

Review

Research Progress on the Application of Intelligent Infrared Drying Technology to Edible Kelp: Equipment Integration, Heat and Mass Transfer, Multiphysics Simulation, and Quality Control

Kai Song ¹ , Yiran Feng ^{1,2,3,*} , Xu Ji ¹  and Qiaosheng Han ^{4,*} 

¹ Department of Mechanical Engineering and Automation, Dalian Polytechnic University, Dalian 116034, China; 240420855000428@xy.dlpu.edu.cn (K.S.); 240420855000425@xy.dlpu.edu.cn (X.J.)

² SKL of Marine Food Processing & Safety Control, National Engineering Research Center of Seafood, Dalian Polytechnic University, Dalian 116034, China

³ Department of Key Laboratory of Marine Food Processing Technology and Equipment of Liaoning Province, Dalian Polytechnic University, Dalian 116034, China

⁴ College of Arts & Information Engineering, Dalian Polytechnic University, Dalian 116499, China

* Correspondence: fengyr@dlpu.edu.cn (Y.F.); hanqs@caie.edu.cn (Q.H.)

Abstract

Kelp is a high-moisture, flexible, sheet-like marine biomass whose drying behavior is strongly affected by the coupled effects of radiative heating, convective vapor removal, internal moisture migration, tissue shrinkage, curling, and material overlap. Traditional sun drying and hot-air drying remain widely used but are limited by long processing cycles, environmental dependence, high energy consumption, and inconsistent product quality. With the development of infrared heating, heat-pump dehumidification, Internet of Things (IoT)-enabled sensing, fifth-generation (5G) mobile communication, multiphysics simulation, and digital control, kelp drying is progressively shifting toward monitored, model-assisted, and intelligent processing. This review critically summarizes recent advances in kelp and related seaweed drying, with particular emphasis on infrared-assisted heat and mass transfer, drying kinetics, coupled computational fluid dynamics–finite element method (CFD–FEM) simulation, quality evaluation, and intelligent control. Representative published studies demonstrate the engineering potential of these approaches. In a suspended infrared-array kelp drying system, an infrared power density of 1.2 kW m^{−2} combined with an air velocity of 3 m s^{−1} maintained the drying temperature at approximately 55–62 °C, while relative humidity decreased from about 80% to 20–30%. Under these conditions, the Page model achieved $R^2 = 0.987$ and RMSE = 0.019, the rehydration ratio exceeded 94%, and the total color difference remained below $\Delta E = 6.5$. A recent CFD–FEM–MATLAB workflow further reported a composite operating-condition index of $J = 0.4535$, with mapped mean and maximum kelp surface temperatures of 62.23 and 63.57 °C, respectively. These quantitative results indicate that the key challenge in infrared kelp drying is not simply to increase heat input, but to coordinate radiation distribution, airflow organization, internal moisture transport, structural response, and quality preservation. Future research should therefore focus on experimentally validated heat–mass-transfer models, adaptive sensing and control, multi-objective optimization, and pilot-scale verification under realistic production conditions.

Keywords: kelp drying; infrared drying; intelligent drying; heat and mass transfer; CFD–FEM coupling; quality control; digital control



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1. Introduction

Kelp is an important commercially valuable marine alga with significant applications in food processing, the extraction of functional compounds, and the utilization of marine biological resources. Fresh kelp harvested from the sea has a high moisture content; if not promptly dehydrated, it is prone to microbial growth, tissue softening, and quality deterioration. Therefore, drying has long been a critical unit operation in the storage, transportation, and subsequent processing of kelp. Compared to common drying materials such as grains, fruits, and vegetables, kelp is characterized by large sheet dimensions, soft tissue, a slippery surface, uneven thickness, and susceptibility to deformation. Its drying process involves not only moisture removal but is also accompanied by tissue shrinkage, curling, changes in surface color, and alterations in rehydration properties. During drying, curling, folding, and local contact between kelp blades may further change the exposed surface area and the pathways for heat transfer and moisture removal, thereby increasing spatial differences in the drying rate. As dehydration proceeds, the main limitation also changes from rapid surface moisture evaporation in the early stage to increasingly restricted internal moisture migration in the middle and later stages. Tissue shrinkage and changes in surface structure may further increase the resistance to moisture transport and contribute to differences between edge and central regions. Consequently, the challenge in controlling the kelp drying process lies not merely in shortening drying time, but in maintaining product quality and batch consistency while improving dehydration efficiency [1–7]. However, in actual production, natural sun-drying and hot-air drying remain the most common methods in kelp processing. Natural sun-drying relies on solar radiation and natural ventilation, requiring low equipment investment; however, it is significantly affected by weather, site conditions, and environmental hygiene, making it difficult to ensure continuous production and consistent product quality. Although hot-air drying improves process controllability, it primarily relies on convective heat transfer, leading to issues such as limited heating rates, high energy consumption, localized stagnation of moist hot air, and insufficient drying uniformity. Particularly when large batches of sheet kelp are stacked or hung for drying, factors such as material overlap, uneven airflow distribution, and delayed water vapor removal can easily lead to a coexistence of localized overdrying and localized moisture retention. This, in turn, affects the product's color, rehydration properties, and storage stability. The loading method is another important factor in large-scale kelp drying. Stacked or flat-bed loading can increase material overlap and restrict local ventilation, whereas suspended drying increases the exposed surface area and improves air circulation but requires suitable hanging spacing, airflow organization, and radiation distribution [8–12].

As seafood processing equipment evolves toward greater efficiency and intelligence, infrared drying and combined drying technologies have gradually emerged as key research areas in kelp drying. Infrared radiation acts directly on the surface of the material, rapidly raising its temperature and thereby enhancing the driving force for moisture evaporation. At the same time, appropriate airflow can remove moist air from the material's surface, reducing mass transfer resistance in the boundary layer. Compared to conventional hot-air drying, infrared-assisted drying offers potential advantages in shortening drying cycles and improving thermal efficiency [13–22]. However, heat input in infrared drying systems is often influenced by a combination of factors, including lamp arrangement, radiation distance, material shading, chamber structure, and airflow organization. Without proper design, this can lead to issues such as uneven radiation fields, localized overheating, and insufficient drying at the edges. Therefore, the key to infrared drying of kelp lies not simply in increasing infrared power, but in achieving a balance between radiation heating, airflow, moisture removal, and quality preservation [23–31]. Furthermore, numerical simulation and intelligent sensing technologies offer new avenues for addressing these challenges.

Computational Fluid Dynamics (CFD) methods can be used to analyze the distribution of temperature, velocity, and radiation fields within the drying chamber; the finite element method (FEM) can further describe the transient thermal response of the material surface; and data processing platforms such as MATLAB R2025b can be utilized for operating condition screening and multi-indicator evaluation. At the same time, advancements in sensor networks, infrared monitoring, Internet of Things (IoT) communication, and fifth-generation (5G) mobile communication technologies are gradually shifting the drying process from traditional empirical judgment toward online sensing and parametric control [32–35]. For high-moisture, sheet-like, and easily deformable materials such as kelp, a single drying process or a single experimental parameter is no longer sufficient to fully reflect the characteristics of the processing process. There is an urgent need to establish a systematic understanding across multiple levels, including equipment structure, heat and mass transfer, material response, quality changes, and intelligent control.

Currently, there are numerous reviews on food and seafood drying technologies; however, reviews specifically focused on intelligent infrared drying for kelp and high-moisture sheet-like seaweed remain relatively scarce. Existing studies have primarily concentrated on comparisons of drying methods, kinetic model fitting, or localized quality evaluation, while discussions regarding the interrelationships among multiphysics coupling, material thermal response, online monitoring, and engineering control in infrared array drying remain insufficient. Furthermore, existing research on intelligent drying still has certain gaps in modeling moisture migration coupling, in-situ sensor calibration, energy consumption and economic evaluation, and continuous-scale validation. Based on these research gaps, this paper reviews typical kelp drying methods, infrared heat and mass transfer, drying kinetic models, multiphysics simulation, quality evaluation, and intelligent control. Particular attention is given to the relationship between the chamber-side temperature, airflow, and radiation fields and the thermal and moisture response of kelp, as well as to how numerical modeling and online monitoring can support equipment design and operating-condition control. In this way, the review connects equipment structure, heat and mass transfer, material response, product quality, and process control within the same discussion rather than considering these aspects separately [8–10,36–40].

2. Review Methodology

This study was conducted as a structured critical review rather than a formal meta-analysis. The relevant literature was collected from major bibliographic databases and publisher platforms using combinations of terms related to kelp and seaweed, drying technologies, heat and mass transfer, numerical simulation, and intelligent control. The main search terms included “kelp”, “Saccharina”, “Laminaria”, “seaweed”, “infrared drying”, “hot-air drying”, “heat-pump drying”, “drying kinetics”, “moisture diffusion”, “CFD”, “FEM”, “sensor”, “intelligent drying”, “machine learning”, and “digital twin” [5,8–10].

Studies were included when they provided information on kelp, seaweed, aquatic-product drying, transferable heat and mass transfer mechanisms, drying kinetics, numerical modeling, product quality, online monitoring, or process control. Duplicate records, studies unrelated to drying, and publications without sufficient methodological information were excluded. The selected studies were then classified according to drying method, operating conditions, heat and mass transfer mechanism, model type, quality indicators, monitoring method, and control strategy. Because considerable differences exist among studies in species, material thickness, initial moisture content, loading method, drying endpoint, and equipment configuration, the results were compared within their original experimental conditions rather than statistically pooled. The final reference set used in

this revised manuscript contains 115 sources, of which 114 were published during 2021–2026 [5,8–10,36–39].

3. Recent Advances in Drying Technologies for Kelp and Aquatic Products

The main topics considered in this review and their relationships are summarized in Figure 1. Different drying methods exhibit significant differences in terms of heat input mechanisms, moisture migration pathways, process stability, and the ability to preserve product quality. For kelp—a type of high-moisture-content, large-sized sheet-like seaweed—the selection of a drying process cannot be based solely on dehydration rate. It must also comprehensively consider heat field uniformity, moisture removal capacity, preservation of tissue structure, energy consumption levels, and suitability for continuous production. Consequently, in recent years, research on the drying of kelp and other aquatic products has gradually shifted from simple comparisons of individual process performance to more systematic approaches, such as combined drying, process modeling, multi-physics analysis, and intelligent control [27,41–53].

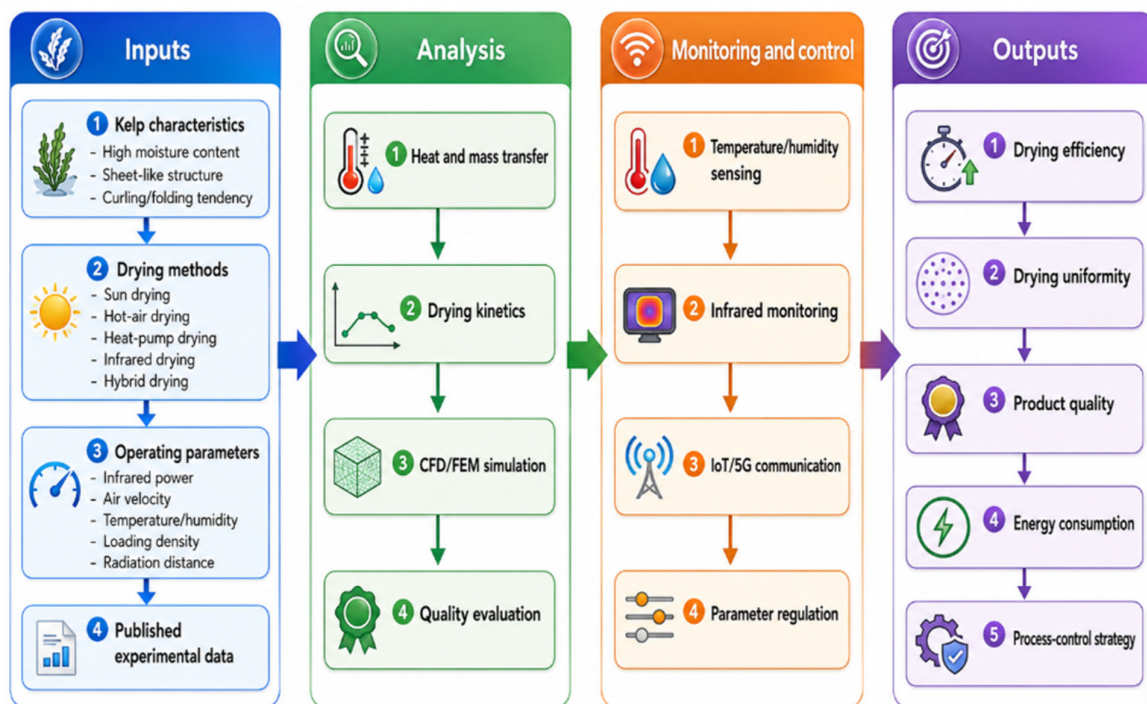


Figure 1. Schematic Diagram of Kelp Drying Technology Classification and Development Pathways.

Currently, natural sun-drying is one of the earliest dehydration methods used in traditional kelp processing, relying primarily on solar radiation and natural ventilation to remove moisture. This method requires low equipment investment and has a low operational threshold, and it still has a certain degree of application in small-scale processing. However, the natural sun-drying process is highly dependent on external environmental conditions; drying rates are significantly affected by light intensity, air humidity, wind speed, and site conditions, making it difficult to establish a stable set of process parameters. Under conditions of continuous rain, high humidity, or poor ventilation, kelp is prone to issues such as prolonged drying cycles, localized moisture regain, increased microbial risks, and fluctuations in batch quality. Therefore, although natural sun-drying offers the advantage of low cost, the uncontrollable nature of the process limits its further application in standardized and large-scale kelp processing. Consequently, human intervention is re-

quired to achieve the drying objective [11,12]. Hot-air drying, which utilizes convective heat transfer between heated air and the material surface, is currently a well-established method for drying agricultural and aquatic products. Compared to natural sun-drying, hot-air drying improves the controllability of temperature and time, thereby mitigating the impact of external environmental fluctuations on the drying process to a certain extent. However, the heat transfer efficiency of hot-air drying primarily depends on air temperature, air velocity, the capacity to exhaust moist air, and the material loading condition. When the airflow distribution within the drying chamber is uneven or localized moist air stagnates, significant variations in heat and mass transfer conditions on the material surface occur, leading to inconsistent drying endpoints. In the case of kelp, its sheet-like, flexible structure is prone to curling, folding, and mutual obstruction during drying. This further impedes the effective circulation of hot air across the material surface, resulting in the coexistence of locally overdried and underdried areas. Therefore, while traditional hot-air drying has achieved a high degree of engineering maturity, there remains room for improvement in terms of energy efficiency, quality preservation, and batch consistency [8–10].

Compared to hot-air drying, heat pump drying is an energy-efficient humidity-control technology developed from the former. Its core principle lies in recovering latent heat from humid air through a refrigeration cycle, thereby enabling continuous dehumidification at lower temperatures. This technology reduces reliance on high-temperature heating, allowing the drying process to occur in a relatively mild thermal environment. This helps minimize the loss of heat-sensitive components, color deterioration, and structural damage. For quality-sensitive materials such as seaweed and seafood, heat pump drying offers certain advantages in maintaining appearance, rehydration capacity, and nutritional stability. However, the effectiveness of heat pump drying depends not only on dehumidification capacity but is also closely related to air circulation patterns, loading density, and chamber design. In the large-scale processing of sheet kelp, improper airflow path design may still lead to localized stagnation of moist air and uneven drying rates. Furthermore, heat pump systems involve complex equipment configurations with relatively high initial investment and maintenance requirements. When used alone, they may struggle to balance rapid dehydration with low-cost operation. Therefore, heat pump drying is better suited as a humidity control and energy recovery unit, coupled with infrared, hot-air, or intelligent control systems to enhance the energy efficiency and stability of the overall drying process [54–61]. Furthermore, as shown in Figure 2, infrared drying applies radiant energy directly to the material surface, enabling the kelp's outer layer to rapidly absorb energy and generate an evaporative driving force. Unlike hot-air drying, which relies on air as the primary heat transfer medium, infrared radiation features fast response times, strong directional energy transfer, and pronounced surface-enhanced heating, making it suitable for the rapid dehydration of sheet-like materials. For kelp, infrared radiation increases the surface temperature of the material, promoting the evaporation of surface moisture; simultaneously, appropriate airflow can promptly remove water vapor, reducing boundary layer humidity and mass transfer resistance, thereby enhancing the migration of moisture from the interior to the surface [23–31]. The advantages of infrared drying are based on a rational heat field distribution and effective moisture removal. The arrangement of infrared lamps, radiation distance, array coverage, material obstruction, and air turbulence all affect the incident radiation intensity and its spatial distribution. When the radiation field is uneven, the central region may experience excessive heating or localized overheating, while the peripheral regions may suffer from insufficient heat input and drying lag. Therefore, infrared drying is not merely a process of increasing infrared power but requires establishing a coordinated relationship among radiation heating, airflow, and moisture removal. Consequently, hot-air-assisted infrared drying is a combined, enhanced

drying method developed on this basis. Infrared radiation primarily provides rapid heat input, while hot air or forced ventilation facilitates water vapor removal and boundary layer renewal. The synergy between the two not only increases the drying rate but also mitigates the problem of localized stagnant moist air, thereby helping to improve drying uniformity. For high-moisture sheet kelp, this method holds significant potential for engineering applications; however, its actual effectiveness still depends on the synergistic optimization of parameters such as infrared power, air velocity, loading density, hanging spacing, and chamber structure. The main characteristics of the drying methods discussed above are summarized in Table 1. As shown in Table 1, each drying method has specific advantages and limitations. Infrared-assisted drying provides rapid heating and good quality retention, but its performance depends strongly on radiation uniformity and airflow conditions. Because the drying conditions and evaluation indices vary among studies, the comparison focuses on their heat and mass transfer characteristics, representative operating conditions, drying efficiency, and main effects on product quality. Quantitative results reported for a suspended infrared-array kelp drying system support this dependence on operating conditions. At an infrared power density of 1.2 kW m^{-2} and an air velocity of 3 m s^{-1} , the drying temperature was maintained at approximately $55\text{--}62^\circ\text{C}$, while relative humidity decreased from about 80% to 20–30%. The corresponding Page-model fit gave $R^2 = 0.987$ and $\text{RMSE} = 0.019$, with a rehydration rate above 94% and ΔE below 6.5. The reported drying time was approximately 6 h, compared with 48 h for the conventional reference process. These results indicate the potential of combined infrared heating and airflow, although direct comparison among different studies still requires consideration of loading method, material thickness, initial moisture content, and the definition of the drying endpoint [34].

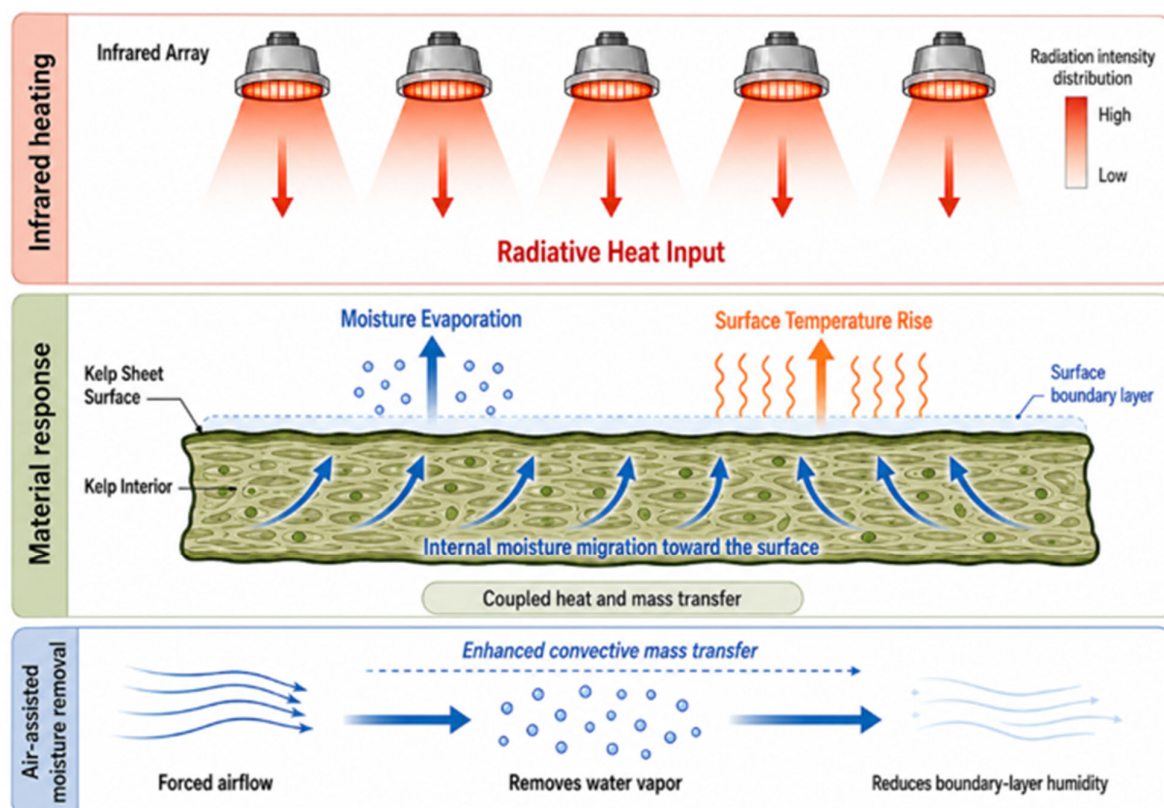


Figure 2. Schematic diagram of heat input and moisture migration during infrared-assisted kelp drying.

Table 1. Comparison of the main drying methods for kelp and related aquatic products based on published studies.

Drying Method	Representative Conditions	Drying Time/Energy	Quality and Rehydration	Main Limitations
Natural sun-drying	Ambient conditions	Long cycle; low external energy demand	Quality strongly affected by weather; variable rehydration	Weather-dependent; poor uniformity
Hot-air drying	Controlled T and airflow	Moderate–long; relatively high energy demand	Prolonged heating may affect color and heat-sensitive compounds	Uneven airflow; local moisture accumulation
Heat-pump drying	20–50 °C; 0.3–1.3 m s ^{−1} ; RH 20–50%	~5 h under representative conditions	Mild temperature favors color and rehydration retention	High initial cost; airflow-sensitive
Infrared drying	Controlled IR power and radiation distance	Rapid heating; potentially high thermal efficiency	Shorter thermal exposure may improve quality retention	Radiation non-uniformity; overheating risk
IR-assisted airflow drying	1.2 kW m ^{−2} , 3 m s ^{−1}	~6 h; 55–62 °C	Rehydration >94%; $\Delta E < 6.5$	Requires coordinated IR–airflow control
Microwave-assisted drying	Microwave-assisted heating	Rapid internal heating	Short process may reduce thermal exposure	Local overheating; difficult scale-up

In summary, with advancements in sensors, the Internet of Things (IoT), numerical simulation, and control algorithms, research on kelp drying is shifting from the improvement of individual equipment to the integration of intelligent systems. The core of intelligent drying lies not merely in connecting equipment to a network, but in establishing a dynamic sensing and feedback adjustment mechanism for the drying process by collecting real-time data on temperature, humidity, radiation intensity, wind speed, and material status. Based on online monitoring data, the system can further adjust infrared power, air velocity, operating time, and the method for determining the drying endpoint, thereby reducing the uncertainty associated with empirical operation. In intelligent drying research, numerical simulation and data processing methods play a crucial supporting role [35,62–65]. CFD can be used to analyze the distribution of temperature fields, velocity fields, and radiation fields within the drying chamber, revealing issues such as local recirculation, heat concentration, and airflow short-circuiting; FEM can be used to describe the transient thermal response of the kelp surface and potential overheating risks; platforms such as MATLAB can further perform statistical evaluation, metric normalization, and operating condition screening of results under multiple operating conditions. These methods shift the optimization of drying equipment from simple trial-and-error experimentation to model-aided design, laying the foundation for subsequent model-driven control and digital twin drying systems. Overall, the trend in kelp drying technology is not toward the complete replacement of one drying method by another, but rather the integration of various technologies for enhanced heat transfer, humidity control and dehumidification, online monitoring, and model optimization. The most promising future path involves using infrared-enhanced heat transfer as the core, combined with hot air or heat pump-based humidity control, multi-point sensing, multi-physics field simulation, and intelligent control, to form an efficient, stable, and controllable kelp drying system suitable for continuous production.

4. Mechanisms of Heat and Mass Transfer in Infrared Drying

During infrared drying, the dehydration behavior of materials is governed by multiple factors, including radiative heat transfer, convective heat transfer, internal moisture migration, and surface evaporation. Unlike traditional hot-air drying, which primarily relies on

air as the heat transfer medium, infrared radiation acts directly on the material's surface or near-surface regions, enabling rapid energy absorption and creating a strong temperature gradient and driving force for moisture evaporation [66–72]. For high-moisture-content sheet-like materials such as kelp, the efficiency advantage of infrared drying primarily stems from its rapid surface heating capability, while drying uniformity and product quality stability depend on the coordinated interaction between the radiation field, the airflow field, and internal moisture migration within the material. The relative importance of these processes changes during drying. At the initial stage, when free water is abundant at the kelp surface, the drying rate is mainly affected by heat input and the removal of water vapor from the surface. As surface moisture decreases, internal moisture migration gradually becomes more important and may become the main resistance to further dehydration. For kelp, this change is also affected by its flexible sheet-like structure. Shrinkage changes the moisture diffusion distance, curling alters the angle and area exposed to infrared radiation, and folding or contact between adjacent blades reduces local airflow and vapor removal. Therefore, the controlling factor during kelp drying is not fixed but changes with moisture content, material morphology, and local heat and mass transfer conditions. As illustrated in Figure 2, these processes are interdependent. Infrared radiation increases the kelp surface temperature and promotes moisture evaporation, while airflow removes the water vapor accumulated near the surface and maintains the external mass transfer driving force. As drying proceeds, however, the migration of internal moisture toward the surface becomes increasingly important; therefore, increasing infrared power or air velocity alone does not necessarily lead to a corresponding improvement in the overall drying rate.

4.1. Mechanisms of Heat Transfer by Infrared Radiation

According to research, the essence of heat transfer via infrared radiation lies in the radiation source transmitting energy to the material in the form of electromagnetic waves. The material's surface absorbs this radiant energy and converts it into thermal energy, causing the surface temperature to rise and promoting moisture evaporation. Since infrared heating does not rely entirely on convective heat transfer between hot air and the material, it offers a rapid temperature response and is suitable for enhanced dehydration of thin-layer or sheet-like materials such as kelp, nori, and sliced fruits and vegetables. The heating effect of infrared radiation is primarily influenced by the power of the radiation source, the wavelength of the radiation, the irradiation distance, the surface absorption rate of the material, and the array configuration. In infrared drying of kelp, the infrared power directly determines the energy input intensity per unit area. Appropriately increasing the infrared power can accelerate surface heating and enhance the rate of moisture evaporation; however, when the power is too high or the radiation distribution is uneven, localized areas may experience overheating, surface hardening, or color deterioration. The surface of kelp contains a large amount of moisture and gelatinous structures, and its heat absorption and moisture loss processes are not entirely uniform. Due to differences in thickness, morphology, and heated surface area, the edge regions often exhibit different heating and dehydration behaviors compared to the central regions [23–31,73]. Therefore, power settings in infrared drying should not be optimized solely to shorten drying time but should also consider thermal field uniformity and quality preservation requirements. Additionally, the arrangement of the infrared array is a critical factor influencing thermal field distribution. Multi-lamp or multi-module infrared arrays can increase the coverage area, but the superposition effect between different radiation sources results in higher heat flux in the central region, while heat input in the peripheral regions remains relatively insufficient. Previous studies on infrared drying systems for kelp have observed a spatial distribution characteristic of “higher heat flux in the center and lower heat flux at the edges”

within the drying zone, indicating that infrared array drying systems require optimization of tube spacing, radiation distance, installation angle, and material suspension position to improve overall uniformity.

4.2. Air Flow and Convective Mass Transfer

As shown in Figure 3, the process illustrates infrared radiation input, surface heating of the kelp, water evaporation, and the removal of water vapor through forced airflow. Although infrared radiation is the primary source of heat input in infrared drying, airflow remains a critical factor in determining whether the drying process proceeds stably. After the kelp surface absorbs infrared energy, surface moisture evaporates rapidly, forming a high-humidity boundary layer near the material. If water vapor is not removed in a timely manner, the increase in local air humidity will weaken the partial pressure difference of water vapor between the material surface and the surrounding air, thereby reducing the subsequent evaporation rate. It can thus be seen that the role of airflow is not only to assist in heat transfer but, more importantly, to renew the boundary layer, remove humid air, and maintain a continuous mass transfer driving force. Air velocity has a dual effect on infrared drying. On the one hand, appropriately increasing the air velocity can reduce the boundary layer thickness, enhance convective mass transfer, and promote the diffusion of water vapor from the material surface into the drying medium; on the other hand, excessively high air velocity may carry away too much heat, reducing the local temperature rise efficiency of infrared heating, and may even cause material oscillation and uneven surface drying. Therefore, in infrared drying, air velocity is not necessarily better the higher it is, but should be matched with the infrared power, material loading density, and drying chamber structure. For suspended kelp drying systems, a well-organized airflow field can reduce the stagnation of moist air between materials and improve drying consistency across different suspension positions. The spatial distribution of the airflow field also affects drying uniformity. Localized recirculation, short-circuit flow, low-velocity stagnation zones, and edge disturbance zones may occur within the drying chamber; these non-ideal flow structures alter local convective heat transfer and moisture removal conditions. CFD analysis indicates that the temperature field, velocity field, and radiation field in infrared kelp drying systems are coupled, with velocity field non-uniformity being one of the key factors affecting local thermal response and drying consistency. Therefore, in the design of infrared drying equipment, the duct structure, inlet and outlet positions, and air circulation methods should be optimized in conjunction with the infrared array layout [74].

4.3. Water Migration Process Within Kelp

Research has shown that the kelp drying process is not a simple surface evaporation process, but rather the result of the combined effects of external heat input and internal moisture migration. In the early stages of drying, the surface free water content of kelp is relatively high, and moisture evaporation is primarily controlled by external heat supply, air humidity, and wind speed. As drying progresses, surface moisture gradually decreases, and the migration of internal moisture toward the surface becomes the primary limiting factor affecting the drying rate. From the perspective of mass transfer, water migration within kelp can be approximated as an effective diffusion process, as shown in Equation (1) [75–77].

$$\frac{\partial M}{\partial t} = \nabla \cdot (D_{eff} \nabla M) \quad (1)$$

where M is the local moisture content and D_{eff} is the effective moisture diffusivity. For biological materials, D_{eff} is not necessarily constant because it is affected by temperature, moisture content, tissue structure, and shrinkage. For kelp, this structural change is

particularly important because the material is thin and flexible. As water is removed, tissue shrinkage, wrinkling, and curling change the effective diffusion distance and surface exposure. Folding or contact between adjacent blades can also restrict local airflow and create high-humidity regions. Therefore, shrinkage may shorten the internal diffusion path in some regions, while tissue collapse or blade contact may increase local mass transfer resistance in others. This explains why exposed edges may become overdried while folded or shielded regions retain more moisture even under the same chamber operating conditions [78].

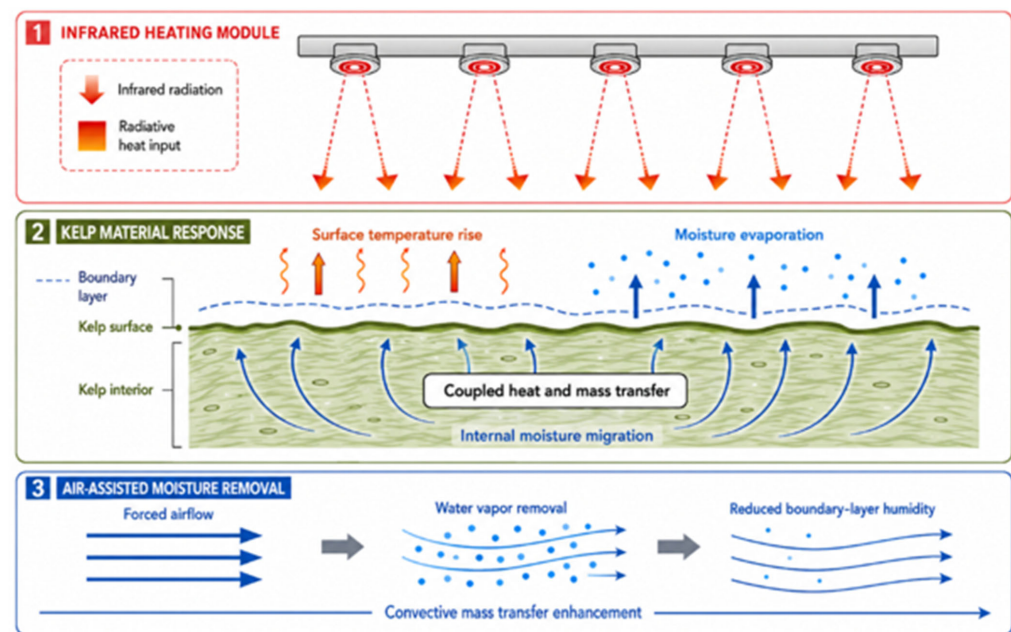


Figure 3. Schematic diagram of the radiation-convection coupled heat and mass transfer mechanism during infrared-assisted kelp drying.

At this stage, moisture migration is influenced by factors such as tissue structure, cell wall integrity, thickness distribution, shrinkage and deformation, and temperature gradients. In particular, for high-moisture-content sheet-like kelp, the internal moisture migration path is relatively short, but changes in material morphology can significantly affect the mass transfer process. Dehydration shrinkage may cause localized curling and surface wrinkling, reducing the heat-exposed area or impairing airflow in certain regions; simultaneously, localized tissue collapse may reduce rehydration capacity and affect post-drying quality. If the surface temperature rises too rapidly, the rapid evaporation of surface moisture may form a relatively dense dried layer, thereby increasing the resistance to further internal moisture migration. Conversely, if external heat input is insufficient and the material remains in a high-moisture state for an extended period, this may lead to sticking, moisture regain, and microbial risks. Therefore, the infrared drying process must maintain a balance between rapid surface evaporation and continuous internal moisture migration. Moisture migration within kelp typically exhibits distinct nonlinear characteristics, which is why empirical or semi-empirical models such as the Page model are commonly used in drying kinetics modeling. Previous studies have shown that the Page model can effectively fit the changes in moisture content during the hanging infrared drying of kelp, indicating the presence of typical decreasing-rate drying characteristics in the middle and late stages of kelp drying. However, relying solely on macroscopic moisture content models makes it difficult to explain the differences in thermal response between different locations; therefore, further analysis combining thermal, flow, and radiation fields is required [73,79–81].

4.4. Heat and Mass Coupling and Mechanisms of Non-Uniform Drying

The core issue in infrared kelp drying lies in the spatial non-uniformity of heat and mass transfer. Infrared radiation determines the energy input to the material surface, airflow determines the efficiency of humid air removal, and the material's own structure determines its internal moisture migration capacity. These three factors do not act independently but are mutually coupled during the drying process. For example, if a certain area receives a higher radiant heat flux, its surface temperature and evaporation rate will increase rapidly; however, if airflow in that area is insufficient, the water vapor generated by evaporation cannot be removed in a timely manner, and the resulting increase in local humidity will then limit subsequent evaporation. Conversely, although ventilation conditions in peripheral areas may be better, drying lag can occur if radiant heat input is insufficient. As shown in Figure 4, this coupling relationship explains why stable operation in infrared drying cannot be achieved by optimizing a single parameter alone. In this figure, panel A shows the spatial distribution of infrared radiation intensity, panel B illustrates the airflow direction, main flow paths, and local recirculation zones, and panel C presents the resulting surface-temperature and drying-state differences of the kelp. The arrows between A, B, and C indicate the coupled influence of radiation, airflow-assisted moisture removal, and material thermal response on drying uniformity. Increasing infrared power alone may boost the average drying rate but also widens local temperature differentials and increases the risk of overheating; increasing air velocity alone may improve moisture removal but may also reduce local temperature rise efficiency; simply extending the drying time may exacerbate color deterioration and increase energy consumption. Therefore, the optimization of infrared drying for kelp should be based on multi-factor coordination, taking into account infrared power, air velocity, loading density, hanging spacing, chamber structure, and end-point control of drying as a unified system. From an engineering perspective, the mechanisms of heat and mass transfer dictate that infrared drying equipment for kelp must possess three fundamental capabilities: first, the ability to provide stable and adjustable radiant heat input; second, the ability to uniformly and effectively exhaust moist air; and third, the ability to perform dynamic control based on online sensing and model analysis. Only by simultaneously meeting these three conditions can one improve drying efficiency while reducing the risks of local overheating, under-drying at the edges, and quality fluctuations. From a process-diagnosis perspective, the dominant limitation can be identified from the combined response of temperature, humidity, airflow, and moisture. A low material temperature together with a slow moisture decrease indicates insufficient heat input, whereas a high surface temperature accompanied by high local humidity suggests that water-vapor removal rather than heating has become limiting. If the surface temperature is adequate and the surrounding humidity is low but the drying rate continues to decrease, internal moisture migration is more likely to control the process. Spatial differences provide additional information: persistent hot regions indicate excessive local radiation, while wet regions associated with low air velocity indicate insufficient ventilation. This diagnosis provides a practical basis for deciding whether infrared power, airflow, material spacing, or drying time should be adjusted [82,83].

4.5. Control Parameters for the Infrared Drying Process

The key operating parameters in infrared kelp drying include infrared power, radiation distance, air velocity, air temperature and humidity, loading density, and drying time. As shown in Figure 5, these operating parameters jointly regulate the infrared drying process and further affect the drying rate, drying uniformity, and product quality. The arrows indicate the direction of influence among the control parameters, drying process, and drying outcomes, while the warning boxes on both sides illustrate the risks of local

overheating caused by excessive infrared power and insufficient moisture removal caused by inadequate airflow. Among these variables, infrared power and air velocity directly affect the balance between heat input and moisture removal. In a suspended infrared kelp drying system, infrared power densities of $0.8\text{--}1.2\text{ kW m}^{-2}$ and air velocities of $1\text{--}3\text{ m s}^{-1}$ were investigated. Under the selected condition of 1.2 kW m^{-2} and 3 m s^{-1} , the drying temperature remained approximately $55\text{--}62\text{ }^{\circ}\text{C}$, while relative humidity decreased from about 80% to 20–30%. These results show that infrared power and airflow should be considered together rather than as independent control variables. A reasonable combination of parameters should keep the material surface temperature within a safe range while maintaining sufficient driving force for moisture evaporation. In addition to individual parameters, the spatial field distribution within the drying chamber should also be considered a key evaluation factor. Average values of temperature, velocity, and radiation fields can only reflect overall conditions and fail to reveal issues such as localized overheating, low-velocity stagnation, or insufficient radiation coverage. Therefore, future control of infrared drying processes should shift from “point parameter control” to “field distribution control,” that is, conducting comprehensive evaluation and dynamic adjustment of heat and mass transfer conditions within the drying chamber through multi-point sensing, infrared thermal imaging, CFD simulation, and model-based prediction methods. By contrast, quantitative limits for radiation distance, loading density, and hanging spacing remain less consistently reported, and these parameters should be included more systematically in future experiments because they directly affect material shading, airflow accessibility, and radiation-field uniformity [28,84,85].

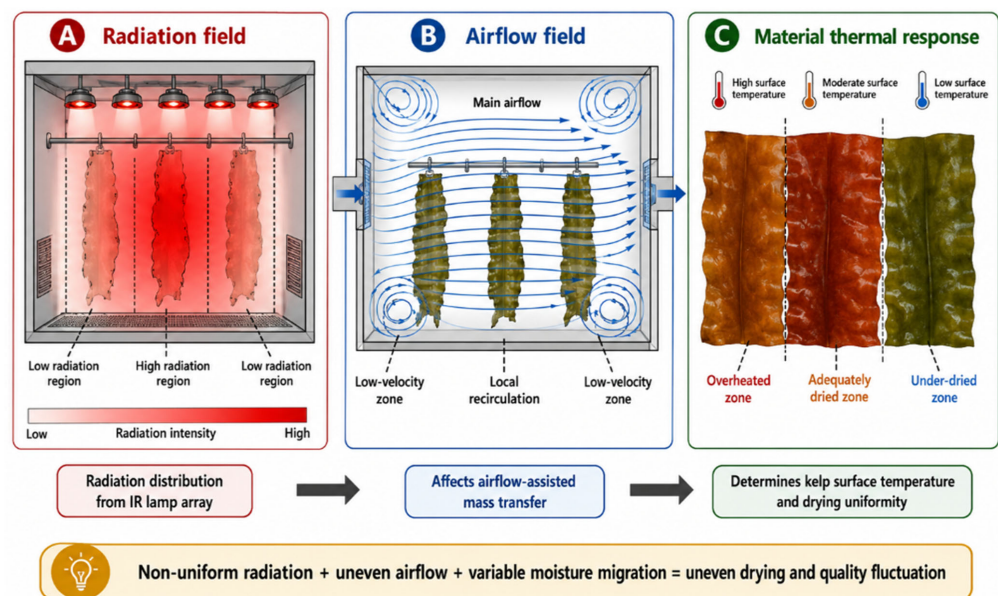


Figure 4. Schematic illustration of spatial inhomogeneity and field coupling during the infrared drying of kelp.

In summary, the advantages of infrared drying lie in its rapid, directional, and highly efficient radiant heat input; however, its stable application depends on the synergistic interaction between airflow, moisture migration, and the thermal response of the material. For high-moisture, sheet-like seaweeds such as kelp, the focus of infrared drying technology development should not remain on increasing heating intensity, but should shift toward elucidating heat-mass coupling mechanisms, controlling non-uniform fields, and optimizing parameters through intelligent control. Where kelp-specific transport or material-property data are unavailable, results from related high-moisture biological materials may provide useful mechanistic references, but the corresponding parameters and operating limits

should be validated before being directly applied to kelp drying. This figure further emphasizes that these parameters interact with each other, and their optimization requires a balance between drying efficiency, drying uniformity, and product quality.

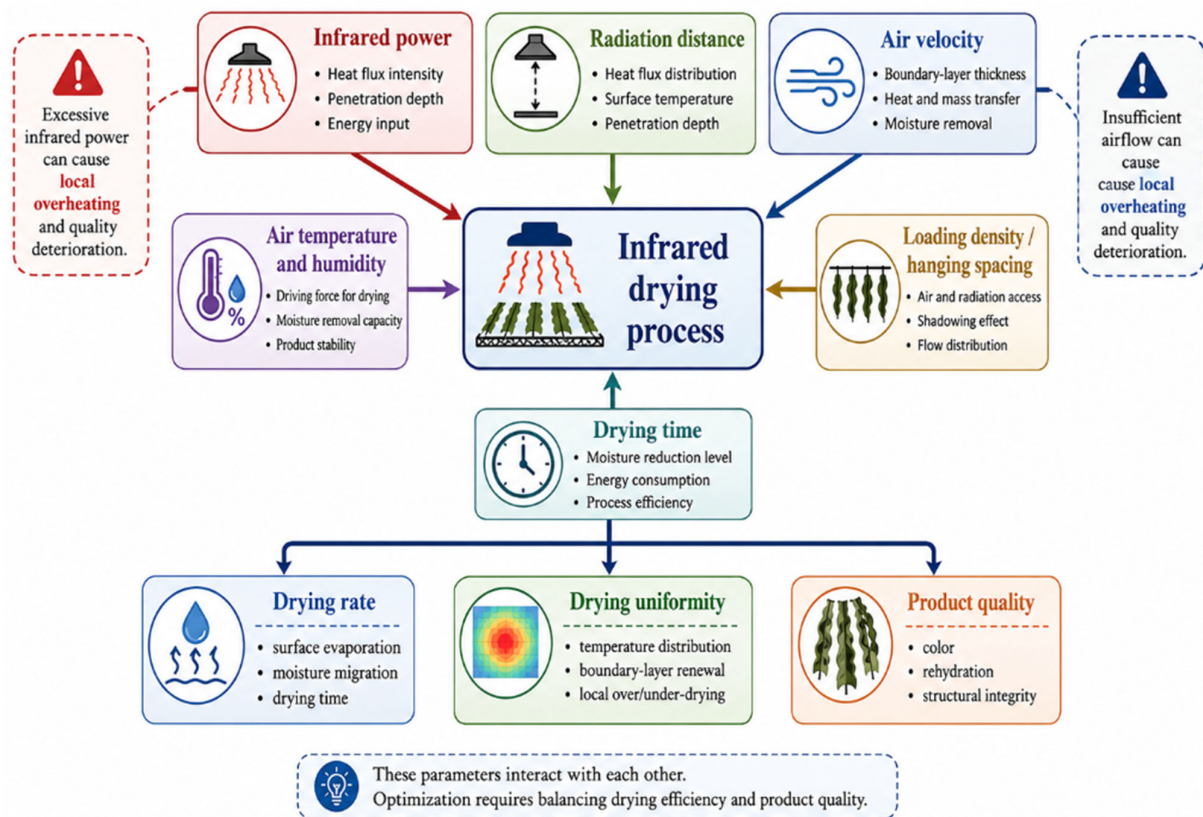


Figure 5. Schematic diagram of key control parameters for infrared drying of kelp and their interrelationships.

5. Kinetics Model and Parameter Characterization of Kelp Drying

Research on the drying kinetics of kelp typically involves several stages, including the setting of process variables, the collection of drying data, the construction of moisture content curves, the fitting of thin-layer models, parameter estimation, and engineering applications. As shown in Figure 6, variables such as infrared power, air velocity, air temperature and humidity, radiation distance, loading density, and drying time collectively determine the heat and mass transfer conditions during the drying process, and further influence the shape of the moisture content curve and changes in model parameters. In this figure, the overall analytical framework of kelp drying kinetics. Part 1 describes the setting of experimental variables, Part 2 presents drying data acquisition, Part 3 shows the construction of moisture ratio curves, Part 4 compares candidate thin-layer models, Part 5 covers parameter estimation and model evaluation, and Part 6 summarizes the interpretation and engineering applications. The arrows indicate the sequential relationship among these stages, while the Page model is highlighted as suitable for describing the nonlinear drying behavior of kelp. Drying kinetics models are essential tools for describing the time-dependent changes in material moisture content and serve as the foundation for drying process optimization and equipment control [15,86–90]. For high-moisture-content sheet-like materials such as kelp, the drying process typically exhibits distinct nonlinear characteristics: during the initial stage, surface free water evaporates rapidly, while in the middle and late stages, the process is gradually constrained by internal moisture diffusion, tissue shrinkage, and changes in surface structure. Therefore, relying solely on drying time

or final moisture content is insufficient to fully characterize the dehydration process; kinetic models are required to quantitatively characterize moisture migration behavior.

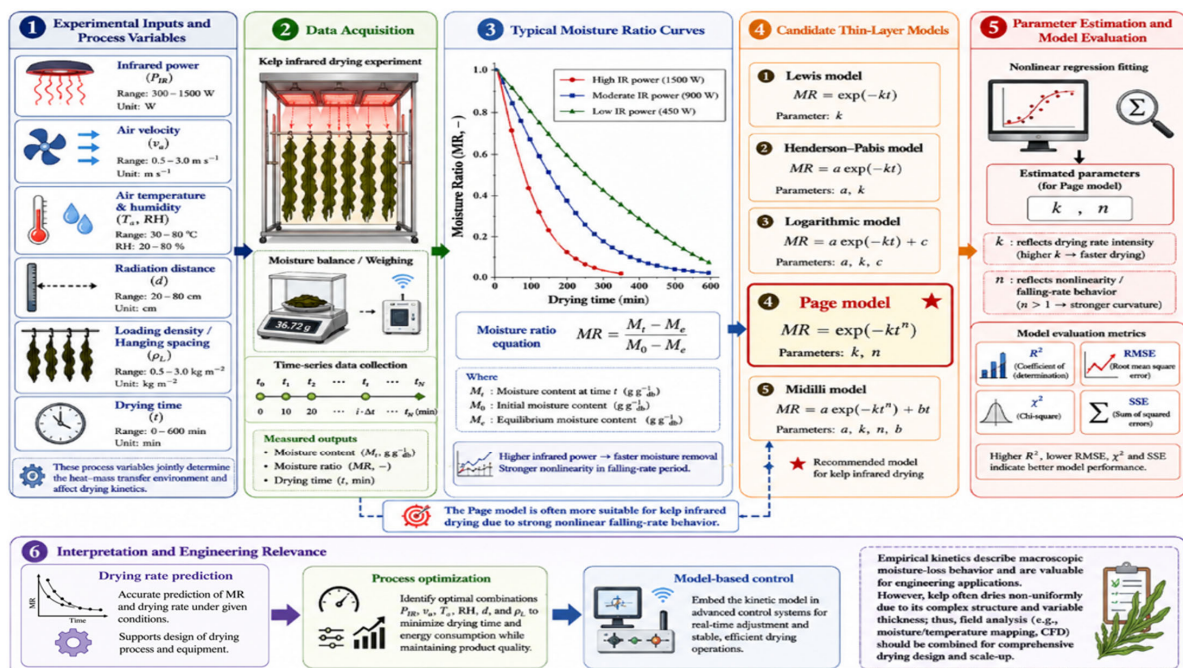


Figure 6. Framework for the Development of a Kelp Drying Kinetic Model, Parameter Estimation, and Engineering Applications.

Common thin-film drying models include the Lewis model, the Henderson–Pabis model, the Logarithmic model, the Page model, and the Midilli model. Among these, the Lewis model is simple in form and can provide a preliminary description of the exponential decay of the moisture fraction over time, but it has limited ability to characterize the nonlinear changes during the rate-decreasing drying stage. The Henderson–Pabis and Logarithmic models introduce correction parameters based on the Lewis model, improving local fitting capabilities; however, the physical significance of their parameters and their scope of applicability remain somewhat limited. In contrast, the Page model, by introducing an empirical exponential correction term, can better describe the nonlinear moisture loss characteristics commonly observed during the drying of food, agricultural products, and aquatic products; therefore, it is well-suited for research on the drying of kelp and other seaweed materials. To facilitate comparison, the representative forms, parameters, and main characteristics of the commonly used thin-layer drying models are summarized in Table 2.

Among these models, the Page model provides a suitable balance between model simplicity and the ability to describe the nonlinear moisture loss behavior of kelp. In this context, the drying kinetics of kelp are typically characterized by the moisture ratio (MR), whose basic form is shown in Equation (2) [91–93].

$$MR = \frac{M_t - M_e}{M_0 - M_e} \quad (2)$$

In the equation, (M_t) represents the moisture content of the material at any given time, (M_0) represents the initial moisture content, and (M_e) represents the equilibrium moisture content. In practical analysis, when the equilibrium moisture content is relatively low, the model can be simplified based on the experimental conditions. The Page model is typically expressed as shown in Equation (3).

$$MR = \exp(-kt^n) \quad (3)$$

Table 2. Comparison of commonly used thin-layer drying kinetic models.

Model	Representative Equation	Parameters	Main Characteristics	Main Limitation
Lewis	$MR = \exp(-kt)$	k	Simple; few parameters	Limited description of nonlinear falling-rate drying
Henderson–Pabis	$MR = a \exp(-kt)$	a, k	Improved flexibility over Lewis	Parameters have limited physical meaning
Logarithmic	$MR = a \exp(-kt) + c$	a, k, c	Better description of late-stage moisture change	More empirical parameters
Page	$MR = \exp(-ktn)$	k, n	Good nonlinear fitting with few parameters; suitable for kelp drying	Empirical; cannot describe spatial non-uniformity
Midilli	$MR = a \exp(-ktn) + bt$	a, k, n, b	High fitting flexibility over a wide drying range	More parameters and possible overfitting

In the equation, (k) is the drying rate constant, reflecting the combined effects of external heat input and the rate of moisture migration; (n) is an empirical exponent used to account for the nonlinear characteristics of the drying process. Generally, a higher value of (k) corresponds to a faster dehydration rate, while the value of (n) is related to the curvature of the drying curve and the characteristics of the rate-decrease phase. Furthermore, during the infrared drying of kelp, infrared power and air velocity are critical factors influencing the model parameters. An increase in infrared power typically enhances heat input to the material surface, increasing the surface evaporation rate and causing the drying curve to decline more rapidly; appropriately increasing the air velocity helps reduce boundary layer humidity and promotes water vapor removal, resulting in better coordination between internal moisture migration and surface evaporation processes. However, when infrared power is too high or airflow velocity is unevenly distributed, localized overheating, excessive drying at the edges, and surface hardening may alter the moisture migration pathways, leading to significant fluctuations in model parameters. Therefore, the kinetic model parameters not only reflect the drying rate but also indirectly reflect the stability of heat and mass transfer processes under different operating conditions.

As shown in Figure 7, the infrared drying curves of kelp typically exhibit distinct decelerating drying characteristics, with the drying rate decreasing gradually after a rapid initial change. Therefore, the model parameters can be used not only for curve fitting but also as important references for optimizing drying conditions and predicting the drying endpoint. Figure 7A indicates that during the infrared drying of kelp, the moisture ratio (MR) exhibits a nonlinear decline over time, with most stages displaying decelerating drying characteristics; Figure 7B explains the physical significance of k and n in the Page model, where k primarily reflects the level of drying rate, while n characterizes the nonlinearity of the curve and the resistance to internal moisture migration; Figure 7C further illustrates that process variables such as infrared power, air velocity, air temperature and humidity, loading density, and radiation distance collectively influence the model parameters and drying uniformity; Figure 7D further presents the progression from experimental data collection and model fitting to parameter identification, model evaluation, and process prediction and control. In the figure, arrows indicate the direction of influence or the analytical sequence, the colored panels distinguish different functional modules, and the upward and downward symbols

represent increasing and decreasing effects, respectively. Therefore, kinetic parameters serve as a crucial link between drying experiments, model fitting, and process optimization.

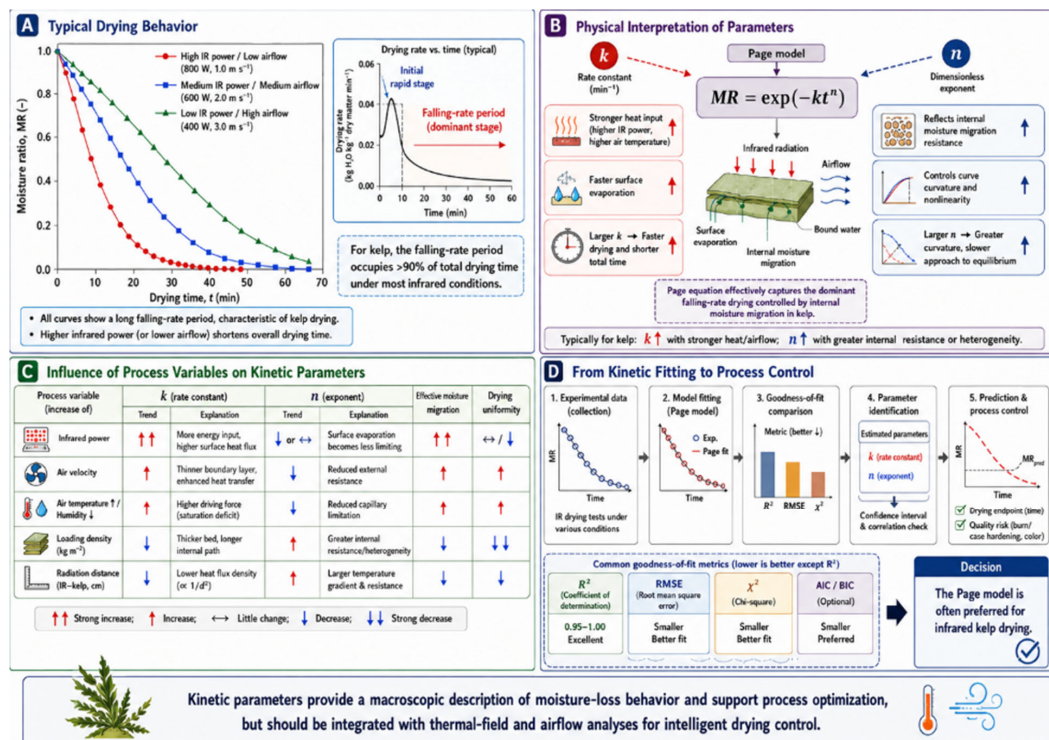


Figure 7. Schematic diagram illustrating the infrared drying kinetics of kelp and an explanation of the model parameters.

Previous studies on suspended infrared kelp drying have shown that the Page model can effectively fit the changes in moisture content during the infrared drying process of kelp, indicating that this type of drying process exhibits typical characteristics of rate-limiting drying. In relevant experiments, the Page model demonstrated high fitting accuracy under representative operating conditions and was able to accurately reflect the moisture loss patterns of kelp under the combined effects of infrared radiation and airflow. However, traditional kinetic models are primarily based on changes in overall moisture content and struggle to directly reveal differences in thermal fields, radiation coverage, and material surface temperature responses at various locations within the drying chamber. Therefore, kinetic models are more suitable for describing macroscopic water loss processes and should not be regarded as the sole tool for fully explaining drying non-uniformity. This limitation is particularly relevant to kelp because its morphology changes continuously during drying. Shrinkage, curling, and folding alter the material thickness, exposed surface area, radiation coverage, and local airflow conditions, while contact between adjacent blades may further restrict moisture removal. Therefore, changes in fitted kinetic parameters should be interpreted together with material morphology and local heat and mass transfer conditions rather than being attributed only to infrared power or air velocity. Consequently, future research on kelp drying kinetics should shift from single-curve fitting toward the integration of multi-source data. On the one hand, empirical models such as those by Page and Midilli can be correlated with process parameters—including infrared power, air velocity, loading density, and ambient humidity—to form parametric models suitable for engineering control. On the other hand, data from CFD, FEM, online moisture detection, and infrared thermal imaging should be integrated to link macroscopic changes in moisture content with local thermal responses, boundary layer conditions, and quality indicators.

This approach will not only enhance the models' ability to explain the drying process but also facilitate the development of predictive models for intelligent control [94–97].

6. CFD–FEM Multiphysics Simulation and Operating Condition Optimization Methods

As kelp drying equipment evolves from traditional hot-air systems toward infrared arrays, suspended conveyors, and intelligent control systems, relying solely on single-point temperature and humidity measurements or overall moisture content changes is no longer sufficient to comprehensively evaluate the drying process. In infrared drying, the temperature field, velocity field, radiation field, and thermal response of the material exhibit significant spatial variations. Particularly under continuous processing conditions for large-sized sheet kelp, factors such as localized radiation superposition, air recirculation, boundary layer humidity changes, and material shading can all affect drying uniformity. Consequently, CFD, FEM, and multi-objective data processing methods have gradually become essential tools for drying equipment design, process analysis, and operating condition selection. As shown in Figure 8, multiphysics simulations of infrared kelp drying typically include steps such as geometric modeling, CFD field reconstruction, extraction of field parameters, heat load mapping, FEM analysis of material thermal response, and MATLAB-based multi-objective operating condition screening. Specifically, Part 1 defines the drying-chamber geometry and operating parameters, Part 2 reconstructs the airflow and radiation fields through CFD, and Part 3 quantifies field uniformity and local extreme values. Part 4 maps the CFD-derived thermal loads to the kelp FEM model, while Part 5 evaluates the transient temperature response of the material. Part 6 applies MATLAB-based multi-objective screening to compare operating conditions, and Part 7 identifies the optimal condition and verifies it experimentally. The arrows indicate the sequential transfer of simulation results and evaluation data among these stages. Among these, CFD methods are primarily used to reconstruct the temperature field, velocity field, and incident radiation field within the drying chamber. By establishing geometric models of the drying chamber, infrared array, air inlets and outlets, and the material suspension area, it is possible to analyze heat distribution and airflow characteristics under different operating conditions. For infrared kelp drying systems, CFD simulations can not only identify differences in heat flux between the central and peripheral regions but also reveal non-ideal flow structures such as local low-velocity zones, recirculation zones, and short-circuiting. This information is crucial for optimizing the arrangement of infrared lamps, duct structures, and loading methods. Previous studies have shown that the temperature, velocity, and radiation fields within the kelp infrared drying chamber exhibit significant spatial non-uniformity, and the organization of the airflow field further influences local heat transfer and the temperature response of the material surface. After obtaining information on the thermal and flow fields on the chamber side, FEM can be further used to analyze the transient thermal response on the kelp material side. Specifically, the radiative heat flux, local air temperature, and convective heat transfer boundary conditions obtained from CFD calculations can be mapped onto the kelp finite element model to determine the temporal distribution of surface temperatures. This method addresses the limitation of pure CFD analysis, which struggles to reflect thermal responses within or on the surface of the material, thereby extending the scope of investigation from “equipment-side field distributions” to “material-side thermal behavior.” For sheet-shaped kelp, FEM analysis helps assess the risk of local overheating, surface temperature gradients, and temperature uniformity, and provides a basis for subsequent quality preservation and control of the drying endpoint [33,35,66–71,78,93].

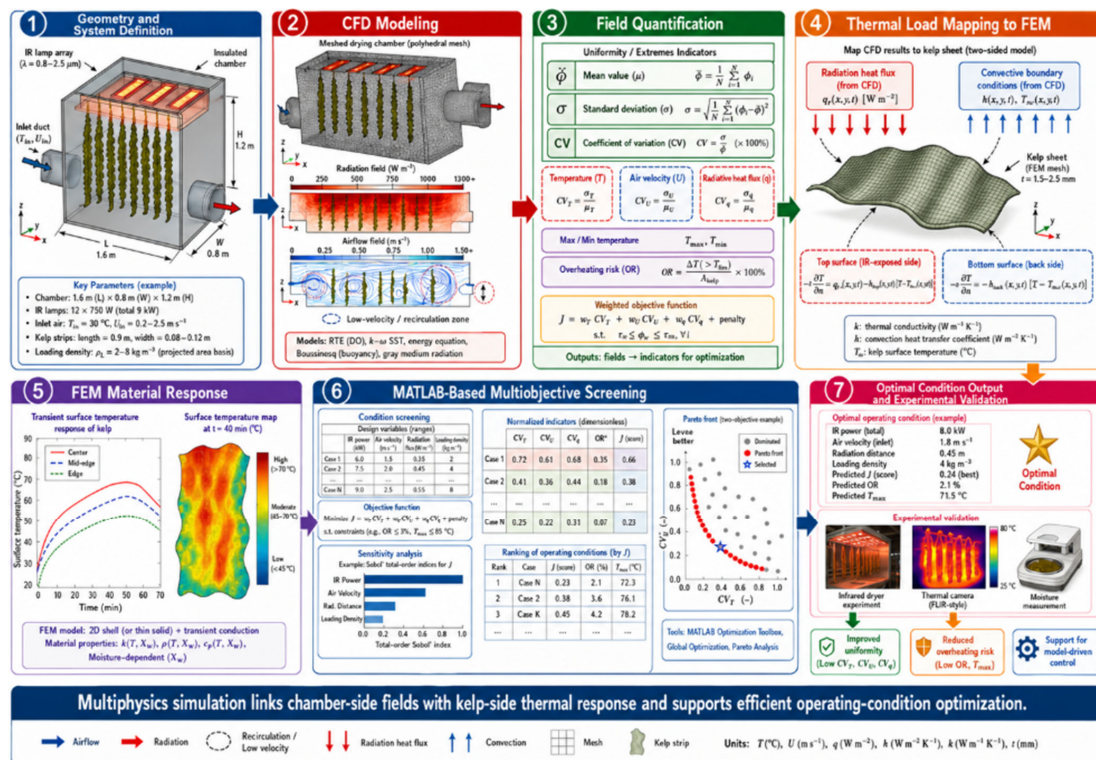


Figure 8. Flowchart of CFD–FEM–MATLAB multiphysics simulation and process optimization for infrared kelp drying.

The advantage of CFD–FEM coupled analysis lies in its ability to establish a link between the drying chamber and the material response. Standalone CFD simulations can describe airflow and radiant heat distribution, but it is difficult to directly determine whether localized overheating of the material has occurred; standalone FEM thermal analysis, on the other hand, relies on reasonable boundary conditions, and without information on the chamber’s side fields, the results may deviate from the actual drying environment [33,66–71,78]. Therefore, mapping the heat load obtained from CFD onto the FEM model allows for a more accurate characterization of the coupling relationship between the infrared array, airflow, and the thermal response of the kelp surface. Related studies have established an integrated CFD–FEM–MATLAB workflow for chamber field reconstruction, thermal load mapping, and operating condition screening in infrared kelp drying, providing a methodological reference for parameter optimization of intelligent drying equipment. In practical use, the three tools serve different functions. CFD is suitable for comparing infrared-array layouts, inlet and outlet positions, airflow rates, and chamber structures by examining temperature, velocity, and radiation distributions. FEM can then use the resulting local thermal boundary conditions to determine whether the selected chamber configuration causes excessive or non-uniform heating of the kelp. MATLAB or similar data-processing platforms can further compare the calculated indicators among different operating conditions and rank candidate combinations of infrared power, airflow, and boundary settings. Thus, these tools are more useful for narrowing the operating window and identifying unsuitable conditions than for directly determining a universal optimum drying condition. However, the level of model validation should be clearly distinguished. Conceptual models are mainly used to explain physical mechanisms; numerical CFD or FEM models predict field distributions under prescribed boundary conditions; experimentally validated models compare numerical outputs with measured temperature, airflow, radiation, or moisture data; and optimization models use these validated relationships to screen or regulate operating conditions. These levels should not be treated as equivalent. For the

reported kelp CFD–FEM–MATLAB study, the CFD model was checked through residual convergence and global mass conservation, and the reconstructed thermal loads were mapped onto the kelp FEM model for transient temperature analysis. The selected condition gave a composite objective value of $J = 0.4535$, with mean and maximum kelp surface temperatures of 62.23 and 63.57 °C, respectively. However, moisture migration and shrinkage were not fully coupled, and the experimental validation remained limited. Therefore, the current framework is more appropriate for thermal-field assessment and operating-condition screening than for direct prediction of complete drying time or product quality.

However, when comparing multiple operating conditions, evaluating a drying system based on a single metric alone is often insufficient. For example, a higher average temperature does not necessarily indicate better drying performance, as local overheating may lead to quality degradation; nor does a higher air velocity necessarily imply optimal mass transfer, as excessively strong airflow may impair temperature rise efficiency or result in energy loss. Therefore, factors such as temperature uniformity, radiation uniformity, velocity field uniformity, and safe temperature ranges must be incorporated into a comprehensive evaluation. A common approach involves extracting the mean, extreme values, standard deviation, and coefficient of variation for the temperature, velocity, and radiation fields, and further constructing a comprehensive objective function to rank and screen different operating conditions. As shown in Figure 9, Figure 9A presents the spatial distribution of the radiation field, Figure 9B illustrates the organization of the airflow field, Figure 9C shows differences in the thermal response and drying risk of the material, and Figure 9D evaluates operating conditions using indicators such as the coefficients of variation for temperature, velocity, and radiation, together with overheating risk. the optimization of operating conditions for infrared kelp drying should simultaneously consider the distribution of the radiation field, the organization of the airflow field, and differences in the thermal response of the material, and should be comprehensively evaluated using indicators such as the coefficient of variation for temperature, the coefficient of variation for velocity, the coefficient of variation for radiation, and the risk of overheating [84,85,98].

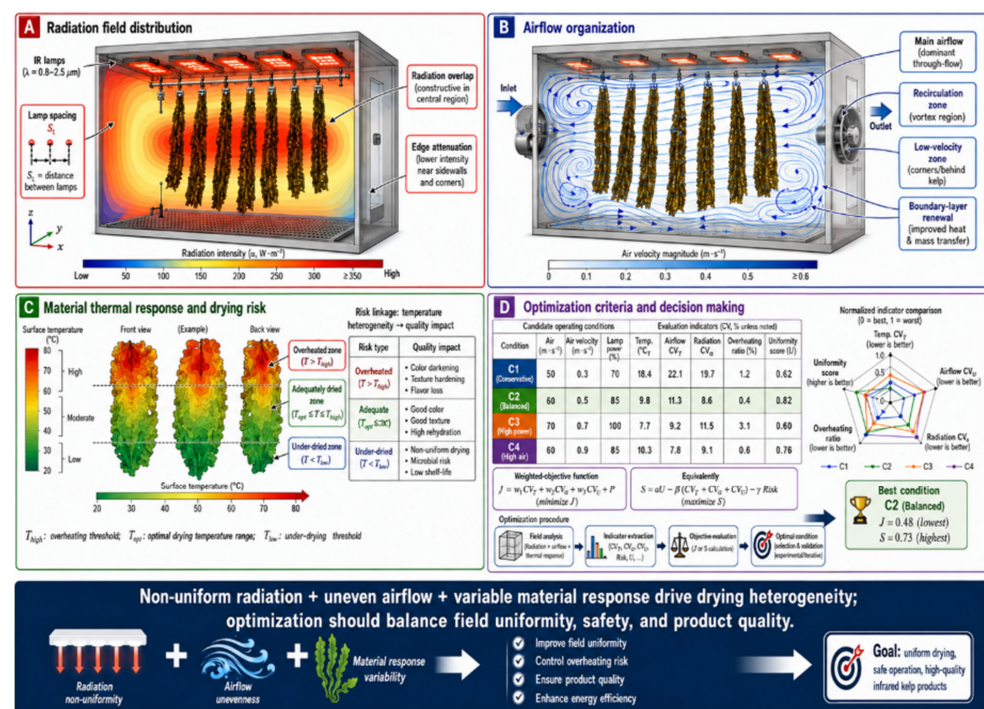


Figure 9. Analysis of field coupling and non-uniformity, and optimization evaluation criteria in infrared kelp drying.

7. Evaluation of Drying Quality and Quality Maintenance Mechanisms

Our research objectives for kelp drying are not limited to reducing moisture content; we must also preserve its color, rehydration capacity, structural integrity, and nutritional quality as much as possible while ensuring safe storage. Therefore, the evaluation of drying quality should be expanded from a single-endpoint assessment of moisture content to a comprehensive evaluation system that includes drying efficiency, appearance quality, structural recovery capacity, and nutritional retention. As shown in Figure 10, the evaluation of dried kelp quality can be conducted in terms of rehydration capacity, color, nutritional components, structural integrity, and quality risks. Among these, rehydration capacity reflects the ability to restore tissue structure; color difference is used to characterize the degree of appearance changes; the retention of nutritional components reflects the impact of the drying process on polysaccharides, proteins, minerals, and iodine; and structural integrity is closely related to cellular structure, pore state, and surface morphology. Process factors such as infrared power, air velocity, loading density, and drying endpoint collectively influence the aforementioned quality indicators [7,11,12,79–81,99–108]. Therefore, quality retention requires strategies such as uniform heating, appropriate air velocity, optimized loading, precise temperature control, and online monitoring. In infrared drying, rapid heating helps shorten dehydration time; however, uneven heat field distribution or localized overheating may lead to color darkening, tissue hardening, and reduced rehydration capacity. Color is one of the most intuitive quality indicators for dried kelp and is typically characterized by the total color difference value. Drying temperature, infrared power, and processing time all affect pigment stability and the degree of surface browning. Moderate infrared heating can reduce quality deterioration caused by prolonged exposure, but excessive radiation or localized heat accumulation may lead to darkening of color, thereby reducing product marketability [24–31,73]. Therefore, changes in color difference can serve as an important indicator for identifying localized overheating and quality deterioration. Additionally, rehydration capacity reflects the ability of kelp tissue structure to recover after drying and is closely related to cellular structural integrity, pore condition, and the degree of surface hardening. Generally, milder and more uniform drying conditions help maintain tissue elasticity and rehydration capacity, whereas excessive drying or localized high temperatures may damage cellular structures, leading to a decrease in rehydration rates. For sheet-shaped kelp, differences in heat exposure between the edge and center regions may also result in inconsistent local rehydration capacity; therefore, rehydration rates should be analyzed in conjunction with temperature field uniformity and the determination of the drying endpoint. Furthermore, the retention of nutritional components is a crucial aspect of evaluating the quality of kelp drying. Kelp contains polysaccharides, minerals, iodine, and various bioactive compounds, all of which may be affected by temperature, oxidative conditions, and drying duration. Longer drying cycles may increase the risk of oxidation and nutrient loss, while excessively high temperatures may destroy heat-sensitive components. Therefore, an ideal drying process should balance dehydration efficiency with nutrient retention by reducing water activity while controlling the intensity of thermal exposure [3,37,42,51–53,90]. From a quality control perspective, the quality of dried kelp is jointly influenced by infrared power, air velocity, loading method, hanging spacing, and the drying endpoint. Infrared power determines the intensity of heat input, air velocity affects water vapor removal and boundary layer renewal, and loading density influences material shading and local ventilation conditions. If the sole objective is to minimize drying time, color and rehydration capacity may be compromised; conversely, an excessive focus on low-temperature, gentle drying may reduce processing efficiency and increase energy consumption. Therefore, quality preservation should be based on a multi-objective trade-off, taking into account drying rate, energy consumption, color difference, rehydration rate,

and the risk of localized overheating simultaneously. Accordingly, the optimal operating condition should not be defined by the minimum drying time alone. A more practical evaluation should simultaneously minimize drying time and energy consumption while limiting color change and moisture non-uniformity and maintaining a high rehydration capacity. Because these objectives may conflict with one another, multi-objective methods can be used to identify a set of acceptable trade-off solutions rather than a single universal optimum. The final operating point can then be selected according to product quality requirements, production capacity, and energy cost.

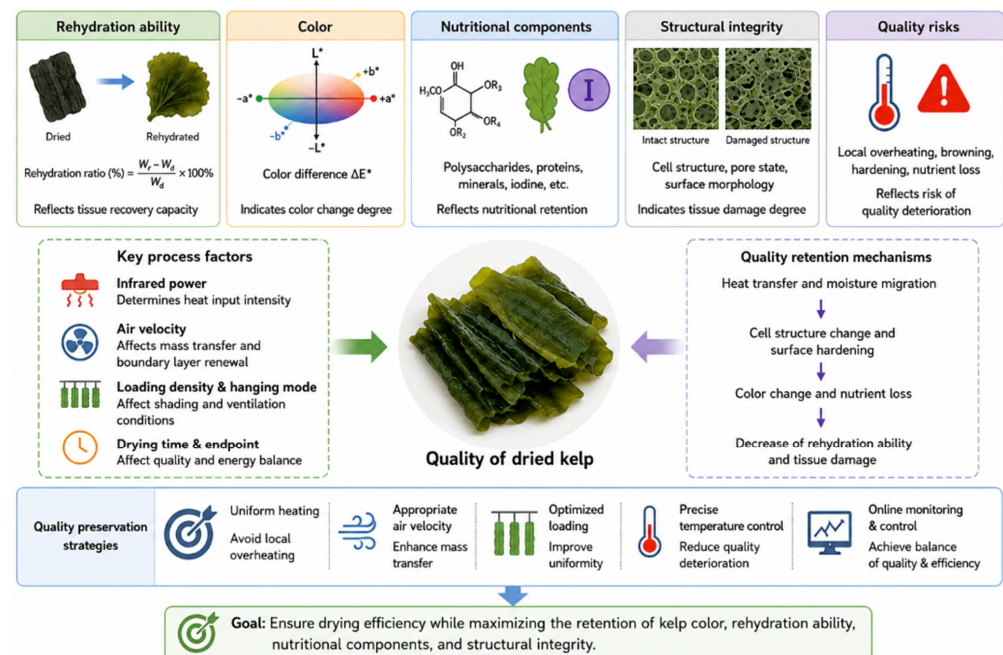


Figure 10. Schematic diagram of quality evaluation indicators and quality retention mechanisms for dried kelp.

In the future, the evaluation of kelp drying quality should be further integrated with online monitoring and model analysis. On the one hand, process information can be obtained through infrared thermal imaging, multi-point temperature and humidity sensing, and online moisture detection; on the other hand, quality indicators can be linked with kinetic models, CFD–FEM thermal response analysis, and multi-objective optimization methods to establish control models for quality prediction. This will enable the determination of the drying endpoint to shift from empirical judgment to data-driven decision-making, and provide support for the standardization and intelligent development of kelp drying equipment [82,83,109–111].

8. Intelligent Monitoring, Model-Driven Control, and Evaluation of Industrial Applications

In this review, “intelligent drying” does not simply refer to the use of sensors, network communication, or a remote monitoring interface. Different levels of process control should be distinguished. Automation executes a predefined drying program; remote monitoring only provides process information; threshold control adjusts equipment when measured variables exceed preset limits; closed-loop control continuously modifies operating variables according to feedback; model-based control uses kinetic or numerical models to predict the process state; adaptive or artificial-intelligence-assisted control updates decisions according to changes in material or operating conditions; and a digital twin further links real-time measurements with a continuously updated virtual model for prediction

and optimization. As kelp drying equipment evolves toward continuous and intelligent operation, drying process control is no longer limited to fixed temperatures, fixed times, and manual judgment based on experience. Due to kelp's characteristics—such as high initial moisture content, uneven sheet structure, and significant batch-to-batch variations—issues such as localized overheating, stagnant moist air, and inconsistent drying endpoints often arise during the actual drying process. Therefore, intelligent monitoring and model-driven control have become key approaches for improving drying stability and product consistency. The foundation of intelligent monitoring lies in the real-time sensing of key drying process parameters. By deploying sensors for temperature, humidity, infrared thermal imaging, air velocity, and equipment operating status, information regarding changes in the thermal and humidity environment within the drying chamber and the state of the material can be obtained. Compared to single-point measurements, multi-point monitoring is more suitable for infrared array drying systems, as such systems typically exhibit spatial variations in radiation fields, airflow fields, and temperature fields [32,34,65,82,83,92,94–97,109–113]. Data transmission via 5G communication and cloud platforms enables remote monitoring, anomaly alerts, and batch data traceability, thereby supporting equipment management and process optimization in continuous production. In terms of control methods, current intelligent kelp drying systems primarily employ threshold control, which involves setting safe ranges for temperature, humidity, or drying endpoints and maintaining process stability by adjusting infrared power, air velocity, and operating time. This method is simple to implement and is suitable for the initial application of intelligent drying equipment. However, due to variations in thickness, moisture content, loading density, and morphology among different batches of kelp, relying solely on fixed thresholds makes it difficult to adapt to complex operating conditions. A more effective approach in the future will be to integrate drying kinetics models, multiphysics simulations, and online monitoring data to form a closed-loop control system comprising “data acquisition–state assessment–model prediction–parameter adjustment.”

In addition, model-driven control provides a basis for more precise parameter optimization in kelp drying. Kinetic models can predict changes in moisture content and the drying endpoint; CFD–FEM models can be used to identify local thermal field irregularities and the risk of overheating; and data processing methods such as MATLAB can be used to filter and rank results under various operating conditions. When these models are integrated with real-time sensor data, the system can dynamically adjust infrared power, air velocity, and drying time based on the state of different batches of material, thereby reducing reliance on manual experience and improving drying efficiency and product quality consistency [62–64,91,92,94–97,110,111,114,115]. Therefore, in addition to process control, energy consumption and economic viability are also critical considerations for the industrial application of kelp drying equipment. Although infrared drying offers advantages such as rapid heating and short drying cycles, it may result in localized energy waste without proper power regulation and airflow organization. Methods such as heat pumps, waste heat recovery, and staged power control can be employed to reduce energy consumption per unit of moisture removal; simultaneously, equipment investment, maintenance costs, capacity enhancement, and labor savings should also be incorporated into a comprehensive evaluation. For industrial applications, the value of drying equipment lies not only in shortening drying time but also in improving batch consistency, reducing reliance on manual labor, and enhancing product quality uniformity.

Overall, the industrial development of intelligent kelp drying must simultaneously address process monitoring, model-based control, energy consumption optimization, and economic feasibility. Future research should further strengthen pilot-scale validation, establish a comprehensive evaluation system that integrates energy consumption per unit,

production capacity, quality indicators, and operating costs, and promote the transition of drying equipment from laboratory prototypes to continuous, standardized, and replicable industrial systems [40,54,56–61,65,74,78,84,85,93,112–115].

9. Current Challenges and Future Directions

Although infrared drying, multiphysics simulation, and intelligent control technologies have opened new avenues for the efficient processing of kelp, existing research still falls short of stable industrial applications. First, the heat-mass coupling mechanisms during the kelp drying process have not yet been fully elucidated. Existing models primarily focus on temperature fields, velocity fields, or changes in moisture content, with insufficient consideration of the interactions between moisture migration, tissue shrinkage, changes in physical properties, and quality evolution. For sheet-like, flexible kelp, curling, thickness variations, and local shading during drying can adversely affect the distribution of thermal and flow fields; therefore, future research requires the development of coupled thermal–humidity–mass–deformation models that more closely mimic actual processing conditions. Second, spatial uniformity in infrared drying systems remains a key issue affecting quality stability. Infrared arrays tend to cause disparities in heat input between central and peripheral regions, while improper airflow organization may create low-velocity zones and localized recirculation areas. Future equipment design should further enhance the coordinated optimization of infrared array layout, air duct structure, and loading methods, and achieve full-field monitoring through infrared thermal imaging, multi-point temperature and humidity sensing, and online moisture detection. Third, intelligent control still needs to transition from threshold-based regulation to model-driven and quality-feedback approaches. Currently, most intelligent drying systems primarily support remote monitoring, alarms, and simple parameter adjustments, and have not yet truly formed a closed-loop system capable of automatically adjusting process parameters based on material conditions. In the future, drying kinetics models, CFD–FEM simulations, machine learning, and digital twin technologies can be integrated to establish control models capable of predicting drying endpoints, energy consumption, and quality variations. The choice of data-driven model should depend on the type and amount of available process data. Artificial neural networks (ANNs), support vector regression (SVR), random forests (RFs), and gradient-boosting models such as XGBoost can be used for nonlinear relationships between operating parameters and drying time, energy consumption, or quality indices. Long short-term memory (LSTM) networks are more suitable when continuous time-series data from temperature, humidity, mass, or moisture sensors are available. Physics-informed neural networks (PINNs) provide another possible route when experimental data are limited but heat and mass transfer equations are available as physical constraints. These models can be implemented together with MATLAB R2025b or Python 3.13-based data-processing and optimization routines. However, their usefulness depends on representative training data and independent validation, and a higher model complexity does not necessarily provide better process control. The functions of these methods should be defined more specifically. Machine-learning models can be trained to estimate the drying endpoint from temperature, humidity, moisture, mass, or image data; predict energy consumption from process and equipment variables; estimate color, rehydration, or other quality indicators; and identify abnormal thermal patterns associated with heater, fan, or sensor faults. These models can also be used as surrogate models for rapid operating-condition optimization. A digital twin extends this approach by continuously updating a virtual representation of the dryer with real-time sensor data, allowing the predicted process state to be compared with the actual system and used for parameter adjustment, fault diagnosis, and operating-condition optimization. Finally, energy efficiency and pilot-scale validation of continuous operations

remain critical constraints to industrialization. Optimal operating conditions obtained under laboratory conditions may not necessarily be applicable to long-term continuous production. Follow-up research should further conduct pilot-scale validation under different seasons, batches, and loading densities, and establish a comprehensive evaluation system that integrates energy consumption per unit, production capacity, equipment investment, maintenance costs, and product quality. Only by achieving a balance among technical feasibility, economic rationality, and operational stability can intelligent kelp drying equipment truly be scaled up for widespread adoption. Scale-up also changes the spatial conditions of infrared drying. As the drying chamber and material load increase, maintaining uniform radiation coverage and airflow becomes more difficult, while blade overlap and local vapor accumulation become more pronounced. Variations in initial moisture content, blade thickness, orientation, and loading density can further increase batch-to-batch differences. In continuous systems, automated loading and unloading must also maintain a stable material spacing because changes in blade position directly affect both radiation exposure and airflow. In addition, long-term operation requires regular calibration and maintenance of temperature, humidity, infrared, and airflow sensors. Therefore, pilot-scale evaluation should include not only drying time and product quality but also radiation and airflow uniformity, loading consistency, sensor stability, equipment reliability, energy consumption, and maintenance requirements [65,78,93,112,113,115].

10. Limitations of This Review

Several limitations should be considered when interpreting this review. First, although multiple literature sources are included, complete coverage of all databases, languages, and industrial reports cannot be guaranteed. Second, kelp-specific studies remain fewer than studies on general food and agricultural-product drying; therefore, some heat and mass transfer mechanisms discussed in this review are based on related high-moisture biological materials and require further validation for kelp. Third, direct comparisons among published studies are limited by differences in kelp species, sample thickness, loading method, initial moisture content, drying endpoint, equipment geometry, and operating conditions. Finally, many studies involving CFD–FEM coupling, intelligent control, machine learning, and digital twins remain at the numerical, laboratory, or prototype stage. These differences should be considered when transferring reported operating conditions to industrial kelp drying [5,6,8–10,66–72].

11. Conclusions

Kelp drying has gradually developed from natural sun-drying and conventional hot-air drying toward more controllable heat-pump, infrared, and combined drying processes. At present, hot-air and heat-pump drying are relatively mature in terms of temperature and humidity regulation, while infrared-assisted airflow drying provides a faster heat input and can improve moisture removal when radiation and airflow are properly matched. Multi-point temperature and humidity sensing, infrared monitoring, and remote data transmission can also be incorporated into existing drying equipment without major changes to the basic drying process. The main problems at this stage are drying uniformity, energy consumption, material overlap, and batch-to-batch differences.

CFD, FEM, and model-based operating-condition analysis are useful for further improving equipment design and process control. CFD can identify non-uniform airflow, temperature, and radiation fields in the drying chamber, while FEM can be used to evaluate the corresponding thermal response of kelp. However, the existing kelp studies are still mainly focused on thermal-field reconstruction and operating-condition comparison. Moisture migration, tissue shrinkage, and long-term experimental validation have not yet been

fully incorporated into these models. Therefore, CFD–FEM coupling and model-based control should currently be regarded as supporting tools for equipment optimization rather than as fully validated predictors of drying time and product quality.

Further development is likely to focus on coupled heat and moisture transfer, deformation of flexible kelp sheets, adaptive control, and digital-twin-based process management. For these approaches to move beyond laboratory studies, models need to be validated against surface temperature, moisture content, energy consumption, rehydration, color, and other quality measurements under different loading densities and production batches. Pilot-scale tests should also consider sensor calibration, automated loading and unloading, equipment maintenance, and operating cost. Thus, future intelligent kelp drying should be evaluated not only by shorter drying time, but by whether drying efficiency, product quality, energy use, and process stability can be maintained simultaneously under continuous production conditions.

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