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DRYING THEORY AND CURRENT TRENDS IN CONVECTIVE AND SOLAR DRYING OF FOOD PRODUCTS

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Abstract: *Population growth, climate change, and increasing pressure on energy resources make low-energy preservation technologies essential. Food drying—especially of fruits and vegetables—remains one of the oldest and most flexible preservation methods, yet the way it is carried out has changed radically: from traditional, uncontrolled sun drying to convective, solar, and hybrid systems optimized through automatic control and thermal energy storage.*

From a review perspective, this paper presents the theoretical fundamentals of convective drying (heat and mass transfer, internal diffusion, the crusting effect, and the role of temperature, relative humidity, and air velocity) and the critical technological parameters that determine product quality. It then synthesizes the common methods used to determine drying kinetics (drying curves and drying-rate curves, performance indicators) and provides a typical experimental example from the literature on apricot fruit drying.

In the trends section, the paper surveys the evolution of solar dryers (direct, indirect, tunnel-type, and greenhouse-type), the development of hybrid systems (solar–biomass, solar–electric, solar–heat pump), the integration of phase change materials (PCMs) for thermal energy storage, and the emergence of “smart” dryers equipped with IoT sensors and real-time monitoring. The socio-economic dimension is also discussed, highlighting the role of solar dryers in reducing post-harvest losses and supporting small-scale producers. Finally, conclusions and development directions are formulated for designers and manufacturers of drying equipment, with an emphasis on the convergence between classical drying theory and green, digital technologies.

Keywords: *Food drying, solar dryer, heat and mass transfer, convective drying, PCM, IoT, hybrid systems*

1. Introduction

Drying is one of the oldest methods of food preservation, initially practiced by directly exposing products to solar radiation. Removing water reduces microbiological activity and slows chemical reactions, enabling fruits and vegetables to be stored for long periods, with relatively low storage and transport costs.

Solar energy—an abundant renewable resource available throughout the year—is naturally associated with food drying. In recent decades, interest in solar drying has increased significantly, both due to the gradual depletion of fossil fuels and because of the pressure to reduce greenhouse-gas emissions. Recent studies and review papers show a steady increase in the number of publications dedicated to solar dryers for agri-food products, with a focus on energy efficiency, quality, and sustainability.

However, the traditional open sun-drying method has major limitations:

- limited control of temperature and humidity;
- risk of contamination by dust, insects, birds, or animals;
- high variability in product quality;
- significant thermal losses, since only a fraction of the incident radiation is effectively utilized.

To overcome these limitations, enclosed solar dryers (cabinet, tunnel, greenhouse) have been developed, where the product is protected from the outdoor environment and process parameters can be controlled more effectively. Recent developments include:

- indirect and hybrid solar dryers that combine solar energy with other sources (biomass, electric heaters, heat pumps) [1].

- integration of phase change materials (PCMs) for thermal energy storage [2].
- the use of sensors and IoT systems for real-time monitoring and control of the drying process [3].

In parallel, the literature emphasizes the need to more tightly link drying theory (describing heat and mass transfer at the product level) with the practical design of equipment: airflow distribution, channel geometry, product placement, integration of auxiliary heat sources, and thermal storage [4].

The purpose of this paper is to provide a focused review of the theoretical basis of convective drying of food products and to synthesize the main current technical trends in solar and hybrid drying, with direct implications for the design and optimization of drying equipment.

2. Method

2.1 The theoretical basis of convective drying

Drying fruits and vegetables is a heat and mass transfer process in which:

- hot air provides the energy required to evaporate water;
- water migrates from the interior of the product to the surface and is then removed by the airflow.

Internal diffusion and thermo-diffusion. At the beginning, free water on the surface evaporates rapidly. Subsequently, water from inner layers migrates toward the surface through internal diffusion, driven by concentration differences and osmotic pressure. At the same time, the temperature gradient between the exterior and the interior generates thermo-diffusion (water migration influenced by the thermal gradient). In convective drying practice, internal diffusion dominates the process, while thermo-diffusion plays a secondary role, because temperature differences inside the product are not very large.

Crust formation. If the evaporation rate at the surface is much higher than the internal diffusion rate of water, a crust (a dry, rigid surface layer) may form, blocking moisture migration from the interior. This phenomenon leads to:

- longer drying times;
- difficult rehydration;
- non-uniform texture and potential skin cracking (e.g., in plums, grapes).

To avoid crust formation, combined control of air temperature and relative humidity is essential, so that surface evaporation does not drastically exceed the internal diffusion capacity.

2.2. Process parameters and optimal conditions

For designers and operators, several parameters are critical:

- **Air temperature:**
    - for most fruits, the literature recommends dryer inlet temperatures of 70–72°C, decreasing to 40–45°C at the outlet;
    - exceeding these limits causes sugar caramelization, browning, loss of aroma and color, and degradation of certain heat-sensitive vitamins.
- **Air relative humidity:**
    - 20–25% at the system inlet, increasing to 60–70% at the outlet;
    - air that is too dry promotes crust formation; air that is too humid slows the process excessively.
- **Air velocity:**
    - it must be high enough to remove water vapor and maintain a moisture gradient between the product and the air;
    - in tunnel dryers, velocities in the 3–5 m/s range are frequently reported; values that are too low lead to rapid air saturation, while values that are too high increase energy losses.
- **Product size and geometry:**
    - reducing characteristic dimensions (thin slices, halves) shortens the diffusion path and increases the evaporation area;

  - common examples: apricots as halves; apples and pears as slices; vegetables as rounds or cubes; grapes and plums as whole fruits.

Optimal process efficiency is achieved when the evaporation rate at the surface is approximately equal to the rate of water migration from the interior. This balance depends on the combination of temperature, relative humidity, air velocity, and the preparation method (cutting, blanching, osmotic pretreatments, etc.).

2.3. Moisture and performance indicators

In the analysis and control of drying processes, two main moisture-content indicators are used:

- Moisture content on a dry basis (dry-solid basis):

$$X_d = \frac{m_w}{m_{usc}}$$

where (m_w) is the mass of water, and (m_{usc}) is the mass of dry matter (dry solids).

- Moisture content on a wet basis (wet material basis):

$$X_u = \frac{m_w}{m}$$

where m is the total mass of the product (water + dry matter).

In addition, practical indicators are used:

- Drying yield – the ratio between the mass of dried product obtained and the mass of raw material used, expressed as a percentage.
- Drying ratio – the amount of raw material required to obtain 1 kg of dried product.

These measures support equipment sizing and enable comparisons between different technologies or process conditions.

2.4. Experimental methods for determining drying kinetics

Drying kinetics are typically determined from the mass–time variation curve. A common experimental setup includes:

- a drying chamber with a controlled hot-air supply (electric heaters or a conventional/solar heat source);
- a system for measuring product and air temperature (thermocouples, resistance temperature detectors);
- automatic control of air temperature (PID controller);
- air velocity measurement (anemometer, micromanometer);
- a precision balance, sometimes integrated into a suspension system that allows continuous monitoring of the sample mass without stopping the process.

From the measured data series m(t)m(t)m(t), moisture content is calculated and the following are plotted:

- the drying curve: moisture content vs. time;
- the drying-rate curve: the (numerical) derivative of moisture content with respect to time.

The analysis of these curves generally highlights three periods: initial heating, the constant-rate drying period, and the falling-rate period.

A frequently cited example in the literature concerns the convective drying of apricots with air heated to 60–100°C, at air velocities on the order of 0.5–1 m/s. In such studies, drying time decreases by several times when moving from moderate temperatures (e.g., 60°C) to higher temperatures (e.g., 100°C), and the maximum drying rate increases almost linearly with temperature up to a certain threshold, beyond which quality degradation becomes significant. Such results underpin practical recommendations for selecting the optimal temperature for each product.

3. Trends in food drying

In recent years, the literature has evolved from isolated descriptions of experimental cases to broader analyses of dryer typologies, methods for enhancing heat and mass transfer, and the integration of these technologies into agri-food value chains. Key directions are summarized below.

3.1. Evolution of solar dryers

Recent reviews show that solar dryers for food products can be grouped into several major categories: direct dryers (the product is exposed inside a glazed chamber), indirect dryers (the product does not “see” the sun directly; the air is preheated in a collector), tunnel-type dryers, and greenhouse dryers [5].

Observed trends include:

- a shift from direct drying to indirect and mixed configurations, to protect the product from direct radiation and to improve temperature control;
- optimization of collector geometry and airflow (guides, plenums, baffles) to ensure uniform air distribution and reduce “dead” zones;
- the use of photovoltaic-powered fans to maintain a constant air velocity, independent of wind variations.

Internationally, there is a shift from simple demonstration prototypes to pre-industrial equipment and solar dryers integrated into farms or cooperatives, with capacities ranging from a few tens to a few hundreds of kilograms per batch [4].

Solar dryers can be categorized based on size, structural/system configuration, and the way solar energy is utilized. Figure 1 presents all identified dryer types.

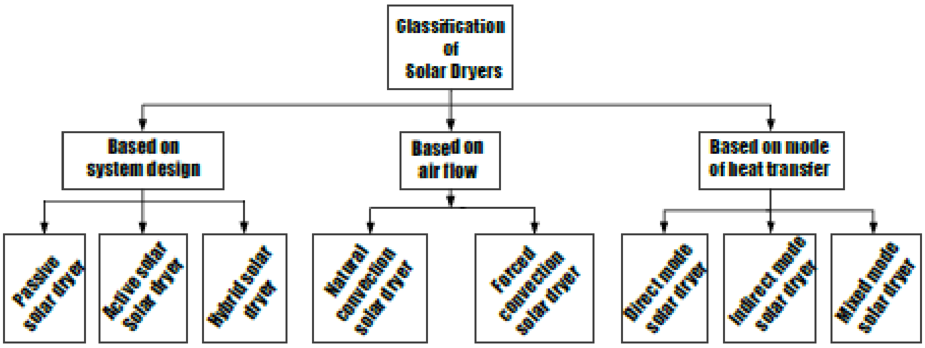

Fig. 1. Classification of solar dryers

The drying technology has seen a transition from the ancient open-air sun drying to the modern smart solar dryers as presented in Figure 2. The transition in the drying technology is as a result of continued increase in research activities in mechanical and electrical engineering (Renewable energy). Dryer designs, performance and efficiency have kept on improving within this transition.

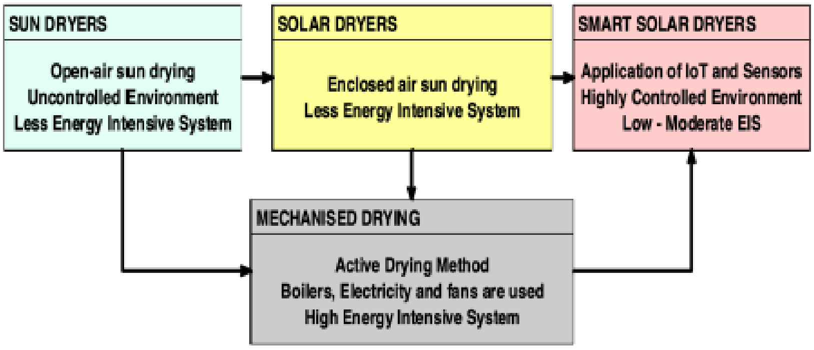

Fig. 2. Transition in solar drying technology

3.2. Hybrid systems: solar + biomass / electric / heat pump

An important direction is the development of hybrid dryers, which combine solar energy with other heat sources in order to ensure:

- process continuity (including during the evening or under low-radiation conditions);
- more precise and stable temperatures;
- shorter drying times and better product quality.

Reviews of hybrid dryers highlight the integration of four main types of sources: electric heaters, biomass (stoves, fire-to-air heat exchangers), thermal energy storage, and, more recently, solar-assisted heat pump (SAHP) systems [1].

Next, the operating modes of the three main drying systems are presented: direct drying (Fig. 3), indirect drying (Fig. 4), and hybrid (solar-thermal) drying (Fig. 5).

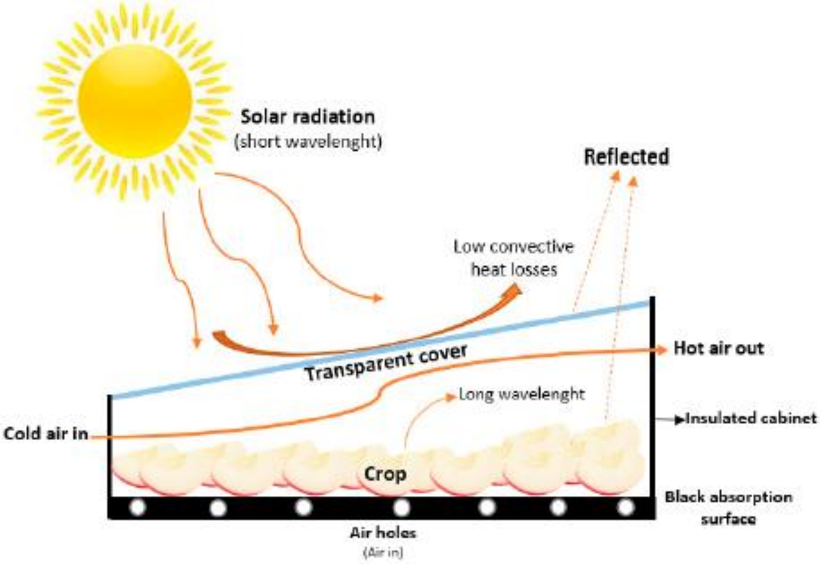

Fig. 3 Schematic of working principle of direct drying method

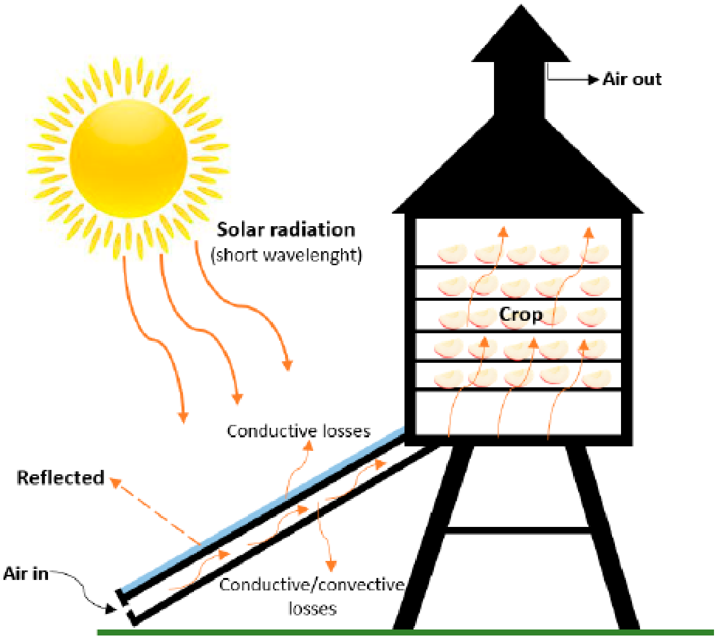

Fig. 4 Schematic of working principle of indirect drying method.

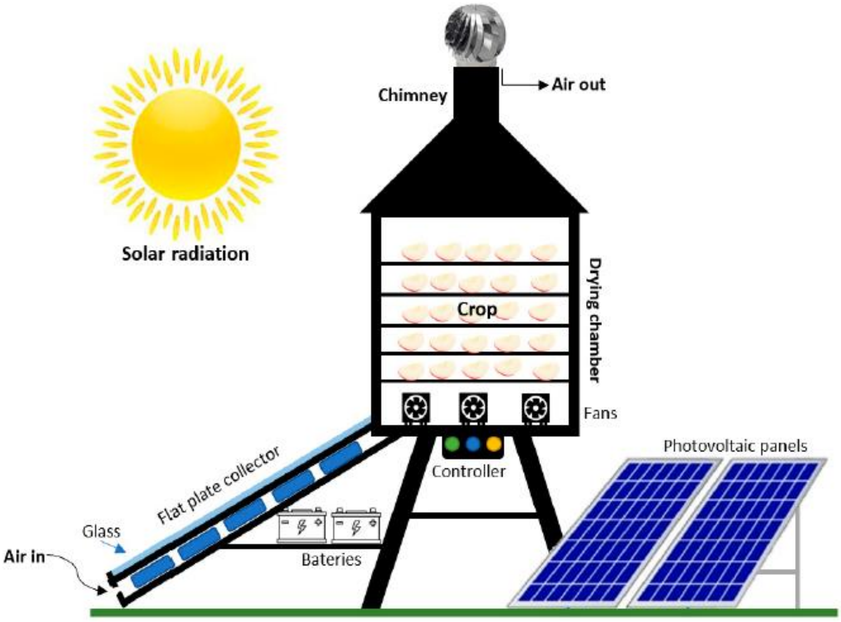

Fig. 5. Schematic of working principle of hybrid (solar–thermal) drying method

The advantages of hybrid systems include:

- increasing overall efficiency (solar energy covers part of the demand, while the remainder is supplied by the auxiliary source);
- reducing drying time by up to 30–50% compared with simple solar drying or natural drying;
- flexibility in adjusting process conditions for different product types.

At the same time, studies show that hybrid solutions must be carefully optimized to avoid overheating and to ensure they do not undermine the “low-carbon” advantage of solar drying.

3.3. Thermal storage using phase change materials (PCM)

The integration of phase change materials into solar dryers is one of the most visible trends in recent years. PCMs (paraffins, hydrated salts, eutectic mixtures, or experimentally, metal alloys) are used to:

- store thermal energy during periods of intense solar radiation;
- gradually release heat when radiation decreases (clouds, afternoon, evening), maintaining a more constant temperature inside the drying chamber.

Numerous studies and reviews show that using PCM in collectors or drying chambers can:

- reduce temperature fluctuations;
- extend the effective drying period by a few hours per day;
- increase overall thermal efficiency and shorten drying times [2].

From a design perspective, the main challenges relate to:

- selecting an appropriate melting temperature for the target product (typically 40–70°C);
- improving thermal conductivity (fins, metal inserts, microencapsulation);
- chemical compatibility and stability over repeated melting–solidification cycles.

3.4. “Smart” dryers: sensors, IoT, and advanced control

Advances in low-cost electronics and wireless communications have led to the concept of the “smart solar dryer”: a dryer equipped with sensors and microcontrollers (Arduino-, ESP-based systems, compact PLCs) capable of measuring and logging, in real time, parameters such as:

- air temperature and humidity at inlet and outlet;
- product temperature;
- air velocity or flow rate;
- solar radiation intensity.

Data can be transmitted to cloud platforms, where it is stored and analyzed, enabling:

- automatic control of fans and valves (on/off or PWM modulation);
- intelligent regulation of auxiliary heat sources (biomass/electric);
- optimization strategies (e.g., keeping the product as long as possible within the “optimal” temperature range for quality) [3].

Some papers even propose integrating radiation sensors or photodetectors into IoT schemes to better correlate atmospheric conditions with drying strategies and to reduce the risk of overheating or insufficient drying [6].

For manufacturers, this trend means that a modern dryer is no longer just a “box with hot air,” but a mechatronic system in which thermal hardware (collector, chamber, fan) is tightly coupled with software (control algorithms, data logging, and potentially web interfaces or mobile apps).

3.5. The socio-economic dimension and small-scale adoption

Beyond technical performance, recent literature highlights the role of solar dryers in:

- reducing post-harvest losses in rural areas;
- increasing farmers’ income by valorizing surplus production;
- diversifying products (dried fruits, dehydrated vegetables, herbs, spices) [7].

Socio-economic reviews show that successful implementation depends not only on thermal efficiency, but also on:

- initial cost and availability of locally sourced materials;
- ease of operation and maintenance (including for users without technical training);
- the existence of distribution networks for dried products;
- institutional support (funding programs, training, quality standards).

For Central and Eastern Europe, including Romania, the climate is favorable for seasonal solar drying, and integrating modern technologies (hybrid systems, PCM, IoT) into solutions affordable for small producers represents an important direction for research and technology transfer.

4. Conclusions and perspectives

Analyzing the theoretical basis and recent trends in food drying allows several conclusions and development directions to be formulated:

1. **Drying theory remains essential in design.** Even as “hardware” technology evolves (new dryer types, new materials, new configurations), sound design starts from understanding the roles of moisture and temperature gradients, internal diffusion, the risk of crust formation, and the relationship between temperature, relative humidity, and air velocity.
2. **Optimal parameters are product-specific.** Inlet ranges of 70–72°C and outlet ranges of 40–45°C, with relative humidities of 20–25% and 60–70%, should be seen as general benchmarks. To ensure maximum quality, each product (apricots, apples, vegetables, aromatic plants) requires fine tuning of temperature, air velocity, and slice thickness.
3. **Solar and hybrid systems are becoming the standard for sustainable applications.** Simple solar dryers are attractive due to low cost, but are limited by weather dependence. Hybrid systems—solar plus an auxiliary source—enable continuous operation, reduce drying time, and facilitate temperature control, with a lower carbon footprint than purely conventional systems.
4. **PCM and thermal storage improve process stability.** Integrating phase change materials into collectors or drying chambers has demonstrated higher energy efficiency and temperature stabilization, especially under variable radiation. Remaining challenges concern design (geometry, thermal contact, compatibility) and cost.
5. **IoT-driven digitalization is changing how dryers are operated.** Low-cost sensors, microcontrollers, and cloud platforms enable remote monitoring and control, batch traceability, real-time optimization, and even predictive algorithms to stop the process at the “optimal” moment in terms of quality versus energy consumption.

6. **Socio-economic impact reinforces the technology’s relevance.** Solar and hybrid dryers can significantly reduce post-harvest losses and increase the incomes of small and medium producers, provided they are designed and implemented with careful attention to the local context (cost, technological culture, market).

Research and industry perspectives

- **Integrating numerical models and experiments.** Developing CFD and heat-and-mass-transfer models calibrated with experimental data will enable faster optimization of dryer configurations before physical prototyping, reducing development costs.
- **Standardization and design guidelines.** Creating design guidelines for different product categories (fruits, vegetables, medicinal plants) that combine drying theory with recommended design parameters (geometry, airflow, temperatures, control strategies) would support equipment manufacturers and end users.
- **Modular dryers for small farms.** Developing modular, scalable dryers that can be easily adapted to available volumes and product types is a promising direction for widespread adoption.
- **Integration into short agri-food supply chains.** Linking dryers with local distribution networks (local markets, cooperatives, traditional-product shops) can turn drying from a purely technological process into a tool for rural development.
- **Life-cycle environmental assessment (LCA).** LCA studies dedicated to solar and hybrid dryers can quantify real benefits in terms of avoided emissions and can guide choices of materials and structural configurations.

By combining a solid foundation in drying theory with recent technical innovations—solar, hybrid, PCM-based, and IoT-enabled—designers and equipment manufacturers can develop robust, efficient, and affordable solutions, suited both to industrial requirements and to the needs of small producers. This type of integrated approach is essential for food drying to remain, in the future as well, a central technology in the transition toward sustainable agri-food systems.

Acknowledgments

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