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Review

The Losses in the Rice Harvest Process: A Review

Xue Qu [1,*], Daizo Kojima [1], Laping Wu [2] and Mitsuyoshi Ando [1]

[1] Department of Agricultural and Resource Economics, The University of Tokyo, Tokyo 113-8657, Japan; akojima@g.ecc.u-tokyo.ac.jp (D.K.); ando@g.ecc.u-tokyo.ac.jp (M.A.)
[2] College of Economics and Management, China Agricultural University, 17 Qinghua East Road, Haidian District, Beijing 100083, China; wulp@cau.edu.cn
* Correspondence: quxue@g.ecc.u-tokyo.ac.jp

Abstract: We review existing studies on rice harvest loss from the aspects of estimation methods, magnitudes, causes, effects, and interventions. The harvest losses examined occurred from the field reaping to storage processes, including threshing, winnowing, and field transportation. We find that existing studies on rice harvest losses have focused on quantitative losses in Asia and Africa. Lack of knowledge, inadequate harvesting techniques, poor infrastructure, and inefficient harvest management practices are considered critical contributors to the losses. The magnitudes and causes of rice harvest losses are now better understood than interventions, which have simply been presented but lack an assessment of the effects and a cost–benefit analysis. Interestingly, reduction in harvest losses may threaten some farmers' profits, such as rural women who make their living from post-production manual operations. Considering the current status of the literature, future researchers should examine how to balance social and individual welfare since farmers are key stakeholders in intervention implementation. A good understanding of the existing researches can help clarify future efforts for loss reduction, thereby reducing the burden of increasing agricultural production and promoting sustainable development of resources and the environment.

Keywords: farming; review; harvest loss; farm loss

Citation: Qu, X.; Kojima, D.; Wu, L.; Ando, M. The Losses in the Rice Harvest Process: A Review. *Sustainability* **2021**, *13*, 9627. https://doi.org/10.3390/su13179627

Academic Editor: Riccardo Guidetti

Received: 30 June 2021
Accepted: 19 August 2021
Published: 26 August 2021

1. Introduction

According to the Food and Agriculture Organization of the United Nations (FAO), food production will have to increase by 70% to feed the world's projected 9.1 billion population by 2050 [1]. For a long time, the dominant view for improving future food supply has been to increase food production; however, this would not achieve the world's growing agricultural demand in an environmentally sustainable manner [2]. Agriculture imposes huge resource and environmental costs in terms of land, water, and greenhouse gas emissions, among others [3]. Research has identified significant food wastage (both food loss and food waste). Thus, reducing food wastage is a critical way to increase the food supply [4–7] without incurring substantial environmental costs [8].

Vast amounts of resources are used to produce, process, and transport food. If this food does not end up being consumed, the resources embedded in the process are wasted and cause environmental degradation [2,9–11]. It is estimated that nearly a quarter of the water, arable land, and fertilizer used globally for food crop production is associated with food wastage [6]. In 2010, China's food waste accounted for more than 10% of the country's total water use [12]. Such a loss in China means about 26.11 million hectares of land were used in vain, which is equal to Mexico's total arable land [13]. With global food wastage causing 3.3 Gtonnes of carbon dioxide emissions, if regarded as a country, food wastage would be the third top emitter, after the United States and China [14]. Reducing food wastage not only increases the food supply and reduces pressure to increase production, but also saves resources and reduces environmental damage. After the food crisis of the early 1970s, preventing food wastage has been widely recognized as a solution to the world's food problems [15,16]. In 2015, the United Nations stated the following aim: "by 2030, halve the per capita global food waste at the retail and consumer level, and reduce food losses along production and supply chains including post-harvest losses" [17]

Food wastage occurs at every stage from the farm to the fork, including in production, reaping, processing, transportation, marketing, and consumption [18–21]. The mechanisms of food wastage differ at each stage. A distinction is therefore made between food loss, which occurs at the front end of the supply chain (mainly at production and distribution levels), and food waste, which occurs at its back end (mainly at the consumption level) [22,23]. Specifically, food loss refers to "a decrease in mass (dry matter) or nutritional value (quality) of food that was originally intended for human consumption," while food waste means "food appropriate for human consumption being discarded, whether or not after it is kept beyond its expiry date or left to spoil" [14] (pp. 8–9). Food loss is dominant in developing countries because it is mainly caused by technical limitations, such as inadequate harvest techniques, poor infrastructure and logistics, lack of storage facilities, and insufficient skills and management [14,24,25]. The proportion of food waste is low in developing countries because consumers buy food as needed [22] and waste is not socially acceptable owing to the relatively high poverty levels [21]. In contrast, agricultural systems in developed countries are more efficient, with better transportation infrastructure and more effective storage facilities, resulting in a lower proportion of food loss [26]. However, food waste is more serious in these countries owing to consumers' excessive consumption habits or high standards of food selection [24,27]. Some fast-growing transition countries, such as China, have recorded high loss and waste at both the front and back ends of the value chain [4].

Owing to differences in definitions and measurement methods [28], the exact magnitude of food loss and waste remains uncertain [29,30]. Estimates vary substantially according to crop, stage in the value chain, region, and so on [20,31]. Therefore, global estimates of loss and waste that ignore these heterogeneities are questioned [31,32]. Estimating the food loss and waste over a wide range (e.g., across regions or supply chain stages) is difficult and meaningless as reduction interventions need to be adapted to regions, stakeholders, and local contexts [2]. As mentioned earlier, developing countries suffer more food losses than food waste. The reduction in income due to food losses is a great threat to farm households in these countries that are already on the verge of food insecurity. Reducing food losses in developing countries is more urgent. Therefore, this study reviewed the researches on food loss while restricting the crops to rice, the stakeholders to farmers, and the supply chain stage to the harvesting process.

As one of the world's three leading food crops, rice feeds almost half of the world's population, making it the most consumed cereal grain [33], especially in low- and lower-middle-income countries [34]. Among rice farmers, processors, and marketers, rice farmers experience the highest loss [35,36]. Losses on farms reduce farmers' incomes, and for farmers in low-income countries living on the edge of hunger, these losses are closely associated with food insecurity [37,38]. Most of the produce is lost during post-harvest handling and on-farm storage [7,22]. The harvest marks the beginning of the cereal supply chain [27] and is the decisive step in determining the yield quality [39] and the subsequent storage quality [40]. The proportion of cereal lost during the harvest process is higher than farm losses at other stages [41], with most farmers losing a considerable amount of cereal during this process [42]. However, over 80% of existing studies focus specifically on on-farm storage loss [29], which means less attention has been paid to losses during the harvest process.

Harvesting operations occur on the field and consist of cutting the stalks or reaping the panicles and bundling for transportation [36]. Cutting or reaping is done by knife, serrated sickle, paddy mower, reaper, or combine harvester [43]. In developing countries, harvesting is mainly done using traditional hand tools (i.e., knife and serrated sickle) [38,39], which are considered inefficient practices [44]. Traditional practices were considered ineffective, not because of the clear evidence of high loss, but because they were distinguished by "ancient" activities uninfluenced by contemporary technology [16]. Harvest loss mainly manifests as physical loss [45]. When cutting or reaping the straws, grains may be scattered across the field, plowed into the soil, and eaten by birds and rodents [23]. However, Qu and colleagues [45] noted that the use of combine harvesters weakens the delineation between the post-processing stages of rice (i.e., reaping, threshing, and winnowing) compared to manual operations, making it difficult to strictly distinguish the losses that occur at these stages. Therefore, they defined the process from field reaping to on-farm storage places as the harvesting process and estimated the harvest loss during this process divided into four stages: reaping, threshing, winnowing, and field transportation. Consequently, the studies on rice harvest loss we reviewed are not only limited to reaping loss, but also include threshing, winnowing, and field transportation loss. Threshing is the process of removing the paddy kernels or grains from the panicles [36,39]. This operation could be done by trampling, banging, pedal thresher, power thresher, and combine harvester [43]. Threshing loss refers to grains remained on the panicles or scattered on the threshing floor [45]. After threshing, the immature grains, rice straw, stones, sand, chaff, and other foreign materials are removed from the threshed paddy by sieving or wind [46], during which paddy may also be removed, resulting in winnowing loss [38]. Field transportation refers to transferring the grain from the field or winnowing places to warehouses, and loss may be caused by spillage [39,45].

Reducing food losses as another crucial way of increasing food supply in addition to increasing production can be beneficial to resource sustainability by not increasing resource inputs and by saving resources already invested. The overarching goal of this review is to analyze the existing researches on rice harvest loss, including the loss that occurs during reaping, threshing, winnowing, and field transportation. We focused on the estimating techniques of harvest loss as well as its extent, causes, effects, and interventions. Overall, this review summarizes the current status and shortcomings of existing rice harvest loss researches and identifies future efforts for loss reduction. In the remainder of this review, we first introduce the method of this research. We then present the main findings. Lastly, we identify the key knowledge gaps and possibilities for future research.

2. Materials and Methods

We reviewed the researches on rice harvest loss by accessing both peer-reviewed articles and national and international reports (e.g., FAO and World Bank) through multiple major databases (e.g., Web of Science, Google Scholar, Scopus, Semantic Scholar, and China National Knowledge Infrastructure), though peer-reviewed articles were preferred. Searched keywords included "food loss" OR "food waste" OR "grain loss" OR "grain waste" OR "crop loss" OR "crop waste" OR "rice loss" OR "harvest loss" OR "post-harvest loss" OR "lost food". Strictly speaking, losses during harvesting are post-production rather than post-harvest losses. However, harvesting is often considered the starting point of the post-harvest management process, and existing studies do not strictly distinguish these stages, so we use "postharvest" for retrieval. In addition, we performed supplemental searches for additional sources by reviewing article bibliographies. The last search was performed in August 2021.

Articles were screened for eligibility using the following inclusion criteria: (1) published in English or Chinese; (2) published in the social sciences rather than the natural sciences or engineering; and (3) estimated the food loss rather than the food waste; (4) estimated the rice harvest loss (or reaping loss, threshing loss, winnowing loss, and field transportation loss) or corresponding causes, impacts, and interventions. After removal of duplicates and the above four inclusion criteria, we then excluded unrelated articles by scanning the titles and abstracts and full-text reading. Finally, we screened 64 studies, including 37 studies that estimated rice harvest losses (Table 1).

3. Results

3.1. Estimation Methods

The first step in reducing losses is to estimate the magnitudes in each stage. Post-harvest losses in rice may be quantitative or qualitative. Quantitative losses result in weight or volume reduction in the potential yield, while qualitative losses result in a reduction in the value of the usable rice owing to physical and chemical changes, such as poor appearance, poor taste, and unpleasant odor [35]. Nonetheless, harvest losses are usually measured as actual physical losses (i.e., quantitative losses). This is partly because qualitative losses are more difficult to measure than quantitative ones [47], and partly because there is often not enough quality awareness to distinguish between grades of rice before it reaches the formal market [48].

Existing studies have taken two main approaches to estimate harvest losses: either by direct measuring what is lost or by using questionnaires to obtain subjective estimates from rice farmers [4]. Direct measurement of losses is usually done by conducting rice harvest experiments in the field and then collecting and weighing the lost rice [49]. Before conducting the experiment, rice losses at each stage need to be clearly determined. The assessment of rice losses from reaping, threshing, winnowing, and field transportation in field experiments is discussed below.

3.1.1. Rice Loss during Reaping

Reaping is done by manual or mechanical methods, and the form of loss varies depending on the harvesting method. There are usually two harvesting methods: combine harvesting (i.e., head-feed and whole-feed) and segmented harvesting (manual reaping and reaper plus manual threshing or thresher) [45]. Alizadeh and Allameh [50] referred to them as indirect harvesting and direct harvesting, respectively. When using segmented harvesting, the losses in the reaping stage include scattering loss and uncut loss [48,51,52]. Scattering loss occurs when rice grains fall in the field as a result of touching or other external forces owing to the influence of various aspects such as harvesting method, crop variety, and maturity when cutting the straw or panicle. Uncut loss occurs when the straw or panicle is not cut because of careless working, lodging, and other reasons. To determine the scattering loss and uncut loss, grains on the ground and the uncut straw or panicle in the sample frame (1 m $\times$ 1 m or other sizes) or experimented plots are collected and weighed [50,51,53]. If the cut straw directly moves to the next threshing operation, then the reaping loss is limited to the description above. However, in some regions, the cut straw is laid in the field for a few days before threshing and bundled for transportation to the homestead or threshing yard [54]. The grains that fall into the field during these days also count as the loss during reaping, or, in other words, stacking loss and bundling loss [55,56]. To assess these losses, plastic sheets are placed under the grain stacks, and the grain that falls on the sheets is collected later for counting [48,53,57].

When using combine harvesters, there is no stacking loss or bundling loss—only scattering loss and uncut loss. Since these harvesters complete the following threshing and winnowing operations at once, the loss here also includes the threshing and winnowing losses described below [50]. Although Hasan and colleagues [58] considered combine harvesting loss to also include cutter bar loss and cylinder loss, they only estimated the total loss. After the completion of combine harvesting, suitable sample frames (1 m $\times$ 1 m or other sizes) are randomly selected in the harvested fields. To estimate the loss, the dropped grains in the field and uncut straws from the sample area are collected and weighed for counting [50,56].

3.1.2. Rice Loss during Threshing

Threshing could also be done by manual or mechanical methods. Manual threshing is done by the grain flail and threshing board or rack in Bangladesh [36], bag-beating and "bambam" (a wooden box) in Ghana [59], and pedal thresher in China [43]. Mechanical threshing employs power threshers and combine harvesters [43,60]. Regardless of the method, losses during threshing are broadly divided into scattering loss and unthreshed loss [48,51]. Manual or mechanical efforts to separate paddy from panicles can result in scattered or spilled rice, leading to scattering loss. After threshing, the rice grains that fall outside the plastic sheets or wooden boxes are collected and weighed [51,59]. Unthreshed loss refers to the grain remaining on the seed head. Assessment of this remaining grain can be done by taking a random sample of straws after threshing and separating the grains on the straws and weighing them [48,51,57,61].

3.1.3. Rice Loss during Winnowing

Loss during winnowing refers to the grain discarded with the straw and external impurities. A suitable sample of straws after winnowing is taken, and the grains blown away with the straw are separated and weighed [56].

3.1.4. Rice Loss during Field Transportation

Losses during transportation in the field are mainly owing to broken packaging, which causes grains to fall to the ground. Measuring losses during transportation requires careful collection of scattered grains or weighing of grain bags at both the start and end of the transportation process [48,53].

Estimates from direct measurements may be more accurate but are time- and resource-consuming [62]. Another commonly used estimation method is the questionnaire survey. Farmers experiencing losses are surveyed using a carefully designed structured questionnaire to elicit their estimates [4]. The accuracy of farmers' self-report data may be questioned compared to direct measurements. However, there is no actual evidence that farmers' measurement errors are larger than the errors in other estimates. Thus, farmer self-reports obtained based on well-designed questionnaires are considered reliable estimates [20]. However, Kannan [63] believed that farmer estimates may be subjective and are best validated by experts. In addition, some estimation methods are rarely used, such as direct observation [54] and modeling [62], which were not observed in the studies we reviewed.

3.2. Magnitude of the Harvest Loss

It is difficult to present a definite figure on rice harvest losses owing to differences in regions, harvesting methods, and varieties, among others. Even in the same region, there can be significant differences by season. Therefore, it is not realistic to describe rice harvest losses with a single figure. The estimation of losses then requires a situation-specific analysis [54]. Thus, rather than attempting to derive an exact loss figure from the reviewed studies, we attempted to determine some characteristics of these data.

Table 1. Harvest losses in some countries and regions.

Countries or Regions		Harvest Losses	Citation(s)
Africa	Nigeria	Quantitative loss: 4.84–9.73% Economic loss: 230.11 billion naira	[37,38,51,64]
	Ghana	Quantitative loss: 3.57–16.14% Economic loss: 64.79 GH₵	[59,60,65,66]
	Sub-Sahara Africa	Quantitative loss: 7.9–13.1%	[67]
	Egypt	Quantitative loss: 1.35–2.49%	[53]
Asia	India	Quantitative loss: 1.60–5.95 kg/quintal; 2.88–3.60%	[56,68–75]
	China	Quantitative loss: 1.23–5.5%	[45,52,55,76–80]
	Bangladesh	Quantitative loss: 1.61–6.95%	[36,57,58,61,81,82]
	Iran	Quantitative loss: 2.26–2.58% Qualitative loss: 0.47–2.44%	[50]
	Myanmar	Quantitative loss: 16.0–28.2% (wet season); 0.9–9.3% (dry season)	[49,55]
	Thailand	Quantitative loss: 1.1–9.3%	[55]
	Indonesia	Quantitative loss: 8.26–8.83%	[83]
	Democratic Republic of Timor-Leste	Quantitative loss: 10.15% Economic loss: USD 9100	[54]
North America	Dominican Republic	Quantitative loss: 12.27–24.82%	[84]

Note: See Appendix A Table A1 for more details.

Table 1 presents the ranges of harvest losses for some countries or regions. Among the studies we reviewed, only one was conducted in North America [84], while the rest examined the Asian and African regions, with more than 70% focused on Asia. Most studies expressed the magnitude of quantitative loss as a percentage, and a few used the absolute weight of loss [37,68,69] and market value [38,54,60], while only one study measured qualitative losses [50]. The losses in reaping and threshing are larger than those in winnowing and field transportation [51,64].

Preliminary data obtained from rice harvesting trials indicate absolute loss in terms of the actual weight of grains. A more common form of quantitative loss is percentage loss [85], which makes comparisons easier [45]. However, different studies calculated the loss percentage with different denominators. Some used the remaining amount in the previous stage as the denominator [85], while others chose the final weight of collected grains at the present stage as the denominator [51,59]. In some, potential yield—the sum of final collected grain and losses—was used as the denominator [45]. However, even if the expressions for losses are the same, losses from different studies, conducted in different regions, seasons, and varieties, cannot be compared [59]. We can still see that most countries or regions in Table 1 have a harvest loss rate of less than 10%.

Traditional manual operations are inefficient [44], which could cause higher losses. The loss due to the use of combine harvesters is smaller than that caused by manual reaping and threshers in Egypt [53]. Similar results were found in Bangladesh [58], Myanmar [49], Dominican Republic [84], and Thailand [55]. However, some findings were contrary. Amusat and colleagues [51] found that mechanical operation causes higher losses at all three stages of reaping, threshing, and winnowing in Nigeria. In particular, threshing loss due to mechanical threshing is more than twice that caused by manual threshing. This is consistent with the findings of the questionnaire survey by Basavaraja and colleagues [74]. Several studies in China, including two field trials [52,79], one farmer survey [45], and a three-year International Development Research Centre survey [55], indicated that losses due to combine harvesting are higher than the total losses from segmented harvesting.

Compared to manual operation, harvesting loss due to combine harvester use is not only influenced by mechanical performance, but also by operators' skill and the land terrain. Operators of combine harvesters may speed up the process to increase the area harvested per unit of time, leading to a high number of uncut plants and thus increasing the loss [77,81]. Since combine harvesters cannot work effectively on land with excessive surface undulations, poor plot topography can greatly affect the work of the machinery [47]. Rice lodging can also make mechanical harvesting difficult and lead to increased losses [79]. However, a rice harvesting trial in Iran by Alizadeh and Allameh [50] showed that there was no significant difference in quantitative loss between combine and segmented harvesting, while the qualitative loss owing to broken, husked, and cracked grains was significantly less in combine harvesting. If the losses due to manual and mechanical operations are compared in one particular stage, the reaping loss caused by reaper use is greater than that by manual reaping in Bangladesh [81], and the threshing loss caused by mechanical threshing is higher than that by manual threshing in Nigeria [51], India [74], Bangladesh [82], and China [55]. However, the winnowing loss due to mechanical winnowers is less than that due to manual operations [70].

Even in manual operation, the loss varies with different methods. Field experiments showed that the reaping loss due to panicle harvesting (1.38%) was less than that due to sickle harvesting (2.93%) [59,66]. Threshing loss was higher using "bambam" than bagging [59,60,66]. Transportation loss also varied by transportation method [63,68,69,76].

Furthermore, it was evident from the available researches data that losses varied with rice varieties, harvesting season, and farm size. High-yield varieties incur greater losses than local varieties in reaping, threshing, and winnowing [69], causing an unfortunate trade-off for farmers [20]. High yields increase the pressure of reaping and threshing operations owing to increased yields, especially when there is a lack of machinery. Additionally, the thin husk and shells of high-yield rice make it more vulnerable to damage during the harvesting process [61]. Early or delayed harvesting can lead to higher loss [71,73]. Overall, the average harvest loss was smaller for large-scale farmers than for small-scale farmers [68,70,80].

3.3. Causes of Harvest Loss

Some studies used questionnaires to directly inquire farmers' understanding of the causes of rice harvest losses [37,47,65,86]. Multiple regression analyses were also applied to estimate the influencing factors of the losses [45,74,77,80,82]. Factors that contribute to harvest losses include environmental, socio-economic, and mechanical [65].

The most important aspect of crop production is the time: excessively early or late harvesting can lead to increased losses [87]. If harvested too early, immature grains can make threshing difficult, resulting in more unthreshed loss [88]. Delayed harvesting may also cause substantial loss owing to shattering and extended exposure to natural incidents, such as attacks by birds and other pests [49,58,59], which is in line with farmers' perspectives [47]. Regression analyses in China confirmed that harvesting in time could reduce harvest loss [77].

A large family could reduce the drudgery involved in harvesting activities and thus reduce harvest losses [89]. Manual harvesting is highly labor-intensive and tedious [90]. If there is not enough labor or access to proper harvesting machinery, the mature rice cannot be harvested in time, causing massive losses [7,39,49,54,87]. The significance of this factor was confirmed in the regression analysis [45,74,77,82].

Farm size also affects the magnitude of losses. Some studies concluded that large-scale farms record smaller losses per unit area than small-scale farms owing to the use of machinery in China [77] and Bangladesh [82]. However, the opposite results have also been observed in India [74].

Losses are sometimes a result of farmers' choices. For example, harvest losses are often greater using machinery than manual operations. However, owing to the lack of sufficient agricultural labor, farmers will not forgo the use of machinery or other faster harvesting methods to reduce losses owing to the growing labor cost, especially for large-scale farmers [59]. Soybean farmers in Brazil increase the forward speed of harvesters to maximize profits by harvesting earlier in the first season to leave time for the second season, although they are clearly aware of the higher losses involved [91].

3.4. Impact of Harvest Loss

The most straightforward impact of rice harvest losses is a reduction in the amount of edible rice, resulting in economic losses and threatening poor people's livelihoods, especially in less-developed countries [54,90,92]. Farmers believe rice harvest losses threaten their food security and thus lead to poverty [47]. In Bangladesh, Begum and colleagues [82] explored the impact of rice harvest loss on farmers' household food security using logistic regression analysis and found that harvest loss has negative and significant relationships with households' probability of food security. Multiple regression analyses showed that rice threshing losses had a significantly negative impact on farmers' income in Nigeria [37].

The impact of these losses on the resource environment has been much discussed. However, there are few specific measurements of the environmental and resource impacts. In Nigeria, the loss of rice from production to milling results in the waste of 2.1 million m^3 of water, 0.5 million hectares of land, and the emission of about 0.65 million tons of carbon dioxide equivalent per year [64]. The loss of rice from reaping to milling in Myanmar leads to an increase in greenhouse gas emissions of about 30–50% per hectare of rice production [49].

3.5. Interventions

Based on the above discussion, some common interventions targeting the reduction in rice harvest losses include improving infrastructure, introducing advanced machinery and equipment, timely harvesting, providing training to farmers, and strengthening pest and disease management [63,72–74,93]. However, proposing interventions is only the first step: What is more important is whether the interventions can be effectively implemented by farmers [7,19], whether they have significant effects [19,20,92,94], and whether cost-benefit analysis presents important results [19,20,47].

Loss interventions should be designed from the perspective of farmers' profits. Whether farmers adopt new technologies and invest in loss reduction is primarily motivated by maximizing household profits, not production [20,44,61]. Although the results of some studies showed that losses in manual operation are lower, this does not mean that manual handling should be encouraged, because if manual operation is delayed owing to the lack of labor, it may lead to greater losses. As farm labor becomes scarce, harvesters and threshers, or combine harvesting, must be used. There is a trade-off between the need for mechanization and its associated higher losses [59]. Soybean farmers in Brazil derive additional time for second season production by harvesting the first season crop quickly [91]. If farmers are persuaded to reduce their harvesting speed to reduce losses, they may not be receptive because it would reduce their profitability. Hybrids and high-yield varieties are more likely to lead to post-harvest losses [20], but this does not mean farmers will abandon them to reduce the rate of loss.

Thus, the extent to which interventions will reduce losses is of concern. Gao and colleagues [76] assumed that by increasing the proportion of combine harvesting, bulk transportation, mechanical drying, and depot storage in China to 100%, the total losses in rice reaping, transportation, drying, and storage can be reduced from 6.9% to 2.6%. Huang and colleagues [79] assumed that if the harvest loss rate of rice combine harvesting in China reaches 3%, the total loss rate of rice reaping, threshing, winnowing, and field transportation can be reduced from 3.02% to 2.76%, saving 540,000 tons of rice, 78,000 ha of land, and 26,000 tons of chemical fertilizer; if all the rice farmland is high standard type, the total loss rate can be further reduced to 2.08%. However, interventions can have other effects besides reducing losses. Rosegrant and colleagues [19] found that increased infrastructure inputs are beneficial in reducing losses, improving social welfare, and have a positive economic rate of return, but the fall in agricultural prices owing to increased food supply can cause producers to experience a loss of benefits. The promotion of mechanical operations will replace labor [94] and thus may threaten the livelihood of farmers who previously depended on manual post-production operations. In Bangladesh, the increased use of mechanical rice milling means would lead to loss of jobs for women previously engaged in manual milling [16]. Ensuring that most participants benefit from mitigation strategies is a challenge to reducing food losses [2].

A cost–benefit analysis of interventions is necessary because any solution should not be more expensive than the lost food itself [54,59]. However, few such analyses have been conducted. Gummert and colleagues [49] argued that higher mechanization increases net income by 30–50%. Hasan and colleagues [58] also indicated that using combine harvesters saves 57.61% costs compared to manual harvesting; however, combine harvesters need to harvest more than 35 hectares per year to be profitable. The 10-year savings from loss reduction due to the introduction of threshing machines in the Democratic Republic of Timor-Leste (approximately USD 33,200) were higher than the associated intervention costs of USD 14,000 [54].

4. Conclusions

Rice is the most essential cereal crop for consumption. More than 3 billion people rely on rice as a staple food [95]. Post-production losses reduce the available quantity of edible rice, causing a huge waste of resources and threatening the food security of farmers. This study reviews the existing research on losses during rice harvesting processes from the field to storage places, including the reaping, threshing, winnowing, and field transportation stages. We focused on the losses in terms of estimation methods, magnitudes of loss, causes of loss, impacts, and interventions.

The measurement of harvest losses is a complex issue. Currently, the main estimation methods are field trials and questionnaires. Field trials are time-consuming and labor-intensive but accurate, and can be designed to compare the losses of different rice varieties and operation methods; however, the estimates are different owing to differences in post-production operations. For example, reaping, threshing, and winnowing losses of combine harvesters cannot be calculated separately. Meanwhile, questionnaire surveys are easy to implement. Although their accuracy has been questioned, farmers' self-reports are still a good source of estimation in the absence of field data. Farmers' perceptions of losses are important because they influence the implementation of subsequent interventions. Only when farmers are aware of the severity of losses will they be willing to adopt mitigation measures.

The loss data from case studies are more effective than those on a global scale. It is difficult to describe rice harvest losses in one specific number because they vary by region, season, variety, post-harvest handling methods, and so on. Much more research has been done on quantitative loss than on qualitative loss. Overall, losses in the reaping and threshing stages were much greater than in winnowing and field transportation. Most of the loss data were presented as a percentage of production, with a few presented as absolute losses and values per unit area. When losses are estimated in percentage form, it should be clear whether the denominator is the actual or potential production or the amount obtained at a given stage, but this detail is not explained in some studies. There is no consistent conclusion as to whether the loss in mechanical operation is greater or less than that in manual operations, which may be related to the study site context. Overall, the loss rate was greater for high-yield rice than for local varieties and for large-scale farmers than for small-scale ones.

The general perception is that lack of knowledge, inadequate harvesting techniques, poor infrastructure, and inefficient harvest management practices are crucial causes of rice harvest losses. These losses not only result in less edible food and reduced income, but also have adverse impacts on the environment and resources. Many interventions have been proposed in the literature, such as improving infrastructure and increasing mechanization rates. However, few studies have conducted in-depth analysis on the effects and cost–benefit ratios of the interventions.

Increasing food supply by reducing losses can reduce the burden of increasing agricultural production, thus reducing the environmental and resource pressure on agricultural production and achieving sustainable development. The literature review helped to clarify the current research status and the direction of future reduction efforts. The review concluded that the magnitude and causes of rice harvest losses are well understood to some extent and that what is more important is the evaluation of the cost-benefit ratios, the effect of interventions, and whether the interventions will have other impacts besides loss reduction. For example, the reduction in prices owing to increased food supply may harm farmers' profits, and the promotion of machinery may lead to unemployment of farmers dependent on post-production manual work for their livelihood. Therefore, how should interventions be implemented if there is a trade-off between loss reduction and farmers' welfare? These are much more important to examine after presenting interventions. In addition, only the harvesting loss was examined in this study; other stages of the supply chain are also critical to loss reduction, which will be left for future research.

Author Contributions: Conceptualization, X.Q. and D.K.; investigation, X.Q., D.K. and L.W.; data curation, X.Q.; software, X.Q.; writing—original draft preparation, X.Q.; writing—review and editing, D.K., L.W. and M.A.; funding acquisition, L.W. and M.A.; All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the 2015 special scientific research project of grain public welfare industry—"Investigation and evaluation of rice harvest loss" (IERHL, 201513004-2), by JSPS KAKENHI Grant Number JP19H03063, and by the scholarship from China Scholarship Council (CSC) under the Grant code-CSC201906350150.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Conflicts of Interest: The authors declare no conflict of interest.

Appendix A

Table A1. Estimations of rice harvest loss.

Method	Date	Region(s)	Magnitude	Citation(s)
Field experiments	2014–2015	Nigeria	Bag-beating: reaping (1.56%), threshing (2.27%), winnowing (1.01%) Bambam: reaping (1.77%), threshing (4.15%), winnowing (1.26%) Machinery: reaping (1.90%), threshing (5.96%), winnowing (1.47%)	[51]
Field experiments, questionnaire	—	Nigeria	Reaping: 4.42%, threshing and winnowing: 4.97%, transportation from field to home: 0.34% Danbaba and colleagues [38] used the above estimation and the 2016 paddy production in Nigeria to calculate the corresponding rice quantity and quality losses: Reaping: 0.78 million metric tons; 104.66 billion naira Threshing and winnowing: 0.87 million metric tons; 117.42 billion naira Transportation from field to home: 0.60 million metric tons; 8.03 billion naira	[38,64]
Questionnaire	2014	Nigeria	Reaping: 0.15 kg per farmer, threshing: 0.25 kg per farmer, winnowing: 0.15 kg per farmer	[37]
Questionnaire	—	Ghana	Farmers' perceptions about harvesting loss 53.7% of farmers thought: 0–9% 36.11% of farmers thought: 10–19% 10.19% of farmers thought: 20–29%	[65]
Field experiments, questionnaire		Ghana	Farmers' perceptions about the total post-harvest loss (from harvesting to milling): 35% of farmers thought: over 40% 35% of farmers thought: 30–39% 15% of farmers thought: 20–29% 10% of farmers thought: 10–19% 5% of farmers thought: 0–9% Harvesting loss at 4*5-m area of rice field experiments: Nerica 1 by panicle: 6450 g (1.13%) Nerica 2 by panicle: 6409 g (1.64%) Average loss of Nerica 1 and 2 by panicle: 6430 g (1.38%) Nerica 1 by sickle: 6925 g (3.25%) Nerica 2 by sickle: 7443 g (2.62%) Average loss of Nerica 1 and 2 by sickle: 7184 g (2.93%) Average loss of Nerica 1: 6688 g (2.10%) Average loss of Nerica 2: 6926 g (2.33%) Threshing loss at 4*5-m area of rice field experiments: Nerica 1 by bag-beating (panicle): 3.98% Nerica 2 by bag-beating (panicle): 0.92% Average loss of Nerica 1 and 2 by bag-beating (panicle): 2.45% Nerica 1 by Bambam (sickle): 5.33% Nerica 2 by Bambam (sickle): 6.96% Average loss of Nerica 1 and 2 by Bambam (sickle): 6.14% Average loss of Nerica 1: 4.65% Average loss of Nerica 2: 3.94% Harvesting and threshing loss at farmers' fields: Farmer 1 (Nerica): harvesting loss (Sickle): 382 g (7.91%); threshing loss (Sac beating): 35 g (0.73%); total loss: 8.65% Farmer 2 (Nerica): harvesting loss (Sickle): 135 g (12.05%); threshing loss (Sac beating): 50 g (4.07%); total loss: 16.14% Farmer 3 (Nerica): harvesting loss (Sickle): 198 g (2.60%); threshing loss (Sac beating): 211 g (3.00%); total loss: 5.60% Farmer 4 (Sikamo): harvesting loss (Sickle): 299 g (8.20%); threshing loss (Sac beating): 144 g (3.73%); total loss: 11.93% Farmer 5 (Nerica): harvesting loss (Sickle): 177 g (3.03%); threshing loss (Sac beating): 36 g (0.53%); total loss: 3.57%	[59,66]

Table A1. *Cont.*

Method	Date	Region(s)	Magnitude	Citation(s)
Field experiments		Nobewam (Ghana)	Qualitative threshing loss: Variety 1: by Bambam (14.3%); by drum (13.8%); by sack (12.8%) Variety 2: by Bambam (12.8%); by drum (15.5%); by sack (10.0%) Average loss of variety 1 and 2: by Bambam (13.49%); by drum (14.65%); by sack (11.37%) Economic threshing loss (GH₵): Variety 1: by Bambam (81.2); by drum (78.7); by sack (72.6) Variety 2: by Bambam (72.6); by drum (88.4); by sack (57.0) Average loss of variety 1 and 2: by Bambam (76.86); by drum (83.51); by sack (64.79)	[60]
Field experiments	2018	Sub-Sahara Africa	Shattering loss during reaping: 2.8% Stacking loss after reaping and before threshing: 4.2% Manual threshing: unthreshed loss (1.9% $\pm$ 1.3%), scattered loss (1.6% $\pm$ 1.3%)	[67]
Field experiments	—	Egypt	Manual reaping and tractor threshing: 2.49% Manual reaping and local thresher: 2.03% Combine harvesting: 1.35%	[53]
Field experiments	2013	India	Reaping: 2.08% $\pm$ 0.79%, collection (including stacking, bundling and transportation up to threshing floor): 0.37% $\pm$ 0.29%, threshing: 1.44% $\pm$ 0.39%, winnowing/cleaning: 0.5% $\pm$ 0.5%	[56]
Questionnaire	2010–2012	West Bengal (India)	Harvest loss: 17.45 kg/acre; 0.78 kg/quintal; 0.78% of harvest amount Mechanical threshing loss: 7.04 kg/acre; 0.31 kg/quintal; 0.31% of threshed amount Manual winnowing loss: 2.94 kg/acre; 0.13 kg/quintal; 0.13% of winnowed amount Transportation loss: head load (0.04 kg/quintal; 0.04% of amount transported), bullock cart (0.34 kg/quintal; 0.34% of amount transported), trolley (0.43 kg/quintal; 0.43% of amount transported), tempo (0.15 kg/quintal; 0.15% of amount transported) Harvest loss by farm size: Marginal size: 0.96 kg/quintal; small size: 0.85 kg/quintal; medium size: 0.74 kg/quintal; large size: 0.58 kg/quintal Average of four sizes: 0.78 kg/quintal Threshing loss by farm size: Marginal size: 0.46 kg/quintal; small size: 0.34 kg/quintal; medium size: 0.28 kg/quintal; large size: 0.23 kg/quintal Average of four sizes: 0.32 kg/quintal Winnowing loss by farm size: Marginal size: 0.20 kg/quintal; small size: 0.15 kg/quintal; medium size: 0.12 kg/quintal; large size: 0.10 kg/quintal Average of four sizes: 0.13 kg/quintal Transportation loss by farm size: Marginal size: 0.71 kg/quintal; small size: 0.61 kg/quintal; medium size: 0.52 kg/quintal; large size: 0.39 kg/quintal Average of four sizes: 0.55 kg/quintal	[68]

Table A1. *Cont.*

Method	Date	Region(s)	Magnitude	Citation(s)
Questionnaire	2011–2012	Assam (India)	Manual harvest loss (early season): Local paddy: 10.83 kg/hectare; 0.25 kg/quintal; 0.25% of harvest amount HYV paddy: 15.89 kg/hectare; 0.59 kg/quintal; 0.59% of harvest amount Manual harvest loss (mid-season): Local paddy: 12.89 kg/hectare; 0.40 kg/quintal; 0.40% of harvest amount HYV paddy: 25.57 kg/hectare; 0.56 kg/quintal; 0.56% of harvest amount Manual harvest loss (late-season): Local paddy: 16.42 kg/hectare; 0.98 kg/quintal; 0.98% of harvest amount HYV paddy: 54.69 kg/hectare; 0.96 kg/quintal; 0.96% of harvest amount Threshing loss (average of manual and mechanical): Local paddy: 0.45 kg/hectare; 1.04 kg/quintal; 1.04% of threshed amount HYV paddy: 0.99 kg/hectare; 1.50 kg/quintal; 1.50% of threshed amount Winnowing loss (average of manual and mechanical): Local paddy: 0.43 kg/hectare; 1.01 kg/quintal; 1.01% of threshed amount HYV paddy: 0.85 kg/hectare; 0.96 kg/quintal; 0.96% of threshed amount Transportation loss from field to homestead: head load (1.38 kg/quintal; 1.38% of amount transported), bullock cart (0.00 kg/quintal; 0.00% of amount transported), trolley (1.85 kg/quintal; 1.85% of amount transported), tempo (0.00 kg/quintal; 0.00% of amount transported), mini truck (1.90 kg/quintal; 1.90% of amount transported), hand cart (1.57 kg/quintal; 1.57% of amount transported). Total (1.67 kg/quintal; 1.67% of amount transported) Harvest loss by farm size: Marginal size: 0.48 kg/quintal; small size: 0.58 kg/quintal; medium size: 0.62 kg/quintal; large size: 0.81 kg/quintal Average of four sizes: 0.62 kg/quintal Threshing loss by farm size: Marginal size: 0.91 kg/quintal; small size: 0.98 kg/quintal; medium size: 1.41 kg/quintal; large size: 1.78 kg/quintal Average of four sizes: 1.27 kg/quintal Winnowing loss by farm size: Marginal size: 0.79 kg/quintal; small size: 0.88 kg/quintal; medium size: 1.02 kg/quintal; large size: 1.22 kg/quintal Average of four sizes: 0.98 kg/quintal Transportation loss by farm size: Marginal size: 1.30 kg/quintal; small size: 1.49 kg/quintal; medium size: 1.79 kg/quintal; large size: 2.11 kg/quintal Average of four sizes: 1.67 kg/quintal	[69]

Table A1. *Cont.*

Method	Date	Region(s)	Magnitude	Citation(s)
Questionnaire	2011–2012	Karnataka (India)	Harvest loss (including combine harvester and manual harvesting): Early season: 33.2 kg/acre; 1.74 kg/quintal; 1.74% of harvest amount Mid-season: 37.4 kg/acre; 1.92 kg/quintal; 1.92% of harvest amount Late-season: 41.4 kg/acre; 1.86 kg/quintal; 1.86% of harvest amount Total: 37.1 kg/acre; 1.90 kg/quintal; 1.90% of harvest amount Manual threshing loss: 21.92 kg/acre; 1.24 kg/quintal Mechanical threshing loss: 25.37 kg/acre; 1.16 kg/quintal Manual winnowing loss: 20.21 kg/acre; 1.14% of winnowed amount Mechanical winnowing loss: 8.33 kg/acre; 0.46% of winnowed amount Transportation loss (from field to homestead or market): head load (0.38 kg/quintal; 0.38% of amount transported), bullock cart (0.62 kg/quintal; 0.62% of amount transported), trolley (0.64 kg/quintal; 0.64% of amount transported), truck (0.80 kg/quintal; 0.80% of amount transported). Total (0.64 kg/quintal; 0.64% of amount transported) Harvest loss by farm size: Marginal size: 2.32 kg/quintal; small size: 1.80 kg/quintal; medium size: 1.99 kg/quintal; large size: 1.26 kg/quintal Average of four sizes:1.90 kg/quintal Threshing loss by farm size: Marginal size: 0.48 kg/quintal; small size: 0.17 kg/quintal; medium size: 0.11 kg/quintal; large size: 0.00 kg/quintal Average of four sizes: 0.20 kg/quintal Winnowing loss by farm size: Marginal size: 0.16 kg/quintal; small size: 0.12 kg/quintal; medium size: 0.04 kg/quintal; large size: 0.00 kg/quintal Average of four sizes: 0.08 kg/quintal Transportation loss by farm size: Marginal size: 0.84 kg/quintal; small size: 0.39 kg/quintal; medium size: 0.55 kg/quintal; large size: 0.52 kg/quintal Average of four sizes: 0.57 kg/quintal	[70]
Questionnaire	2011–2012	Punjab (India)	Mechanical harvest loss (HYV paddy): Early stage: 93.70 kg/acre; 3.40 kg/quintal; 3.40% of harvested amount Mid-season: 38.30 kg/acre; 1.40 kg/quintal; 1.40% of harvested amount Late-season: 53.60 kg/acre; 1.90 kg/quintal; 1.90% of harvested amount Transportation loss by tractor-trolley (to the market): 0.063 kg/quintal; 0.0002% of amount transported Harvest loss by farm size: Marginal size: 1.19 kg/quintal; small size: 1.66 kg/quintal; medium size: 1.64 kg/quintal; large size: 1.52 kg/quintal Average of four sizes:1.54 kg/quintal Transportation loss by farm size: Marginal size: 0.09 kg/quintal; small size: 0.09 kg/quintal; medium size: 0.05 kg/quintal; large size: 0.06 kg/quintal Average of four sizes: 0.06 kg/quintal	[71]

Table A1. *Cont.*

Method	Date	Region(s)	Magnitude	Citation(s)
Questionnaire	2010–2012	Tamil Nadu (India)	Tiruvarur district: Harvest loss of HYV paddy (including mechanical (over 90%) and manual harvesting): Early season: 92.32 kg/acre; 3.87 kg/quintal; 3.87% of harvest amount Mid-season: 51.2 kg/acre; 2.21 kg/quintal; 2.21% of harvest amount Late-season: 87.63 kg/acre; 3.68 kg/quintal; 3.68% of harvest amount Threshing loss of HYV paddy (including mechanical and manual threshing): 2.11 kg/quintal Winnowing loss of HYV paddy (including mechanical and manual threshing): 0.18 kg/quintal Transportation loss by tempo (to the market): 0.56 kg/quintal Villupuram district: Harvest loss of HYV paddy: Early season (mechanical harvesting): 71.75 kg/acre; 2.96 kg/quintal; 2.96% of harvest amount Mid-season (mostly mechanical harvesting): 69.79 kg/acre; 2.87 kg/quintal; 2.87% of harvest amount Late-season (mechanical harvesting): 89.3 kg/acre; 3.60 kg/quintal; 3.60% of harvest amount Threshing loss of HYV paddy (including mechanical and manual threshing): 0.83 kg/quintal Transportation loss by tempo (to the market): 0.65 kg/quintal Harvest loss by farm size: Tiruvarur district: marginal size: 3.12 kg/quintal; small size: 3.08 kg/quintal; medium size: 3.14 kg/quintal; large size: 3.07 kg/quintal; average of four sizes:3.10 kg/quintal Villupuram district: marginal size: 3.36 kg/quintal; small size: 3.19 kg/quintal; medium size: 2.94 kg/quintal; large size: 3.16 kg/quintal; average of four sizes:3.16 kg/quintal Average of two districts: 3.13% Threshing loss by farm size: Tiruvarur district: marginal size: 1.73 kg/quintal; small size: 1.57 kg/quintal; medium size: 2.77 kg/quintal; large size: 1.38 kg/quintal; average of four sizes: 2.11 kg/quintal Villupuram district: marginal size: 1.12 kg/quintal; small size: 1.07 kg/quintal; medium size: 0.46 kg/quintal; large size: 0.83 kg/quintal; average of four sizes:0.83 kg/quintal Average of two districts: 1.47% Winnowing loss by farm size: Tiruvarur district: marginal size: 0.15 kg/quintal; medium size: 0.46 kg/quintal; large size: 0.10 kg/quintal; average of four sizes:0.18 kg/quintal Transportation loss by farm size: Tiruvarur district: marginal size: 0.73 kg/quintal; small size: 0.56 kg/quintal; medium size: 0.50 kg/quintal; large size: 0.44 kg/quintal; average of four sizes:0.56 kg/quintal Villupuram district: marginal size: 0.84 kg/quintal; small size: 0.54 kg/quintal; medium size: 0.40 kg/quintal; large size: 0.65 kg/quintal; average of four sizes:0.65 kg/quintal Average of two districts: 0.61%	[72]

Table A1. *Cont.*

Method	Date	Region(s)	Magnitude	Citation(s)
Questionnaire	2011–2012	Uttar Pradesh (India)	Harvest loss of HYV paddy (including mechanical and manual harvesting): Early season: 40.65 kg/acre; 0.92 kg/quintal; 0.92% of harvest amount Mid-season: 55.81 kg/acre; 3.69 kg/quintal; 3.69% of harvest amount Late-season: 36.36 kg/acre; 1.43 kg/quintal; 1.43% of harvest amount Winnowing loss of HYV paddy: 2.71 kg/acre, 1.28 kg/quintal, 1.28% of winnowed amount Transportation loss: head load (0.14 kg/quintal; 0.14% of amount transported), bullock cart (1.70 kg/quintal; 0.88% of amount transported), trolley (0.51 kg/quintal; 0.51% of amount transported), tempo (0.72 kg/quintal; 0.72% of amount transported). Total (0.49 kg/quintal; 0.49% of amount transported) Harvest loss by farm size: Marginal size: 2.53 kg/quintal; small size: 3.19 kg/quintal; medium size: 1.56 kg/quintal; large size: 2.45 kg/quintal Average of four sizes:2.71 kg/quintal Threshing loss by farm size: Marginal size: 1.78 kg/quintal; small size: 1.23 kg/quintal; medium size: 0.58 kg/quintal; large size: 0.98 kg/quintal Average of four sizes: 1.28 kg/quintal Winnowing loss by farm size: Marginal size: 0.64 kg/quintal; small size: 0.41 kg/quintal; medium size: 0.10 kg/quintal; large size: 0.16 kg/quintal Average of four sizes: 0.40 kg/quintal Transportation loss by farm size: Marginal size: 0.49 kg/quintal; small size: 0.62 kg/quintal; medium size: 0.41 kg/quintal; large size: 0.31 kg/quintal Average of four sizes: 0.48 kg/quintal	[73]
Questionnaire	2003–2004	Karnataka (India)	Harvesting loss: 0.40 kg/quintal, threshing loss: 0.52 kg/quintal, cleaning/winnowing loss: 0.20 kg/quintal, transportation loss: 0.50 kg/quintal	[74]
Field experiments	2010	Karnataka (India)	Combine harvester: 2.88%–3.60%	[75]
Literature review	2010	China	Combine harvesting: 1.5% Segmented harvesting: 4.4% Harvesting loss (average of combine harvesting and segmented harvesting): 2.7% Package transportation loss (from field to homestead or storage): 1% Bulk transportation loss (from field to homestead or storage): 0.3% Transportation loss (average of package transportation and bulk transportation): 0.9%	[76]

Table A1. *Cont.*

Method	Date	Region(s)	Magnitude	Citation(s)
Questionnaire	2014	China	Farmers' perceptions about harvest loss (from cutting, threshing, to packaging) in nationwide: 26.93% of farmers thought: less than 3% 29.20% of farmers thought: 3–4% 18.30% of farmers thought: 4–5% 13.07% of farmers thought: 5–6% 5.68% of farmers thought: 6–7% 6.82% of farmers thought: over 7% Farmers' perceptions about harvest loss (from cutting, threshing, to packaging) in east region: 26.38% of farmers thought: less than 3% 23.77% of farmers thought: 3–4% 18.55% of farmers thought: 4–5% 12.75% of farmers thought: 5–6% 6.38% of farmers thought: 6–7% 12.17% of farmers thought: over 7% Farmers' perceptions about harvest loss (from cutting, threshing, to packaging) in central region: 24.39% of farmers thought: less than 3% 32.52% of farmers thought: 3–4% 13.82% of farmers thought: 4–5% 16.67% of farmers thought: 5–6% 8.13% of farmers thought: 6–7% 4.47% of farmers thought: over 7% Farmers' perceptions about harvest loss (from cutting, threshing, to packaging) in west region: 19.28% of farmers thought: less than 3% 35.43% of farmers thought: 3–4% 26.46% of farmers thought: 4–5% 13.00% of farmers thought: 5–6% 3.59% of farmers thought: 6–7% 2.24% of farmers thought: over 7% Farmers' perceptions about harvest loss (from cutting, threshing, to packaging) in northeast: 65.15% of farmers thought: less than 3% 22.72% of farmers thought: 3–4% 6.06% of farmers thought: 4–5% 1.52% of farmers thought: 5–6% 1.52% of farmers thought: 6–7% 3.03% of farmers thought: over 7%	[77]
Field experiments		Zhejiang (China)	Sickle reaping: scattered loss (0.09%), stacking loss (0.21%), uncut loss (0.11%) Combine harvester: scattered loss (0.89%), uncut loss (0.95%) Pedal thresher: unthreshed loss (0.5%), splash loss (0.16%), scattered loss (0.16%) Electronical thresher: unthreshed loss (0.67%), splash loss (0.26%), scattered loss (0.59%) Combine harvester: unthreshed loss (1.32%), splash loss (0.34%), scattered loss (included in scattered loss in cutting stage)	[52]

Table A1. *Cont.*

Method	Date	Region(s)	Magnitude	Citation(s)
Field experiments, questionnaire	2019	Heilongjiang (China)	Harvest loss in field experiments: Loss by Kubota, 25% moisture content, 0.25 m stubble height, 11–12 km/h harvest speed: 545.87 ± 5.26 kg/hm^2 Loss by Kubota, 25% moisture content, 0.25 m stubble height, 8–9 km/h harvest speed: 436.43 ± 17.75 kg/hm^2 Loss by Kubota, 25% moisture content, 0.25 m stubble height, 5–6 km/h harvest speed: 171.46 ± 1.62 kg/hm^2 Loss by Kubota, 21% moisture content, 0.17 m stubble height, 11–12 km/h harvest speed: 108.7 ± 3.36 kg/hm^2 Loss by Kubota, 21% moisture content, 0.17 m stubble height, 8–9 km/h harvest speed: 46.8 ± 1.98 kg/hm^2 Loss by Kubota, 21% moisture content, 0.17 m stubble height, 5–6 km/h harvest speed: 13.4 ± 0.98 kg/hm^2 Loss by Yanmar, 25% moisture content, 0.25 m stubble height, 11–12 km/h harvest speed: 530.67 ± 7.12 kg/hm^2 Loss by Yanmar, 25% moisture content, 0.25 m stubble height, 8–9 km/h harvest speed: 447.07 ± 7.49 kg/hm^2 Loss by Yanmar, 25% moisture content, 0.25 m stubble height, 5–6 km/h harvest speed: 253.87 ± 2.73 kg/hm^2 Loss by Yanmar, 21% moisture content, 0.17 m stubble height, 11–12 km/h harvest speed: 211.37 ± 11.3 kg/hm^2 Loss by Yanmar, 21% moisture content, 0.17 m stubble height, 8–9 km/h harvest speed: 80.40 ± 17.75 kg/hm^2 Loss by Yanmar, 21% moisture content, 0.17 m stubble height, 5–6 km/h harvest speed: 46.43 ± 1.62 kg/hm^2 Harvest loss by farmers' perception: 3–5%	[78]
Field experiments	2016	China	Harvest loss (including reaping loss, threshing loss, winnowing loss, and transportation loss from field to homestead) Combine harvester: The Northeast Plain (3.02%), Yangtze River basin (3.17%), Southeast Coast (4.12%). Average nationwide (3.44%) Segmented harvesting: The Northeast Plain (1.41%), Yangtze River basin (1.81%), Southeast Coast (1.76%). Average nationwide (1.66%) Harvest loss nationwide: 3.02%	[79]
Questionnaire	2016	China	Segmented harvesting: reaping loss (2.48%), threshing loss (0.76%), winnowing loss (0.42%), transportation loss (0.22%) Combine harvesting: loss from reaping to winnowing (3.27%), transportation (0.12%) Average nationwide harvest loss: 3.65%	[45]
Questionnaire	2016	China	Harvest loss (from reaping to field transportation): Small-scale farmer: 4.59% Middle-scale farmer: 3.90% Large-scale farmer: 2.60%	[80]
Field experiments	1979–1980	Bangladesh	Threshing loss: By bullock treading: 2.54% By hand beating and bullock treading: short straw (0.60%), long straw (1.45%) By pedal thresher: short straw (1.82%), long straw (3.49%) Overall: cutting loss: 1.45%, field stacking: 0.50%, transportation loss from field to farmyard: 0.53%, threshing loss: 1.79%	[61]

Table A1. *Cont.*

Method	Date	Region(s)	Magnitude	Citation(s)
Questionnaire		Bangladesh	Mymensingh region: Harvesting loss: Aman season (2.45%), Boro season (2.47%); Aus season (3.00%) Threshing loss: Aman season (1.80%), Boro season (2.23%); Aus season (2.96%) Transportation loss: Aman season (1.59%), Boro season (2.01%); Aus season (1.64%) Khulna region: Harvesting loss: Aman season (1.54%), Boro season (1.40%); Aus season (0.21%) Threshing loss: Aman season (0.62%), Boro season (0.83%); Aus season (1.50%) Transportation loss: Aman season (0.69%), Boro season (1.03%); Aus season (0.25%) Dinajpur region: Harvesting loss: Aman season (1.51%), Boro season (1.78%); Aus season (2.06%) Threshing loss: Aman season (1.11%), Boro season (1.28%); Aus season (0.45%) Transportation loss: Aman season (0.62%), Boro season (0.93%); Aus season (0.84%) Comilla region: Harvesting loss: Aman season (1.07%), Boro season (1.02%); Aus season (0.89%) Threshing loss: Aman season (0.73%), Boro season (0.74%); Aus season (0.71%) Transportation loss: Aman season (0.63%), Boro season (0.71%); Aus season (0.54%) Nationwide: Harvesting loss: Aman season (1.60%), Boro season (1.62%); Aus season (1.91%) Threshing loss: Aman season (0.87%), Boro season (1.13%); Aus season (1.07%) Transportation loss: Aman season (1.10%), Boro season (1.22%); Aus season (1.79%)	[36]
Field experiments	2013	Rangpur (Bangladesh)	Harvesting loss (shattering loss): Korean self-propelled reaper: 1.66%; China self-propelled reaper: 1.50%; BRRI reaper (power tiller-operated): 1.45%; manual reaping: 1.40%	[81]
Field experiments	2018	Bangladesh	Manual operation (6.08%): shatter loss (0.74%), cutting loss (0.68%), gathering loss (0.31%), carrying loss (0.23%), threshing loss (3.35%), cleaning loss (0.78%) Combine harvester (from reaping to cleaning): 1.61%	[58]
Field experiments	2008–2010	Bangladesh	Aus season: BR26: Reaping loss by sickle (2.1%); Field transportation loss by trolley (0.2%), by head carry (0.65%), by shoulder carry (0.75%); threshing loss by ODT (1.21%), by CDT (1.98%); winnowing loss by *Kula* (0.25%), by winnower (0.25%) BRRI dhan27: Reaping loss by sickle (2.15%); Field transportation loss by trolley (0.195%), by head carry (0.84%), by shoulder carry (0.79%); threshing loss by ODT (1.1%), by CDT (1.2%); winnowing loss by *Kula* (0.17%), by winnower (0.26%) Aman season: BR23: Reaping loss by sickle (1.88%); Field transportation loss by trolley (0.16%), by head carry (0.49%), by shoulder carry (0.69%); threshing loss by ODT (1.07%), by CDT (2.27%); winnowing loss by *Kula* (0.22%), by winnower (0.24%) BR11: Reaping loss by sickle (2%); Field transportation loss by trolley (0.23%), by head carry (0.66%), by shoulder carry (0.63%); threshing loss by ODT (0.86%), by CDT (2.26%); winnowing loss by *Kula* (0.21%), by winnower (0.29%) Boro season: BRRI dhan28: Reaping loss by sickle (1.83%); Field transportation loss by trolley (0.15%), by head carry (0.51%), by shoulder carry (0.72%); threshing loss by ODT (1.1%), by CDT (2.14%); winnowing loss by *Kula* (0.17%), by winnower (0.28%) BRRI dhan29: Reaping loss by sickle (1.94%); Field transportation loss by trolley (0.24%), by head carry (0.81%), by shoulder carry (0.72%); threshing loss by ODT (1.13%), by CDT (1.96%); winnowing loss by *Kula* (0.18%), by winnower (0.16%) Cutting loss: Aus season (2.13%); Aman season (1.94%); Boro season (1.89%) Field stacking g loss: Aus season (0.69%); Aman season (0.97%); Boro season (0.83%) Field transportation loss: Aus season (0.57%); Aman season (0.48%); Boro season (0.53%) Threshing loss: Aus season (3.09%); Aman season (3.23%); Boro season (3.16%) Threshing loss: Aus season (0.47%); Aman season (0.48%); Boro season (0.39%)	[57]

Table A1. *Cont.*

Method	Date	Region(s)	Magnitude	Citation(s)
Questionnaire	2009–2010	Bangladesh	Reaping loss: Aman season (1.95 kg/quintal); Boro season (1.66 kg/quintal) Threshing loss: Aman season (0.64 kg/quintal); Boro season (0.56 kg/quintal) Winnowing loss: Aman season (0.32 kg/quintal); Boro season (0.24 kg/quintal)	[82]
Field experiments	2010	Iran	Quantitative loss: Reaping loss: T1 (1.60%); T2 (1.48%); T3 (1.54%) Threshing loss: T1 (0.98%); T2 (1.04%); T3 (1.12%) Reaping + threshing loss: T1 (2.58%); T2 (2.52%); T3 (2.26%); T4 (2.27%); T5 (2.4%) Qualitative loss: T1 (2.05%); T2 (2.44%); T3 (2.41%); T4 (0.47%); T5 (0.75%) The average quantitative loss of T1–T3: 2.58%; The average quantitative loss of T4–T5: 2.33%. The average qualitative loss of T1–T3: 2.30%; The average qualitative loss of T4–T5: 0.61%. Quantitative losses are the result of shattering and losing of grain and non-threshed panicles during reaping and threshing. Qualitative losses are owing to broken, husked, and cracked grains from environmental and mechanical impacts. T1–T3 are regarded as indirect harvesting, T4–T5 are regarded as direct harvesting. Note: T1: Manual harvesting (cutting with sickle) + tractor-driven thresher. T2: Rice reaper + tractor-driven thresher. T3: Rice reaper + threshing by a universal combine equipped with pick-up header. T4: Head-feed rice combine harvester. T5: Whole-crop rice combine harvester.	[50]
Field experiments	2014–2015	Myanmar	Wet season 2014: Harvesting loss: IPR (16.0%); FP1W (28.2%); FP4W (23.63%) Manual cutting and handing loss: IPR (13.6%); FP1W (20.8%); FP4W (14.4%) In-field stacking loss: FP1W (0.3%); FP4W (0.6%) Threshing loss: IPR (2.4%); FP1W (7.2%); FP4W (8.7%) Dry season 2015: Harvesting loss: IPRc (1.7%); FP (9.3%) Manual cutting and handing loss: FP (6.7%) Threshing loss: FP (2.6%) Combine harvesting loss: IPRc (1.7%) Dry season 2016: Harvesting loss: IPRc (0.9%); FP (4.0%) Manual cutting and handing loss: FP (1.8%) Threshing loss: FP (2.2%) Combine harvesting loss: IPRc (0.9%) Note: IPR: manual cutting, threshing immediately after cutting using improved thresher FP1W: manual cutting, stacking 1 week in field, less developed thresher FP4W: manual cutting, stacking 4 weeks in field, less developed thresher IPRc: combine harvester FP: manual cutting, threshing immediately after cutting using less improved thresher	[49]
Field experiments	1981	Indonesia	Traditional ani-ani method: shattered and dropped losses (1.40%); uncut losses (4.48%); foot-treading threshing losses (2.38%) Sickle method: shattered and dropped losses (1.28%); uncut losses (1.92%); beating threshing losses (5.63%)	[83]
Questionnaire, direct observation, focus group discussion	2015	Democratic Republic of Timor-Leste	Manual harvesting loss: 3.5% in harvesting stage; 3.5% of the initial quantity; USD 3140 Transportation loss from field to homestead: 1.5% in the transportation stage; 1.45% of the initial quantity; USD 1300 Thresher machine loss: 5% in the threshing stage; 4.75% of the initial quantity; USD 4260 Manual winnowing: 0.5% in the winnowing stage; 0.45% of the initial quantity; USD 400	[54]

Table A1. *Cont.*

Method	Date	Region(s)	Magnitude	Citation(s)
Field experiments	1979	Dominican Republic	Harvest loss by region: Central-Northeast: 17.41% Northwest: 21.58% Southwest: 14.25% Harvest by size (tarea): 1–50: 18.24% 51—100: 24.82% 101+: 12.27% Harvest loss by harvest method: Manual: 20.32% Mechanized: 13.37% Harvest loss by hand-threshing method: Stick: 19.52% Platform: 22.01% Drum: 17.72%	[84]
—	—	—	Sickle reaping loss in Indonesia: wet season (0.7%), dry season (0.5%) Average loss as a percentage of estimated potential yield: Traditional hand cutting loss: Thailand (9.3%); Myanmar (1.9%) Shoulder power reaper: Thailand (5.2%); Myanmar (5.4%) Reaper-binder: Thailand (5.2%); Myanmar (5.2%) Combine harvester: Thailand (1.1%); Myanmar (2.1%) Field stacking and bundling: Bangladesh (0.6%); Myanmar (0.5%) Loss in China (Zhejiang) in 1987/1989 (Average loss as a percentage of production): Harvest: by sickle (0.43%), by combine harvester (3.38%). Average loss (0.85%) Threshing: by pedal thresher (0.80%), by motor thresher (1.52%). Average loss (1.31%)	[55]

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