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Mechanisms and Process Optimization for Traditional Freeze-Air-Drying of Pollock (Mentaiko)

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ABSTRACT

Global climate change poses significant challenges to the production of dried Pollock—a traditional delicacy of China's Korean & Manchu ethnic minority. The traditional sun-drying process relies on specific temperature, humidity, and ventilation conditions; however, changes in these environmental factors threaten this valuable cultural heritage. This study systematically analyzes the physical and biochemical mechanisms involved in the drying process, focusing on the effects of temperature, humidity, illumination, and microbial activity. Based on our findings, we propose an artificial environmental scheme to partially replace the increasingly unsuitable natural conditions, thereby ensuring the quality of dried Pollock and the preservation of traditional techniques. By optimizing the traditional process, this work offers innovative solutions to mitigate the impact of climate change on the culinary culture of China's Korean & Manchu ethnic minority.

Introduction

Pollock (Gadus chalcogrammus, also known as Mentaiko), a cold-water marine fish found in the northern Pacific Ocean, holds significant cultural and dietary importance for the Korean & Manchu ethnic group in China(*1, 2*). Since the 1980s, when the pollock processing industry began flourishing in the Yanbian Korean Autonomous Prefecture, freeze-air-dried pollock has become a signature specialty of the region. Each winter, residents of Yanbian set up wooden frames in their yards to dry pollock. This practice reflects their reliance on and wise use of the natural environment and showcases the preservation of their culinary traditions. Over time, dried pollock has evolved from a daily food item to an essential part of festivals and gifts, enhancing its cultural and economic value(*3*).

Freeze-air-drying pollock is a complex process involving physical, chemical, and biological changes (*4*). Repeated freezing and thawing cycles break cell and tissue structures, accelerating moisture evaporation. Under cold temperatures during the process, proteins slowly oxidize and break down into amino acids over time, imparting a unique flavor and reducing the fishy odor. (*5*). Additionally, low temperatures, dryness, ventilation, and ultraviolet rays from sunlight inhibit the growth of bacteria and molds, preventing spoilage during drying(*6, 7*). The traditional method utilizes the natural environment in cold winters for drying pollock, resulting in reactions different from those in high-temperature drying methods used in southern coastal areas (*4*). Consequently, the dried pollock produced in Yanbian offers unique advantages in texture, flavor, with almost no unpleasant fishy smell.

According to traditional practices, drying pollock demands strict environmental conditions, including large variation in temperature, low humidity, ventilation, and adequate sunlight. The optimal conditions involve sub-freezing temperatures and dry environments that allow moisture to evaporate gradually without hardening the meat. The freeze-air-drying process utilizes daily cycles of freezing at night and thawing during the day, but daytime temperatures must remain low enough to inhibit bacterial growth (*8*). Dry, clean air with sufficient sunlight are also essential to inhibit microbial activity. The unique geographical features of the Yanbian region—surrounded by the Changbai Mountains, characterized by fresh, unpolluted air and significant day-night temperature variations—provide an ideal environment for the traditional natural freeze-air-drying pollock (*9*) (*10*).

However, global climate change has posed new challenges to this tradition in Yanbian (*11, 12*). As average temperatures rise annually—as shown in Figure 1(a)—the optimal time window (marked by green shadow) for drying pollock is gradually shortening, making it difficult to ensure high-quality production using traditional methods(*13*). Furthermore, climate warming increases temperature instability during the drying process, leading to unpleasant odors that affect product quality. Although modern drying techniques can produce dried pollock efficiently, these products often have a harder texture and lack the distinctive taste of fish dried using traditional methods(*14*).

To address these challenges and preserve this valuable tradition, it is essential to study the physical, chemical, and biological changes that occur during freeze-air-drying process. By identifying key influencing factors and designing optimized artificial environments that mimic natural conditions, we seek to ensure the continuous production of high-quality dried pollock, preserving both its cultural significance and meeting modern demands.

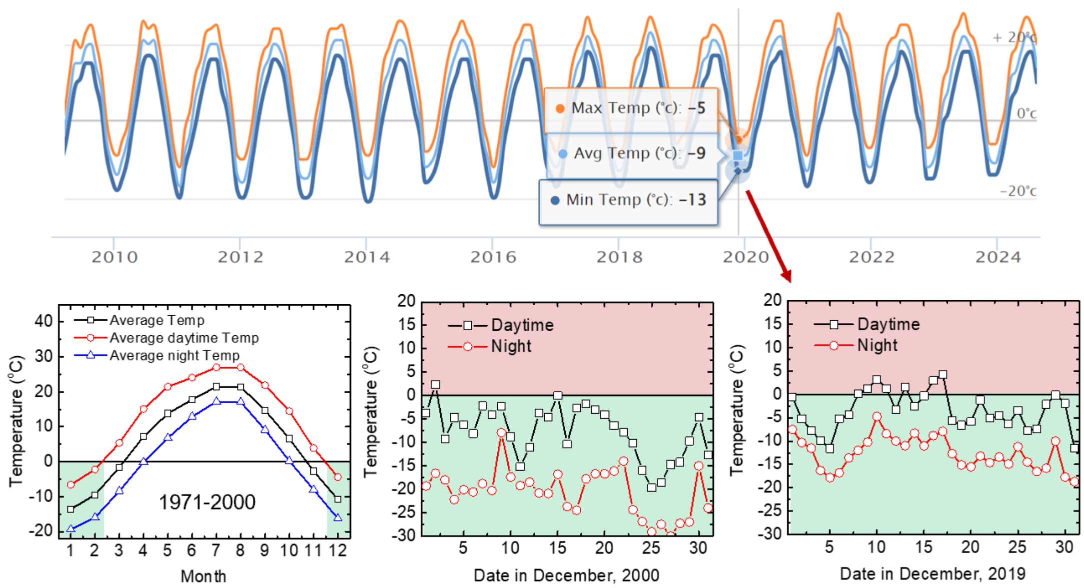

Figure 1. (a) Monthly averaged maximum, minimum and average temperatures for the months from 2009 to 2024. (b) The monthly temperatures variation averaged from 1971 to 2000. The daytime highest temperature and night lowest temperature for the December in (d) 2000 and (d) 2019.

Results and Discussion

Controlling temperature is crucial to ensuring the quality of dried pollock. Figure 1(b) shows the monthly average daytime and nighttime temperatures from January to December between 1971 and 2000 [13]. Interviews with factory managers and technicians at pollock processing plants in the Yanbian region (Yanbian Hualong Marine Products Co., Ltd.) revealed that the optimal time for drying pollock is from mid-November to next March. During this period, the average daily high temperature is close to 0 °C, and the average nighttime low may drop below -15 °C. For example, in December 2000 (see Figure 1(c)), although daily temperatures fluctuate, only one day's daytime high exceeds 0 °C, with the rest remaining below freezing. Such temperature variations are crucial for drying pollock. We will analyze the effects of temperature from both physical and biological perspectives.

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Physical Changes During Freeze-Air-Drying Process

After cleaning, evisceration, and brining, pollock are hung at elevated locations for drying. Winter's low temperatures cause the moisture inside the fish to freeze rapidly. As water-containing cells and tissues expand upon freezing, cell structures are damaged, softening the firm flesh. By midday, when ambient temperatures approach 0 °C and sunlight warms the fish surface above ambient temperature, the ice crystals within the fish begin to melt due to the lower freezing point in the slightly saline environment. Sunlight and ventilation promote moisture evaporation. Repeated cycles of freezing, melting, evaporation, and refreezing further damage tissue structures, accelerating moisture loss and resulting in a softer texture and superior mouthfeel. This low-temperature dehydration is a remarkable natural process.

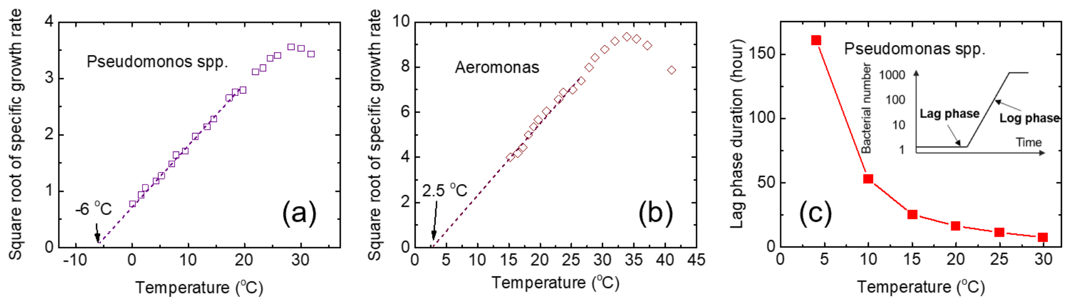

Figure 2. The specific growth rate of (a) *Psedomonos* spp. and (b) *aeromonas* as a function of temperature.(*15*) The dashed lines extrapolate the critical temperatures where bacterial stops grow. (c) Dependence of lag phase duration on temperature.(*16*) The inset illustrates the lag phase and log phase growth regions at a certain temperature.

In exceptionally cold winters, when daytime temperatures remain well below 0 °C, dried pollock can still be produced over an extended drying period. However, the fish tends to have a harder texture, making it less suitable for direct consumption and more appropriate for soups. In recent years, as shown in Figure 1(a), average temperatures since 2010 have been rising, increasing the likelihood of warmer winters (*17*). Figure 1(d) illustrates that in December 2019, daytime highs exceeded 0 °C for several consecutive days, reaching nearly 5 °C. While higher temperatures can promote moisture loss and softening the flesh, prolonged periods above 0 °C can activate microbial activities, leading to spoilage and mold growth (*15*).

Biochemical Changes During Freeze-Air-Drying Process

Fish are highly susceptible to spoilage due to aquatic microorganisms. Sparse connective tissues segment fish muscle into small groups, providing easy pathways for bacterial infiltration. As a marine fish, pollock is exposed to numerous psychrophilic microorganisms present in the ocean. Even after evisceration and low-temperature storage, microbial proliferation is only slowed(*18*). Once temperatures become favorable, these microorganisms reproduce rapidly, leading to spoilage. Primary spoilage bacteria such as *Pseudomonas* spp. and *Aeromonas* spp. decompose tissues, producing compounds like indole, thiols, ammonia, hydrogen sulfide, and skatole, resulting in unpleasant odors in dried pollock (*19, 20*).

Figures 2(a) and 2(b) show early experimental data on the growth rates of *Pseudomonas* spp. and *Aeromonas* spp. at different temperatures(*15, 21*). *Pseudomonas* spp. exhibit significant variations in growth rates, peaking around 30 °C and decreasing as temperatures drop; they are psychrotolerant, growing even at 0 °C and ceasing growth around -6 °C. In contrast, *Aeromonas* spp. have an optimal growth temperature of approximately 35 °C, with activity diminishing at lower temperatures and stopping around 2.5 °C. Clearly, these microorganisms can proliferate even in refrigerated environments at 4 °C, leading to spoilage.

Besides temperature, humidity and oxygen levels also influence microbial growth. During the initial stages of drying, the high moisture content makes pollock particularly prone to spoilage if ambient temperatures exceed bacterial activity thresholds. Physically, drying requires ambient temperatures near 0 °C to melt ice crystals and promote moisture evaporation. Conversely, to prevent spoilage, temperatures need to remain below -6 °C. Although this seems contradictory, the characteristics of microbial activity allow us to balance the physical and biochemical processes.

Balance Between Physical and Biochemical Processes

At 0 °C, although *Pseudomonas* spp. reach their active threshold temperature, population doesn't surge immediately due to a lag phase (*16, 18*). During this period, microorganisms need time to adjust their structures to adapt to the environmental changes before exponential growth. The lag phase duration is temperature-dependent—the lower the temperature, the longer the lag phase. As shown in Figure 2(c), at 0–5 °C, *Pseudomonas* spp. remain active but have a lag phase exceeding 100 hours. However, even during this time, bacterial numbers gradually increase, and importantly, they secrete enzymes like proteases and lipases, which degrade proteins and fats, leading to softened textures and off-flavors. To keep fish fresh, the safe storage time at 0–5 °C should be approximately 10 hours, significantly less than the lag phase. Consequently, maintaining the fish temperature around 0–5 °C for up to 10 hours ensures both effective dehydration and biological safety. It is important to note that due to solar radiation, the fish temperature can be about 5 °C higher than the ambient temperature. Therefore, the optimal daytime ambient temperature should be near 0 °C.

The above analysis demonstrates that the suitable conditions for winter drying of pollock are very narrow. If temperatures are too low, moisture does not evaporate easily, and the flesh remains hard. If temperatures exceed bacterial activity thresholds, spoilage occurs. The drying process requires a delicate balance, reflecting both natural conditions and traditional wisdom.

Development Of a Controlled Freeze-Air-Drying System

We recognized that the optimal temperature and time window for drying pollock are extremely narrow. Traditional methods limit production to just over three-4 months each year. With the growing popularity of Korean & Manchu ethnic cuisine, demand for this traditional delicacy has increased significantly. At the same time, global warming has led to more frequent warm winters; even the Yanbian region, shielded by the Changbai Mountains, cannot fully resist the intrusion of warm air masses. A severe consequence of warm winters has intensified temperature fluctuations, increasing the probability of consecutive days with high daytime temperatures. Under these conditions, naturally dried pollock is not only in short supply but also faces declining quality, with batches potentially spoiling and causing significant economic losses.

System Design and Operation Temperature

Through factory visits and analysis of the physical changes and biochemical reactions during the drying process, we identified the key parameters for producing high-quality dried pollock. Based on these findings, we designed and constructed a small-scale drying device capable of controlling temperature, humidity, airflow, and light exposure while inhibiting microbial growth.

Figure 3(a) illustrates a schematic diagram of the system. The apparatus includes a transparent low-temperature chamber with automatic temperature control, a UV lamp, an incandescent lamp, surrounding and fish body temperature sensors, and a fan. The chamber's minimum temperature can be reduced to below -25 °C, matching Yanbian's extreme winter lows. The UV lamp simulates the ultraviolet radiation under clear northern winter skies, promoting beneficial oxidation and fermentation while generating ozone to inhibit microbial growth. A fan directs airflow onto the fish surface, enhancing moisture evaporation. Two temperature sensors monitor the ambient temperature in the chamber and the fish body temperature, ensuring accurate control throughout the drying process.

Figures 3(b) and 3(c) display the set temperature cycles and the UV lamp's switching schedule, respectively. Experimental tests found that the fish temperature under illumination is about 5–7 °C higher than the chamber's set temperature. Therefore, we set the chamber's thawing temperature to -2 °C and the deep-freezing temperature to -22 °C, lasting 10 hours and 5 hours, respectively. The corresponding fish temperatures are 3–5 °C and -19 – -17 °C, respectively. The 10-hour thawing period fully utilizes the biological safety window, preventing bacterial proliferation while promoting drying under air circulation. Further, we activate the UV lamp for the first and last 15 minutes of the thawing period to sterilize and inhibit bacterial growth.

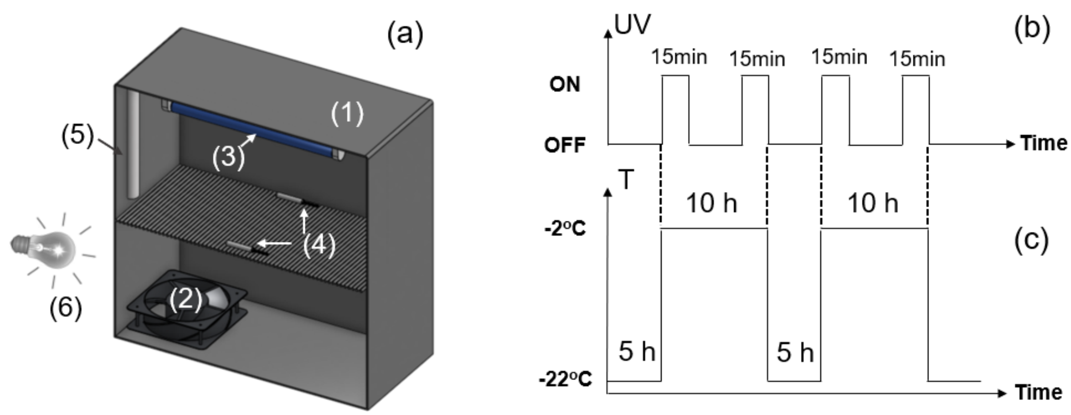

Figure 3. (a) Schematic diagram of the freeze-drying cooler: (1) Temperature-controlled cooler; (2) Fan; (3) UV lamp; (4) Temperature sensors; (5) LED; (6) Incandescent lamp. (b) Cycles of UV illumination and the cooler's set temperatures.

Implementation and Results

Figure 4(a) shows the actual system we constructed. We modified an ice cream storage cabinet with a temperature range from +5 °C to -30 °C, covering the winter day-night variations in Yanbian. To simulate sunlight, we replaced the freezer door with a transparent double-layer insulated glass door, ensuring insulation while allowing transmission of near-infrared to near-ultraviolet wavelengths. A 100 W incandescent lamp simulates visible and near-infrared light, while a 15 W quartz UV lamp emits ultraviolet light down to 253.7 nm for sterilization.

To reduce humidity, we employed two methods. First, we placed moisture-absorbing desiccants inside the freezer, which, although less effective at low temperatures, contributed to slight humidity reduction. Second, we created a temperature gradient inside the freezer by relocating the refrigeration unit's temperature sensor (T sensor3 in Figure 4(a)) and positioning the fish near the cabinet door. Irradiation by the incandescent lamp further increases the temperature gradient between fish and the inner part of the freezer. Such gradient causes water vapor from the warmer fish area to migrate toward colder zones and condense, reducing humidity around the fish. The fan further promotes moisture diffusion from the fish to the low-temperature zone.

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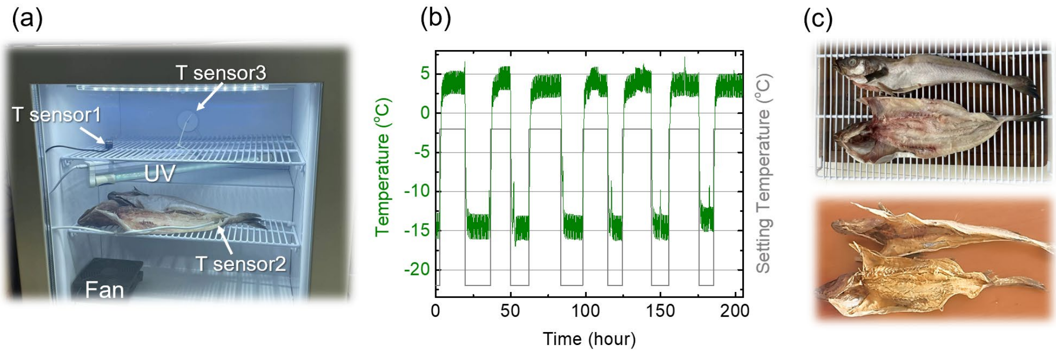

Figure 4. (a) Custom-designed freeze-drying system. T sensors 1-3 monitor the temperatures of environment, fish, and the heat-exchange wall. UV lamp is placed on top of fish, and fan is set at the bottom. (c) Measured temperature on fish (left) and the setting temperature of the cooler (right). (c) Upper and lower panels depict the freshly cleaned fish and freeze-air-dried fish.

Figure 4(c) (upper image) shows the fresh pollock we processed. Following traditional methods, we removed the gills and viscera, cleaned the fish thoroughly, and applied only salt to the surface. One fish had the bones removed, yielding softer meat suitable for direct consumption, while the other retained the bones. Figure 4(b) presents 200 hours of temperature data recorded during the experiment. The set temperature cycled between -22 °C and -2 °C, causing the fish to undergo deep-freezing and thawing phases. During the freezing phase, moisture inside the fish froze completely after about 2 hours. When switching to the thawing phase, the fish temperature gradually increased, stabilizing between 2–5 °C, and the ice began to melt. The warm phase lasted for 10 hours, fully utilizing the biological safety window and accelerating moisture evaporation. We activated the UV lamp for sterilization at the beginning and end of this phase.

Under controlled temperature, humidity, light exposure, and microbial conditions, we successfully produced dried pollock after approximately 14 days of cycles of freezing, thawing, drying, sterilization, and refreezing. The final product, shown in **Figure 4(c)** (lower image), closely resembles traditionally air-dried pollock in appearance, texture, and taste. This indicates that we successfully simulated the traditional drying process.

Evaluation and Potential Improvements

Comparative analysis shows that the dried pollock produced in our controlled environment matches the quality of traditionally dried products and offers improvements in some aspects. The fish meat's structure is well preserved, resulting in a moderately soft texture preferred by consumers. The flavor is pure, retaining the unique aroma without excessive fishy smell or off-flavors, due to precise control of conditions and effective microbial inhibition. Strict microbial control also enhances hygiene and safety.

However, some shortcomings exist. First, the chamber's humidity at 0 °C is ~50%, higher than Yanbian's natural winter humidity. Improving dehumidification by increasing the temperature gradient and better sealing of the freezer's door to prevent external moisture ingress is necessary. A drier environment would accelerate drying. Second, the equipment consumes significant energy because our experiments were conducted in Shanghai, where the average temperature is about 25 °C, requiring continuous cooling. In northern regions during winter, natural cooling in winter certainly reduces energy costs. Third, the dried fish's aroma is slightly less intense compared to high-quality, traditionally dried products. Further optimizing biochemical reactions—such as adjusting light exposure to promote Maillard reactions and controlling fat oxidation—could enhance flavor.

Based on our results, this controlled drying process bears significant potential for large-scale production. Constructing large cold storage facilities and drying pollock in batches can significantly shorten production cycles. By optimizing temperature, humidity, light exposure, and microbial control, stable, year-round production of high-quality dried pollock is achievable. Our effort could revitalize the pollock industry, meet growing market demand, and promote the preservation and development of traditional Korean & Manchu cuisine.

Conclusion

Global climate change is rapidly affecting both human societies and traditional cultures. The production of dried pollock—a cherished delicacy among China's Korean & Manchu ethnic minority—is highly dependent on specific natural environmental conditions. As the climate warms, traditional air-drying methods face increasing challenges, threatening the quality and availability of dried pollock. This study thoroughly analyzed the physical, chemical, and biological changes that occur during the drying process of pollock. We identified key parameters essential for producing high-quality dried pollock and developed a controllable artificial drying environment that mimics traditional conditions.

Our findings present a viable solution to mitigate the impact of climate change on traditional food production. While the use of artificial drying environments modifies traditional methods, it does not diminish the cultural significance of dried pollock. Instead, it effectively preserves this traditional practice against environmental fluctuations. By integrating modern technology with traditional techniques, we enhance production efficiency and product quality, meeting the growing market demand. Additionally, this approach provides new opportunities for promoting Korean & Manchu ethnic culture on an international scale.

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