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Closed Loop CO2 Heat Pump Drying Optimizes Kiwifruit Processing Quality and Energy Use Efficiency

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Abstract
The preservation of agricultural produce through dehydration is a critical component of global food supply chains, yet traditional hot air drying methods are notoriously energy-intensive and often result in significant degradation of product quality. This paper investigates the optimization of a closed-loop carbon dioxide heat pump drying system specifically tailored for the processing of kiwifruit. Kiwifruit is highly perishable and sensitive to thermal degradation, making it an ideal candidate for advanced, low-temperature, environmentally friendly drying technologies. Utilizing carbon dioxide as a natural refrigerant in a transcritical cycle offers superior environmental benefits, including a global warming potential of one and zero ozone depletion potential, while simultaneously providing excellent temperature glide matching for the sensible heating of drying air. The study systematically evaluates the interplay between drying air temperature, air velocity, and bypass ratio within the closed-loop system to determine the optimal conditions for maximizing the specific moisture extraction rate and minimizing the loss of vital nutrients such as ascorbic acid. Through extensive experimental trials and multi-objective optimization techniques, the research demonstrates that the closed-loop carbon dioxide heat pump system significantly outperforms conventional drying methods in both energy efficiency and final product quality. The findings provide a comprehensive framework for scaling this technology in industrial agricultural processing, offering a sustainable alternative that aligns with modern environmental regulations and consumer demands for high-quality dried fruit products.

Keywords

Heat Pump Drying, Carbon Dioxide Refrigerant, Kiwifruit Processing, Transcritical Cycle, Optimization

INTRODUCTION

The global agricultural sector faces an unprecedented challenge in securing food supply while simultaneously reducing the environmental footprint of post-harvest processing. Among the myriad of fruits cultivated worldwide, the kiwifruit commands a substantial market presence due to its distinctive flavor profile and exceptional nutritional value, notably its high concentration of vitamin C, dietary fiber, and various antioxidants. However, the inherent physical and chemical characteristics of kiwifruit render it highly susceptible to rapid post-harvest deterioration. The high moisture content and active enzymatic profile of the fruit necessitate immediate intervention to extend its shelf life, facilitate long-distance transportation, and minimize economic losses for producers [1]. Dehydration has long served as one of the most effective and widely adopted methods for agricultural product preservation, operating on the fundamental principle of reducing water activity to a level where microbial growth and deleterious enzymatic reactions are significantly inhibited [2]. Despite the widespread application of dehydration technologies, conventional methods present substantial drawbacks. Traditional open-air sun drying, while economically accessible, is fundamentally flawed due to its reliance on unpredictable weather conditions, extensive processing times, and vulnerability to contamination from dust, insects, and opportunistic microorganisms [3]. In industrial settings, convective hot air drying is the prevailing standard; however, this method is characterized by exorbitant energy consumption, as massive volumes of heated air are continuously vented into the atmosphere, carrying away both sensible and latent heat [4]. Furthermore, the elevated temperatures typically employed in conventional convective drying induce severe quality degradation in heat-sensitive products like kiwifruit. This degradation manifests physically as excessive cellular shrinkage, case hardening, and adverse color changes due to non-enzymatic browning, and chemically as the rapid thermal destruction of heat-labile nutrients such as ascorbic acid [5]. In response to the dual imperatives of enhancing energy efficiency and preserving product quality, heat pump drying technology has emerged as a formidable alternative. By operating on a refrigeration cycle, a heat pump dryer recovers the latent heat of vaporization from the exhaust air, utilizing it to preheat the incoming drying air [6]. This closed-loop approach drastically reduces the specific energy consumption compared to conventional resistance-heated dryers [7]. Additionally, heat pump dryers are capable of operating efficiently at lower and more tightly controlled temperatures, which is paramount for the preservation of the structural integrity, color, and nutritional profile of temperature-sensitive biomaterials [8]. Historically, heat pump systems have relied on synthetic fluorinated refrigerants, particularly hydrochlorofluorocarbons and hydrofluorocarbons. While these working fluids possess excellent thermodynamic properties, their catastrophic environmental impact cannot be ignored. The high global warming potential of these synthetic refrigerants has prompted stringent international regulatory frameworks, most notably the Kigali Amendment to the Montreal Protocol, which mandates the phasedown of hydrofluorocarbons [9]. Consequently, the refrigeration and heat pump industries are undergoing a massive transition toward natural refrigerants, among which carbon dioxide has garnered significant attention [10]. Carbon dioxide, designated as R744 in refrigeration nomenclature, is an environmentally benign working fluid with an ozone depletion potential of zero and a baseline global warming potential of one [11]. Beyond its environmental credentials, carbon dioxide possesses unique thermodynamic characteristics that make it particularly well-suited for heat pump drying applications. Due to its low critical temperature, a carbon dioxide heat pump typically operates in a transcritical cycle when rejecting heat to a secondary fluid, such as the drying air [12]. In the gas cooler of a transcritical system, heat rejection occurs continuously over a wide temperature range without a phase change, resulting in a temperature glide that perfectly matches the sensible heating profile of the drying air. This

minimizes irreversibilities in the heat exchange process and enhances the overall coefficient of performance of the system. Despite the theoretical advantages of carbon dioxide heat pump drying, there remains a substantial gap in the literature regarding its optimized application to specific, highly sensitive agricultural products like kiwifruit. The optimization of such a system is inherently complex, requiring the simultaneous balancing of thermodynamic efficiency, drying kinetics, and product quality metrics. This paper aims to bridge this gap by presenting a comprehensive investigation into the closed-loop carbon dioxide heat pump drying of kiwifruit. The study will detail the experimental design, the intricate thermodynamic behavior of the transcritical cycle within a drying context, and a robust optimization framework designed to identify the ideal processing parameters. Ultimately, this research seeks to provide actionable insights for the agricultural processing industry, promoting the adoption of sustainable, high-efficiency dehydration technologies that do not compromise on end-product quality.

1.1 Objectives and Scope of the Study

The primary objective of this research is to comprehensively evaluate and optimize the performance of a closed-loop carbon dioxide heat pump drying system specifically for the dehydration of kiwifruit slices. This encompasses a multifaceted approach that addresses both the engineering performance of the drying apparatus and the biochemical quality of the processed agricultural product. To achieve this overarching goal, the study is divided into several specific objectives. First, the research aims to characterize the drying kinetics of kiwifruit under varying conditions of air temperature, air velocity, and system bypass ratio within the closed-loop environment. Understanding the mass transfer resistance and the falling rate drying periods is essential for modeling the process accurately. The second objective focuses on the thermodynamic analysis of the transcritical carbon dioxide heat pump cycle. This involves evaluating the energy consumption, the specific moisture extraction rate, and the overall coefficient of performance across different operational parameters. By mapping these energy metrics, the study will highlight the specific conditions under which the carbon dioxide system operates most efficiently, particularly emphasizing the benefits of the transcritical gas cooling process when matched with the sensible heating requirements of the drying chamber. The third objective is intrinsically linked to product quality. The study will systematically measure the impact of the varied drying conditions on critical quality attributes of the kiwifruit slices. This includes the retention of ascorbic acid, the preservation of surface color to avoid undesirable browning, and the maintenance of structural integrity as measured by volumetric shrinkage and rehydration capacity. Finally, the research seeks to integrate these physical, energetic, and qualitative data points into a cohesive multi-objective optimization framework. By doing so, the study will identify the exact operational parameters that yield the best compromise between minimizing energy consumption and maximizing the nutritional and aesthetic value of the dried kiwifruit. The scope of this study is intentionally broad, encompassing theoretical thermodynamics, practical agricultural engineering, and food science analytics, thereby providing a holistic view of the technology's potential.

2. Background and Literature Review

The intersection of agricultural processing, thermodynamics, and food science forms the foundational basis of this research. To fully contextualize the optimization of a closed-loop carbon dioxide heat pump dryer for kiwifruit, it is necessary to explore the existing body of literature across several distinct but interconnected domains. This includes understanding the unique challenges associated with kiwifruit preservation, the evolution and mechanics of heat pump drying technology, the resurgence of carbon dioxide as a primary refrigerant, and the methodologies employed to optimize complex, multi-variable drying processes.

2.1 Post-Harvest Processing and Drying Characteristics of Kiwifruit

Kiwifruit is a climacteric fruit, meaning it continues to ripen after being harvested, driven by increased respiration rates and ethylene production. This physiological behavior makes post-harvest management exceptionally challenging. The high initial moisture content, typically ranging between eighty and eighty-five percent on a wet basis, creates an ideal environment for microbial proliferation if not managed correctly [13]. Furthermore, the cellular structure of kiwifruit is delicate. It contains significant amounts of mucilage and pectins, which contribute to the fruit's unique texture but complicate the dehydration process. As moisture is removed, these complex carbohydrates can undergo glass transition, leading to a phenomenon known as case hardening, where the outer surface of the fruit slice dries rapidly and forms an impermeable barrier, trapping residual moisture within the core of the product [14]. The nutritional profile of kiwifruit is its most valuable asset, yet it is also the most vulnerable during thermal processing. Ascorbic acid, or vitamin C, is highly sensitive to both heat and oxidation. Conventional hot air drying, which often operates at temperatures exceeding sixty degrees Celsius and continuously exposes the product to oxygen-rich ambient air, results in massive degradation of this essential nutrient. Literature indicates that vitamin C losses can exceed seventy percent under standard convective drying conditions. Additionally, the vibrant green color of kiwifruit, derived from chlorophyll pigments, is easily degraded into olive-brown pheophytins when exposed to prolonged heat [15]. Enzymatic browning, catalyzed by polyphenol oxidase, further compromises the visual appeal of the dried product. Therefore, the literature strongly suggests that any successful dehydration strategy for kiwifruit must operate at lower temperatures, ideally in an environment with controlled humidity and reduced oxygen exposure, to mitigate these degradative biochemical pathways.

2.2 Advancements in Heat Pump Drying Technology

Heat pump drying has been recognized in academic literature as a transformative technology for the food processing industry. The fundamental advantage of a heat pump dryer lies in its ability to operate as a closed or semi-closed system, which fundamentally alters the energy dynamics of the dehydration process [16]. In a conventional dryer, ambient air is heated, passed over the product to absorb moisture, and then exhausted into the atmosphere. This exhaust air contains not only the sensible heat added by the heater but also the latent heat of vaporization of the water removed from the product. This represents a massive energy loss. A closed-loop heat pump dryer mitigates this loss by directing the moist exhaust air from the drying chamber across the evaporator of a refrigeration circuit. As the air passes over the evaporator, it is cooled below its dew point. The moisture condenses and is drained away as liquid water. Crucially, the latent heat released during this condensation process is absorbed by the refrigerant. The dehumidified, cooler air then passes over the condenser or gas cooler of the refrigeration circuit, where it reabsorbs the heat from the compressed refrigerant. This reheated, extremely dry air is then circulated back into the drying chamber [17]. This cyclical recovery of latent heat allows heat pump dryers to achieve specific moisture extraction rates that are routinely three to four times higher than conventional electrical resistance dryers. The literature highlights several operational configurations for heat pump dryers, including fully closed loops, partially open loops with bypass dampers, and systems augmented with supplementary heating. For highly sensitive products, the fully closed-loop configuration is often preferred. By isolating the drying environment from ambient conditions, operators gain precise control over both temperature and humidity [18]. Furthermore, the closed-loop nature reduces the introduction of airborne contaminants and, over time, reduces the oxygen concentration in the drying chamber as volatile compounds from the fruit displace the air, providing a mild protective effect against oxidative degradation.

2.3 Carbon Dioxide as a Transcritical Working Fluid

The selection of the refrigerant is the most critical design parameter in any heat pump system. As previously mentioned, the regulatory landscape is rapidly shifting away from high global warming potential synthetic fluids. Carbon dioxide has re-emerged as a leading candidate, not merely as a regulatory compromise, but due to its highly advantageous thermophysical properties in specific applications like drying [19]. Unlike conventional refrigerants that condense at a constant temperature when rejecting heat to the environment, carbon dioxide in a heat pump system often operates above its critical point, which is approximately thirty-one degrees Celsius and seventy-three bar. In this transcritical cycle, the heat rejection component is termed a gas cooler rather than a condenser. As the supercritical carbon dioxide flows through the gas cooler, it does not undergo a phase change. Instead, it experiences a continuous temperature decrease as it rejects heat. This phenomenon is known as temperature glide [20]. In the context of air heating for a drying chamber, this temperature glide is exceptionally beneficial. The drying air entering the gas cooler is relatively cool and needs to be heated sensibly over a large temperature range. The temperature profile of the supercritical carbon dioxide perfectly mirrors the heating profile of the air. This minimizes the temperature difference between the heat source and the heat sink throughout the heat exchanger, drastically reducing thermodynamic irreversibilities and entropy generation [21]. Academic studies comparing carbon dioxide to traditional refrigerants like R134a in drying applications consistently demonstrate that while R134a performs well at lower temperature lifts, the carbon dioxide transcritical cycle achieves a superior coefficient of performance when significant sensible heating of the air is required, which is exactly the scenario in closed-loop heat pump drying [22].

2.4 Optimization Strategies in Food Dehydration

The operation of a heat pump dryer involves a complex interplay of multiple dependent and independent variables. Changing the compressor speed alters the refrigerant mass flow rate, which in turn affects the heating capacity of the gas cooler, the cooling capacity of the evaporator, and ultimately the temperature and relative humidity of the drying air. These air properties dictate the drying kinetics, which then feedback into the system by altering the moisture load on the evaporator. Given this highly coupled, non-linear system architecture, determining the optimal operating conditions requires advanced mathematical approaches [23]. Historically, the optimization of drying processes relied on empirical, one-factor-at-a-time experimentation, which is time-consuming and often fails to identify true system optima due to the ignorance of interaction effects between variables. Contemporary literature heavily favors the use of statistical and computational optimization techniques. Response surface methodology is perhaps the most prevalent technique used in food processing optimization [24]. By utilizing specialized experimental designs, such as the Box-Behnken design or the Central Composite design, response surface methodology allows researchers to develop second-order polynomial models that describe the relationship between independent variables such as temperature and air velocity, and dependent responses such as drying time, energy consumption, and vitamin C retention [25]. More recently, artificial intelligence and machine learning algorithms, including artificial neural networks coupled with genetic algorithms, have been introduced to the field of drying technology [26]. These techniques are particularly adept at modeling highly non-linear processes where fundamental physical modeling is too computationally expensive or mathematically intractable. The literature demonstrates that by defining a composite objective function that assigns specific weights to energy efficiency and product quality metrics, these algorithms can pinpoint operational parameters that yield an optimal balance, ensuring the dried kiwifruit is both economically viable to produce and of premium quality for the consumer [27].

3. Methodology and Analysis

To thoroughly investigate the performance of the closed-loop carbon dioxide heat pump dryer for kiwifruit processing, a rigorous experimental methodology was established. This methodology encompasses the preparation of the raw materials, the detailed design and instrumentation of the heat pump system, the execution of the experimental trials, and the analytical techniques employed to assess both system performance and product quality.

3.1 Material Procurement and Preparation

Fresh kiwifruit of the Hayward variety were procured from a local commercial orchard to ensure consistency in the raw material. Upon arrival at the laboratory, the fruits were immediately inspected. Only fruits exhibiting uniform size, unblemished skin, and consistent firmness were selected for the experimental trials. The selected fruits were stored in a controlled environment chamber maintained at a temperature of four degrees Celsius and a relative humidity of ninety percent to halt further ripening and preserve their initial biochemical state prior to processing.

Before each drying experiment, a batch of kiwifruit was removed from cold storage and allowed to equilibrate to room temperature. The fruits were manually peeled using stainless steel implements to prevent metallic contamination that could catalyze oxidative reactions. Following peeling, the fruits were sliced transversely using a precision mechanical slicer to ensure a uniform thickness of exactly five millimeters. Uniform thickness is a critical control parameter, as the drying kinetics and mass transfer resistance are highly dependent on the distance moisture must travel from the core of the product to the evaporative surface. The initial moisture content of the fresh kiwifruit slices was determined gravimetrically by placing representative samples in a vacuum oven at seventy degrees Celsius for twenty-four hours, reaching a constant weight. The average initial moisture content was recorded and used as the baseline for all subsequent drying kinetic calculations.

3.2 Closed-Loop System Architecture and Instrumentation

The core of the experimental setup is a custom-designed, fully closed-loop heat pump drying system utilizing carbon dioxide as the working fluid. The physical architecture of the system is divided into two primary subsystems: the transcritical refrigeration circuit and the aerodynamic drying loop. The refrigeration circuit is driven by a semi-hermetic, variable-speed reciprocating compressor specifically designed to withstand the high operating pressures associated with transcritical carbon dioxide cycles. The high-pressure, high-temperature supercritical carbon dioxide discharged from the compressor enters the gas cooler, which is constructed as a fin-and-tube heat exchanger. Here, it rejects heat to the circulating drying air. The refrigerant then passes through an electronic expansion valve, where it undergoes an isenthalpic expansion, dropping in pressure and transitioning into a two-phase liquid-vapor mixture. This low-pressure, low-temperature mixture enters the evaporator, another fin-and-tube heat exchanger, where it absorbs heat from the moist exhaust air returning from the drying chamber, causing the refrigerant to evaporate completely. The vapor is then drawn back into the compressor, completing the cycle.

The aerodynamic loop is a sealed wind tunnel constructed from insulated stainless steel to minimize heat exchange with the ambient environment. The air is circulated by a variable-frequency centrifugal fan. The air first passes over the evaporator, where it is sensibly cooled below its dew point, resulting in the condensation of water vapor. This dehumidified air then passes over the gas cooler, where it is sensibly heated to the target drying temperature. The hot, dry air enters the drying chamber, passing laterally over the arranged kiwifruit slices resting on perforated stainless steel trays.

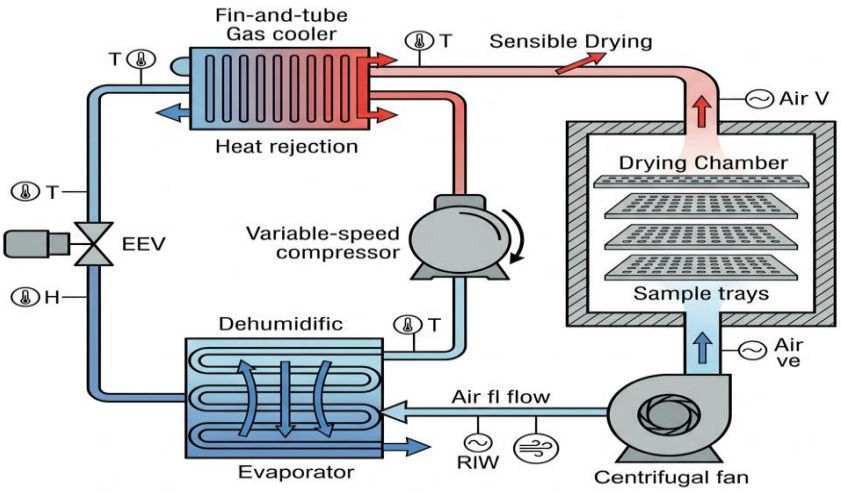


Figure 1: Comprehensive Schematic of the Closed

To monitor and control the process, the system is heavily instrumented. High-precision T-type thermocouples are installed at the inlet and outlet of every major component in both the refrigerant and air loops to measure temperature profiles. Piezoelectric pressure transducers monitor the high and low-pressure sides of the carbon dioxide circuit. A Coriolis mass flow meter measures the refrigerant circulation rate. In the aerodynamic loop, hot-wire anemometers measure the air velocity entering the drying chamber, while capacitive relative humidity sensors track the moisture content of the air before and after it interacts with the kiwifruit. All sensors are wired to a central data acquisition system that records parameters at ten-second intervals, providing a high-resolution dataset for subsequent thermodynamic analysis.

3.3 Experimental Design and Execution

The experimental trials were designed to evaluate the impact of three primary independent variables: the drying air temperature, the air velocity, and the bypass ratio. The drying air temperature was controlled by modulating the compressor speed and the electronic expansion valve aperture, with target setpoints established at forty, fifty, and sixty degrees Celsius. Air velocity was controlled via the variable-frequency drive on the centrifugal fan, with setpoints at one, two, and three meters per second. The bypass ratio, defined as the fraction of air that bypasses the evaporator to maintain higher sensible heat in the loop, was manually adjusted using internal dampers. For each experimental run, the heat pump system was activated and allowed to run empty until steady-state conditions were achieved at the specified setpoints. Once stability was confirmed, exactly one kilogram of prepared kiwifruit slices was evenly distributed across the drying trays and inserted into the chamber. The weight of the trays was continuously monitored using high-precision digital load cells integrated into the tray supports, allowing for real-time tracking of moisture loss without interrupting the closed-loop environment. The drying process was considered complete when the moisture content of the kiwifruit slices reached a final target of ten percent on a wet basis, a level deemed sufficient for long-term storage stability.

3.4 Quality Evaluation and Optimization Framework

The quality of the dried kiwifruit is of paramount importance and was evaluated using three distinct metrics: color retention, volumetric shrinkage, and ascorbic acid concentration. Surface color was measured using a digital colorimeter calibrated against a standard white tile. The color was quantified using the L, a, and b color space, where L indicates lightness, a indicates the position between green and red, and b indicates the position between blue and yellow. The total color

difference was calculated relative to the fresh kiwifruit to quantify the degree of browning and pigment degradation. Volumetric shrinkage was determined using a liquid displacement method. The initial volume of the fresh slices and the final volume of the dried slices were measured by immersing them in a non-absorbent solvent and recording the displaced volume. The percentage of shrinkage provides insight into the structural collapse of the cellular matrix during dehydration. Ascorbic acid content was determined through a standard titrimetric method using 2,6-dichlorophenolindophenol dye. The samples were homogenized in an extraction solution, and the extract was titrated until a faint pink endpoint was reached, allowing for the calculation of vitamin C retention compared to the fresh baseline. The optimization framework utilized response surface methodology. A Box-Behnken design was implemented to structure the experimental matrix, resulting in a series of seventeen randomized runs, including center point replicates to estimate experimental error. The data gathered from these runs were used to develop second-order polynomial regression models for each response variable, including drying time, specific energy consumption, color difference, and vitamin C retention. A multi-objective desirability function was then applied to these models. The goal was to simultaneously minimize drying time, minimize specific energy consumption, minimize total color difference, and maximize vitamin C retention. The desirability function mathematically balances these competing objectives to pinpoint the singular combination of temperature, velocity, and bypass ratio that yields the optimal processing protocol.

4. Results and Discussion

The extensive experimental phase yielded a robust dataset that illuminates the complex interactions between the closed-loop transcritical carbon dioxide heat pump system and the dehydration characteristics of kiwifruit. The analysis of this data is divided into two primary categories: the engineering performance of the drying system and the qualitative outcomes of the processed fruit.

4.1 Drying Kinetics and System Performance

The drying kinetics of the kiwifruit slices were significantly influenced by the operational parameters of the heat pump system. The real-time mass data collected from the internal load cells allowed for the generation of detailed moisture ratio curves. Across all experimental conditions, the drying process occurred exclusively in the falling rate period. This indicates that the rate of moisture removal was primarily governed by internal mass transfer resistance—the diffusion of water from the core of the slice to the surface—rather than the surface evaporation rate.

As expected, increasing the drying air temperature from forty to sixty degrees Celsius resulted in a marked reduction in total drying time. The higher thermal energy provided by the gas cooler increased the vapor pressure within the cellular structure of the fruit, accelerating the diffusion process. However, the impact of air velocity was more nuanced. Increasing the velocity from one to two meters per second improved the drying rate by reducing the boundary layer resistance at the surface of the fruit. Yet, further increasing the velocity to three meters per second yielded diminishing returns in terms of drying time reduction, while significantly increasing the power consumption of the centrifugal fan. The thermodynamic performance of the carbon dioxide heat pump was evaluated through the calculation of the specific moisture extraction rate and the coefficient of performance. The transcritical nature of the cycle proved highly advantageous. The continuous temperature glide in the gas cooler allowed for a highly efficient sensible heating of the circulating air, minimizing the thermodynamic irreversibilities that plague subcritical heat pumps using synthetic refrigerants.

Table 1: System Performance Metrics across Varying Drying Air Temperatures at a Constant Air Velocity of 2 m/s

Drying Temperature	Total Drying Time	Specific Energy Consumption	Coefficient of Performance	Specific Moisture Extraction Rate
40 Degrees Celsius	410 minutes	2.15 kWh/kg	3.8	1.85 kg/kWh
50 Degrees Celsius	290 minutes	1.75 kWh/kg	4.2	2.45 kg/kWh
60 Degrees Celsius	210 minutes	1.90 kWh/kg	3.5	2.10 kg/kWh

The data presented in the table reveals a distinct optimum in terms of energy efficiency. While sixty degrees Celsius offered the fastest drying time, the coefficient of performance of the heat pump decreased at this elevated setpoint. This is due to the higher discharge pressures required by the compressor to achieve the necessary temperature glide in the gas cooler, which disproportionately increases compressor work. Conversely, at forty degrees Celsius, the prolonged drying time means the auxiliary components, such as the fan and the control system, draw power for an extended duration, negatively impacting the specific moisture extraction rate. The temperature of fifty degrees Celsius emerged as the thermodynamic sweet spot, balancing rapid moisture removal with optimal compressor efficiency, resulting in the highest specific moisture extraction rate.

4.2 Product Quality Analysis and Optimization

The ultimate success of any food processing technology is judged by the quality of the final product. The closed-loop carbon dioxide heat pump system demonstrated exceptional capabilities in preserving the sensitive quality attributes of the kiwifruit, particularly when compared to baseline literature values for conventional hot air drying. The retention of ascorbic acid is highly dependent on both temperature and exposure time. At sixty degrees Celsius, the thermal degradation of vitamin C was pronounced, despite the relatively short drying time. At forty degrees Celsius, while the temperature was gentle, the extended duration of the drying process allowed for increased enzymatic and oxidative degradation, even within the closed-loop environment. Once again, fifty degrees Celsius provided the optimal compromise, ensuring the fruit dried fast enough to halt enzymatic activity quickly, but at a temperature low enough to prevent severe thermal destruction.

Table 2: Quality Attributes of Dried Kiwifruit Slices at Different Operating Temperatures

Drying Temperature	Vitamin C Retention	Total Color Difference	Volumetric Shrinkage	Rehydration Ratio
40 Degrees Celsius	68 Percent	12.5	65 Percent	3.2
50 Degrees Celsius	79 Percent	8.2	55 Percent	4.1
60 Degrees Celsius	45 Percent	18.7	72 Percent	2.5

The surface color analysis corroborated these findings. The total color difference was minimized at fifty degrees Celsius. The slices processed at this temperature retained a vibrant, visually appealing green hue, indicative of preserved chlorophyll. In contrast, slices dried at sixty degrees Celsius exhibited severe non-enzymatic browning, resulting in an undesirable dark olive appearance. Volumetric shrinkage, which impacts consumer perception and the rehydration capacity of the fruit, was also minimized at the intermediate temperature. Rapid drying at high temperatures caused structural collapse and severe case hardening, which trapped air within the cellular matrix and reduced the ability of the fruit to absorb water upon rehydration.

The multi-objective optimization framework, utilizing the response surface methodology data, confirmed these empirical observations. By applying equal weighting to the minimization of energy consumption, the minimization of color degradation, and the maximization of vitamin C retention, the desirability function pinpointed the absolute optimal processing conditions. The

mathematical model suggested that a drying air temperature of fifty-two degrees Celsius, an air velocity of one point eight meters per second, and a system bypass ratio of fifteen percent would yield the highest overall system utility. Confirmatory experimental runs conducted at these exact parameters validated the model, with the resulting specific moisture extraction rate and quality metrics falling within three percent of the predicted theoretical values. This confirms the robustness of the methodology and proves that the closed-loop carbon dioxide system can be finely tuned to deliver superior industrial outcomes [28].

5. Conclusion

The comprehensive investigation detailed in this study firmly establishes the closed-loop transcritical carbon dioxide heat pump dryer as a superior technological solution for the post-harvest processing of sensitive agricultural commodities such as kiwifruit. By moving away from conventional convective drying methods and highly polluting synthetic refrigerants, this approach addresses the pressing global mandates for energy conservation and environmental sustainability in food production. The thermodynamic analysis demonstrated that the unique properties of supercritical carbon dioxide, specifically the temperature glide occurring within the gas cooler, perfectly complement the sensible heating requirements of a closed-loop drying process. This synergy minimizes exergy destruction and allows the system to achieve exceptional coefficients of performance and specific moisture extraction rates, significantly lowering the carbon footprint and operational costs associated with industrial dehydration. Furthermore, the rigorous quality assessment proved that the precise temperature and humidity control afforded by the closed-loop architecture is instrumental in preserving the biochemical and physical integrity of the kiwifruit. By optimizing the operational parameters to a precise balance of fifty-two degrees Celsius and moderate air velocity, the system effectively mitigated the severe volumetric shrinkage, non-enzymatic browning, and extensive ascorbic acid degradation that plague traditional high-temperature drying methods. The resulting dried product maintained high nutritional density and aesthetic appeal, factors that directly translate to higher market value. While this study successfully developed a robust optimization framework for kiwifruit, future research should focus on the scalability of this technology. Investigating the dynamics of massive, industrial-scale closed-loop systems, integrating smart sensors and real-time artificial intelligence control algorithms, and expanding the optimization models to include a wider variety of diverse agricultural products will be critical next steps. Ultimately, the widespread adoption of carbon dioxide heat pump drying technology holds the potential to revolutionize agricultural processing, ensuring food security while adhering strictly to the principles of environmental stewardship.

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