Post-Harvest Grain Drying Technologies

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1. Background

Post-harvest grain processes cover those from harvest to the final sale, which includes harvesting, drying, storage, processing, logistics, and sales. According to incomplete statistics from the FAO, grain losses due to various reasons are extremely severe each year, including quantitative losses, quality degradation, food grains being converted to animal feed, and nutrient depletion. The post-harvest grain losses vary significantly across different countries. Currently, post-harvest grain losses not only exacerbate the number of people suffering from global hunger, but also contribute to issues of nutritional imbalance in populations. This not only affects global food security, but will also impact global economic development and political stability.

Harvesting is the first and most crucial step in ensuring grain quality. For instance, the timing of the harvest in the grain harvesting process, which primarily relies on mechanized harvesting, can impact the maturity and quality of the grains. The selection and precise control parameters of the harvesting machinery will also affect the quantity and quality of the harvested grains. The grain drying process effectively connects the grain harvesting with subsequent processes such as processing, logistics, and storage. This process serves as a quality guarantee for various post-harvest grain processes, and therefore, proper post-harvest grain drying is of utmost importance.

There are two ways to dry grains. One is the traditional natural drying, which is mainly limited by factors like drying location and weather conditions. The other is mechanical drying, which has problems like high energy consumption, heavy environmental pollution, and inconsistent drying quality.

2. Post-Harvest Cleaning and Drying Technologies for Three Major Staple Grains

2.1 Natural Drying

The harvested grains can be dried using the traditional natural drying method. This traditional method first requires selecting a clean, tidy, and well-ventilated drying location, then drying based on suitable weather conditions. During the drying process, manual periodic turning is necessary to prevent inconsistent quality caused by one side being over-exposed while the other side remains under-exposed. Natural drying offers advantages like zero mechanical input costs and uniform drying quality, but it's heavily constrained by location and weather conditions, involving time-consuming and labor-intensive processes with low efficiency. This method is best suited for smallholder farmers in medium to high-temperature drying regions with low production volumes.

2.2 Mechanical Drying

2.2.1 Post-harvest corn drying

Currently, corn harvesting in China predominantly uses ear-based mechanical harvesting, followed by threshing, with corn kernels then moving into various processes. As shown in Figure 1, the harvested corn kernels first pass through vibrating screens and winnowing machines to remove impurities. Since corn's waxy layer easily attracts unclean and unsafe substances, the physical reduction method shown in Figure 1 (R) can be used to make it cleaner and safer. After reduction, the corn kernels enter the drying process, which helps to improve corn drying efficiency.

Figure 1. Corn Vibrating Screen (L) and Toxin Degradation Instrument (R)

Corn mechanical drying primarily uses hot air for dehydration. Traditional continuous hot air drying first heats the air, then allows the hot air to come into contact with corn to quickly remove moisture, achieving the goal of corn drying. As shown in Figure 2, the continuous corn drying tower features a drying layer where hot air flows from bottom to top, while corn moves from top to bottom, creating a counter flow. In the tempering[1] layer, the corn is primarily influenced by natural air, bringing it to a near-equilibrium state. Through multiple such cycles, the corn drying process is completed.

Figure 2. Continuous Corn Drying Tower

[1]Note: "Tempering" refers to the process of halting heating and maintaining the temperature of grains during the drying process.

For different target application scenarios of corn, various types of drying equipment can be selected, as specifically shown in Table 1.

Table 1. A Quick Overview of Corn Drying Technologies

Grain variety	Type of drying equipment	Cost range/US$ 10K	Principle of operation	Application scenario	Target group
Corn	Cross-flow dryer	2.1—6.9	Hot air blows horizontally through the grain, removing moisture evenly.	Corn drying for medium-sized yields	Small and medium-sized farmers or cooperatives
	Mixed-flow dryer	6.9—11	Mixed flow of hot air enhances drying uniformity and efficiency.	Corn drying with high moisture content or after concentrated acquisition	Grain depots, large cooperatives, and processors
	Tower dryer	5.5—13.8	Hot air flows in layers with high drying efficiency.	Drying of centrally purchased corn or corn that needs to be processed quickly in large quantities	Grain depots, and processors
	Roller dryer	1.4—4.1	The grain tumbles in the rotating drum, with hot air blowing away its moisture.	Corn drying for scattered plantings	Small-scale cooperatives or small and medium-sized farmers
	In-bin drying system	1.4—3.5	Forced ventilation and dehumidification using a fan at the bottom of the grain bin.	Drying of corn stored with low moisture content	Small-scale cooperatives, and grain depots

2.2.2 Post-harvest rice drying

Rice has a unique structure, with a hard outer shell covered in awns that easily collect and adsorb other substances. Therefore, before drying, vibrating classifiers and air separators (as shown in Figure 3) are used to remove organic and inorganic impurities. Additionally, the awns' adsorptive properties can cause repeated moisture absorption during the drying process. Since these awns can also easily harbor microorganisms and lead to mold growth, a dewaxing machine is used to remove the awns before drying. Cleaned rice with impurities and awns removed helps improve drying efficiency.

Figure 3. Rice Vibrating Classifier (L) and Air Separator (R)

Rice is heat-sensitive material, meaning that rice reacts strongly to temperature. Therefore, rice drying typically uses the mechanical drying method to ensure its post-harvest safety. As shown in Figure 4, low-temperature cyclic drying is performed in a closed system, which is beneficial for environmental sustainability and the physical and mental well-being of workers. For rice, the heating temperature should not exceed 50°C (except for rice seeds), and the heat medium temperature is generally controlled below 80°C. The heat medium temperature control varies depending on rice varieties, drying machinery, and purposes, which is crucial for preserving the rice quality.

Figure 4. Low-Temperature Cyclic Rice Drying System

Similarly, for different target application scenarios of rice, various types of drying equipment can be selected, as specifically shown in Table 2.

Table 2. A Quick Overview of Rice Drying Technologies

Grain variety	**Type of drying equipment**		**Principle of operation**	**Application scenario**	**Target group**
Rice	Cyclic dryer	3.5—8.3	Multiple cycles of drying and tempering, using hot air and low-temperature for gradual dehydration.	Ideal for high-humidity areas and scenarios requiring high rice quality	Medium-sized cooperatives
	Cyclic drying unit	5.5—9.7	Multiple cyclic drying units working in series boost overall drying efficiency.	Farmers of different sizes, especially those with a high need for continuous operation	Large and medium-sized cooperatives
	Roller dryer	2.1—5.5	Rice tumbles and heats up inside a roller, removing moisture.	Rice drying for small-scale yields	Smallholder farmers
	Low-temperature air drying system	4.1—9.7	Drying rice in low-temperature, dehumidified air helps maintain its quality after drying.	Drying of premium rice.	Grain depots, or processors
	Infrared dryer	2.8—6.9	Heating with infrared spectrum acts directly on the inside and outside of the rice to quickly remove moisture.	Ideal for special high-humidity areas or scenarios requiring high drying speeds	Farmers with special needs or small-to-medium sized rice processors

2.2.3 Post-harvest wheat drying

In China, wheat is primarily harvested using mechanized methods. After harvesting, it's inevitable that wheat will contain various impurities and metal contaminants. Therefore, a wheat magnetic separator (based on the principle of magnetic differences between wheat and impurities) should be used to remove metal debris, such as iron filings and metal fragments. The wheat that has been cleared of impurities then proceeds to drying and processing stages, which not only protects the equipment but also improves its efficiency. To ensure that the wheat entering the machine is clean and plump, it is recommended to use the color sorter shown in Figure 5 (R). It employs image processing technology to perform a 360-degree comprehensive scan of wheat samples, evaluating their fullness and color based on specific models, and removing any wheat grains that do not meet the quality standards.

Figure 5. Wheat Magnetic Separator (L) and Color Sorter (R)

Currently, wheat drying equipment can utilize an adaptive closed-loop segmented temperature-variable drying method. Adaptive closed-loop control means comparing the actual state of target parameters with the set state after each drying cycle. When the two are consistent, drying stops; when differences exist, the discrepancy is fed back to the control end, promptly adjusting control parameters such as hot air temperature, hot air flow rate, and wheat flow rate, until the target parameter setting is met. The wheat segmented temperature-variable drying mainly involves adjusting the hot air temperature according to the moisture content of the wheat. For instance, when the wheat's initial moisture is high, high-temperature heating media can be used for rapid moisture reduction; when the wheat's moisture drops to around 20%, the heating media temperature gradually decreases, allowing moisture to slowly evaporate from the inside out. This drying process ensures both drying efficiency and maintains the drying quality.

Figure 6. Wheat Temperature-Variable Drying System

Similarly, for different target application scenarios of wheat, various types of drying equipment can be selected, as specifically shown in Table 3.

Table 3. A Quick Overview of Wheat Drying Technologies

Grain variety	Type of drying equipment	Cost range/US$ 10K	Principle of operation	Application scenario	Target group
Wheat	Cross-flow dryer	2.1—6.9	Hot air blows horizontally through the grain, processing it in batches.	Wheat drying for small-scale yields	Small and medium-sized farmers or cooperatives
	Mixed-flow dryer	6.9—11	Mixed flow of hot air enhances drying uniformity and efficiency.	Ideal for efficient processing of wheat in large quantities	Grain depots, or processors
	Tower cyclic dryer	5.5—9.7	Multiple drying cycles ensure stable wheat quality.	Scenarios requiring high uniformity of wheat drying	Grain depots, processors and farmers
	Mobile dryer	1.4—4.1	Equipment is flexible, allowing for quick drying in fields or on-site locations.	Decentralised small-scale wheat drying; it is easy to move and operate.	Small and medium-sized farmers
	In-bin drying system	1.4—3.5	Forced ventilation in the grain bin, gently reducing moisture.	Drying and storage of wheat with low moisture content	Small-scale cooperatives, and grain depots

3. Key Control Technologies for the Grain Drying Process

The process of grain drying is essentially about removing moisture from grains and preserving their quality. Moisture content and quality are the two key factors in the grain drying process.

3.1 Grain Moisture Measurement Technology

Grain moisture, depending on its form, can be divided into free water and bound water, with the drying process primarily removing the free water component. Moisture content in grains plays a crucial role in preserving nutrients and flavor; moreover, moisture is also a key foundation for microbial growth. Therefore, setting the right target moisture level for grains is critically important - it helps maintain quality while simultaneously suppressing or preventing microbial proliferation. The target moisture level should be set based on the post-drying purpose and process. For instance, if rice is dried and then moved to storage, its target moisture level should be set at 13.0% ± 0.5%; if it is dried and then moved to processing, its target moisture level should be set at 16.0% ± 0.5%.

There are multiple methods for measuring moisture content during grain drying, such as resistive, capacitive, microwave, infrared, and constant weight methods. Among these, resistive moisture measurement is widely used in practical applications, characterized by its ease of operation, low cost, and quick results. Its principle involves applying voltage to the grain, where different moisture contents result in varying current flows (higher moisture leads to lower resistance and higher current); a formula is then used based on this relationship to determine the grain's moisture content. However, this method has one drawback: equipment needs calibration before use to ensure measurement accuracy. Additionally, microwave and infrared moisture measuring instruments, due to their complex system operations and high costs, are currently primarily used in laboratory research and have not been widely used in practical applications.

Figure 7. Resistive Moisture Measuring Instrument (L) and Resistive Moisture Measuring Circuit (R)

Drawing on the unique absorption and desorption properties of grains, Chinese grain research scholars have constructed a national grain parameter database and equilibrium humidity calculation formula based on extensive experimental data, as shown in Formula (1). This formula describes the relationship between grain temperature, moisture content, and humidity, allowing the calculation of the third parameter when two are known. For instance, if grain temperature and humidity are already known, the moisture content can be calculated through inversion, as shown in Formula (2).

Grain equilibrium relative humidity (simplified five-parameter method):

$$ERH = \frac{1}{1 + EXP(A + B \cdot EMC^{\alpha} + C \cdot t_{\alpha}^{\beta})} \tag{1}$$

Grain equilibrium moisture content (simplified five-parameter method):

$$EMC = \sqrt[\alpha]{\frac{\ln(1 - ERH) - \ln ERH - A - C \cdot \mathrm{t}_{\alpha}^{\beta}}{B}} \tag{2}$$

Where, ERH represents the grain equilibrium relative humidity; EMC represents the grain equilibrium moisture content; A, B, C, α, β are parameters for different varieties of grains in adsorption and desorption states (which can be obtained from a reference table).

3.2 Grain Drying Quality Control Technology

The quality of grain drying is primarily influenced by drying equipment and process control parameters. Among these, different heat sources and radiator structures of drying equipment have varying impacts. For instance, biomass heat sources can easily produce coal tar during combustion, which may cause secondary contamination if directly in contact with grains; diesel and other high-molecular-weight energy sources generate volatile substances during burning, potentially affecting the flavor of grains. Therefore, it is recommended to add appropriate purification structures to the combustion chamber and heat exchanger parts of the drying equipment, and to adopt an indirect heating method for grain drying.

Research team from the Academy of National Food and Strategic Reserves Administration conducted a study on "Rice Drying Quality Control Technology". This technology is based on experimental data from rice drying tests using different heat sources, along with drying quality data. It constructs a relationship model and vividly creates a "drying quality process diagram". By consulting this diagram, one can predict the quality state of dried rice through drying control parameters, and conversely, determine the corresponding drying control parameters based on post-drying quality requirements. As shown in Figure 8, assuming the initial moisture content of rice is 25%, with air humidity at 55%, hot air temperature controlled at 43°C, and a tempering ratio[2] of 2, the rice is dried, resulting in a head rice yield of over 69%; conversely, the same applies.

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[2]Note: "Tempering ratio" refers to the ratio between the time of maintaining grain temperature after stopping heating during the drying process and the heating time of grains during the drying process.

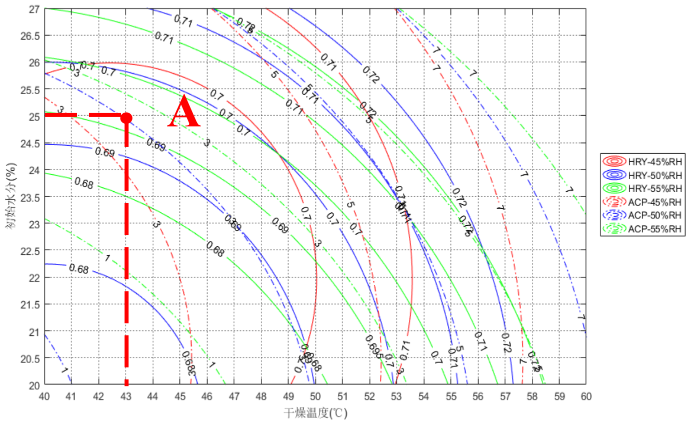

Figure 8. Quality Control Diagram for Rice Drying with a Tempering Ratio of 2

3.3 Case Studies of Grain Cleaning and Drying Solutions for Farmers

For farmers, there are two main types of grain drying equipment: "stationary", as shown in Figure 9 (L) and "mobile", as shown in Figure 9 (R).

Figure 9 (L) shows the grain drying and storage bin for farmers. Its structure is mesh-style, generally supported by multiple main support pillars on all sides, with a specific grid-sized screen mesh used around the perimeter. The top is made of steel plates with a certain slope, and the bottom is a load-bearing base plate. The bottom is slightly elevated above the ground to prevent moisture and rodent or insect infestation, while the sloped roof ridge helps prevent rain and snow loads. Natural drying can be realized by placing it on a well-ventilated, dry, and flat surface, loading no more than 70% of the capacity with grains, and allowing natural wind to blow through the grain pile and carry away moisture and heat. This grain bin is characterised by low cost (US$1300-2100) and simple structure, but there is a risk of mold and heat buildup for grains in the middle and lower parts due to poor ventilation. It is recommended that this grain bin be used in dry areas with low humidity.

Figure 9 (R) shows the natural rotary grain drying and storage bin for farmers. It makes use of the environment resources (high temperature, dryness, etc.) in different regions, and loads grains into a rotating drum with a grid designed according to grain particle size. It has conveyor belts and rollers beneath the drum, and ventilation ducts with a certain perforation rate in the middle of the drum. All these components are organically combined and placed on a base. The working principle is as follows: the conveyor belts and rollers rotate at an extremely low angular velocity, which drives the large drum to rotate slowly and evenly at a certain angle. This allows hot, dry air from the outside to enter the grain pile and, through ventilation ducts and external screen structures, undergo moisture and heat exchange with the grains to achieve the drying purpose. This equipment is suitable for various regions and can flexibly combine with different heat source devices based on the natural environmental resources to achieve the drying purpose. In high-temperature drying areas, natural wind can be used directly; in medium and low-temperature drying areas, heating devices can be added to ventilation sections; in high-humidity areas, dehumidification devices can be added to ventilation sections. Currently, a series of natural rotary grain drying and storage bins ranging from 10 to 50 tons have been developed, which can meet the needs of farmers with varying grain production volumes.

This equipment has been used for drying rice, corn, and wheat—the three major staple grains—in different regions of China. After drying, the grain moisture content is uniform within ±0.5%, and the color is comparable to that of naturally sun-dried grains, with low energy consumption. This equipment is low-cost (priced at $18,000-19,000 for a 15-ton capacity), has low energy consumption, excellent drying quality, and is easy to operate, making it a preferred choice for grain drying among farmers.

Figure 9. Grain Drying and Storage Bin (L) and Natural Rotary Grain Drying and Storage Bin (R) for Farmers

4. Green and Energy-Efficient Grain Drying Technologies

4.1 Clean Energy

To meet the requirements of low carbon and carbon neutrality, an increasing number of green energy sources are replacing traditional fossil fuels, becoming new clean energy options in the field of grain drying, such as air-source heat pumps, wind and solar energy.

A heat pump converts low-grade energy from the natural environment to high-grade energy and outputs it for various uses. Take air-source heat pump grain drying technology, for example. It can convert 1 part of low-grade energy into 4 parts of high-grade energy, thus outputting energy four times the original amount for grain drying. Typically, its coefficient of performance (COP) is not less than 3. Currently, air-source heat pump technology is widely applied for grain drying in high-temperature regions, which can meet the requirements for high-quality, green, and efficient drying processes.

4.2 AI and Digital Twin

With the application of information technologies such as AI, big data, and digital twin, the grain drying sector has seen faster and better development. Intelligent drying systems based on IoT, big data analysis, and AI can monitor key parameters like heat medium temperature, humidity, and speed in real-time. By utilizing a "mechanism + data" dual-driven model, these systems can precisely control the drying curve and achieve on-demand drying, significantly improving drying efficiency and product quality stability. Moreover, remote monitoring and fault warning functions make operational management more convenient and efficient, reducing human errors and lowering operational costs. The widespread application of these systems marks the official entry of drying operations into a new era of precise control and efficient management.

4.3 Case Studies of New Grain Cleaning and Drying Solutions

As shown in Figure 10, the upgraded coal-fired hot air grain drying equipment achieves higher combustion efficiency, meets emission standards, allows for precise control, enables continuous production, and ensures uniform drying quality. A coal pulverizing unit added to the front end boosts combustion efficiency; desulfurization and denitrification units, along with a multi-stage bag filter, ensure that post-combustion emissions meet standards; a PLC system with closed-loop feedback control maintains the drying hot air temperature within ±1℃, achieving precise control; and a negative pressure closed-loop ash removal method enables continuous production and improves efficiency. These upgrades result in more precise drying control, ultimately ensuring uniform and high-quality grain drying. This equipment has been demonstrated in parts of China and shows promising results for both grain and food drying.

Figure 10. Upgraded Coal-fired Hot Air Grain Drying Equipment

Downflow/counterflow grain dryers are currently one of the most widely used dryer models in the grain drying sector. It boasts high processing capacity (5-60 t/h), significant moisture reduction (16-19%), high initial grain moisture content (reaching 30% and above), substantial drying output (maximum drying capacity up to 13 t/h), and results in grains with excellent color, superior quality, and uniform moisture after drying. The equipment's interior is primarily composed of air intake vents and angular ventilation boxes. The grain feeding hopper is positioned at the center of the drying layer's top, with two counter-rotating augers synchronously distributing grains evenly along the longitudinal ends and lateral sides to ensure uniform heating. The grains flow from top to bottom outside the angular box, with hot air entering through the intake vents and crossing horizontally through the grains. Moist exhaust gases are expelled through the exhaust port of the angular box. After drying, the grains enter the tempering layer for balancing, completing the drying process through multiple repetitions. As shown in Figure 11, in addition to the aforementioned features, the rice downflow/counterflow dryer with a capacity of 500t/d, employs a low-temperature rice drying technique to ensure the quality of the dried rice.

Figure 11. Rice Downflow/Counterflow Drying Equipment with a Capacity of 500t/d

5. Development and Challenges of Grain Drying Technologies

In the context of new circumstances, as grain drying continues to develop, we need to seize opportunities and proactively face challenges:

First, in terms of grain drying foundational theory and control methods, we should continuously develop drying objectives and improve drying control models based on the characteristics of grain materials, and utilize new control technologies to regulate the drying process in real-time, such as applying and expanding grain drying quality-oriented regulation technologies.

Second, we should foster the integrated application of multidisciplinary and multi-domain technologies to continuously update grain drying technologies. For instance, AI, IoT, big data, and digital twin technologies can provide online real-time displays of grain drying processes and control parameters, accurately analyze the current state of grain drying, and predict drying changes, thereby ensuring grain drying quality and improving drying efficiency.

Third, we should draw on technologies from other countries and secure policy support. For example, we can regularly organize multi-country and multi-regional technical exchanges and academic forums, allowing scholars to share their latest research findings and companies to introduce their experiences. At the same time, subsidies for grain drying facilities similar to that for agricultural machinery can be introduced, to facilitate the widespread adoption of new grain drying equipment.