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Review

Hazard Analysis of Traditional Post-Harvest Operation Methods and the Loss Reduction Effect Based on Five Time (5T) Management: The Case of Rice in Jilin Province, China

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Abstract: Traditional post-harvest operation methods applied in rice fields lack advanced management knowledge and technology, which has led to post-harvest losses. We proposed the concept of Five Time (5T) management for the first time. 5T management divides the whole life cycle of rice into different growth time interval to complete process management. This paper mainly introduces the management of rice grain period, that is, the post-harvest management period, including the operation process management of harvesting, field stacking, drying, warehousing, and storing. In 2019, our research team formulated the 5T management method, which considers the entire post-harvest process, and carried out a pilot application of this method at the Jilin Rice Industry Alliance of Jilin Province. Moreover, to promote the 5T management method, our research team carried out follow-up experiments in rice production enterprises and found severe post-harvest rice losses. This paper combined a large number of literature and the basic theory research of rice post-harvest to analyze the traditional methods for post-harvest processing and the associated rice losses. By implementing the 5T management method, 4.33% of losses incurred during the T_1 harvesting period could be recovered. In the T_2 field period, drying rice within 48 h after harvesting could reduce losses by 2.5%. In the T_3 drying period, the loss rate could be reduced by 1.6% if traditional drying methods were replaced by mechanical drying and by 0.6% if cyclic drying was implemented to prevent over-drying. In the T_5 storage period, the loss rate of 7% could be reduced by adopting advanced grain storage technologies such as low-temperature storage. Overall, the rice loss rate could be reduced by 15.43%, which is equivalent to a yield of 32.68 million tonnes of rice. The important factors in each period are strictly controlled in the 5T management method to prevent the post-harvest losses caused by flawed concepts and improper management and to increase the amount of usable fertile land.

Keywords: rice; 5T management; post-harvest loss; loss reduction

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1. Introduction

Food supply is the lifeblood of national economies. Only by ensuring food security can we ensure the security of our rice bowl. Following the outbreak of COVID-19, how to ensure food security is a topic of concern for all countries. Food production is a strategic industry that ensures the health of the world and the global population. Countries have improved food production technology and management methods to ensure the sustainable and stable growth of food production [1–5], reduce the loss and consumption of food post-harvest, and ensure food security.

In developing countries, the post-harvest loss of grain is severe due to a lack of knowledge and technology in post-harvest management, poor storage facilities, and other reasons [6–8]. In developed countries, grain losses in the middle stage of the supply chain are relatively low due to the application of advanced technologies and effective crop processing and storage systems [9]. Reducing the post-harvest losses of grains, particularly in developing countries, is a sustainable method to increase grain supplies and reduce pressure on natural resources, which can eliminate hunger and improve the livelihoods of farmers on a large scale [10]. R. J. Hodges et al. [11] found that losses in the quantity and quality of food can occur in any link along the post-harvest chain, from harvesting to crop processing, marketing, and food preparation; at the end of this chain, consumers decide to eat or discard food, the latter of which results in very large economic losses. It is estimated that post-harvest loss of grain varies from 20% to 35% in different regions of the world [12]. China's post-harvest losses of grain are huge, exceeding 100 billion kg per year, equivalent to 7.5% of the total grain output [13]. In African countries, the land used to grow grains is a valuable resource for agriculture, but the post-harvest loss of grains, which reaches between 20% and 40%, leads to wasted resources [14,15]. D. Sarkar et al.'s research found that in the process of grain threshing and cleaning, a large amount of grain overflows its containers and is lost, and this loss of grain could be as high as 4% of the total yield [16]. A study conducted in India found that delays in harvesting increased losses from wheat pulverization by approximately 67% (from 1.5% to 2.5%) [17]. In the grain drying stage, the loss of Zambian maize during high platform drying was 3.5% [15], while the loss during natural drying in Zimbabwe was 4.5% [17]. D. Grover showed in their research that in developing countries such as India, approximately 50–60% of grain is stored in warehouses with traditional structures, which are built without any scientific design and cannot guarantee long-term protection of crops from insect pests [18]. It has been estimated that maize loss is as high as 59.48% after 90 days of storage in conventionally structured warehouses [19].

Rice is one of the most widely distributed crops in the world and is the staple food of approximately 50% of the world's population. A study on the post-harvest loss of rice in Nigeria found that rice loss was equal to approximately 19% of the planted area [20]. A study by Kannan et al. on the post-harvest loss of rice in India estimated that the lack of harvesting machinery and equipment resulted in delayed harvesting and increased rice loss by 10.3% (1.74–1.92%) [21]. Liu Houqing from China stated that the loss of weight from rice due to over-drying is more than 2% of the total weight, and that the direct economic loss is more than 5% when the effects of over-drying are combined with the crushing that occurs during milling [22]. Alavi reported that the loss rate during rice processing and transportation in southeast Asia was 2–10% [23]. In a study of rice shattering in China, it was found that the loss rate due to natural shattering was only 0.47%, while the loss rates due to collision shattering and slapping shattering, which accounted for a large proportion of rice loss, were 9.75%. By reducing unsuitable activities during harvesting operations, harvest quality can be guaranteed. This would greatly reduce harvest losses [24].

Therefore, post-harvest management of rice is particularly important, but basic research on the post-harvest management of rice is insufficient, and traditional post-harvest rice management methods are not based on advanced knowledge or the application of technology, leading to the loss of rice [25]. Many researchers have also begun to study post-harvest management of rice [26–29]. When grouped according to complex decision-making processes, such as the management of rice post-harvest with multi-stage coupling practices, post-harvest management is divided into five stages: rice harvest, field stacking, drying, warehousing, and storage. These stages compose the 5T management method, for which a pilot application and promotion programme was conducted at the Jilin Rice Industry Alliance in Jilin Province. Moreover, when implementing the 5T management method, our research team carried out follow-up tests with rice production enterprises according to regulations, and found that the 5T management method reduced post-harvest losses in each stage. The 5T management method fundamentally controls the factors resulting in post-harvest loss of rice, organically combines quality management with operation process management, reduces post-harvest rice loss, improves post-harvest rice loss reduction technology, and considerably increases the yield of rice.

2. 5T Management

The concept of Five Time (5T) management was proposed by our research team for the first time. 5T management tried to apply the concepts of industrial space management and process management to modern agriculture. According to the natural characteristics of whole life cycle [30–33], crop production can be divided into five time intervals (i.e., the large 5T): the seed period (T_A), seedling period (T_B), rice shoot period (T_C), grain period (T_D), and product period (T_E). According to the natural characteristics of grain period, the grain period (T_D) can be divided into five time intervals (i.e., the small 5T): harvest (T_1), field stacking (T_2), drying (T_3), warehousing (T_4), and storage (T_5), as shown in Figure 1. The time intervals integrate the object, owner, owner time, etc., to facilitate scientific observation and management [34]. The rice grain period (T_D) encompasses the whole process of rice growth, from pre-planting to fully grown plants and consumption; this process is called the peri-harvest period operation process. The term "peri" is a borrowed medical term that refers to careful perinatal nursing [35,36]. In this paper, the application of 5T management to carry out chain management of post-harvest collection and storage of rice is investigated.

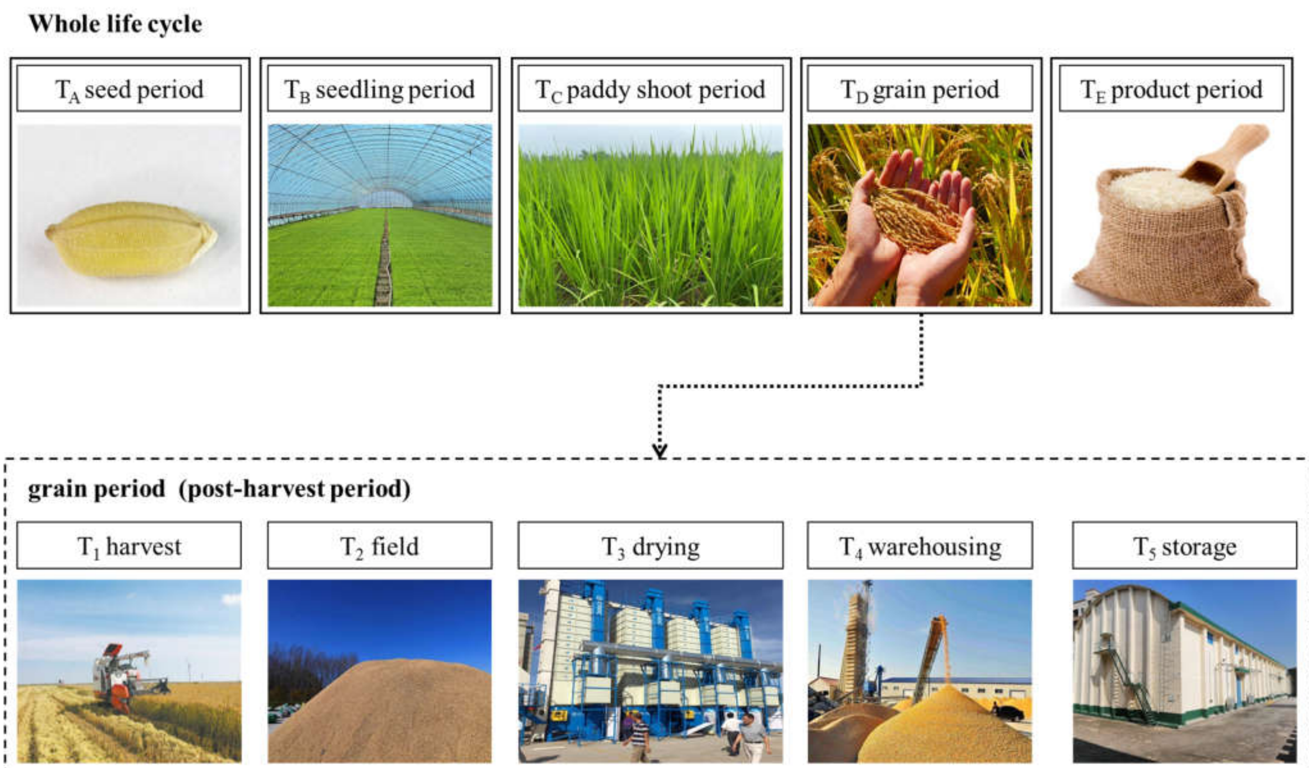


Figure 1. Division of the 5T rice management periods.

The 5T management method is applied in the post-harvest period of rice collection and storage; it relies on timely harvesting, short times in the field, low temperature drying, moisture control, fresh storage, and other management concepts to control the quality and safety of the product. Production technologies, production processes, management processes, products, and other elements of rice harvesting are organically combined, and the operation is optimized to achieve the minimum environmental impact, the lowest resource waste, the lowest post-harvest loss of rice, the best management mode, and the optimal level of economic growth. After investigating the production management mode and production processes of the rice industry, our research team compiled a draft of the 5T management technical code, carried out experiments in several areas that tested 5T management indexes, and promulgated the 5T management technical code [37], as shown in Table 1.

Table 1. Technical codes for 5T post-harvest management for high-quality rice (Source: Jilin DB22/T 3113–2020 [37]).

Period	Necessary Indicators	Necessary Indicator Parameters			Sufficient Indicators	Sufficient Indicator Parameters		
		A Grade	B Grade	C Grade		A Grade	B Grade	C Grade
T_1	Harvesting time deviance (variation coefficient)	± 2 d (4.4%)	± 3.5 d (7.8%)	± 5 d (11.1%)	Loss	≤ 2.0%	≤ 2.3%	≤ 2.7%
	Harvesting moisture	24%	24%	—	Harvesting time	—	—	—
T_2	Mechanical harvesting time	≤ 6 h	≤ 8 h	≤ 12 h	Storage temperature	≤ 20 °C	≤ 25 °C	—
	Semi-mechanical harvesting time	≤ 12 h	≤ 16 h	≤ 24 h	Loss	≤ 0.1%	≤ 0.15%	≤ 0.2%
					Mould	≤ 0.5%	≤ 1.0%	≤ 1.5%
T_3	Accumulated drying temperature	≥ 300 (°C·h)/%	≥280 (°C·h)/%	≥ 270 (°C·h)/%	Final moisture	15%	14.5%	14.5%
	Drying precipitation rate	0.5%/h	0.7%/h	0.8%/h	Rice temperature	≤ 30 °C	≤ 35 °C	≤ 40 °C
					Loss	≤ 0.1%	≤ 0.15%	≤ 0.2%
T_4	Closing time	≤ 1 d	≤ 1.5 d	≤ 2 d	Impurity rate	≤ 0.5%	≤ 0.8%	≤ 1.0%
	Closing moisture	15%	14.5%	14.5%	Loss	≤ 0.06%	≤ 0.08%	≤ 0.1%
T_5	Average storage temperature	15 °C	20 °C	25 °C	Delivery moisture	≤ 15%	≤ 14.5%	≤ 14.5%
	Annual storage accumulated temperature	≤ 8395 °C·d	≤ 10,220 °C·d	≤ 12,045 °C·d	Mould	≤ 0.5%	≤ 1.0%	≤ 1.5%
					Fatty acid values	≤15.0 (mg·100 g^{-1})	≤20.0 (mg·100 g^{-1})	≤ 25.0 (mg·100 g^{-1})

3. Hazard Analysis of Traditional Post-harvest Operation Methods and Positive Effects of 5T Management

3.1. T_1 Harvest Period

3.1.1. Rice Dry Matter Loss in the T_1 Period

Farmers have a habit of harvesting rice as late as possible. They think the later the rice is harvested, the fuller the grain is and the higher the yield is. Late harvesting also reduces the cost of drying as the seeds have less moisture [38–40]. Related studies have found that different harvest dates not only affect the quality of rice [41], but also the yield, this can result in dry matter loss during rice harvest. Delayed harvesting will reduce rice yield rather than increase the harvest. In 2019, our research team conducted an experiment in Jilin and Gongzhuling, Jilin Province, China. Three varieties of rice were selected, and 10 m × 10 m test areas were selected for each variety. A total of 15 holes of rice were taken from each variety every day. Samples were collected for 30 days, then we conducted threshing and shelling treatment, and measured the 1000-grain weight after drying. The best harvest date was defined as the date in the growth process when the weights of the grain dry matter (dry matter was converted to weight with the standard value of moisture content (15.0%)) of three varieties of rice (Jijing528, referred to as JJ528, Wuyoudao4, referred to as WYD4, and Jijing816, referred to as JJ816) were the highest, and the corresponding number of days after heading and the relationship between rice dry matter weight and days after heading were analysed.

Starting from the dry matter weight on the best harvest date, a curve analysis was performed for all the dry matter weight data and the change in dry matter weight of the three samples with days after heading, as shown in Figure 2.

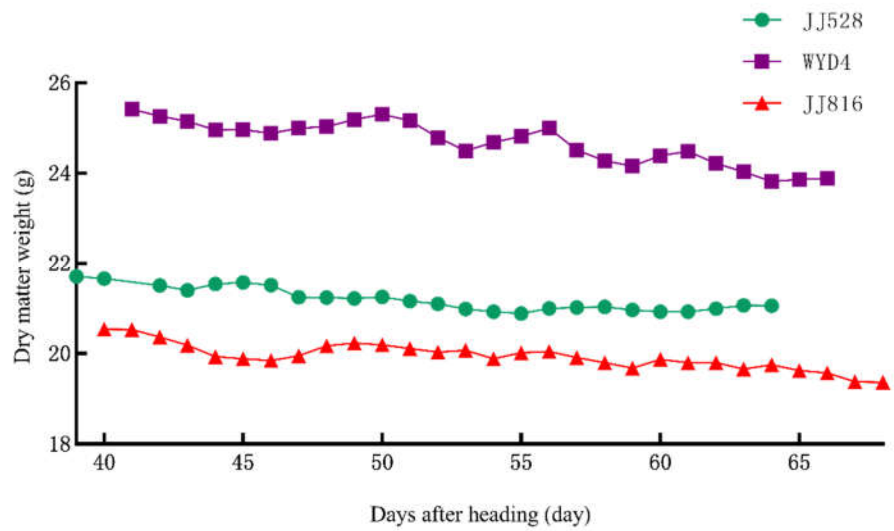


Figure 2. The relationship between rice dry weight and days after heading in 2019 was tested.

The figure shows that the curves of dry matter weight of several samples followed a downward trend, and that the dry matter weight decreased with the heading date. Taking the best harvest date as the starting point, linear regression was carried out on the experimental data measured for each rice variety, and the corresponding regression equation and correlation coefficient (R^2) were obtained, as shown in Table 2.

Table 2. Regression equation and correlation coefficient of each rice variety in 2019.

Variety	Regression Equation	R^2 Value
JJ816	Y = −0.0292x + 21.512	0.7291
WYD4	Y = −0.0569x + 27.729	0.8127
JJ528	Y = −0.0302x + 22.759	0.7775

According to the regression curve and results of the correlation coefficient analysis, the coefficient of the first-order term of different samples is negative, indicating that the curve has a downward trend, and the R^2 values are 0.7291, 0.8127, and 0.7775, indicating that the fitting degree is good and that the trend line is reliable. In other words, if rice is not harvested at the right time, the yield will decrease, rather than increase, as the number of days after heading increases.

According to observations of this harvest, the best rice harvesting period is approximately 45 to 55 days after heading [22]. Delayed harvesting is defined as 56 days after heading, and the dry matter weight at 55 days after heading is set as a standard for dry matter weights. This standard sets the rice harvest loss rate as 0%, and the loss rates at 60, 65, 70, 75, and 80 days after heading were calculated for the three varieties. The results of this calculation are shown in Table 3.

Table 3. Dry matter weights (based on a standard 15% moisture content) and loss rates of three varieties on different days after heading.

Days After Heading (Day)	JJ528		JJ816		WYD4	
	Dry Matter Weight (g)	Loss Rate (%)	Dry Matter Weight (g)	Loss Rate (%)	Dry Matter Weight (g)	Loss Rate (%)
55	19.91	0.00	24.60	0.00	21.10	0.00
60	19.76	0.73	24.32	1.16	20.95	0.72
65	19.61	1.47	24.03	2.31	20.80	1.43
70	19.47	2.20	23.75	3.47	20.65	2.15
75	19.32	2.93	23.46	4.63	20.49	2.86
80	19.18	3.67	23.18	5.78	20.34	3.58

As these data show, the later rice is harvested, the smaller their dry matter weight, and the greater the loss rate, which represents the latent loss of rice dry matter. In the experimental site, rice harvesting generally occurs approximately 75 days after heading. According to the 5T management method, the best time to harvest rice is 55 days after heading; therefore, there is a difference of 20 days between the actual local harvest time and the best harvest time. The average loss rate of the three varieties was 3.47%. In other words, in the T_1 harvest period, timely harvesting according to the 5T management method can reduce the dry matter loss by 3.47%.

3.1.2. Loss Due to Grain Shattering in the T_1 Period

Losses due to natural shattering and mechanical shattering occurred in the harvest period. The more mature the rice was, the easier the over-ripe grains fell off the plant. Part of the rice loss was as seeds do not fall directly onto the cutting table during mechanical harvesting [42–44]. To calculate and verify rice loss during harvest, our research team conducted a field test of rice loss due to shattering. The loss rate after harvest due to shattering was tested in four areas of Jilin Province: Taonan, Taobei, Jilin, and Jiutai. We selected a test variety in each area, three test sites in each test field, measured an area of 1 m^2 at each test site, collected the shattering grain of rice on the ground, weighed the weight of the shattering grain, and finally obtained the average value of shattering grain per square meter. The sample conditions are shown in Table 4.

Table 4. Sample information.

Location	Taonan	Taobei	Jiutai	Jilin
Latitude and longitude	East longitude 122°47′ North latitude 45°20′	East longitude 122°51′ North latitude 45°37′	East longitude 125°50′ North latitude 44°9′	East longitude 126°23′ North latitude 43°59′
Variety	Suijing18 (referred to as SJ18)	Hongke181 (referred to as HK181)	Jihong6 (referred to as JH6)	Wuyoudao4 (referred to as WYD4)
Harvest date	25.09.2020	05.10.2020	17.10.2020	03.10.2020
Heading date	20.07.2020	25.07.2020	28.07.2020	02.08.2020
Days after heading (day)	60	70	79	61
Yield ($kg \cdot hm^{-2}$)	9000	10,000	8000	4670

The varieties collected from Taonan were harvested early, and the harvest was completed on approximately 20 September. The harvest in Taonan was timely, with relatively low amounts of grain shattering. Observations from this harvest are shown in Figure 3a. The varieties in Taobei were harvested on 5 October, and the plants in this location were also harvested in a timely manner. Compared with Taonan, the granulation of the soil was slightly higher in Taobei, as shown in Figure 3b. The samples in Jiutai were harvested on 17 October, indicating a delayed harvest. Due to snowfall in Jiutai, evidence of shattering on the ground was not clear; therefore, it was necessary to remove the snow from the investigation sites and collect evidence of shattering. After the snow was cleared, the severity of grain shattering in Jiutai, as shown in Figure 3c, became apparent. In Jilin, the samples were harvested on 3 October, which was a timely harvesting date. After snowfall in Jilin, it was necessary to clear the snow to observe the state of grain shattering. After the snow was cleared, we could see that the state of grain shattering in the rice field was not positive, as shown in Figure 3d.

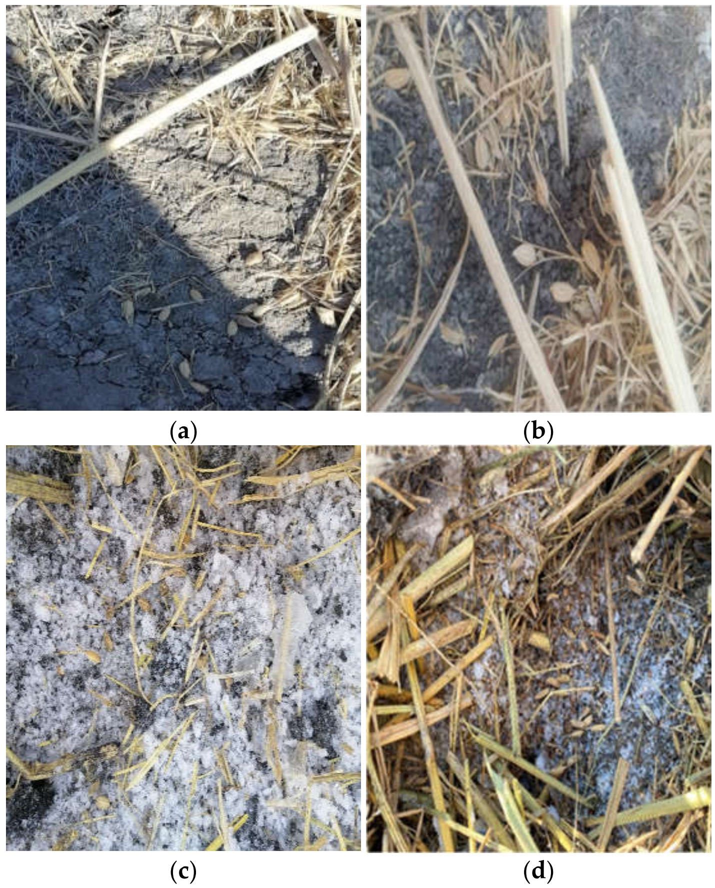


Figure 3. The state of grain shattering in each region: (**a**) Grain shattering in Taonan, (**b**) Taobei, (**c**) Jiutai, and (**d**) Jilin.

After collecting the shattered grains from the ground, impurities were removed with a sieve, and the shattered grains were placed in a sealed bag and weighed for calculation. The loss rate due to grain was calculated according to the following formula:

$$L = \frac{m}{(m_1/10/667) \times 1000} \quad (1)$$

where L is the rate of grain loss due to shattering in the rice field (%); m refers to the weight of rice per square metre of shattered grain (g); and m_1 refers to the yield of rice (kg).

The loss of rice in each region is shown in Table 5.

Table 5. Loss rate due to grain shattering.

Location	Taonan	Taobei	Jiutai	Jilin
Variety	SJ18	HK181	JH6	WYD4
Days after heading (day)	60	70	79	61
Sample area(m^2)	3	3	3	3

Shattered grain weight(g)	35.2	49.0	151.3	61.0
Average weight (g/m^2)	11.7	16.3	50.4	20.3
Yield (kg·hm^{-2})	9000	10,000	8000	4670
Loss rate (%)	0.87%	1.09%	4.2%	2.9%
Average loss rate (%)	3.02%			

As shown in Table 4, due to the late harvest time in Jiutai, there was severe shattering of the JH6 variety, and the shattering loss rate was relatively high, at 4.2%. The grain losses for the SJ18 and Hk181 varieties were 0.87% and 1.09%, respectively, due to the early harvest time. The grain loss for the WYD4 variety was also very severe. Although the harvest of WYD4 was not delayed, the loss rate, which may have been caused by mechanical harvesting, was 2.9%. According to the average loss rate of the four regions, the average loss rate due to grain shattering was 3.02%.

The experimental analysis showed that, in addition to dry matter loss, there was also a field shattering loss of 3.02% in the T_1 harvesting period. Therefore, paddies should be harvested in a timely manner, and the best harvest date is 45 to 55 days after the heading of rice plants; during this period, losses caused by shattering due to delayed harvesting and mechanical harvesting can be recovered.

3.2. T_2 Field Period

Stacking in the field means that operations related to the harvesting of rice plants are not carried out in time and the plants are stacked only in open air. As shown in Figure 4, after harvesting, rice plants are not dried within a reasonable amount of time and are stored in the field or stacked in a temporary site. During this post-harvest period, there is danger of mildew. When rice plants are stored together, their temperatures will rise suddenly, and the moisture contents of the rice plants will be high. As there is no ventilation inside stacked rice plants, they will sprout and become mildewed, resulting in very large losses [45–48]. In 2019, our research team determined the CO_2 concentration and temperature change process of newly harvested rice plants in a natural stowage environment at the rice test site in Jilin city. The sample was the rice just harvested by the farmers, and the rice was stacked together without timely drying. The CO_2 concentration and temperature of a small part of the grain pile were monitored for 7 days. Due to the high moisture content of paddies and the temperature and humidity of the surrounding environment, mildew and cracking were likely to appear in the grain piles.

Figure 4. Rice plants were piled in the field after harvest.

Newly harvested rice plants have a high moisture content, strong vitality, and vigorous respiration, so the temperatures and CO_2 concentrations of undried grain piles increase with increased open-air stacking time, as shown in Figure 5. Heat and mildew develop easily when plants are stored in these environments. Existing studies have shown that there is a good correlation between changes in CO_2 concentration and the activities of mould in grain piles, and that increases in CO_2 concentration can be detected in the early stage of mildew development on grains [49–51].

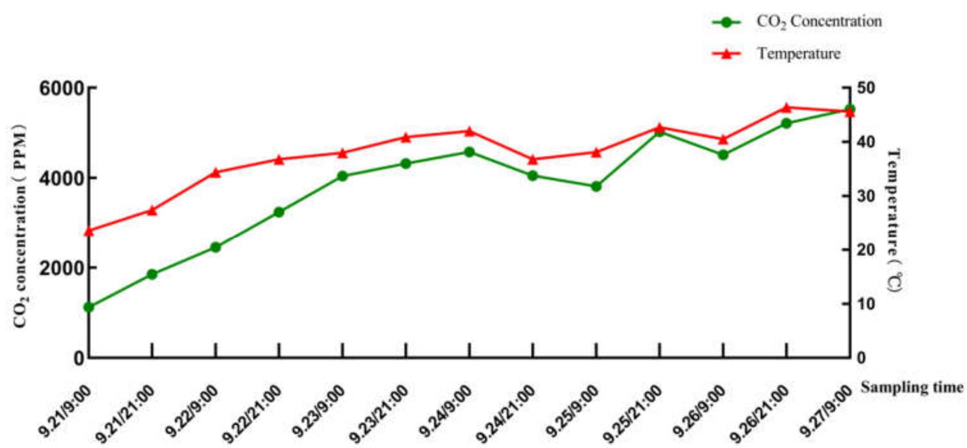


Figure 5. Curves of the temperature and CO_2 concentration of a rice plant stack.

In addition to the increase in CO_2 concentration and temperature, stacking rice plants in open air makes them prone to mildew and causes changes in the cracking rate of the grains. As shown in Figure 6, at 21:00 on 25 September (the fourth day of rice plant stacking), the cracking rate of plants in the upper layer of the grain pile rose rapidly due to the large temperature difference between day and night, dew on the surface of the grain pile in the morning, sun exposure at noon, and cloudy and rainy weather, affecting the quality of the rice.

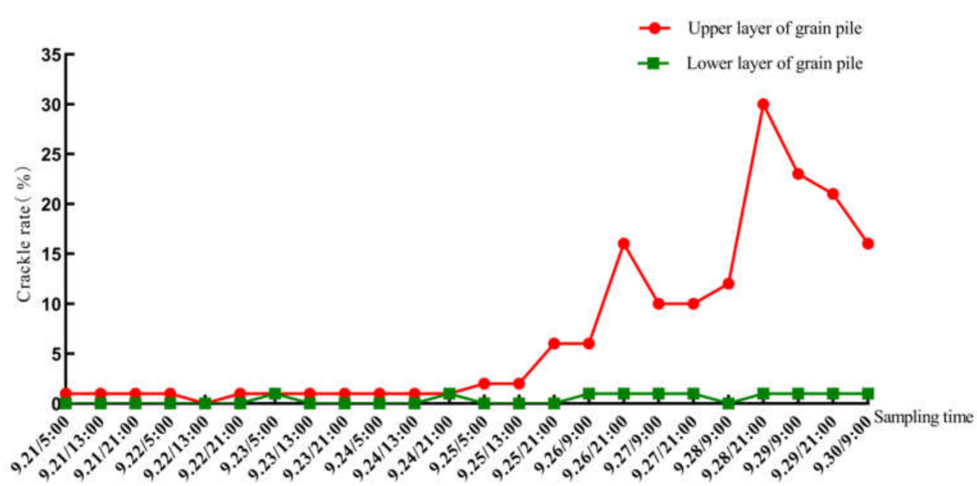


Figure 6. Change curve of the cracking rate of grains not dried sufficiently quickly.

When newly harvested rice plants are stacked in a field [52], some of their life-sustaining processes continue. The plants continue respiration, which consumes dry matter. Due to the high moisture content of rice plants during harvest, the mass of the dry matter consumed by respiration and mould metabolism leads directly to the loss of plant biomass [53,54]. As the amount of time spent in stacks increases, the abundance of mycotoxins that form in the stacks and rice loss also increase. The rate of loss due to rice plant stacking after harvest can reach 3.5% [55].

According to the 5T management method, the amount of time that rice plants are stacked in fields or temporary sites should be minimized and, generally, plants should not be stored in this way for more than 48 h [37]. By reducing the amount of time that plants are stacked, the moisture content inside the plants will not increase, the air temperature around the stacks will not continue to rise, the CO_2 concentration in the stacks will be relatively low, and the grains will not be susceptible to mildew and mycotoxin damage after harvest [56,57]. Moreover, reducing the time that plants spend in stacks will reduce exposure to fluctuations in air temperature and humidity between morning and evening, dew and rain, which will lead to reductions in the cracking rate of the grains and ensure the quality and taste of the rice [58,59].

3.3. T_3 Drying Period

The accumulated experience of farmers has led to certain ideological errors and habits in the traditional process of drying rice plants, such as bundling and drying plants in the air along the road [60,61]. Producers also tend to adopt these low-cost operational strategies over 5T management approaches.

At present, the traditional drying process of baling and drying is still practiced on some farms. However, when rice plants are baled and dried, they are affected by the ambient temperature and humidity, and the moisture content of the bales will gradually decrease, which promotes cracking [60,62,63]. To verify the damage caused by baling and drying, our research team carried out a baling and drying test in Jilin city in 2019, the samples were 30 holes of rice, then tied them up, as shown in Figure 7.

Figure 7. Rice baling test in Jilin city.

Data collected in the test on the moisture content of the bale and the loss rate due to grain cracking are shown in Table 6. Samples were taken at 6:00 am and 6:00 pm from 28 September to 3 October. Samples were taken at only 6:00 pm on 4 October due to weather conditions, as shown in Table 6.

Table 6. Moisture content and cracking rate of grains in a baling and drying test.

Sampling Date	6:00		18:00	
	Moisture Content (%)	Cracking Rate (%)	Moisture Content (%)	Cracking Rate (%)
28.9	26.63	0	20.41	1.33
29.9	20.41	1.33	14.77	0.67
30.9	17.23	2.67	14.47	2.00
1.10	14.28	2.67	12.04	4.00
2.10	12.47	2.67	10.76	3.33
3.10	11.49	3.33	11.45	4.67
4.10	—	—	31.50	17.00

During the test, the rice plants were baled and dried immediately after harvest. With the passage of time, the moisture content of the bale decreased, and the cracking rate decreased sharply. Rainfall occurred during this test (3 October: overcast conditions turned to rain, 13 °C~5 °C, 3.7 mm of precipitation; 4 October: rainfall turned to clear conditions, 6 °C~2 °C, 21.8 mm of rainfall), after which the moisture content of the bales and the cracking rate increased rapidly. The quality of the rice bales was damaged, as shown in Figure 8.

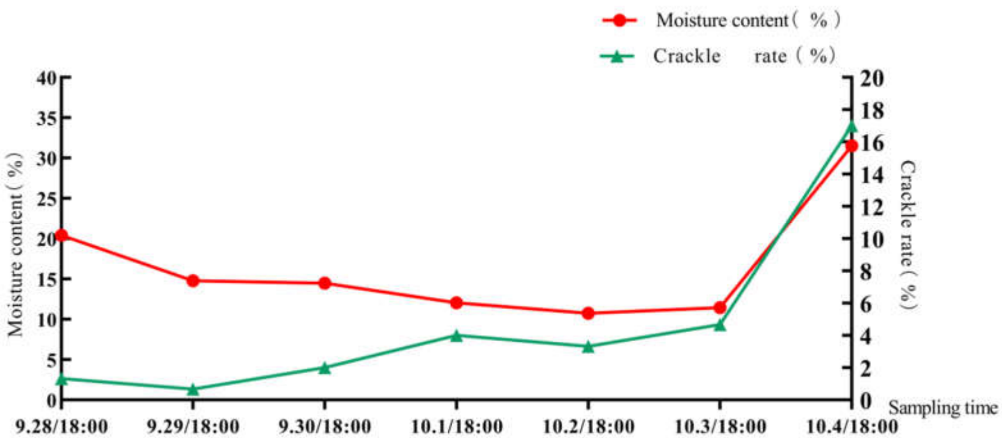


Figure 8. Cracking rates of rice before and after rainfall events during the baling and drying test.

Road drying, shown in Figure 9, is the most common drying method used by farmers. According to relevant studies, road drying has three main hazards: first, it leads to the destruction of seed germs and affects the germination rates of seeds; second, it causes grains to be repeatedly crushed by vehicles, and leads to grain losses due to adhesive tire tape and extrusions from asphalt pavement; and third, it exposes grains to road dust, vehicle exhaust and asphalt pollution, which contain harmful substances [64,65]. According to a survey, grains that were sun-dried on asphalt pavement contained more than 12 times more polycyclic aromatic hydrocarbons and other harmful substances than grains that were sun-dried on ordinary sun-drying surfaces [66].

Figure 9. Road drying in Jilin city.

Therefore, the two natural drying methods, bundling and road drying, are lacking in advanced practices and are unsustainable to some extent, resulting in the post-harvest loss of rice; indeed, the loss of rice due to road-drying has been shown to reach 3% [67].

According to the 5T management method, harvested rice plants should be mechanically dried in the shortest time possible, and a sustainable mechanical drying process should be selected. There are purchase or lease options for mechanical drying machines. Producers can reduce drying time by increasing the drying temperature, which can reduce the cost of use. However, with rapid drying at high temperatures, grains are prone to forming fissures due to the rise in internal stress and surface sclerosis [68–70]. Moreover, newly harvested plants are prone to vitrification, which causes grains to be brittle and crack, due to moisture and temperature changes during the drying process. Increased cracking rates will increase the rates of damaged rice plants, which will lead to a decrease in the final yield, a decrease in the edibility of the grains, and deterioration of the appearance and taste of the grains, thus significantly reducing the value of the plants subsequent to processing. It has been suggested that a low-temperature drying method should be used to ensure the quality of high-moisture rice [71–73]. In related studies, it was found that the loss rate due to mechanical drying was 1.4%, while the loss rate due to over-drying after rapid precipitation was greater than 2% [22].

In 5T management, the T_3 drying period is a key stage, as it allows rice plants to be dried safely rather than damaged. A low-temperature or variable-temperature drying process should be adopted to allow high-moisture grains to reach safe moisture levels. Batch-type recirculating grain dryers are a better option than traditional methods for drying [37,74]; the temperature of the hot air in these dryers should be maintained between 45 °C and 50 °C, the moisture content should remain at ≤ 3% and the drying rate should be ≤ 0.8%/h. With rapid drying with a high moisture content, if the grain temperature exceeds 50 °C, the cracking rate will increase sharply. Therefore, during the drying process, the grain temperature should not exceed 50 °C [75,76]; the key is to prevent cracking due to drying and reductions in edibility and taste.

3.4. T_4 Warehousing Period

After drying, rice plants that are not stored at low or quasi-low temperatures in warehouses within a reasonable amount of time may experience cracking due to moisture absorption from the environment, thus leading to a decline in quality [77–79]. Zhang Jianian analysed cracking caused by hygroscopic absorption by rice plants in artificially controlled environments with different temperatures and relative humidity levels. Under the condition of constant relative humidity, when the air temperature is high, the water content of rice increases rapidly, and more cracks occur after moisture absorption. When the temperature was 20℃ and the relative humidity was 97%, the total cracking rate of rice with moisture content of 11% was 32.0%. Under the same moisture content, the total cracking rate of rice was 65.0% at the temperature of 40℃ and relative humidity of 96%, which was 2.3 times of that at 20℃. The results indicated that rice plants that were not stored in warehouses after harvesting absorbed moisture and dew from the environment over time, thus increasing the risk of cracking [80].

Kunze and Hall pointed out that changes in moisture have a greater effect than changes in temperature on cracking and that the main cause of cracking in grains is moisture absorption by low-moisture grains. The occurrence of grain cracking due to moisture absorption is far more serious than the occurrence of grain cracking during drying [81,82]. Cheng Qiuqiong found that the longer rice plants with low moisture contents (IMC ≤ 14%) were placed in hygroscopic environments, the higher the cracking rate was; furthermore, the cracking rate did not continue to rise after the moisture content due to moisture absorption reached approximately 20%, and the decrease in the rice yield generally occurred 24 h before exposure [83].

The 5T management method suggests that the rice plants should be stored or processed within 24 h after drying. There is a large difference in temperature between day and night during the harvest season. When the temperature and humidity change, obvious fissures or cracks will appear on rice plants. Therefore, it is necessary to control the storage time of plants to reduce cracking, improve the quantity of optimal-quality rice after processing, and improve the yield and quality of rice [82,84]. With the 5T management method, the moisture content of dried rice is reduced, and the storage time is short, so there is little rice loss. Moreover, there are no data in the relevant literature about grain loss during warehousing, so rice loss during this stage was not calculated in this paper.

3.5. T_5 Storage Period

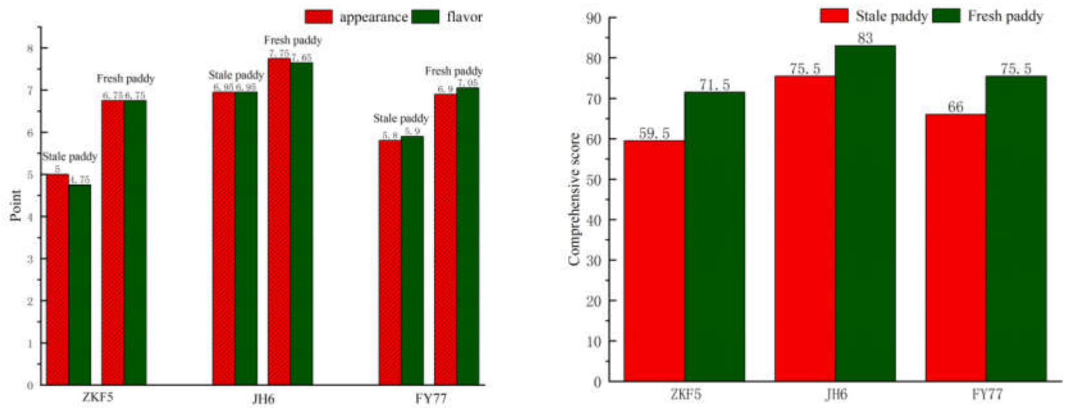
The number of microorganisms tended to decline in rice plants stored at safe moisture levels. Ensuring that the moisture contents and abundances of mould in stored rice plants remain at a safe level will guarantee the microbial safety of rice throughout the storage period [85–88]. The quality of stored rice is also related to the accumulated temperature during the storage period. At higher accumulated temperatures, there was a significant correlation between the volatile components of japonica rice and fungal communities. The results showed that an accumulated temperature between 650 and 1000 °C·d is optimal for inhibiting the growth of mould and controlling the deterioration of aspects related to quality, such as flavour [89–91]. Yang Huiping found in an experiment on japonica rice that low-moisture, high-temperature storage can delay the increase in fatty acid contents, while low-temperature, low-moisture storage can significantly inhibit the increase in fatty acid contents [92]. The odour emitted by japonica rice increases with increased storage time under different temperature and moisture conditions, and the level of odour changes quickly in the early stages of storage. Low-temperature, low-moisture storage can delay the change in the level of odour emitted by japonica rice [93–95]. Research by Chen Yongchun indicated that the optimal storage temperature of rice was 14–118 °C [96].

In 2020, our research team conducted a comparative test on the palatability of rice stored for one year and newly harvested rice. In the test, a SATAKE STA1B rice taste analyser was employed, and spectrophotometric determination was carried out through the reflection and transmission of near-infrared light and visible light bands. The comparative test data are shown in Table 7. The results of the test showed that newly harvested rice from the JJH6 variety had the highest comprehensive score (83 points), while the lowest comprehensive score (59.5) was for rice from the ZKF5 variety that had been stored for one year.

Table 7. Palatability of fresh rice and rice stored for one year.

Variety	Rice Stored for One Year			Fresh Rice		
	Appearance	Flavour	Comprehensive Score	Appearance	Flavour	Comprehensive Score
ZhongKeFa5 (Referred to as ZKF5)	5	4.75	59.5	6.75	6.75	71.5
JiHong6 (Referred to as JH6)	6.95	6.95	75.5	7.75	7.65	83
FangYuan77 (Referred to as FY77)	5.8	5.9	66	6.9	7.05	75.5

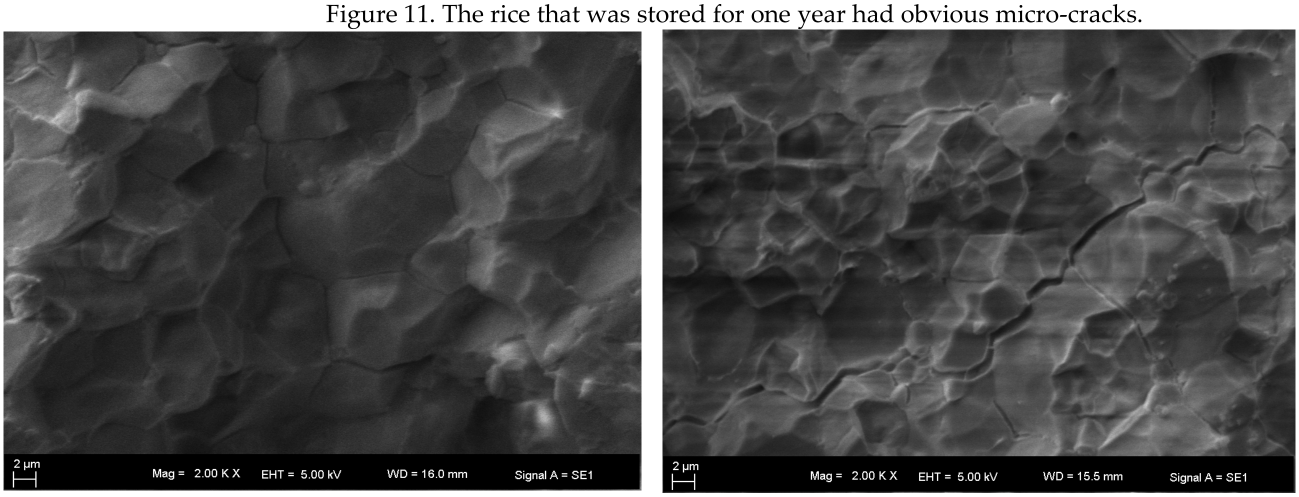
A comparison of the palatability of three varieties of rice that were stored for one year or freshly harvested is shown in Figure 10. After storage for one year, the appearance, taste, and comprehensive scores of the three varieties of rice decreased obviously. The score for the appearance of ZKF5 decreased by 1.75 points, the score for flavour decreased by 2 points, and the comprehensive score decreased by 12 points. Variety JH6 had the smallest decreases in appearance, flavour, and comprehensive score, with the score for appearance decreasing by 0.8, the score for flavour decreasing by 0.7, and the comprehensive score decreasing by 7.5.



(**a**) (**b**)

Figure 10. Comparison of palatability between fresh rice and rice stored for one year: (**a**) comparison of scores for appearance and flavour; (**b**) comparison of comprehensive scores.

Excessive storage times and high storage temperatures will lead to grain cracking [97,98]. Our research team also compared the microstructure of fresh rice with those of rice that had been stored for one year. Figure 11a shows newly harvested rice, and Figure 11b shows rice that was stored for one year. The relevant test results are shown in Figure 11. The rice that was stored for one year had obvious micro-cracks.



(**a**) (**b**)

Figure 11. Comparison of the microstructures of newly harvested rice and rice stored for one year: (**a**) microstructure of fresh rice; (**b**) microstructure of rice stored for one year.

Although there has been a rapid development of storage technologies, the development has been unbalanced geographically, and storage technology is still in the stage of being both basic and advanced. According to preliminary estimates, the losses caused by farmers using traditional methods of grain storage can reach 9% [18], while the losses of grains stored long term can reach more than 10%.

The T_5 storage period is the most important stage after grain harvesting. Having moisture in granaries and stored rice is not always safe. Microorganisms and pests can consume nutrients from rice grains during storage, and improper grain storage will cause changes in grain quality. A large number of microorganisms produce mycotoxins, which render grain useless [99,100]. The 5T management method states that appropriate control measures, such as the application of advanced grain storage technologies and low-temperature storage, should be adopted. For the highest palatability, the temperature of grains should be kept below 15 °C [101], moisture content should be controlled during storage, and the moisture contents of rice stored outside warehouses should be maintained at 14.5–15%. Through reasonable control in all periods of storage and the application of accurate operations and indexes, the 5T management method limits the occurrence of cracking and micro-cracks in rice grains, thus maintaining freshness and preserving aroma.

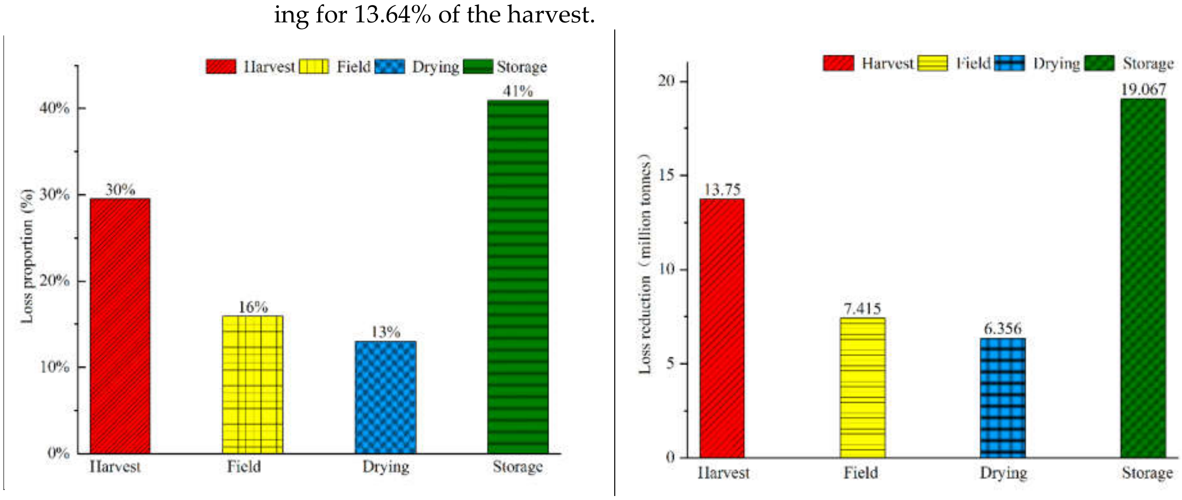
4. Loss Reduction Effect of 5T Management on Rice Post-harvest

In conclusion, we calculated the loss rate associated with each period in the process of rice harvesting and storage, as shown in Table 8. The maximum rice loss rate occurred during the T_5 storage period (9.0%), followed by the harvest period (6.49%, including 3.47% in dry matter loss and 3.02% in loss due to grain shattering and mechanical harvesting), and the T_2 field period (approximately 3.5%). The loss rate in the T_3 period due to natural drying period was 3%, the loss rate due to mechanical drying was 1.4%, and the loss rate due to over-drying was 2%. The comprehensive loss rate in traditional rice harvesting and storage operations was 21.99%.

Table 8. Rice loss rate in traditional harvesting methods in different periods.

Periods	Harvest	Field	Drying			Storage
			Traditional drying	Over-drying	Mechanical drying	
Loss rate	6.49%	3.5%	3%	2%	1.4%	9%

The post-harvest loss of rice and the proportion of rice lost were calculated on the basis of China's rice output in 2020 of 211.86 million tonnes [102]. As shown in Figure 12, the post-harvest loss of rice was 50.82 million tonnes. When traditional methods were applied rather than the 5T management method, the highest loss of rice occurred in the storage period and totalled 19,067 million tonnes, accounting for 40.93% of the harvest; the lowest loss occurred in the drying period and totalled 6.356 million tonnes, accounting for 13.64% of the harvest.



(**a**) (**b**)

Figure 12. (**a**) Loss proportion and (**b**) loss reduction in rice in different periods.

In conclusion, we obtained the loss rate for each period of the rice harvesting and storage process, as shown in Table 8. The largest rice loss rate (9.0%) occurred during the T_5 storage period, followed by the harvest period (6.49%, including 3.47% in dry matter loss and 3.02% due to grain shattering and mechanical harvesting), and the T_2 field period (approximately 3.5%). The rice loss rate in the T_3 natural drying period was 3%; the loss rate due to mechanical drying was 1.4%, and the loss rate due to over-drying was 2%. The comprehensive loss rate when traditional post-harvest rice management was applied was 21.99%.

By grouping data according to observations related to the options for monitoring and control of different rice varieties and raw grain processing (e.g., harvesting, drying, and storage technology), combined with observations about the popularization of standards, research field operations, and related experiences in production, which serve as a foundation, it was possible to analyse the reduction in post-harvest rice loss after implementing the 5T management method.

Two-thirds of the rice losses that occur in the T_1 harvesting period could be recovered by the 5T management method, and the losses that occur in this period due to dry matter loss and grain shattering could be reduced by two-thirds. Therefore, we determined that the 5T management method can reduce the rice loss rate in the T_1 harvesting period to 4.33% and can reduce the post-harvest loss to 9.17 million tonnes. In the T_2 drying period, rice plants are kept in stacks for too long, leading to a loss rate of 3.5%, with more than 1% of the loss being due to fungus. This loss rate will cause a reduction in the economic benefits of rice; therefore, the time rice plants are kept in stacks in the field should be reduced, which will reduce the rice loss rate to less than 1%. If the 5T management method is followed and the drying or stacking times are not more than 48 h, the loss rate due to stacking plants in the field could be reduced by 2.5%, which is equal to a reduction of 5.3 million tonnes. The loss rate due to road drying is 3%; this includes the influences of weather and the environment, to which rice plants are exposed during traditional operation methods. The rice loss rate due to mechanical drying is 1.4%; therefore, drying losses caused by road drying could be reduced to 1.6% (3.39 million tonnes) by switching from road drying to mechanical drying. However, producers sometimes raise the temperature of the hot air used to dry plants to increase the drying rate and reduce the cost and time of drying, or apply unsuitable drying methods; in these cases, the loss rate caused by over-drying is 2%, and the loss rate of mechanical drying is 1.4%. By applying the 5T management method, the loss rate could be reduced by 0.6%, which is equivalent to reducing the loss by 1.27 million tonnes of rice. The processing time in the T_4 period is short, and generally, after mechanical drying, the moisture in the rice is low; the rice is stored and processed immediately after the T_4 period, so the loss rate in this period can be ignored. In the T_5 storage period, the rice loss rate was 9% when traditional storage methods were applied. If the advanced, scientific grain storage technologies described in the 5T management method are applied and farmers build technologically advanced grain storage silos and correctly use grain storage devices, the rate of rice loss is guaranteed to be less than 2%; thus, the rice loss rate would be reduced by 7%. The weight of rice lost post-harvest would be reduced by 14.83 million tonnes, as shown in Figure 13. Furthermore, the total reduction in the rate of rice lost during the harvesting and storage process is 15.43%; therefore, the weight of rice lost post-harvest would be reduced to 32.68 million tonnes, which is approximately equal to the annual rice production of Heilongjiang Province.

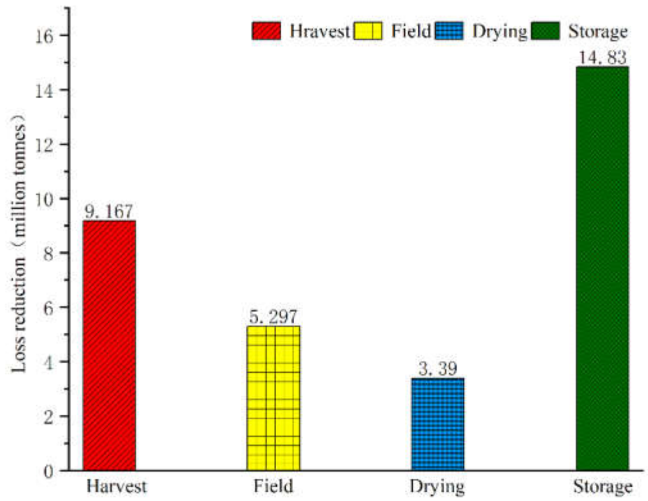


Figure 13. Rice loss reduction in different periods after implementing 5T management.

5. Discussion and Conclusions

1. The dry matter weight of rice decreased with heading time, and the results of the analysis indicated that delayed harvesting time is partially responsible for the loss, as it causes latent reductions in dry matter. Although this part of the loss can easily be ignored, the results show that when rice was not harvested at the optimal time, the dry matter loss reached 3.47%, and the loss due to falling grains reached 3.02%. Therefore, when the 5T management method is applied and rice is harvested at the optimal time, the loss rate can be reduced by 4.33%, which is equivalent to 9.17 million tonnes of rice.
2. With the increase in the amount of time plants spend stacked in the field, the probability of mildew affecting the plants and the grain cracking rate increase. When rice plants are kept in stacks for long periods, the loss rate will be 3.5%. According to the 5T management method, rice plants should be dried immediately after harvest, and the amount of time they remain stacked in the field should not exceed 48 h. Following these guidelines can reduce the loss rate during field stacking by 2.5%, which is equivalent to a reduction of 5.3 million tonnes.
3. Traditional natural drying methods result in a loss rate of 3%. However, common low-cost mechanical drying methods cause uneven levels of drying in rice, and cause the cracking rate to increase, resulting in a 2% loss rate due to over-drying. According to the 5T management method, a low-temperature or variable-temperature drying process should be adopted for rice, and the average rate of moisture reduction should not be higher than 0.8%/h to ensure the quality of the grains. Mechanical drying can reduce the loss rate of natural drying by 1.6%, which is equivalent to approximately 3.39 million tonnes of rice. Proper mechanical drying can reduce the loss rate of over-drying by 0.6% (approximately 1.27 million tonnes of rice).
4. Rice should be stored or processed immediately after drying. If rice is left too long after drying without being stored or processed, it will absorb ambient moisture, resulting in fissures or cracks and grains that are easily broken during processing. According to the 5T management method, the warehousing time should be strictly controlled, and rice should be stored or processed within 24 h after drying; following these guidelines can reduce the rate of grain damage, improve the percentage of high-quality rice obtained from a harvest, and improve rice yield and quality.
5. If rice is not processed after drying, it should be stored in an appropriate amount of time, and the storage process should be reasonably controlled. Traditional rice

storage methods result in a 9% loss rate. According to the 5T management method, the moisture content in rice should be controlled before storage, and low-temperature storage technology should be adopted to slow ageing; these practices could reduce the rate of loss during storage (7%), which is equivalent to a rice yield of 14.83 million tonnes.

It is generally believed that implementing new technologies requires large investments and high costs, which makes farmers hesitant to adopt these new approaches. The implementation of 5T management returns high-quality and affordable products. In addition, new technologies can reduce the amount of labour needed and promote the adoption of new techniques and management methods. The implementation of 5T management in the post-harvest period of rice can reduce loss rates by 15.43%; this is equal to a rice yield of 32.68 million tonnes, which is greater than the annual rice yield of Heilongjiang Province. Assuming that 1.2 RMB is equal to 1 kg of rice, the comprehensive value of lost rice has reached RMB 78.432 billion. If the cost for a set of drying equipment is RMB 500,000, then 150,000 sets of drying equipment could be purchased with the money lost due to processing losses.

The refined 5T management strategy ensures the management and control of details in the process of rice harvesting and storage. According to the key for high-quality rice described by the 5T post-harvest management method, if new technologies and practices, such as timely harvesting, avoiding stacking, low-temperature drying, timely warehousing, and low-temperature storage can be popularized, losses in dry matter, losses due to damaged grains, and losses due to low-quality rice and storage can be recovered every year. The implementation of the 5T management method could prevent losses caused by incorrect ideas and improper management during the post-harvest period of rice; increase the amount of useful fertile land; change concepts and habits related to agricultural production; and promote the development of high-quality food engineering, circular agriculture, farmland preservation, rural revitalization, food appreciation, and respect for agriculture.

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