

Design and Development of a Smart Solar Dryer for Agriculture

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Abstract — After harvest, a large part of the food that farmers grow is lost because it stays wet, grows mould, or is spoiled by rain and insects. Open-sun drying is cheap but slow and weather-dependent; fuel- or grid-powered dryers are fast but too costly for small farmers in remote areas. This paper combines the findings of fourteen recent research papers and proposes a simple design for a smart solar dryer: a solar air collector, a solar panel with battery, an optional heat-storage box (phase change material, PCM), sensors for temperature, humidity, airflow and weight, a low-cost controller (ESP32, NodeMCU or Arduino), wireless links (Wi-Fi, GSM or LoRa) and a phone/cloud dashboard. The reviewed papers show that solar dryers cut drying time by 40–70 % compared with open sun drying, hybrid and PCM dryers reach about 25–45 % efficiency, smart IoT control can save 20–30 % of energy and reduce post-harvest loss by 15–25 %, and the investment is usually recovered in 1.1–2.7 years. PID and fuzzy control keep temperature within ± 1 – 2 °C, against ± 5 – 10 °C for simple on–off control. The paper also explains each main component in plain words with photos and shows how a temperature-controlled dryer can protect the germination of soybean and sunflower seed. It is a review-based design study: it contains no new experiments, and its calculations are estimates that must be tested.

Keywords: Smart Solar Dryer, IoT, PID Control, Phase Change Material, Sensors, Seed Germination, Soybean, Sunflower

I. INTRODUCTION

A. Background

By 2050 the world population may reach about 9.7 billion, yet around one-third of all food produced (close to 1.3 billion tonnes every year) is lost before it is eaten. In East Africa, post-harvest losses are 10–15 % for cereals, 20–25 % for root crops and about 45 % for fruits. Most of this loss is caused by moisture, because wet produce lets bacteria, yeast and mould grow. Drying lowers the “water activity” of the product: bacteria need at least 0.91, fungi can grow down to about 0.6, and a product dried below 0.6 can be stored for a long time. Drying also makes produce lighter, so packing and transport cost less.

B. The Problem

Open sun drying is easy and cheap, but it is slow (10–15 days for grain in India), needs a large open area and depends fully on the weather; rain, dust, insects, birds and animals can spoil the product. Machine dryers are faster but need electricity or fuel and careful temperature control, which small farmers in remote places often cannot afford. Ordinary solar dryers are “passive”: they cannot react to a passing cloud, a change in humidity or the real moisture in the product, so someone must check the trays by hand.

A smart solar dryer fixes this by adding sensors, automatic control and remote monitoring. Indian prototypes

show that cheap Arduino, NodeMCU and ESP boards, thermocouples and relays are enough; better designs add heat storage, load cells under the trays and variable-speed fans. A 2026 review describes a shift from “dry for a fixed time” to “dry until the product is ready”.

C. Objectives of This Paper

- To summarise solar drying technology and the sensors, controllers, communication and control methods used in IoT solar dryers.
- To propose a simple design for a smart solar dryer of about 10 kg batch size, with worked calculations for drying load, collector area and power, and to describe each main component in easy language.
- To explain how the dryer can help keep and improve soybean and sunflower seed germination, to compare performance and cost, and to list limits and future work.

This is a review-based design study. All performance numbers come from the cited papers; the design calculations in Section III are estimates based on stated assumptions and must be checked by experiments.

II. LITERATURE REVIEW

A. How Drying Works

Sunlight heats the product and the air; heat pushes water to the surface and moving air carries the vapour away. Drying first proceeds at a steady surface rate set by air temperature, humidity and speed, then slows because water must travel from deep inside the product. Hotter, faster air dries faster but damages colour, texture and nutrients, so solar dryers run at 40–60 °C for most farm products (safe maximums range from about 45 °C for wheat to 70 °C for bananas and potato chips). Dryers are judged by drying time, efficiency and specific moisture extraction rate (SMER, kg of water removed per kWh).

B. Types of Solar Dryers

Solar dryers are grouped by how they heat and how air moves. A direct dryer lets sunlight fall on the product under a clear cover: cheap and simple but hard to control. An indirect dryer heats air in a separate collector and passes it over the product in a dark chamber: better control and quality, higher cost. Mixed-mode dryers use both. Natural-convection (passive) dryers use no extra energy but work badly in weak sun; forced-convection (active) dryers use fans and are more efficient and easier to control.

Dryer type	Typical efficiency	Peak temperature	Remarks
Direct (box/cabinet)	10–25 %	45–70 °C	50–70 % faster than open sun; good for herbs and small fruits
Indirect	20–40 %	50–70 °C	40–60 % faster; 5–15 % heat lost in ducts; cost about USD 100–500
Hybrid / mixed-mode	25–45 %	50–75 °C	Solar+electric 25–35 %; solar+PCM 28–40 %; solar+PV fan/heater 22–32 %
Greenhouse (passive)	12–23.5 %	up to 64 °C	Tomato flakes 23.49 %; lima beans 12.03 %; black gravel bed reached 64.4 °C
Forced vs natural air flow	67.66 % vs 59.74 %	—	Average efficiency, forced vs natural convection
Solar heat-pump assisted	up to 77.45 %	—	2–3 times a normal dryer; higher cost and complexity

Table 1: Reported performance of solar dryer types in the reviewed papers

C. Greenhouse Solar Dryers

Greenhouse dryers are cheap, easy to build and usable all year. A single-span east–west greenhouse received almost 8 % more sunlight over a year than other designs, and a Quonset (half-tunnel) shape reached up to 72 °C inside. Adding a solar air heater, evacuated-tube collector or heat storage improves results: a hybrid greenhouse dryer with evacuated tubes cut drying time by 34.09 % (ginger), 47.36 % (tomato) and 61.90 % (bottle gourd), and a hybrid dryer with heat storage dried bitter gourd flakes in 6 hours against 15 hours in the open, with a payback of only 0.49 years.

D. Heat Storage and Hybrid Heating

Sunlight comes and goes, so a dryer needs storage or backup heat. Sensible storage (pebbles, gravel) is cheap but holds little energy. Phase change materials (PCM), most often paraffin wax, store heat while melting and release it at almost

constant temperature while freezing. A large greenhouse dryer with paraffin PCM dried chilli from 74.7 % to 10 % moisture in 2.5 days, against 3.5 days without PCM and 11 days in the open, and a natural-convection PCM dryer kept the chamber about 6 °C warmer after sunset (28.2 % efficiency, 1.57-year payback). Hybrid dryers add backup heat from biomass, electric heaters or LPG. Heat-pump and desiccant systems can be two to three times as efficient but cost too much for a small-farmer unit, so they are left as future extensions.

E. IoT-enabled Smart Solar Dryers

The Internet of Things (IoT) links sensors, controllers, networks and cloud software so that a farmer can watch and control a machine from a phone. Closed-loop IoT drying systems have been reported to cut energy use by 20–30 % and post-harvest loss by 15–25 %. Table 2 shows four prototypes from the supplied papers.

Study	Hardware	Control and connection	Result / limit
Harischandrakar et al.	Arduino Mega 2560, K-type thermocouple, 2-channel relay, two DC fans, solar panel	Preset temperature limits; MQTT to an IoT platform and app with live chart	Monitoring and server tests shown; no drying numbers given
Jagadeesh et al.	ESP8266 NodeMCU, L298 driver, 12 V fans, solar panel + diode, 3-cell LiPo battery, display, multimeter	Fan speed set from temperature; Wi-Fi remote monitoring	Only qualitative results (steady power, faster and even drying); humidity sensor left for future
Sarkar et al.	Arduino Uno, relay module, V/I display, 12 V VRLA battery, inverter, solar panel, LCD	Automatic control with heating coil and fan; phone link proposed	Panel up to 10 V, boosted to 30 V DC at about 1 A; drying in a few hours
Bidyalakshmi Devi & Kalnar	Arduino Mega 2560, evacuated-tube collector, paraffin PCM, PV + battery, hot-air blower, NTC sensors, load cell per tray, OLED	Exhaust-fan speed holds 55–60 °C; load cells show the end point	10–15 kg, six trays; design study, no measured drying data

Table 2: Smart solar dryer prototypes in the reviewed papers

These prototypes show that a “monitor and switch” system is cheap to build, but most give only qualitative results, only the last adds tray weight sensors, and none uses PID or intelligent control or compares itself with open sun drying under controlled conditions. The design in Section III tries to fill this gap.



Fig. 1: (left). Arduino-based smart solar grain dryer prototype.

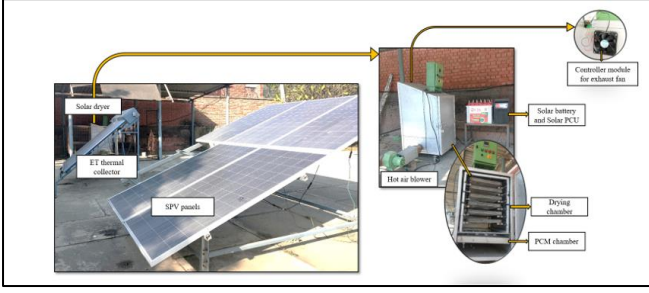


Fig. 2: (right). Developed dryer with evacuated-tube collector, PV panels, blower, battery, PCM chamber and control unit.

F. Crop and Post-harvest Background

Soybean is India's main Kharif (monsoon-season) oilseed, sown in late June and harvested in late September to early October. About 70 % of India's rain falls between June and September, so harvest and drying often happen in humid or wet weather, a strong reason for an enclosed, controllable dryer. Germinating soybean for three days improved its nutrition and cut tannins, but the sprouts needed 48–72 hours of sun drying and fungus appeared from day five; a controlled dryer can make this step shorter and safer. Sunflower seed germination depends on water, temperature and other conditions, so seed must not be overheated or over-dried (Section V). Satellite pod detection, image-based quality checks and cold-plasma seed treatment appear in the papers only as ideas for the future.

G. Research Gaps

Most cheap prototypes only monitor and lack closed-loop, quality-aware control; weight-based end-point detection has been proposed but not shown with measured data; rural internet, sensor calibration and cost still block adoption; few studies test performance, cost and environment together; and no supplied paper tests the effect of a smart dryer on seed germination, which Section V proposes to do.

III. SYSTEM DESIGN AND METHOD

A. Design Idea

The proposed dryer is an indirect, forced-air, hybrid solar dryer that can also work in mixed mode. It (i) uses the sun for both heat (collector) and electricity (PV panel) so it works off-grid; (ii) adds a small storage or backup heater to steady the temperature; (iii) controls chamber temperature and airflow in a closed loop with sensors at the inlet, outlet and trays; and (iv) keeps cost low with common controllers and modules. Figure 3 shows the plan.

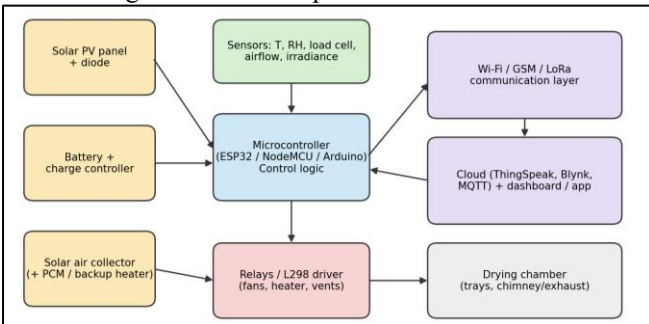


Fig. 3: Proposed smart solar dryer architecture.

B. Design Inputs

Item	Value	Basis
Batch mass, m_p	10 kg (fresh)	Lower end of the 10–15 kg capacity
Start / end moisture (wet basis)	85 % / 12 %	Example values for a high-moisture crop (ginger); replace with the real crop
Start temperature of product	25 °C	Devi & Kalnar
Target chamber temperature	55 °C (band 50–60 °C)	Inside the 40–65 °C usual for produce. Seed lots need a cooler setting (Section V).
Specific heat of product, C_p	2 kJ/kg·K	Devi & Kalnar
Sunlight available	5.5 kWh/m ² per day	India average quoted; use local data
Collector efficiency (assumed)	about 30 %	Inside the 20–40 % range for indirect dryers
Air speed	0.5–3 m/s	Range used in IoT dryers

Table 3: Design inputs for a 10 kg batch

How Much Heat Is Needed

First, the water to be removed, using the relation:

$$m_w = m_p (M_i - M_f) / (100 - M_f) \quad (1)$$

For 10 kg of product, $m_w = 10 \times (85 - 12) / (100 - 12) = 8.30$ kg. The latent heat of evaporation at product temperature t_{pr} is:

$$H_{fg} = 4.186 [597 - 0.56 (t_{pr} + 273)] \quad (2)$$

At 55 °C this gives $h_{fg} \approx 1,730$ kJ/kg. The total heat needed is:

$$Q = m_p C_p \Delta T_p + m_w h_{fg} \quad (3)$$

so $Q \approx 10 \times 2 \times (55 - 25) + 8.30 \times 1,730 \approx 600 + 14,350 \approx 14,950$ kJ, or about 4.15 kWh per batch. This is an ideal figure. Real dryers lose heat through walls and exhaust. The system efficiency is $\eta_{dryer} = (m_p C_p \Delta T_p + m_w h_{fg}) / Q_a$, where Q_a is the energy received by the collector.

C. Collector and Chamber Size

If a batch must finish in one day (about 8 useful hours) with 30 % collector efficiency, the sunlight needed is about $4.15 / 0.30 \approx 13.8$ kWh, which at 5.5 kWh/m² per day means about 2.5 m² of collector. With a 20–30 % margin for cloudy spells the practical size is about 3 m². An evacuated-tube collector may need less area, but dust and duct losses of 5–15 % argue for keeping the margin.

The collector is a single- or double-glazed flat-plate air heater with a black absorber, tilted at about the local latitude $\pm 15^\circ$ and joined to the chamber by insulated ducts. The chamber is a mild-steel or stainless-steel cabinet with about 2.5 cm of glass-wool insulation, six perforated trays and hot air entering at the bottom; one prototype uses $77 \times 65 \times 96$ cm for 10–15 kg. Food-grade mesh trays, insect screens and a rain-proof chimney protect the product, a key advantage over open drying.

D. Heat Storage and Backup Heater

For night use or low sunlight, a paraffin-wax PCM box is placed in the air path between collector and chamber. Storing 30 % of the daily heat (about 1.25 kWh, or 4,500 kJ) with a paraffin latent heat of about 200 kJ/kg (an assumed value; check the supplier's data sheet) needs about 22 kg of wax, so full night drying with PCM alone is heavy and costly. A lighter choice is a small PCM buffer plus an electric or biomass backup heater switched by a relay when sunlight drops below about 400 W/m²; the backup can be left out in the cheapest version.

E. Power Supply

A PV panel feeds a charge controller and battery (with a series diode to stop reverse current) and supplies the 12 V DC

fans, controller, sensors and radio. Example (component powers assumed, not from the papers): two 6 W fans plus 1.5 W for controller, sensors and radio give about 13.5 W, or about 135 Wh over 10 hours. A 12 V, 20 Ah battery holds 240 Wh (a 50 % depth-of-discharge margin), and a 50 W panel at about 4 peak-sun hours yields about 200 Wh, which is enough. A voltmeter/ammeter allows energy monitoring and SMER calculation.

F. Sensors and Actuators

Temperature and humidity are measured at the collector outlet, chamber inlet and exhaust. Load cells under at least two trays estimate moisture from weight loss, and a small irradiance sensor on the collector helps control (Table 4).

Function	Device	Accuracy	Where / note
Air / chamber temperature	Type-K thermocouple with amplifier, PT100 or DHT22	±0.1–0.5 °C	Collector outlet, chamber inlet, exhaust, product surface
Relative humidity	DHT22 or HIH6130 (capacitive)	±2 % RH	Inlet and exhaust
Product moisture	Load cell + HX711 amplifier	±0.01 g	Under two or more trays; moisture from weight loss
Sunlight	Pyranometer / silicon cell	±5 W/m ²	On the collector plane
Air flow control	12 V DC fans via L298 driver or PWM MOSFET	—	Speed follows temperature error

Table 4: Proposed sensors and actuators

G. Controller, Communication and Cloud

An ESP32 or NodeMCU (ESP8266) board is recommended for its built-in Wi-Fi and low cost; an Arduino Mega 2560 suits designs needing many pins. The link depends on the site: Wi-Fi (about 50–100 m) where internet exists, sending data to ThingSpeak or Blynk; GSM (SIM800L/SIM900) for remote farms, with SMS or GPRS alerts for overheating or “batch done”; LoRa (about 1–15 km, very low power) for many dryers in one village or cooperative; and Bluetooth Low Energy for set-up and calibration with a phone. Data go by MQTT to a dashboard showing live temperature, humidity, weight-loss curves and battery level. Because rural internet

can fail, the control loop runs locally (edge control) and data are stored until the link returns.

H. Control Method

The controller keeps chamber temperature steady by changing fan speed (and the backup heater if fitted). On–off control is simplest but swings ±5–10 °C. PID control (typical $K_p = 1–10$, $T_i = 10–100$ s, $T_d = 1–10$ s, tuned by Ziegler–Nichols) gave under 5 % overshoot, settling in under 5 minutes and error below 1 °C. Fuzzy logic needs no process model and can cut overshoot below 3 % and settling time by 20 % compared with PID when sunlight changes. Neural networks predicted drying behaviour with R^2 above 0.98 (Table 5).

Method	Handles non-linearity	Tuning	Typical accuracy	Complexity
On–off	Poor	None (band, e.g. 55 ± 5 °C)	±5–10 °C swings	Very low
PID	Moderate	Manual or Ziegler–Nichols	<5 % overshoot, <1 °C error	Low
Fuzzy logic	Excellent	Expert rules	RMSE 1–2 %	Medium
ANN / machine learning	Excellent	Trained from data	$R^2 > 0.98$, RMSE < 1 %	High (needs data)

Table 5: Control methods for solar dryers

For a first prototype, a PID loop on the ESP32 with an on–off fallback is recommended; fuzzy or learning controllers can be added after field data are logged.

The set-point moves inside a crop-specific band (typically 40–65 °C and 0.5–3 m/s) as sunlight and humidity change, the backup source starts when sunlight drops, and drying stops when quality targets are met (reported rules: final moisture below 15 %, change within 2 % between readings, colour change $\Delta E < 20$). Here the end point is mainly found from tray weight loss; colour sensing is optional.

I. Software, Test Plan and Care

The program repeats every 5–10 seconds: read and filter the sensors, update the PID output, set fan PWM and any backup heater, compute moisture from tray weights, check the end-point rules, save data locally and send it when connected. Safety rules come first: above the crop maximum by a set margin the heater is switched off and the fan set to maximum, and an impossible sensor value sends the system to a safe default with an alert.

After building, the dryer should be tested against open sun drying (and, if possible, a passive solar dryer) with

the same product, batch size and slice thickness, measuring drying time and moisture curves, efficiency, SMER (kg/kWh), temperature evenness and controller overshoot and settling time, product quality (colour, nutrients, water activity below 0.6), and cost and payback. Drying data can be fitted to the Page, Henderson–Pabis and logarithmic models using R^2 , RMSE and reduced chi-square, and the germination

test of Section V (Proposed Germination Test) is added for seed.

Routine care: clean the collector glass, check seals, insulation and fans, inspect the battery and wiring, and recalibrate the temperature, humidity and load-cell sensors at the start of each season against a reference thermometer and a known weight, since sensor drift is a known cause of poor control.

IV. MAIN COMPONENTS EXPLAINED SIMPLY

Each main part of the smart solar dryer is explained below in plain words, with a photo where one is available (photos from the supplied papers; facts from those papers unless stated).

A. Power Parts

	Solar (PV) panel What it is: A flat panel of solar cells that turns sunlight into DC electricity. What it does here: Charges the battery and runs the fans, controller and sensors, so the dryer needs no grid power. Good to know: One prototype's panel gave up to 10 V, boosted to about 30 V DC at about 1 A; a series diode blocks reverse current. Example size here: about 50 W (Section III (Power Supply)).
	Battery (12 V VRLA / lead-acid) What it is: A rechargeable store of electricity (photo: 12 V, 42 Ah sealed lead-acid). What it does here: Keeps the fans and electronics running on cloudy days and at night. Good to know: A 3-cell lithium pack is a lighter alternative; a charge controller prevents over-charging. Example here: 12 V, 20 Ah (240 Wh) for about 135 Wh per day.

B. Controller (the "Brain")

	Arduino board (Uno / Mega 2560) What it is: A low-cost microcontroller board programmed in the Arduino IDE. What it does here: Reads temperature, decides when fans or heater switch, and sends data out. Good to know: Mega 2560: ATmega2560 chip, 256 KB flash, 8 KB SRAM, 54 digital pins (15 PWM), 16 analog inputs, 5 V.
	ESP8266 NodeMCU (Wi-Fi controller) What it is: A small controller board with Wi-Fi built in. What it does here: Receives temperature data, drives the fans through the motor driver and sends readings online. Good to know: Low cost and no extra Wi-Fi module; the newer ESP32 is recommended here for the same reason.

C. Sensors and Displays

	Temperature sensor and digital display What it is: A probe (K-type thermocouple or NTC thermistor) with a display showing chamber temperature. What it does here: Tells the controller the temperature so fans speed up or slow down; checked against a reference thermometer. Good to know: K-type works from about -200 to $+1,300$ °C, gives about $25\text{--}40$ μV per °C and needs an amplifier chip before an Arduino can read it.
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D. Switching and Air-moving Parts

	Relay module What it is: An electrically operated switch: a small signal closes contacts that carry a larger current. What it does here: Switches the fans and the backup heater on and off. Good to know: Typical contacts 10–30 A at 250–400 V AC, coil 5–24 V DC, switching 5–20 ms (general values; depend on model).
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The L298 motor driver lets a weak controller pin drive and change the speed of a 12 V DC motor, and sits between the NodeMCU and the two fans. The fans, powered from the battery, bring in dry air and remove wet air, shortening drying time and giving even drying.

E. Collector and Drying Chamber

	Solar air collector and drying chamber What it is: A black metal absorber under glass heats the air; the chamber is an insulated box with trays. Photo: greenhouse dryer with a quadruple-pass collector. What it does here: The collector supplies hot air and the chamber holds the product in thin layers. Good to know: Multi-pass collectors can give more heat than single-pass ones of the same area.
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V. SOYBEAN AND SUNFLOWER SEED GERMINATION

This section shows how a smart solar dryer can help keep and improve the germination of soybean and sunflower seed. Two points first:

- A dryer cannot make seed better than its own quality; it can prevent germination loss from heat damage, mould and wrong moisture.
- The supplied papers do not test the effect of a smart dryer on germination. Points marked (general practice) come from common seed-technology guidance, not the 14 papers, and should be confirmed with a seed authority such as ICAR-IISR or a local seed laboratory.

A. What Seed Needs to Germinate

A seed germinates if it is alive and has the right conditions: water, a suitable temperature, often light, nutrients and a

growing medium. Seed age and mould growth also matter. A seed dried too little can grow mould, and one dried too hot or too much can lose its ability to sprout, which is why drying is so important.

B. Why the Dryer's Temperature Setting Matters

The 55 °C design target in Section III suits foods such as ginger or chilli, but seed must stay alive. Common practice uses cooler air of about 40 °C or lower and dries soybean to about 11–13 % moisture and sunflower to about 8–9 % for safe storage; oil-rich seeds are easily damaged by heat and damp (all general practice). The smart dryer should therefore have a separate “seed profile” with a lower temperature limit, slower drying and an automatic stop at target moisture (Figure 4).

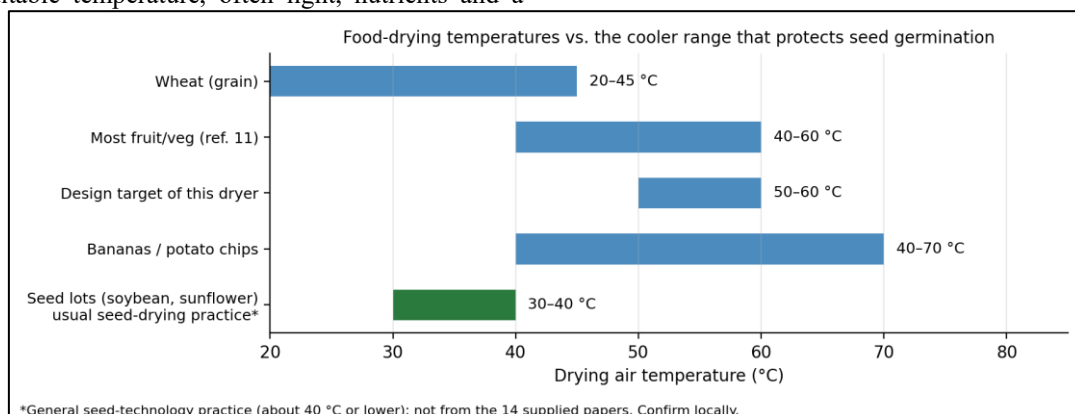


Fig. 4. Drying temperatures used for food compared with the cooler range usually used for seed (general practice, not from the supplied papers).

C. How the Smart Dryer Protects Germination

Risk to germination	Smart dryer feature
Heat damage (chamber too hot)	PID control holds temperature within $\pm 1-2^{\circ}\text{C}$; a low “seed profile” limit; cut-off if above limit (the seed profile is a design proposal)
Over-drying (seed dried too much, cracks)	Load cells on trays stop drying at target weight
Under-drying (seed stays damp, mould)	End-point rule: moisture $\leq$ target and weight change near zero; humidity sensor at exhaust
Slow drying in wet weather (mould)	Enclosed chamber, fans, backup heater or PCM buffer keep drying going in cloudy weather
Mould during sprouting or long drying	Shorter, controlled drying; sprouts are dried quickly. Fungus appeared from day 5 of germination

Table 6: Risks to seed germination and the dryer feature that reduces each

D. Soybean: Soaking and Germination

Kayembe and Jansen van Rensburg soaked soybeans for 24 hours, germinated them for one to six days at $22-26^{\circ}\text{C}$, then sun-dried the sprouts for 48–72 hours; this aimed at feed quality, not sowing germination rate. Crude protein rose from 39.1 % in raw seed to 45.1 % after six days, and condensed tannins fell most after 2–4 days (by 46–55 %). Fungus appeared from day five and polyphenols rose after five to six days, so three days was recommended. Open sun drying for 48–72 hours is slow and risks new mould: a temperature-controlled dryer can dry sprouts faster and more evenly and stop at the correct moisture. This is a proposal that still needs testing.

E. Sunflower

Sunflower (*Helianthus annuus*) is a leading oilseed rich in oil (especially oleic acid), protein, fibre, vitamins and antioxidants. The supplied paper covers nutrition, health value and production, not germination. Because oil-rich seed is easily hurt by heat and damp (general practice), the same seed profile as in Section V (Why the Dryer’s Temperature Setting Matters) (cooler air, about 8–9 % target moisture, automatic stop) is proposed, changing only the profile and tray loading.

F. Cold Plasma: A Possible Add-on

Cold (non-thermal) plasma was reviewed for maize, not soybean or sunflower. Short treatments made seed surfaces take up water more easily and killed bacteria and fungi, with germination of 96.0 % after 2.5 minutes in one study, but 240–300 s stopped germination in another. It is not shown for soybean or sunflower and the equipment is expensive, so it is listed only as future work.

G. Proposed Germination Test

A simple experiment follows the school-level activity sheet method: change only one variable (the dryer profile), keep a

control, count germinating seeds over several days and measure growth rate as plant height divided by time.

Group	Drying treatment	What to measure
A (control)	Open sun drying to target moisture	Germination % at day 7 and day 10; seedling height $\div$ days
B	Smart dryer, seed profile (about 40°C or lower, stop at target moisture)	Same
C	Smart dryer, food profile (55°C)	Same, to show the effect of heat
D (optional)	Smart dryer, seed profile, sprouted seed dried for feed use (soybean only)	Protein, tannins, moisture, mould

Table 7: Proposed germination test for soybean and sunflower seed

Use at least four replicates of 100 seeds per group from the same seed lot, with the same watering, and record moisture before and after drying. No results are claimed: the expected outcome (highest germination in group B, lower in C) is a hypothesis based on the heat-sensitivity of seed.

VI. RESULTS AND DISCUSSION

This section discusses the results reported in the reviewed papers for the proposed design; no new experimental data are presented.

A. Drying Performance

Enclosed solar dryers dry faster than open sun: 50–70 % faster for direct dryers, 40–60 % for indirect dryers, and 34–62 % less time for greenhouse systems; one hybrid system with storage needed 6 hours instead of 15. Hybrid systems raise chamber temperature by about $10-20^{\circ}\text{C}$ over plain indirect dryers. For the proposed 10 kg dryer, the 4.15 kWh daily heat need matches a $2.5-3\text{ m}^2$ collector but leaves little margin in monsoon weather, which supports a backup heater or storage.

B. Value of Storage and Hybrid Heating

Hybrid heating makes drying more stable rather than much more efficient at any moment: PCM dryers show small gains in instant efficiency (13.1 % against 11.4 % for chilli) but a large gain in drying time, because heat is available after sunset. The trade-off is weight and cost, about 22 kg of paraffin for real night storage (Section III (Heat Storage and Backup Heater)), so a small PCM buffer or an electric/biomass backup is more practical for a small-farmer machine.

C. Effect of Smart Control

The biggest benefit of smart control is stability and energy saving. IoT systems held temperature within $\pm 2^{\circ}\text{C}$ and reduced energy use by 20–30 %; PID gave under 1°C steady error against $\pm 5-10^{\circ}\text{C}$ swings for on–off control. Controlled drying kept more antioxidants and better texture, and tray weight sensors prevent over-drying. The same features keep seed from being overheated or over-dried (Section V). Table

8 shows how the proposed design fills the gaps in the four prototypes.

Feature	Harischandrakar	Jagadeesh	Sarkar	Devi & Kalnar	Proposed
Solar PV + battery	Panel	Yes	Yes	Yes	Yes
Tray weight sensing	No	No	No	Yes	Yes
Wireless / IoT	MQTT	Wi-Fi	Proposed	No	Wi-Fi / GSM / LoRa
Closed-loop control	Threshold	Fan speed	Relay	Fan speed	PID + rules
Heat storage / backup	No	No	No	PCM + blower	Optional PCM / heater
Seed profile (germination)	No	No	No	No	Yes
Measured results	No	No	Limited	No	To be tested

Table 8: Feature comparison of reviewed prototypes and the proposed design

D. Cost

Solar dryers cost about USD 100–500 for basic indirect models and USD 3,000–5,500 for hybrid or one-tonne systems, about 45 % less than electric convective dryers. IoT parts cost roughly USD 50–300, adding 5–15 % to the total. Reported payback is 1.1–2.7 years (0.49–2.35 years for greenhouse dryers), with internal rates of return of 38–84 %, and IoT may bring payback under two years. Because electronics are a small part of the cost, the extra cost of intelligence is small compared with the savings. However, a dryer owned by one small farmer can be uneconomic, so shared or cooperative use is suggested.

E. Environment and Society

Replacing fuel or grid energy with sunlight reduces greenhouse gas emissions; life-cycle studies of greenhouse dryers report net CO₂ savings of about 28–36 tonnes over equipment life. Less post-harvest loss raises farm income and food security, and protection from dust, insects and birds lowers spoilage and mycotoxin risk.

F. Use Case: Soybean, Sunflower and Other Crops

In a soybean cooperative, harvest falls at the end of the monsoon, when rain and humidity threaten field drying. A shared group of smart dryers could be watched by one operator over LoRa or GSM, with each batch stopping at target moisture from the tray weight-loss curve. The same dryers could dry seed lots with the cooler seed profile, process germinated soybean, and, off-season, dry chilli, ginger, fruit and herbs, which also shortens payback.

Crop settings (maximum temperature, target moisture, layer thickness) must be set per crop; Table 3 is a high-moisture example and does not transfer to grains and oilseeds. Extension services and research institutes can supply tested profiles to store in the controller.

VII. CHALLENGES AND LIMITS

Table 9 lists the main practical challenges and the remedy used in this design.

Challenge	What happens	Remedy in this design
Sensor error and drift	Cheap sensors drift and suffer in heat and damp	Regular calibration; spare sensors; sanity checks; use RTD/thermocouple for control
Rural internet	Cloud-only systems fail when the	Local control; data buffering; GSM or LoRa instead of Wi-Fi

	network is down	
Cost and scale	Small units are hard to make viable	Modular build; shared ownership; optional PCM/heater
Weather changes	Sunlight, humidity, wind and rain vary	Backup heater or PCM buffer; adaptive set-points; sunlight-based rules
Seed safety	Food temperatures can damage seed	Separate low-temperature seed profile; germination test (Section V (Proposed Germination Test))

Table 9 Challenges and proposed remedies

Limits of this study: it uses secondary data from studies with different products, climates, methods and efficiency definitions, so comparisons are only indicative. Several prototype papers give only qualitative results. The Section III calculations rest on assumptions (collector efficiency, PCM latent heat, component power), the power budget is unmeasured, the seed temperatures and moistures in Section V are general practice rather than from the supplied papers, and the effect of the smart dryer on germination is untested. Several supplied papers are not about drying and were used only for background.

VIII. FUTURE SCOPE

- Build a prototype and run field trials against open sun drying on soybean, sunflower, maize, chilli, ginger and fruits, using the test plans in Section III (Software, Test Plan and Care) and Section V (Proposed Germination Test), and store validated seed profiles in the controller.
- Self-learning control (reinforcement learning, machine-learning predictors) and digital twins combining physics-based models with live sensor data to optimise quality, energy and PCM sizing.
- Camera-based quality checks (for example VGG19-type models) and satellite crop-stage products such as Sentinel-1 pod detection, to grade product, detect the end point and forecast dryer demand.
- Combine drying with germination-based soybean processing or cold-plasma seed treatment tested on soybean and sunflower.
- Desiccant beds, heat pumps or better storage materials for humid climates, and village-scale networks of LoRa-connected dryers with a shared dashboard.

IX. CONCLUSION

This paper combined the findings of fourteen recent papers into a simple, design-focused study of smart solar dryers. Enclosed solar dryers dry about 40–70 % faster than open sun; hybrid and PCM dryers keep temperature steady at about 25–45 % efficiency; sensors, low-cost controllers and wireless links allow closed-loop control within about ± 2 °C, may save 20–30 % of energy and allow remote monitoring; and payback of about 1–3 years is attractive, especially for shared use.

A 10 kg dryer was proposed with a collector of about 3 m², a PV–battery supply, multi-point temperature and humidity sensing, tray weight measurement, an ESP32-class controller with PID control and safety rules, and Wi-Fi, GSM or LoRa links; the batch heat need is about 4.15 kWh for the assumed crop. A low-temperature seed profile with weight-based stopping is proposed to protect soybean and sunflower germination, with a simple test to prove it. Open tasks are experiments, sensor calibration and seed-safe control under real weather.

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