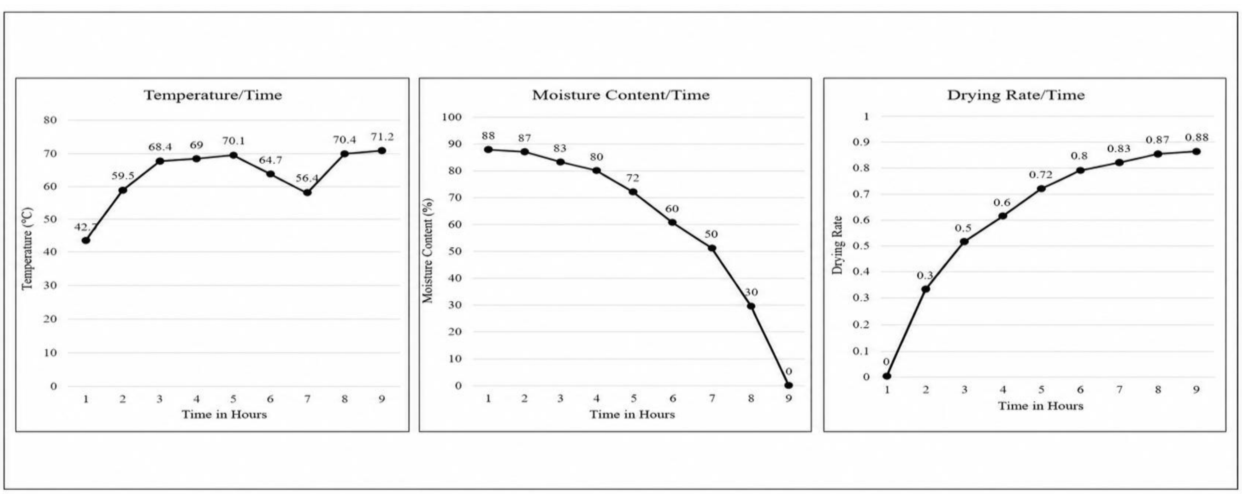


Fig. 6. *Performance and kinetic evaluation curves for Fenugreek in the indirect solar dehydrator.*

Comparative Discussion

1. Kinetic Acceleration: Spinach required 11 hours of forced convection inside the dehydrator to achieve complete dehydration (0% moisture, final mass 8g) with a drying rate of 0.92. Under Open Sun Drying and Shadow Drying, spinach required 5 days and 4 days, respectively. Coriander reached complete dehydration in 9 hours (0% moisture, final mass 15g , drying rate 0.85) inside the dehydrator, compared to 4 days under sun and shadow modes. Fenugreek achieved complete drying in 9 hours (0% moisture, final mass 12g , drying rate 0.88), compared to 4 days for outdoor solar and indoor fan modes.
2. Thermal Dynamics: Chamber temperatures reached peak values between 70.1 ^{o}C and 76.1 ^{o}C during peak solar irradiance hours. Transient drops in drying air temperature (e.g., 31.0 ^{o}C during Hour 7 in spinach trials) corresponded directly to intermittent cloud cover.
3. Quality & Sensory Attributes: Vegetables dried in the indirect dehydrator retained vibrant natural green pigmentation due to light isolation inside the wooden cabinet. The forced air stream concentrated aromatic volatile compounds, producing an intense herbal scent free from dust, insect fragments, or microbial degradation

Conclusions

An off-grid, low-cost forced-convection indirect solar dehydrator was designed, fabricated, and experimentally validated for leafy green vegetables. Key findings from this research include:

1. Spinach Dehydration: Reduced moisture content from 92% to 0% (100 g initial to 8 g final mass) within 11 hours, achieving a maximum drying rate of 0.92.
2. Coriander Dehydration: Reduced moisture content from 85% to 0% (100 g initial to 15 g final mass) within 9 hours, achieving a maximum drying rate of 0.85.
3. Fenugreek Dehydration: Reduced moisture content from 88% to 0% (100 g initial to 12 g final mass) within 9 hours, achieving a maximum drying rate of 0.88.
4. Performance Advantage: Compared to traditional Open Sun Drying and Shadow Drying (which required 4–5 days), the forced-convection solar dehydrator accelerated drying times by over 80%, eliminated UV degradation, and protected biomass from environmental contamination.

Nomenclature

- A_c : Solar collector absorber area (m^2)
- C_p : Specific heat capacity of air (J/kg.^{o}C)
- DR: Drying rate (dimensionless)
- I: Incident solar radiation intensity (W/m^2)
- L_w : Latent heat of vaporization of water (J/kg)
- $\dot{m}_a$: Mass flow rate of air (kg/s)
- m_i : Initial product mass (kg)
- m_w : Total mass of evaporated water (kg)
- MC_i : Initial moisture content (% wet basis)
- MC_f : Final moisture content (% wet basis)
- Q_d : Total drying energy required (J)
- T_i : Collector inlet ambient temperature (^{o}C)
- T_o : Collector outlet temperature (^{o}C)
- T_{co} : Drying chamber entry temperature (^{o}C)
- T_f : Drying chamber exhaust outlet temperature (^{o}C)
- W_o : Initial sample wet mass (g)
- W_d : Final dry mass (g)
- W_t : Instantaneous sample mass at time t (g)
- η_c : Solar thermal collector efficiency (%)

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