Open Applied Science
https://openappscience.science

Solar Drying Technologies and Product Quality in Smallholder Food Processing

Madeline R. Lopez*

Department of Bioresource Engineering, Faculty of Engineering, McGill University, Montreal, Quebec, Canada

Corresponding author: madeline.r.lopez@mcgill.ca

Abstract

The transition from traditional open sun drying to advanced solar drying technologies represents a critical step toward enhancing food security and economic stability for smallholder farmers in developing regions. Despite the evident advantages of solar dryers in reducing post-harvest losses, a comprehensive understanding of the precise mechanisms linking localized microclimatic conditions within these systems to the final nutritional and organoleptic quality of the processed food remains limited. This paper investigates the intricate relationship between solar drying technologies and product quality using finite element modeling as a primary analytical tool. By simulating the coupled heat and mass transfer processes inherent in the dehydration of organic cellular structures, the study provides a detailed spatial and temporal analysis of temperature distribution and moisture gradients. The findings elucidate how structural design choices in small-scale indirect solar dryers directly influence the retention of heat-sensitive micronutrients and the preservation of desirable physical attributes such as color and texture. Through rigorous computational analysis, this research bridges the gap between theoretical thermodynamics and practical agricultural applications, offering evidence-based recommendations for optimizing drying protocols and equipment design tailored to the constraints and needs of smallholder food processing enterprises.

Keywords: Solar Drying; Finite Element Modeling; Food Quality; Smallholder Agriculture; Product Quality

1. Introduction

1.1 Context of Smallholder Food Processing

Agricultural systems in developing nations are predominantly characterized by the overwhelming presence of smallholder farmers who cultivate limited parcels of land and rely heavily on family labor. These small-scale agricultural enterprises form the backbone of rural economies, providing essential sustenance and income for billions of individuals globally. However, the viability of these operations is perpetually threatened by significant post-harvest losses, which occur primarily due to inadequate processing, poor storage infrastructure, and limited access to reliable preservation technologies. In tropical and subtropical regions, where ambient temperatures and humidity levels are highly conducive to microbial proliferation and enzymatic degradation, the rapid deterioration of harvested crops is a pressing concern [1]. Consequently, food preservation techniques are not merely value-adding processes but absolute necessities for ensuring food security and economic resilience.

Dehydration, or drying, is one of the oldest and most widely utilized methods for extending the shelf life of agricultural produce. By reducing the moisture content of the food to a level that inhibits the growth of bacteria, yeasts, and molds, drying effectively halts spoilage and significantly reduces the weight and volume of the product, thereby facilitating easier and more cost-effective transportation and storage [2]. Traditionally, smallholder farmers have relied almost exclusively on open sun drying. This conventional method involves spreading the freshly harvested produce on the ground, woven mats, or elevated racks, and exposing it directly to solar radiation and natural wind currents. While open sun drying is inherently inexpensive and requires no specialized equipment or external energy inputs, it is fraught with severe limitations. The produce is entirely at the mercy of unpredictable weather conditions, vulnerable to contamination from dust, dirt, and animal excrement, and susceptible to heavy losses from insect infestations and foraging by rodents and birds [3].

To mitigate the myriad disadvantages associated with open sun drying, there has been a concerted global effort to introduce and promote enclosed solar drying technologies among smallholder communities. Solar dryers utilize the greenhouse effect and carefully designed airflow dynamics to elevate the drying air temperature and reduce its relative humidity, thereby accelerating the moisture removal process in a controlled and protected environment. These systems range from simple direct-mode tent dryers, where the product is exposed to direct sunlight within a translucent enclosure, to more sophisticated indirect-mode cabinet dryers, where a separate solar collector heats the air before it is channeled over the drying trays [4]. The adoption of these technologies has the potential to revolutionize smallholder food processing by drastically reducing drying times, minimizing contamination, and enabling farmers to produce higher-quality dried goods that can command premium prices in local and regional markets.

1.2 Challenges in Solar Drying and Product Quality

Despite the clear operational advantages of enclosed solar drying systems, the relationship between the drying process and the resulting quality of the food product is highly complex and heavily dependent on specific technological parameters. The concept of product quality in dehydrated foods is multifaceted, encompassing nutritional retention, organoleptic properties such as color, flavor, and aroma, and physical characteristics including texture, rehydration capacity, and structural integrity. When organic tissues are subjected to thermal dehydration, they undergo a series of profound physical, chemical, and biochemical transformations. The application of heat energy facilitates the vaporization of internal moisture, but it simultaneously initiates undesirable reactions if the processing conditions are not meticulously controlled [5].

One of the primary challenges in solar drying is the inherent variability and intermittency of solar radiation, which translates to fluctuating thermal inputs and unsteady drying kinetics. In poorly designed or inadequately managed solar dryers, these fluctuations can lead to severe quality degradation. For instance, excessively high temperatures, often localized in specific areas of the drying chamber due to uneven airflow distribution, can cause thermal degradation of heat-sensitive vitamins, most notably ascorbic acid and certain B-complex vitamins [6]. Furthermore, prolonged exposure to high temperatures can trigger non-enzymatic browning reactions, such as the Maillard reaction, which negatively alters the color and flavor profile of the final product.

Conversely, if the drying air temperature is too low or the airflow is insufficient to carry away the evaporated moisture, the drying process becomes protracted. Extended drying times create a favorable window for enzymatic browning and the proliferation of resilient microbial strains, ultimately compromising the safety and aesthetic appeal of the food. Another critical issue frequently encountered in small-scale drying operations is case hardening. This phenomenon occurs when moisture is removed from the surface of the food product at a rate faster than it can diffuse from the interior core. The rapid desiccation of the surface forms a rigid, impermeable crust that effectively traps the remaining moisture inside the product, leading to incomplete drying and a high risk of internal rotting during subsequent storage [7].

Understanding and mitigating these quality-degrading phenomena require a profound comprehension of the heat and mass transfer mechanisms occurring simultaneously within the drying chamber and within the cellular structure of the food itself. Empirical field testing and trial-and-error approaches, while useful for basic operational guidelines, are often insufficient for optimizing dryer designs or establishing precise drying protocols that guarantee consistent product quality. Therefore, there is a critical need for advanced analytical methodologies that can accurately predict the microclimatic conditions within solar dryers and their direct impact on the biophysical properties of the processed food.

2. Background and Literature Review

2.1 Evolution of Solar Drying Technologies

The historical trajectory of solar drying technologies reflects a continuous endeavor to harness solar energy more efficiently while exerting greater control over the drying environment. The earliest documented interventions aimed at improving traditional sun drying involved simple structural modifications, such as elevating the drying surfaces to reduce contamination from the ground and utilizing dark-colored absorbing materials to increase local temperatures. However, these rudimentary improvements failed to address the fundamental issues of weather dependency and exposure to ambient elements [8]. The conceptual leap occurred with the advent of the enclosed solar dryer, which fundamentally shifted the paradigm from passive environmental exposure to active microclimate management.

Direct solar dryers were among the first enclosed systems to gain widespread attention. In these designs, the drying chamber itself acts as the solar collector. A transparent cover, typically made of glass or ultraviolet-stabilized polyethylene, allows short-wave solar radiation to enter the chamber, where it is absorbed by the product and the internal surfaces. These surfaces re-radiate long-wave thermal energy, which is trapped by the transparent cover, creating a localized greenhouse effect. While direct dryers are relatively simple to construct and highly effective at raising internal temperatures, they have distinct drawbacks. The direct exposure of the food product to intense ultraviolet radiation can cause severe bleaching and the destruction of light-sensitive nutrients [9]. Furthermore, because the heating and drying occur in the same space, controlling the airflow and preventing localized overheating can be exceedingly difficult.

To circumvent the issues associated with direct radiation exposure, indirect solar dryers were developed. These systems structurally separate the solar energy collection function from the food dehydration function. An indirect dryer typically comprises a distinct flat-plate solar air heater connected to an opaque drying cabinet. Ambient air is drawn into the collector, heated as it flows over a dark, thermally conductive absorber plate, and subsequently channeled into the drying chamber where it passes over the food trays. This configuration ensures that the product is dried entirely by convective heat transfer in the dark, preserving color and light-sensitive vitamins [10]. The airflow in these systems can be driven by natural convection, relying on the buoyancy of heated air, or forced convection, utilizing small direct-current fans powered by photovoltaic panels to ensure consistent mass flow rates. Mixed-mode solar dryers combine features of both direct and indirect systems, utilizing a separate collector to pre-heat the air while also allowing some direct solar radiation into the drying chamber.

In recent years, the focus of solar drying research has shifted toward hybridization and thermal energy storage to address the intermittent nature of solar radiation. Hybrid solar dryers integrate supplementary heat sources, such as biomass burners or electric heating elements, to maintain continuous drying operations during the night or periods of heavy cloud cover [11]. Thermal energy storage systems, utilizing sensible heat materials like rocks and water or latent heat materials like phase change substances, capture excess solar energy during peak sunshine hours and release it gradually when solar insolation diminishes. These advancements represent a significant technological maturation, yet their successful implementation in smallholder contexts heavily depends on striking a delicate balance between thermodynamic efficiency, construction costs, and the ultimate impact on product quality.

2.2 Product Quality Metrics in Food Processing

In the context of agricultural value chains, quality is the predominant determinant of marketability and economic return. For dried food products, quality cannot be distilled into a single parameter; rather, it is a composite of several biochemical, physical, and sensory attributes that collectively define the product's acceptability to consumers and its nutritional value. Evaluating the efficacy of a solar drying technology therefore necessitates a comprehensive assessment of how the specific drying kinetics influence these diverse quality metrics [12].

Nutritional retention is arguably the most critical quality parameter, particularly in regions where dried fruits and vegetables serve as essential dietary supplements during off-seasons. Vitamins, especially water-soluble vitamins like ascorbic acid and various B vitamins, are highly labile and susceptible to degradation through thermal, oxidative, and photolytic pathways. The degradation kinetics of these nutrients are complex and heavily influenced by the temperature-time history of the product during drying. Extended exposure to moderate heat can sometimes be more destructive to specific vitamins than brief exposure to higher temperatures. Additionally, the retention of provitamin A carotenoids, which are vital for preventing nutritional blindness in developing regions, is highly sensitive to oxidative cleavage, a process accelerated by prolonged exposure to oxygen and light in direct solar dryers [13].

Organoleptic properties, encompassing color, flavor, and aroma, are immediate indicators of quality that strongly influence consumer purchasing decisions. Color degradation is primarily driven by browning reactions. Enzymatic browning is catalyzed by polyphenol oxidase enzymes when cellular structures are disrupted and exposed to oxygen. Thermal processing eventually denatures these enzymes, but slow drying rates at lower temperatures can provide a window for significant enzymatic discoloration before the enzymes are inactivated. Non-enzymatic browning, particularly the Maillard reaction between reducing sugars and amino acids, is highly temperature-dependent and accelerates rapidly at elevated temperatures and intermediate moisture levels [14]. The preservation of volatile flavor and aroma compounds is equally challenging, as these low-molecular-weight substances are easily lost through vaporization along with the evaporating water.

Physical and structural properties also undergo profound changes during dehydration. As water is removed from the cellular matrix, the internal turgor pressure collapses, leading to cellular shrinkage and macroscopic deformation of the product. The rate of drying heavily influences the extent and nature of this shrinkage. Rapid drying can lead to rigidification of the outer layers while the interior remains moist, causing internal stresses that manifest as cracking or case hardening. The microstructural changes also dictate the product's rehydration capacity, which is the ability of the dried tissue to reabsorb water and return to its original form prior to consumption or further processing. Severe structural collapse and the thermal degradation of hydrophilic cellular components drastically reduce rehydration capacity, resulting in a tough, unpalatable texture [15].

2.3 Role of Finite Element Modeling

The empirical evaluation of all the aforementioned quality parameters under varying weather conditions and dryer configurations is an exhaustive, resource-intensive, and time-consuming endeavor. To overcome these empirical limitations, researchers and engineers have increasingly turned to computational modeling techniques, with Finite Element Modeling emerging as a particularly powerful tool for simulating the complex physics of the drying process. Finite Element Modeling is a numerical method used to solve partial differential equations that describe physical phenomena across a continuous domain. It works by discretizing the complex geometry of the drying system and the food product into a finite number of small, simple, and interconnected subdomains called elements.

In the context of solar drying, Finite Element Modeling is utilized to simulate the coupled heat and mass transfer processes. The governing equations are derived from the fundamental principles of conservation of mass, momentum, and energy. By applying appropriate boundary conditions and material properties, the model iteratively calculates the variables of interest, such as temperature, moisture concentration, and airflow velocity, at the discrete nodal points connecting the elements. This allows for a highly detailed, spatially and temporally resolved visualization of the transport phenomena occurring within the system [16].

The application of Finite Element Modeling in agricultural engineering provides unparalleled insights into the microclimatic conditions surrounding the food product. It enables researchers to identify stagnant airflow zones, localized temperature hotspots, and areas of high relative humidity within the drying chamber without the need to construct multiple physical prototypes. More importantly, when extended to the food product itself, these models can simulate the internal diffusion of moisture and the conduction of heat through the shrinking cellular matrix. By coupling these transport models with kinetic models of biochemical degradation, researchers can predict the spatial distribution of nutrient loss and color degradation within a single slice of fruit or vegetable [17]. This predictive capability is invaluable for optimizing dryer designs, establishing optimal loading densities, and designing dynamic operational protocols that maximize moisture removal while minimizing quality deterioration, thereby providing concrete, actionable evidence for smallholder food processing initiatives.

3. Methodology and Finite Element Modeling Design

3.1 Conceptual Framework and System Description

To systematically investigate the linkages between solar drying technologies and product quality, this study employs a comprehensive numerical simulation approach based on a representative indirect solar cabinet dryer commonly utilized by smallholder cooperatives. The conceptual framework is predicated on the understanding that the external weather variables drive the thermal performance of the solar collector, which in turn establishes the boundary conditions for the drying chamber. These internal microclimatic conditions subsequently dictate the rate of internal heat and mass transfer within the food product, which ultimately governs the biochemical reaction kinetics responsible for quality degradation.

The physical system modeled consists of a flat-plate solar air collector coupled to a vertical drying cabinet containing multiple horizontal trays. The solar collector features a single transparent cover, a corrugated metallic absorber plate painted matte black to maximize solar absorptance, and a layer of fiberglass insulation on the bottom and sides to minimize parasitic heat losses to the ambient environment. The drying cabinet is similarly insulated and designed to facilitate forced convective airflow, driven by a direct-current exhaust fan located at the upper outlet.

For the purpose of the simulation, tomato slices were selected as the standard biological material due to their high initial moisture content, their significance in smallholder agricultural value chains, and their high susceptibility to both thermal and oxidative quality degradation. The geometry of the tomato slice was approximated as a perfect cylinder with a specific initial radius and thickness. The modeling domain encompasses the entire fluid volume of the drying chamber and the solid domain of the individual food slices distributed across the drying trays.

To ensure the computational tractability of the complex fluid-structure interaction, several fundamental assumptions were established. The fluid flow was considered to be three-dimensional, turbulent, and incompressible, with the physical properties of the air treated as temperature-dependent variables. The tomato slices were modeled as homogeneous, isotropic porous media. While biological tissues are inherently heterogeneous, this macroscopic assumption is standard in dehydration modeling and provides sufficient accuracy for predicting aggregate heat and mass transfer behavior [18]. The shrinkage of the product during drying was incorporated dynamically, with the spatial mesh of the solid domain deforming proportionally to the loss of moisture volume.

3.2 Finite Element Modeling Parameters and Boundary Conditions

The mathematical formulation of the drying process requires the simultaneous solution of the Navier-Stokes equations for the fluid flow, the energy conservation equations for both the fluid and solid domains, and the mass transport equations describing the movement of water vapor in the air and liquid water within the food product. The Finite Element Analysis software was configured to handle these highly nonlinear, coupled partial differential equations using a transient solver, enabling the tracking of variables from the initial fresh state to the final target moisture content.

The spatial discretization of the computational domain was achieved using a hybrid meshing strategy. The fluid volume within the main drying chamber was discretized using unstructured tetrahedral elements to accommodate the complex flow pathways around the structural supports and trays. Conversely, the solid domains of the tomato slices and the immediate boundary layer regions were meshed using structured hexahedral elements. This approach ensures high resolution and numerical stability in the regions where the steepest temperature and moisture gradients are anticipated. Grid independence studies were meticulously conducted to verify that the simulation results were not artifacts of the mesh density.

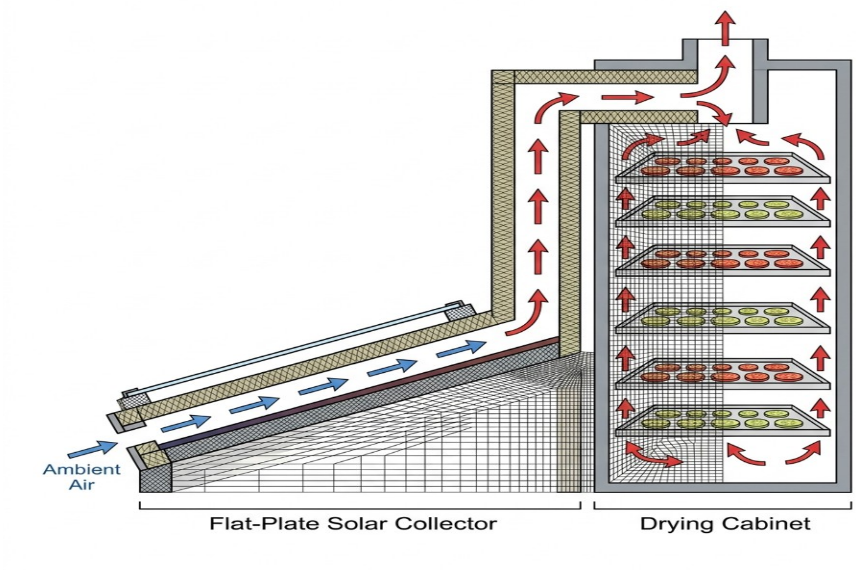

Figure 1: Comprehensive Schematic of the Indirect Solar Dryer Finite Element Model

The accuracy of any numerical simulation is inextricably linked to the fidelity of the assigned boundary conditions and thermophysical material properties. The solar irradiance, ambient temperature, and ambient relative humidity were defined using time-dependent functions derived from actual meteorological data representing a typical clear-sky harvest day in a subtropical agricultural region. The inlet of the solar collector was assigned a pressure inlet boundary condition, while the outlet of the drying cabinet was assigned a velocity outlet boundary condition corresponding to the volumetric flow rate of the extraction fan.

Table 1: Thermophysical Properties of the Modeled Food Product and Air

Property	Food Product (Tomato)	Drying Air
Initial Moisture Content (Wet Basis)	94.5%	Variable based on RH
Specific Heat Capacity	3980 J/(kg K)	1006 J/(kg K)
Thermal Conductivity	0.55 W/(m K)	0.026 W/(m K)
Density	1050 kg/m³	1.16 kg/m³
Effective Moisture Diffusivity	Temperature Dependent	N/A

The convective heat and mass transfer coefficients at the interface between the flowing air and the surface of the food product were not assumed as constant values; rather, they were dynamically calculated by the software based on the local turbulent flow characteristics and fluid properties at each computational time step. The internal diffusion of moisture within the tomato slices was modeled using Fick's Second Law of Diffusion, incorporating an effective moisture diffusivity term that varies exponentially with the local tissue temperature, adhering to the Arrhenius relationship [19]. Furthermore, empirical kinetic degradation models for ascorbic acid (Vitamin C) and overall color change (measured by total color difference coordinates) were integrated into the post-processing phase. These models utilized the spatiotemporal temperature and moisture profiles generated by the finite element solver to calculate the cumulative quality loss at every nodal point within the food geometry throughout the entire duration of the simulated drying process.

4. Results and Discussion of Simulated Outcomes

4.1 Heat and Mass Transfer Characteristics

The execution of the finite element simulations provided extensive, high-resolution datasets detailing the transient behavior of the indirect solar drying system. The analysis of the fluid flow dynamics revealed significant spatial variations in the microclimate within the drying cabinet. Despite the use of a forced convection fan, the simulation indicated the presence of distinct airflow channeling. The heated air exhibited a tendency to bypass the central regions of the densely loaded trays, flowing preferentially along the vertical walls of the cabinet where the aerodynamic resistance was lower.

This nonuniform airflow distribution had immediate and profound consequences for the heat transfer characteristics. The temperature contour plots demonstrated substantial stratification within the drying chamber. The trays located closest to the heated air inlet experienced significantly higher convective heat fluxes, resulting in rapid surface heating of the product. Conversely, the trays situated in the upper sections and the central zones of the lower trays resided in lower-velocity, lower-temperature microclimates. Consequently, the rate of sensible heat transfer to the interior of the food product in these stagnant zones was markedly reduced.

The temporal evolution of the internal moisture gradients within individual tomato slices corroborated the complex physics of agricultural dehydration. During the initial phase of drying, moisture was readily available at the surface of the slices, and the evaporation rate was entirely controlled by the external convective conditions (the constant rate period). However, this phase was exceedingly brief. The process rapidly transitioned into the falling rate period, where the drying kinetics became entirely governed by the internal resistance to moisture diffusion.

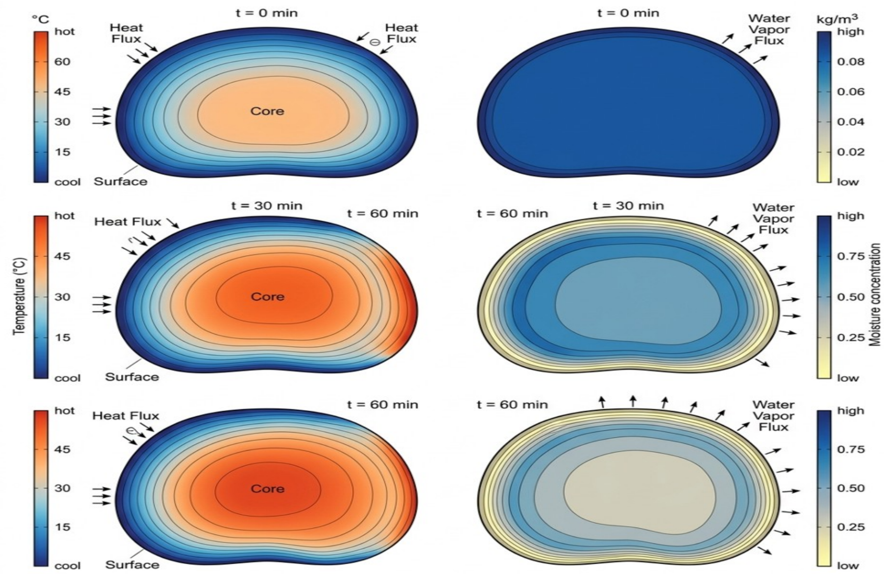

Figure 2: Spatiotemporal Temperature and Moisture Concentration Contour Plots

The simulations explicitly visualized the development of steep moisture concentration gradients. The outer boundary elements of the simulated food slices exhibited rapid moisture depletion, approaching the equilibrium moisture content within the first few hours of simulated daylight. Meanwhile, the core elements remained highly saturated. Because the effective moisture diffusivity is strongly temperature-dependent, the uneven temperature distribution across the trays exacerbated the disparities in internal moisture transport. Slices in the high-temperature zones experienced faster internal diffusion, but they also exhibited signs of severe surface rigidification. The software's dynamic mesh deformation accurately captured the volumetric shrinkage, demonstrating how the rapid desiccation of the outer layers constrained the overall structural collapse, leading to internal porosity changes and the onset of simulated case hardening.

4.2 Impact on Nutritional and Organoleptic Quality

The integration of biochemical kinetic models with the finite element heat and mass transfer data provided the most critical evidence linking the dryer technology's performance directly to the final product quality. The spatial mapping of ascorbic acid degradation within the food product revealed that nutrient loss is not uniform but highly localized, entirely dependent on the specific temperature-time history experienced by each microscopic region of the tissue.

The simulation results indicated that the highest rates of ascorbic acid destruction occurred in the outer layers of the tomato slices located on the trays nearest to the hot air inlet. In these regions, the combination of elevated temperatures and exposure to continuous airflow created the most aggressive environment for thermal oxidation [20]. Although the interior core of these slices remained cooler for a longer duration due to evaporative cooling, the rapid heating of the surface layers resulted in significant cumulative nutrient degradation by the time the core reached the target moisture content.

Table 2: Simulated Nutrient Retention and Color Degradation Indices

Location in Dryer	Average Final Moisture	Ascorbic Acid Retention	Color Change Index (ΔE)
Bottom Trays (Near Inlet)	8.2%	42.5%	18.4 (Severe browning)
Middle Trays (Central)	12.5%	68.1%	8.2 (Moderate change)
Upper Trays (Near Outlet)	15.1%	74.3%	5.1 (Slight change)

The data presented in Table 2 clearly quantifies the severe quality disparities resulting from the nonuniform microclimate. The slices on the bottom trays achieved the lowest final moisture content, ensuring excellent microbial stability, but this came at the extreme cost of losing over half of the initial Vitamin C content and suffering severe color degradation. The high Color Change Index indicates significant non-enzymatic browning, likely rendering the product visually unappealing to consumers. This browning is directly correlated with the prolonged exposure to high temperatures after the surface moisture had been depleted, allowing the matrix temperature to rise rapidly toward the dry-bulb temperature of the incoming air [21].

Conversely, the product located on the upper trays exhibited significantly better retention of ascorbic acid and maintained a color profile much closer to the fresh state. However, the simulation revealed a critical flaw: the final moisture content of these slices remained unacceptably high due to the low-temperature, high-humidity exhaust air passing over them. If these processing conditions were replicated in a real-world smallholder scenario, the product from the upper trays would be highly susceptible to fungal spoilage during subsequent packaging and storage.

These computationally derived outcomes provide incontrovertible evidence that simply enclosing the drying process and adding a heat source is insufficient for producing high-quality dehydrated foods. The finite element modeling demonstrates that the spatial architecture of the dryer and the resulting fluid dynamics are intimately linked to the localized biochemical reactions within the food. Without proper airflow management and temperature regulation, a single batch of product can exhibit massive variations in quality, undermining the economic viability of the processing operation [22].

5. Conclusion and Implications for Smallholder Farmers

5.1 Summary of Findings

This study has systematically investigated the intricate connections between solar drying technologies and the resulting quality of dehydrated agricultural products through the rigorous application of finite element modeling. By creating a high-fidelity numerical simulation of an indirect solar cabinet dryer, the research successfully visualized and quantified the complex, coupled mechanisms of fluid dynamics, convective heat transfer, and internal moisture diffusion. The computational evidence unequivocally demonstrates that microclimatic irregularities within the drying chamber—specifically, uneven airflow distribution and localized temperature stratification—are the primary drivers of inconsistent product quality.

The integration of biochemical degradation kinetics into the physical transport models provided a spatially resolved analysis of nutrient loss and color change. The findings illustrate a fundamental trade-off in poorly optimized systems: regions experiencing the highest heat flux achieve safe moisture levels rapidly but suffer severe thermal degradation of sensitive micronutrients like ascorbic acid, alongside significant non-enzymatic browning. Conversely, stagnant zones within the dryer preserve nutritional and aesthetic qualities but fail to achieve the requisite moisture reduction, leaving the food vulnerable to post-processing spoilage. The simulation of structural shrinkage and surface rigidification further highlighted how aggressive localized drying rates induce case hardening, trapping internal moisture and degrading the product's physical integrity and rehydration capacity.

5.2 Practical Implementation and Future Directions

The insights generated from these finite element models have profound practical implications for smallholder farmers and agricultural cooperatives seeking to upgrade their food processing capabilities. The evidence strongly suggests that training and operational protocols are just as critical as the physical hardware. Smallholders must be educated on the necessity of dynamic dryer management. The severe quality gradients observed in the simulation strongly advocate for the implementation of systematic tray rotation schedules during the drying cycle. By periodically exchanging the positions of the trays, operators can ensure that all products experience a more uniform temperature-time history, thereby standardizing the drying rate and the final quality across the entire batch [23].

Furthermore, the modeling results highlight critical areas for structural optimization that can be achieved with locally available materials. Modifying the internal geometry of the drying cabinet, such as incorporating simple internal baffles or utilizing variable mesh sizes on the drying trays, can significantly improve airflow distribution, forcing the heated air through the product layers rather than allowing it to bypass along the walls.

Future research endeavors should focus on expanding the application of finite element modeling to a broader spectrum of indigenous crops utilized by smallholders, each with unique cellular structures and degradation profiles. Additionally, integrating the predictive models with low-cost microcontrollers and sensors could pave the way for smart, affordable solar dryers that automatically adjust airflow rates based on real-time microclimatic data. By continuing to bridge the gap between advanced computational thermodynamics and practical agricultural engineering, the scientific community can provide smallholder farmers with the robust, evidence-based technologies necessary to minimize post-harvest losses, produce high-quality marketable goods, and secure long-term economic resilience.

References

1. Flandes, J.; Giraldo-Cadavid, L.F.; Alfayate, J.; Fernández-Navamuel, I.; Agusti, C.; Lucena, C.M.; Rosell, A.; Andreo, F.; Centeno, C.; Montero, C.; et al. Bronchoscopist’s perception of the quality of the single-use bronchoscope (Ambu aScope4TM) in selected bronchoscopies: A multicenter study in 21 Spanish pulmonology services. Respir. Res. 2020, 21, 320.

2. Mehta, A.C.; Muscarella, L.F. Bronchoscope-Related “Superbug” Infections. Chest 2020, 157, 454–469.

3. Ofstead, C.L.; Quick, M.R.; Wetzler, H.P.; Eiland, J.E.; Heymann, O.L.; Sonetti, D.A.; Ferguson, J.S. Effectiveness of Reprocessing for Flexible Bronchoscopes and Endobronchial Ultrasound Bronchoscopes. Chest 2018, 154, 1024–1034.

4. Amrutha, M.; Uma, C.; Sivagurunathan, P. Dinesh Crystallised chitosan + vitamin-E coated drug-eluting stents to prevent restenosis and stent associated infections. Int. J. Res. Pharm. Sci. 2020, 11, 929–936.

5. Aranaz, I.; Alcántara, A.R.; Civera, M.C.; Arias, C.; Elorza, B.; Heras Caballero, A.; Acosta, N. Chitosan: An overview of its properties and applications. Polymers 2021, 13, 3256.

6. Reynolds, S.; Zurba, J.; Duggan, L. A single-centre case series assessing the Ambu(®) aScopeTM 2 for percutaneous tracheostomies: A viable alternative to fibreoptic bronchoscopes. Can. J. Respir. Ther. 2015, 51, 43–45.

7. Harmsen, R.A.G.; Tuveng, T.R.; Antonsen, S.G.; Eijsink, V.G.H.; Sørlie, M. Can we make chitosan by enzymatic deacetylation of chitin? Molecules 2019, 24, 3862.

8. Marshall, D.C.; Dagaonkar, R.S.; Yeow, C.; Peters, A.T.; Tan, S.K.; Tai, D.Y.; Gohs, S.K.; Lim, A.Y.; Ho, B.; Lew, S.J.; et al. Experience with the Use of Single-Use Disposable Bronchoscope in the ICU in a Tertiary Referral Center of Singapore. J. Bronchol. Interv. Pulmonol. 2017, 24, 136–143.

9. Lachkar, S.; Crombag, L.M.; Musani, A.I. How Interventional Pulmonologists Can Address Climate Change. Respiration 2023, 102, 207–210.

10. Reshad, R.A.I.; Jishan, T.A.; Chowdhury, N.N. Chitosan and its broad applications: A brief review. J. Clin. Exp. Investig. 2021, 12, em00779.

11. Hemmami, H.; Ben Amor, I.; Ben Amor, A.; Zeghoud, S.; Ahmed, S.; Alhamad, A.A. Chitosan, its derivatives, sources, preparation methods, and applications: A review. J. Turk. Chem. Soc. Sect. A Chem. 2024, 11, 341–364.

12. Kaya, M.; Baran, T.; Erdoğan, S.; Menteş, A.; Aşan Özüsağlam, M.; Çakmak, Y.S. Physicochemical comparison of chitin and chitosan obtained from larvae and adult Colorado potato beetle (Leptinotarsa decemlineata). Mater. Sci. Eng. C 2014, 45, 72–81.

13. Lewandowska, K.; Sionkowska, A.; Grabska, S.; Michalska, M. Characterisation of chitosan/hyaluronic acid blend films modified by collagen. Prog. Chem. Appl. Chitin Its Deriv. 2017, 22, 125–134.

14. García Cruz, D.M.; Gomez Ribelles, J.L.; Salmerón Sánchez, M. Blending polysaccharides with biodegradable polymers. I. Properties of chitosan/polycaprolactone blends. J. Biomed. Mater. Res. 2008, 85B, 303–313.

15. Rinaudo, M. Chitin and chitosan: Properties and applications. Progress. Polym. Sci. 2006, 31, 603–632.

16. Shah, R.; Stodulka, P.; Skopalova, K.; Saha, P. Dual crosslinked collagen/chitosan film for potential biomedical applications. Polymers 2019, 11, 2094.

17. Novikov, V.Y.; Derkach, S.R.; Konovalova, I.N.; Dolgopyatova, N.V.; Kuchina, Y.A. Mechanism of heterogeneous alkaline deacetylation of chitin: A review. Polymers 2023, 15, 1729.

18. Thakur, A.; Wanchoo, R.K.; Soni, S.K. Chitosan hydrogel beads: A comparative study with glutaraldehyde, epichlorohydrin and genipin as crosslinkers. J. Polym. Mater. 2014, 31, 211–223.

19. Sánchez-Cid, P.; Jiménez-Rosado, M.; Rubio-Valle, J.F.; Romero, A.; Ostos, F.J.; Rafii-El-Idrissi Benhnia, M.; Perez-Puyana, V. Biocompatible and thermoresistant hydrogels based on collagen and chitosan. Polymers 2022, 14, 272.

20. Alemdar, N. Synthesis of chitosan-based hydrogel by using photopolymerization technique. Anadolu Univ. J. Sci. Technol. A-Appl. Sci. Eng. 2016, 17, 391–400.

21. Michel, S.E.S.; Dutertre, F.; Denbow, M.L.; Galan, M.C.; Briscoe, W.H. Facile synthesis of chitosan-based hydrogels and microgels through thiol–ene photoclick cross-linking. ACS Appl. Bio Mater. 2019, 2, 3257–3268.

22. Mao, J.; Kondu, S.; Ji, H.; McShane, M.J. Study of the near-neutral pH-sensitivity of chitosan/gelatin hydrogels by turbidimetry and microcantilever deflection. Biotechnol. Bioeng. 2006, 95, 333–341.

23. Lin, X.; Wang, X.; Zeng, L.; Wu, Z.L.; Guo, H.; Hourdet, D. Stimuli-responsive toughening of hydrogels. Chem. Mater. 2021, 33, 7633–7656.