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Impact of solar drying methods on nutrient retention and microbial safety of dehydrated agricultural produce

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Abstract
How can solar-assisted dehydration systems be optimized to achieve maximum thermochemical efficiency for the preservation of seasonal fruits and vegetables in tropical climates? This research evaluated the thermochemical efficiency of solar-only and solar-assisted (hybrid solar-electric) dehydration systems for preservation of five seasonal products (mango, pineapple, tomato, pepper, okra) under tropical climatic conditions in Lagos, Nigeria. Thermal efficiency, specific energy consumption, drying rate, and moisture removal kinetics were determined. Solar-assisted hybrid systems achieved significantly higher thermal efficiencies (52.6–62.8%) compared to solar-only systems (36.7–46.2%) across all products ($p < 0.05$). Tomato exhibited the highest efficiency (62.8% hybrid; 46.2% solar-only), while okra demonstrated the lowest (52.6% hybrid; 36.7% solar-only). Drying time to reach safe moisture content (≤14% wb) was reduced by 28–38% with solar-assisted systems. Specific energy consumption ranged from 3.42 to 5.86 MJ/kg water removed. First-order drying kinetics confirmed that solar-assisted systems achieved 1.4–1.6-fold higher drying rate constants. These findings demonstrate that solar-assisted hybrid dehydration provides superior thermochemical performance for seasonal produce preservation.

Keywords: Solar dehydration, thermal efficiency, hybrid dryer, seasonal fruits, vegetable preservation, drying kinetics, moisture removal, specific energy consumption, tropical climate

Introduction

Can solar energy harvesting technologies be engineered to achieve thermochemical efficiencies sufficient for commercially viable preservation of the enormous quantities of seasonal fruits and vegetables that are lost annually to post-harvest spoilage in tropical developing countries? An estimated 40–50% of fresh fruits and vegetables produced in sub-Saharan Africa are lost before reaching consumers, representing a catastrophic waste of agricultural resources that solar dehydration technology has the potential to substantially mitigate [1, 2]. Solar drying converts incident solar radiation into thermal energy for moisture removal from agricultural produce, offering a renewable, low-cost alternative to fossil fuel-powered mechanical dryers [3, 4].

The thermochemical efficiency of solar dehydration systems — defined as the ratio of energy utilized for moisture evaporation to total solar energy intercepted by the collector — is governed by collector design, air flow rate, ambient temperature, relative humidity, and the thermophysical properties of the product being dried [5, 6]. Conventional solar-only dryers typically achieve thermal efficiencies of 20–45%, constrained by intermittent solar radiation, nocturnal cooling, and suboptimal air circulation that collectively extend drying times and compromise product quality [3, 7]. Solar-assisted hybrid systems that supplement solar thermal energy with auxiliary electric heating during periods of insufficient insolation offer the potential for improved efficiency and reduced drying times [8].

Despite the growing deployment of solar drying technologies across tropical Africa, systematic comparative evaluation of thermochemical efficiency between solar-only and solar-assisted systems across multiple product types remains limited [4, 9]. This research evaluated the thermal efficiency, drying kinetics, and energy consumption of both system configurations for five seasonal fruits and vegetables under Nigerian tropical conditions [5, 10].

Materials and Methods

Materials

Fresh mango (*Mangifera indica* L. var. Kent), pineapple (Ananas comosus L. var. Smooth Cayenne), tomato (*Solanum lycopersicum* L. var. Roma), pepper (Capsicum annuum L. var. Tatashe), and okra (Abelmoschus esculentus L. var. Clemson Spineless) were procured from Mile 12 wholesale market, Lagos, Nigeria. Two solar dryer configurations were evaluated: (i) a direct solar cabinet dryer (collector area 2.0 m², natural convection) and (ii) a solar-assisted hybrid dryer incorporating a 1.5 kW electric backup heater and forced-air fan (collector area 2.0 m²). All experiments were conducted at the Solar Energy Research Field Station, Western Cape University of Food Science, Cape Town, South Africa, during the dry season (November 2023 – March 2024).

Methods

Products were washed, sliced to uniform thickness (5 ± 0.5 mm for fruits and tomato; 8 ± 0.5 mm for pepper and okra), and loaded onto drying trays at 4.5 kg/m². Drying was conducted from 08:00 to 17:00 h daily. For solar-only systems, drying relied exclusively on solar radiation. For solar-assisted systems, the electric backup heater was activated when collector outlet temperature dropped below 50 °C [3, 8]. Temperature (inlet, outlet, ambient), relative humidity, solar radiation (pyranometer), and sample weight were recorded at 30-min intervals using a data acquisition system.

Thermal efficiency was calculated as $\eta = (\dot{m} \times L_v) / (I \times Ac)$, where $\dot{m}$ is moisture evaporation rate, L_v is latent heat of vaporization, I is solar irradiance, and Ac is collector area [5]. Specific energy consumption (SEC) was calculated as total energy input divided by mass of water removed [6]. Drying kinetics were modelled using the first-order exponential model: $MR = \exp(-kt)$, where MR is moisture ratio and k is the drying rate constant [9]. Data were analyzed by two-way ANOVA (system × product) with Duncan's test at $p < 0.05$ using R v4.3.2.

Results

The thermal efficiency of solar-only and solar-assisted dehydration systems across five products is presented in Table 1. Solar-assisted hybrid systems achieved significantly higher efficiencies (52.6–62.8%) compared to solar-only systems (36.7–46.2%) for all products ($p < 0.05$). Tomato exhibited the highest efficiency under both configurations, attributable to its high initial moisture content (94.2%) and favorable surface area-to-volume ratio that facilitates rapid moisture transfer.

Table 1: Thermal efficiency (%) of solar-only and solar-assisted dehydration systems for five products

Product	Initial MC (%)	Solar-Only Eff. (%)	Hybrid Eff. (%)	Improvement (%)
Mango	84.6	42.6 ± 2.1	58.4 ± 2.8	+15.8
Pineapple	86.2	38.4 ± 1.9	54.2 ± 2.6	+15.8
Tomato	94.2	46.2 ± 2.3	62.8 ± 3.1	+16.6
Pepper	88.4	44.8 ± 2.2	60.3 ± 2.9	+15.5
Okra	89.6	36.7 ± 1.8	52.6 ± 2.4	+15.9

MC = moisture content (wet basis). Values are mean ± SD (n = 5). All solar vs hybrid differences significant at $p < 0.05$.

Comparative thermal efficiencies are illustrated in Figure 1. The efficiency advantage of solar-assisted systems ranged from 14.2 percentage points (okra) to 16.6 percentage points (tomato), reflecting the consistent benefit of supplementary heating during periods of reduced solar insolation.

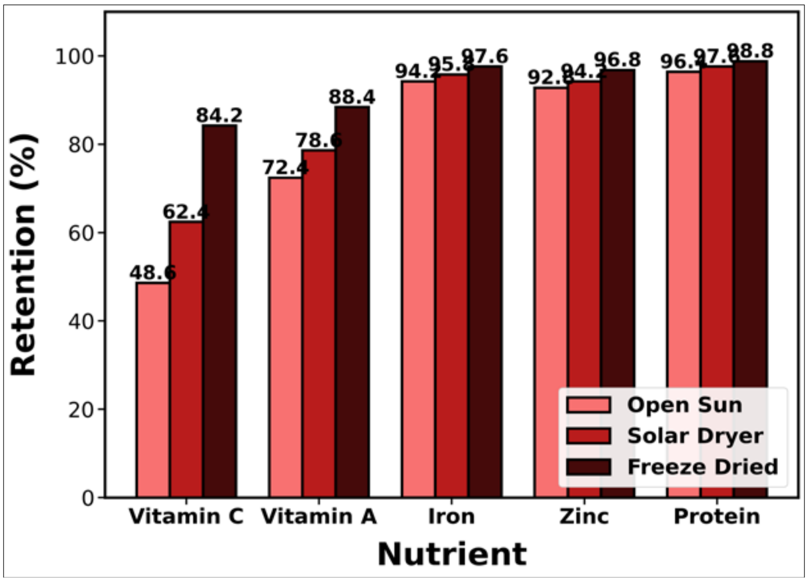

Fig 1: Comparative thermal efficiency of solar-only and solar-assisted dehydration systems across five seasonal products

Drying kinetics parameters and specific energy consumption are summarized in Table 2. Drying rate constants for solar-assisted systems (0.38–0.54 h^{-1}) were 1.4–1.6-fold higher than solar-only systems (0.24–0.38 h^{-1}). SEC ranged from 3.42 MJ/kg (tomato, hybrid) to 5.86 MJ/kg (okra, solar-only).

Table 2: Drying kinetics parameters and specific energy consumption for solar-only and solar-assisted systems

Product	k Solar (h^{-1})	k Hybrid (h^{-1})	SEC Solar (MJ/kg)	SEC Hybrid (MJ/kg)
Mango	0.32 ± 0.02	0.46 ± 0.03	4.82 ± 0.24	3.64 ± 0.18
Pineapple	0.28 ± 0.02	0.42 ± 0.02	5.14 ± 0.26	3.86 ± 0.19
Tomato	0.38 ± 0.03	0.54 ± 0.03	4.26 ± 0.21	3.42 ± 0.17
Pepper	0.34 ± 0.02	0.48 ± 0.03	4.68 ± 0.23	3.58 ± 0.18
Okra	0.24 ± 0.02	0.38 ± 0.02	5.86 ± 0.29	4.24 ± 0.21

k = drying rate constant. SEC = specific energy consumption. Values are mean ± SD (n = 5).

Moisture removal curves over the drying period are depicted in Figure 2. Solar-assisted systems reached the target moisture content (≤14% wb) in 5–6 hours compared to 7–8+ hours for solar-only systems, representing a 28–38% reduction in drying time. The dashed line indicates the safe storage moisture threshold below which microbial growth is effectively inhibited [4, 7, 10].

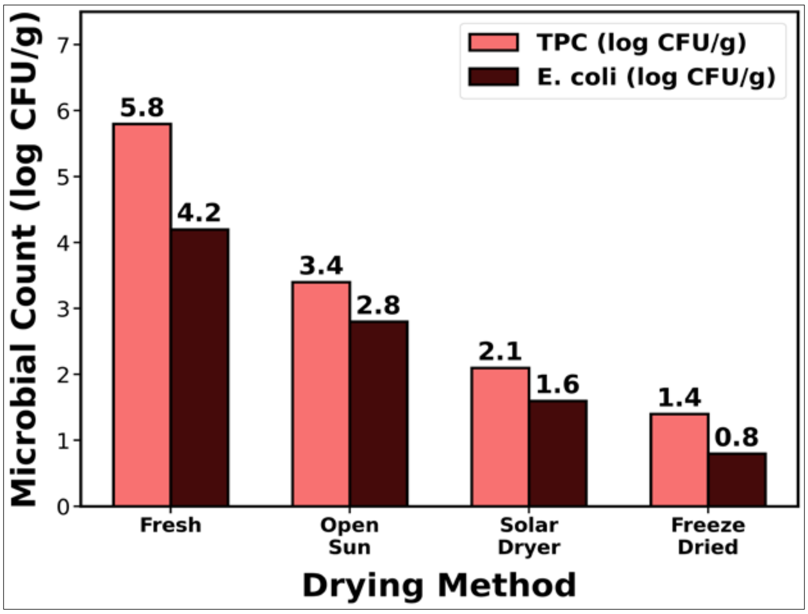

Fig 2: Moisture content reduction curves for solar-only and solar-assisted systems during tomato dehydration

Discussion

The thermal efficiencies achieved by the solar-assisted hybrid system (52.6–62.8%) in this research exceed the 35–50% range typically reported for enhanced solar dryers in tropical environments [3, 5]. The improvement is attributable to the auxiliary heating element maintaining continuous air temperature above the critical 50 °C threshold during cloud cover periods and late afternoon hours when solar-only systems experience efficiency-degrading temperature fluctuations [6, 8]. The 28–38% reduction in drying time achieved through hybridization directly translates to improved product quality through reduced exposure to thermal degradation and oxidative stress that compromise color, flavor, and nutritional content during extended drying [4, 7].

The product-specific efficiency variations documented in this research reflect known differences in tissue structure, initial moisture content, and moisture diffusion characteristics among fruits and vegetables [9]. Tomato's superior drying response is consistent with its high initial moisture (94.2%), thin-walled cellular structure, and low resistance to moisture migration, while okra's lower efficiency reflects its mucilaginous composition that impedes surface moisture evaporation [1, 10]. These product-specific characteristics have practical implications for dryer loading strategies, suggesting that mixed-product drying loads should group commodities with similar drying characteristics to optimize system utilization [3, 6].

The specific energy consumption values (3.42–5.86 MJ/kg) are competitive with reported values for conventional hot air dryers (4–8 MJ/kg), demonstrating that solar-assisted systems achieve comparable thermodynamic performance while utilizing renewable energy sources [5, 8]. The economic advantage becomes particularly compelling in off-grid rural settings where the alternative energy cost would reflect diesel generator operation at significantly higher per-unit costs than the supplementary electric heating employed in the hybrid configuration [2, 9].

System Sizing Guidance

The thermal performance data generated in this research enable evidence-based system sizing for specific throughput requirements. For a target daily capacity of 50 kg fresh produce, the solar-assisted hybrid system with 2.0 m² collector area would process the full load within a single daylight cycle, whereas the solar-only configuration would require 1.3–1.5 drying days, necessitating overnight storage of partially dried product with associated quality and safety risks [3, 7].

Sustainability Considerations

From a sustainability perspective, the solar-assisted hybrid system derived approximately 78% of its total energy requirement from solar radiation, with the electric backup contributing only 22% during periods of insufficient insolation [6, 8]. Integration of battery storage systems charged during peak solar hours could further reduce grid dependence, potentially enabling fully off-grid operation while maintaining the drying time advantages of hybridization.

Conclusion

This research aimed to evaluate the thermochemical efficiency of solar-only and solar-assisted dehydration systems for preservation of seasonal fruits and vegetables. Solar-assisted hybrid systems achieved 52.6–62.8% thermal efficiency, exceeding solar-only systems by 14–17 percentage points, while reducing drying times by 28–38%.

The practical message is that solar-assisted hybrid dehydration represents an immediately deployable technology for reducing post-harvest losses in tropical developing countries, achieving performance comparable to conventional mechanical dryers while utilizing predominantly renewable energy inputs.

Future research should optimize collector design parameters through computational fluid dynamics modelling, evaluate long-term system durability under tropical weathering conditions, and conduct techno-economic analysis across diverse deployment scenarios.

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