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Advances in Rice Harvest-to-Storage Technologies in Asia: A Systematic Review

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ABSTRACT

Postharvest losses in paddies frequently occur during harvesting, threshing, drying, storage, and milling. This review aimed to synthesise the available evidence on technologies that address such losses across different postharvest stages. Using the PRISMA framework, we conducted a Scopus search on 18 August 2025 ("postharvest losses" AND paddy). Of the records retrieved, 23 met the inclusion criteria. For each study, we extracted the stage, technology, comparator, study design, and reported outcomes. These outcomes included mass loss, head rice yield (HRY), proportion of broken grains, moisture content (MC), time to reach the target MC, energy or cost per kilogram, insect and rodent damage or mortality, and seed germination. Units were standardized (dry-basis of MC). A random-effects meta-analysis was planned where at least three comparable contrasts were available; otherwise, a structured synthesis was applied. The evidence was strongest for drying and storage innovations. Small-scale recirculating dryers lowered the MC from approximately 20–25% to 11–13% within 4.0–4.7 hours at 39–40°C, whereas bag–bin systems reduced the MC from 35.4% to 8.7–13.4% over 11.7 hours at 39–55.6°C. Engineered drying was cost-competitive in wet seasons (Tk 0.74–0.87kg^{-1} versus Tk 1.00kg^{-1} for sun-drying), yielding a benefit–cost ratio of 1.9–2.4 with a payback period of under one year. Hermetic storage minimized moisture drift, insect damage, and breakage while increasing seed germination by 11.2 percentage points. RF heating was highly effective against insects, and attractant- or air-assisted traps enhanced capture. Rodent damage at community stores remained significant, although interventions reduced losses (e.g., from 14 to 4% and from 8.2 to 1.2%). At the milling stage, a 12-ton recirculating dryer improved mill capacity utilization from 33.3 to 60%. In summary, a tailored package of stage-specific measures—mechanical threshing, recirculating or fixed-bed drying calibrated by bed thickness, hermetic storage combined with RF or IPM approaches, and coordinated community rodent control—can reduce losses from the usual double-digit levels to low single digits at treated points while improving HRY. Successful scaling will require extension systems that emphasize evidence-based measurement and the mobilization of performance-linked financing (PLF).

Keywords: Head rice yield, Hermetic storage, Mechanical drying, Paddy, Postharvest losses.

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INTRODUCTION

Global rice production is highly concentrated, with China and India each accounting for 27% of the total world output, equivalent to approximately 145–145.28 million tonnes per year (USDA, 2025). Globally, floods and droughts are major causes of rice yield losses, with extreme floods alone accounting for an average annual reduction of 4.3% in global rice yields (USDA, 2025). In Asia, which produces more than 90% of the world's rice, countries face significant production losses, primarily due to extreme weather events linked to climate change. In developing countries, significant losses of up to 54% occur globally during the postharvest handling, storage, processing, and distribution stages (USDA, 2025). According to the FAO (2022), substantial losses in the Asia Pacific region occur throughout rice production systems, particularly in the pre- and postharvest stages, which may

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reach 49% under certain conditions (FAO, 2022). In comparison, China reached an 8% yield loss due to climate change over a 20-year period and India in certain West Bengal and Bihar countries experienced losses of 7% per flood event (FAO, 2022; USDA, 2025). Thailand expected a 3.27% decline in production for the 2023/2024 harvest season, with the Philippines facing significant losses from typhoons in 2023 (FAO, 2022; USDA, 2025). Moreover, Indonesia experienced a 2.45% decrease in paddy production in 2024 (a decrease of 1.32 million from 2023) due to prolonged drought conditions associated with El Nino (FAO, 2022; USDA, 2025).

Indonesia's push for food self-sufficiency has made reducing postharvest losses in rice a matter of national importance. Every percentage point of grain saved between the field and the market adds directly to domestic supply, helps to stabilise consumer prices, and reduces reliance on imports when monsoon seasons bring uncertainty. Since expanding irrigation is expensive and water resources are limited, maintaining grain that has already been produced is often the fastest and least risky way to increase national rice availability. Because expanding the area of irrigation is costly and water-constrained, recovering grain already produced is one of the fastest, lowest-risk paths to a new "supply" (Jha et al., 2020). The stakes are international. Rice underpins the diet and livelihood of billions of people across Asia. Similar smallholder-dominated chains from South Asia to Southeast Asia face humidity, pest pressure, and infrastructure gaps that systematically erode quality and quantity with measurable costs and environmental externalities (Huynh et al., 2013; Cardoen et al., 2015; Bandumula, 2018; Chang et al., 2024). A rigorous synthesis of stage-specific interventions—harvest/threshing, drying, storage and milling—is therefore timely for Indonesia and globally: it clarifies which technologies reliably deliver head–rice yield and loss reductions under real monsoon conditions and it informs policy packages that trade off time, cost and water constraints at scale (Thiruchelvam 2005).

Paddies (*Oryza sativa*) underpin diets, livelihoods, and price stability across much of Asia. However, a nontrivial share of harvested rice never becomes edible rice because it is either lost or degraded between harvest and retail. These postharvest losses arise from (i) spillage and shattering during harvest and threshing; (ii) slow or uneven drying that leaves grains above safe moisture, encouraging fissuring, moulding, and quality downgrades; (iii) insect and rodent damage during storage; and (iv) milling practices that reduce head rice yield (HRY) and increase the broken rice fraction (BRF). This challenge extends well beyond Indonesia. Across Asia, rice underpins diets, incomes, and rural employment, yet losses at various stages of the supply chain quietly undermine both food security and farmer livelihoods. Spillage during harvest, uneven or slow drying that leaves grain at unsafe moisture levels, insect damage during storage, and breakage during milling all contribute to a sizeable gap between the quantity harvested and the rice that actually reaches consumers. In markets where rice prices are politically sensitive, even a small percentage of avoidable losses can translate into enormous financial and social costs (Nasiru et al., 2025).

Fortunately, a wide range of technologies have been developed to address these problems. Compared with manual methods, mechanical harvesters and threshers reduce spillage and improve separation at the farm level (Munawar et al., 2024). Drying innovations—such as fixed-bed and recirculating systems—help farmers reach safe moisture levels quickly, even during wet seasons. Hermetic storage prevents insect and moisture drift, whereas nonchemical approaches such as radiofrequency (RF) treatment add another layer of protection. Community-level rodent control and better sensing tools, such as drone-based crop maturity checks, also show promise for reducing hidden losses. However, despite this technological progress, policymakers and practitioners face several barriers. The first is fragmented evidence: engineering studies often focus on drying time or energy use, whereas agronomy studies may report yield or grain quality, with little consistency in units or definitions. The second is context dependence: performance depends heavily on local conditions, such as initial grain moisture, ambient temperature, or storage duration. The third challenge is implementation: while many trials demonstrate technical feasibility, far fewer provide clear insights into adoption costs, labour requirements, or real-world performance under monsoon conditions.

Recent work published between 2020 and 2025 provides clearer insights into technologies capable of reducing losses under monsoon-affected Asian conditions. Advancements in mechanical and hybrid drying systems, such as recirculating dryer and bag-bin configurations, have led to substantial improvements in energy efficiency, drying uniformity and operational resilience during the wet season (Saha et al., 2023; Saeed & Tariq, 2024). Studies on hermetic storage have revealed consistent benefits across both seed and grain systems, with supergrain and PICS bags reducing moisture drift, suppressing insect populations and increasing seed germination by more than 10 percentage points (Alam et al., 2022; Rupasinghe, 2024; Khandai et al., 2025). Complementary nonchemical approaches, such as radiofrequency (RF) thermal treatment and moisture imaging, increase disinfestation efficiency and allow improved monitoring of grain conditions (Krittigamas et al., 2012; Ramli et al., 2024). Rodent impact has received renewed attention, with village-scale assessments in Myanmar demonstrating that unmanaged rodent populations can consume or damage more than 10% of stored grain, reinforcing the need for coordinated community-level management rather than solely households (Htwe et al., 2016). Parallel to these biological control technologies, systemic innovations such as microwarehousing models in India have emerged, reducing postharvest losses by 35–40% while providing farmers with credit access through warehouse receipts (Singh et al., 2023). Adoption-oriented studies point to education, risk perception, extension contracts and information-sharing networks as major determinants of technology uptake (Muthukumar et al., 2020; Chang et al., 2024). Additionally, micro warehousing models and warehouse receipt systems have emerged as scalable options for reducing losses while improving farmer liquidity (Singh et al., 2023). Climate-smart models further show that combining postharvest loss reduction with conservation agriculture can reduce irrigation requirements by up to 26% and buffer climate-induced yield penalties (Jha et al., 2020). Together, these findings highlight a new generation of postharvest innovations that are not only technically effective but also financially viable and socially scalable across the diverse ecologies of Asia. These recent developments demonstrate that technological innovation alone is insufficient. Successful postharvest improvement requires complementary social, financial and institutional mechanisms that support sustained and widespread use across the Asian context.

Across Asia, a considerable proportion of harvested rice never reaches consumers because it is lost or degraded during the postharvest period. These losses arise at multiple points of the supply chain during harvesting and threshing, throughout drying, during months of storage and finally at milling, where factors such as spillage, slow moisture reduction, insect and rodent infestation, and grain fissuring can substantially reduce both quantity and quality. For countries where rice underpins national food security, even a small percentage of loss has major implications for domestic supply, farmer income, and price stability, particularly under monsoon conditions where the moisture load is high and drying opportunities are limited (Qaisar et al., 2024). Although many technologies have been introduced to address these issues, ranging from mechanical threshers and fixed bed dryers to hermetic bags, radiofrequency disinfestation, rodent management, and microwarehousing, the existing scientific evidence remains scattered. Most published studies focus on a single stage of the postharvest chain, often using differing measurement approaches, moisture bases or quality definitions. As a result, it is difficult for policymakers or practitioners to form a coherent understanding of which interventions work reliably across diverse agroecological settings or how individual technologies interact to influence outcomes such as head rice yield, moisture uniformity, or insect suppression. The lack of an integrated synthesis means that decision-makers are often confronted with fragmented data, making it challenging to design postharvest strategies that are technically robust, financially viable, and suitable for smallholder systems.

This study responds to that gap by systematically bringing together evidence from the full harvest-to-storage continuum. By reviewing technologies such as harvesting and threshing, drying, storage and milling, interventions can consistently reduce losses and improve downstream grain quality under monsoons in Asia.

MATERIALS & METHODS

Search, Evaluation and Grading of the Literature

The identification of articles was carried out according to the PRISMA guidelines (Page et al., 2021a; 2021b). The research question—focusing on technologies to reduce postharvest losses in paddies—was structured via the PICO framework: population = paddy (*Oryza sativa*) in smallholder-dominated systems; intervention = stage-specific postharvest technologies (harvesting/threshing, drying, storage, milling); comparison = conventional practices (manual harvesting, sun drying, open storage, standard milling) versus improved technologies; outcomes = grain loss reduction, head rice yield (HRY), broken rice fraction, moisture content (MC), energy/cost efficiency, pest control, and seed viability.

The literature search was conducted in Scopus up to 18 August 2025 via the following terms: TITLE-ABS-KEY ("postharvest loss*" OR "harvest-to-storage" OR "paddy drying" OR "paddy storage") AND TITLE-ABS-KEY ("*Oryza sativa*" OR rice OR paddy"). This search produced 33 records. The complete selection process is illustrated in Fig. 1. The literature search was conducted in Scopus (cut-off: 18 August 2025), with supplementary checks in Web of Science. The search terms were designed around the PICO framework and included "postharvest loss*", "harvest-to-storage", "paddy drying", and "paddy storage" in combination with "*Oryza sativa*" or "rice". The initial search was conducted via two major academic databases, Scopus (n=663) and Web of Science (n=2), resulting in a total of 663 articles for preliminary assessment. Following the first stage of screening, 352 articles were identified as relevant, as they addressed themes related to harvest-to-storage technologies. These original research papers as well as review papers, book chapters, books, conference papers, and short surveys were excluded because they were irrelevant to the scope of this study. Additionally, two Web of Science records were removed due to redundancy. A more detailed evaluation of the remaining 351 articles was then performed using specific inclusion criteria. Studies reporting on postharvest loss, harvest storage, paddy drying, or storage practices are needed. At this stage, three articles were excluded for failing to meet the criteria, 155 articles did not report any harvest loss, 79 articles did not focus on rice, and 90 articles were not based in Asian countries and were therefore removed because of irrelevance. After completing the selection process, a total of 23 articles were retained for data extraction and further analysis following the PRISMA guidelines (Page et al., 2021a; Budiarto et al., 2024; Sugiharto et al. 2025).

Visualisation via Scimago Graphica

To aid interpretation, data on rice production and postharvest losses across Asian countries were compiled from the FAO and regional sources (2022 data). This dataset was uploaded into Scimago Graphica (version 1.0.51). Different visualisation modules were applied as follows:

The word cloud (Fig. 2 & 4) is used to display the relative frequency of rice-producing countries and the distribution of reported postharvest losses. Country names were weighted by production volume or estimated loss percentage. Bubble Chart (Fig. 3 & 5): used to represent absolute rice production (million tonnes) and absolute

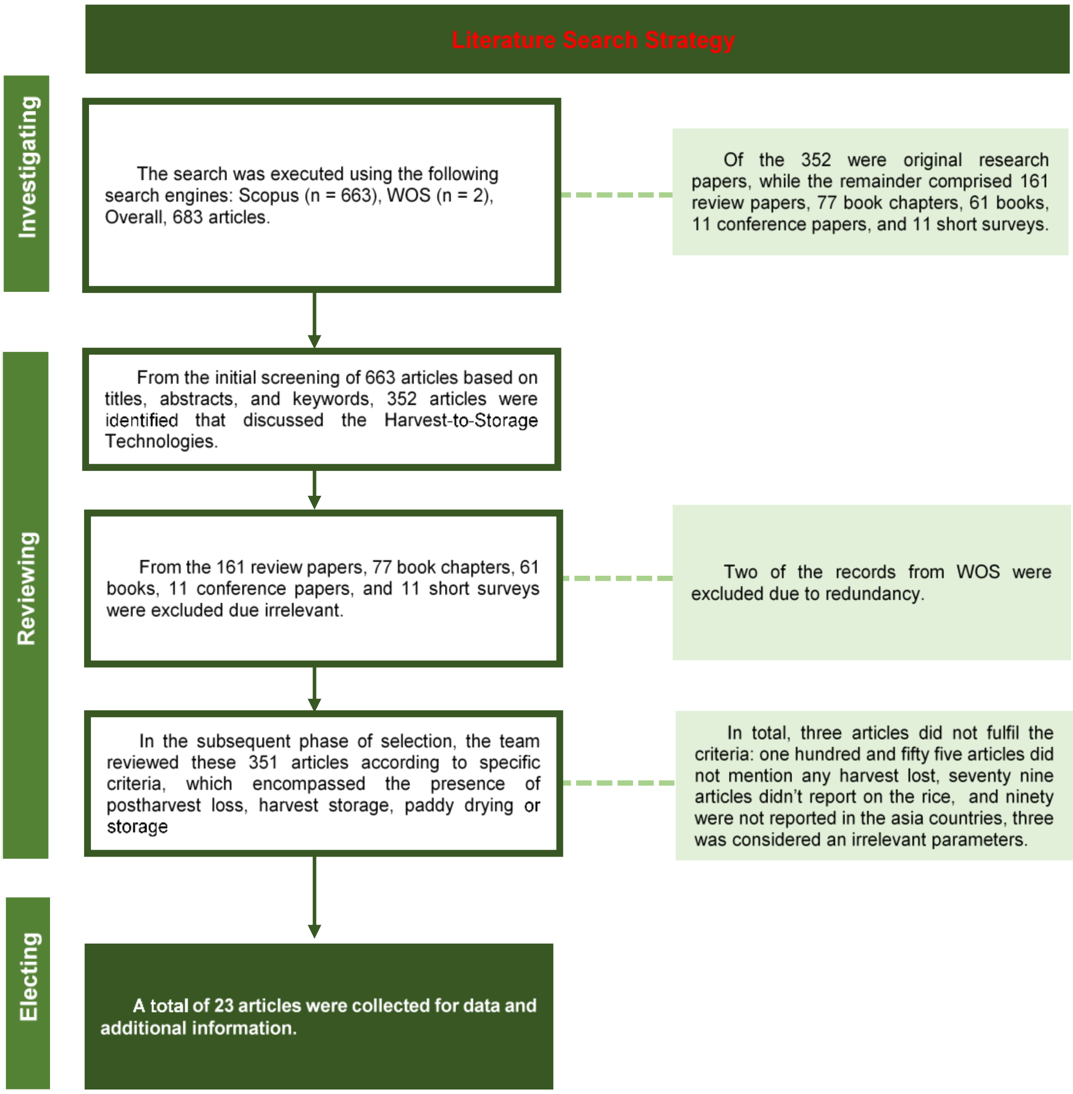

Fig. 1: Summarise the screening and selection process for the studies included in this review, following the PRISMA framework.

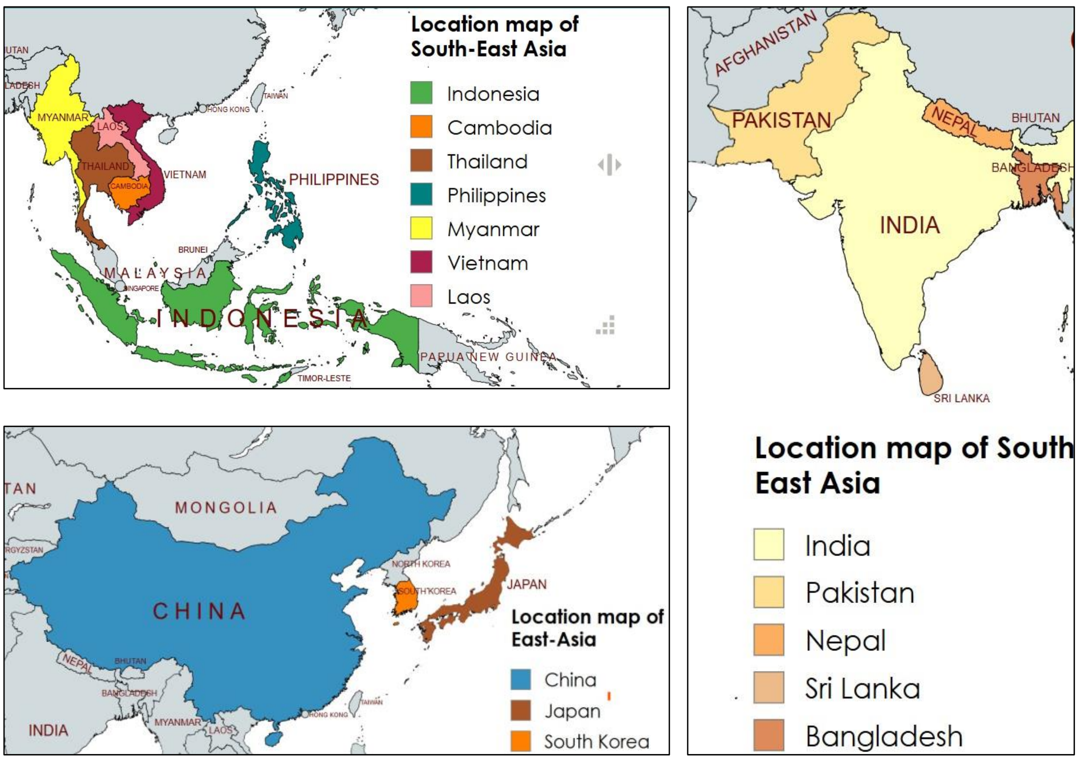

Fig. 2: Location Map of study Area Countries in Asia.

Fig. 3: Word Cloud of Rice Producing Countries in Asia.

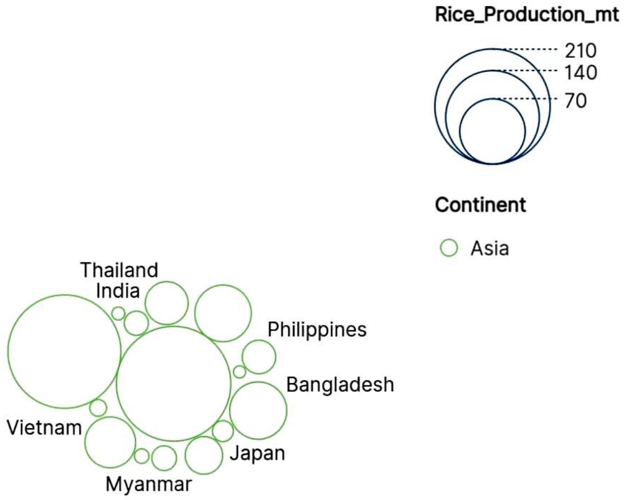

Fig. 4: Bubble Chart of Rice Production in Asia.

Fig. 5: Word Cloud Rice Production Loss Countries in Asia.

postharvest losses (million tonnes), respectively. Bubble size was scaled to the magnitude of production or loss, while color coding was used to distinguish countries. Graph formatting: All Fig. were standardised with consistent labelling, legends, and export settings for clarity. These graphics allowed the synthesis of secondary datasets to complement the evidence extracted from the literature, providing a broader regional context for the review findings.

RESULTS AND DISCUSSION

Across 23 Scopus-index studies spanning harvest, threshing, drying, storage, and milling, a consistent pattern emerged: engineered drying and protected storage target the largest and most variable portions of postharvest loss while improving head rice yield (HRY) and operational reliability in monsoon-affected supply chains (Table 1). Recirculating and fixed-bed systems—most prominently the BAU-STR—reliably shorten the time to safe moisture from days to hours at moderate temperatures, reduce drying losses, and, in wet seasons, match or beat the unit costs of sun-drying, with subyear paybacks in field deployments (Saha et al., 2017; Saha et al., 2018). At larger throughputs or after very wet harvests, a reengineered bag–bin configuration achieves safe moisture in a single ~12-hour run while lowering labor per ton relative to flatbeds and keeping total drying handling costs competitive, demonstrating suitability for aggregation nodes such as mills or cooperatives (Orge et al., 2020). Process parameters are not incidental: initial moisture, drying-air temperature/flow, and especially bed thickness deterministically shape kinetics; thinner beds at ~40 °C reach safe moisture sooner and limit over- or underdrying, helping to preserve downstream HRY (Kumoro et al., 2019). According to recent studies from 2020--2025, the results of this review strongly agree with new evidence on postharvest technologies in Asian areas affected by monsoons. Recent research on drying methods, especially BAU recirculating and STR-type systems, supports our conclusion that engineered dryers reliably reduce the time needed to reach safe moisture levels, ensure even drying, and offer cost-effective or less expensive drying options during wet seasons (Saha et al., 2023). Similarly, the performance of the bag–bin and hybrid drying setups tested in the 2023–2024 studies matches our findings, showing that controlled air drying greatly reduces handling losses and increases the amount of high-quality rice produced later. In the area of protected storage, our results match those of Alam et al. (2022) and Khandai et al. (2025), who reported that hermetic bags stop insect growth, keep moisture levels steady, and increase seed germination by more than 10 percentage points. These results show that storing grains in airtight containers under low-oxygen conditions is one of the better ways to keep them safe in hot, humid areas. New methods that do not use chemicals, such as radiofrequency treatment (Balingbing et al., 2025; Ramli et al., 2024), support our finding that the use of heat to control insects is a better option when chemicals are not allowed or preferred. Additionally, recent studies on how mice damage stored grains and community-based solutions, such as those seen in Myanmar since 2020, support our conclusion that people need to work together at the village level to reduce grain loss. Additionally, new ideas such as small-scale storage units and warehouse systems that track grain ownership, tested in 2023, match our idea that keeping grains safe needs to be accompanied by better funding and rules to make it work on a larger scale. Together, these studies support the step-by-step plan discussed in this review and confirm that mixing with better drying

Table 1: Advances in Harvest-to-Storage Technologies in Asia

No	References	Country conducted research	Interventions	Results
1	Balingbing et al., 2025	India (Assam)	Hermetic Super Grain Bag (SGB) vs traditional gunny bag for rice seed/grain storage	SGB reduced moisture fluctuations and giving better germination (+11.2%), lowered insect infestation and broken grains; superior option for smallholder storage.
2	Tho et al., 2021	Vietnam (Mekong Delta)	"One Must Do, five reductions" (1M5R) package – certified seeds + reductions in seed rate, fertiliser, pesticide, water, and postharvest losses	Adoption cut costs by 10%, raised price +4.5% perkg, increased profit by 10%, ROI +22%; improved grain quality but no yield gain.
3	Inoue et al., 2009	Thailand/SE Asia	Mix-drying using rice husk or absorbents with wet paddy	Reduced moisture to safe levels (<17%) within hours, prevented fermentation, maintained rice quality; low-cost alternative to mechanical dryers.
4	Cardoen et al., 2015	India	Assessment of postharvest losses of rice and biomass residues	Rice losses estimated at 5–15%; total agricultural losses ~13% (≈90 Mt/year); storage and transport are main causes; significant methane emissions from waste.
6	Ramli et al., 2025	Philippines	Use of RF sensing (Radio Tomographic Imaging, RTI) for rice storage monitoring	Nondestructive monitoring of rice moisture content; cost-effective and repeatable for maintaining grain quality
7	Saha et al., 2017	Bangladesh	Field performance of Bangladesh Agricultural University Straw Type Recirculating (BAU-STR) dryer for paddy	Reduced moisture to safe storage levels in 4–5 hrs; drying efficiency ~57–66%; lower cost (Tk. 0.74–0.87/kg) than sun drying; payback <1 year
8	Saha et al., 2018	Bangladesh	Evaluation of BAU-STR dryer vs Solar Bubble Dryer (SBD) vs sun drying	BAU-STR dried rice to 12% MC in 4–6 hrs with ~0.45% loss; SBD took 16–18 hrs and could not reach <14% MC; BAU-STR produced higher head rice yield (66%)
9	Krittigamas et al., 2012	Thailand	Radio frequency (RF) thermal treatment for insect control in rice storage	RF at 27.12 MHz: 100% mortality of rice moth at 70°C (150 sec), lesser grain borer at 70°C (180 sec), and rice weevil at 50°C (15 min); effective eco-friendly alternative to fumigation
10	Thiruchelvam, 2005	Sri Lanka (Anuradhapura & Polonnaruwa)	Efficiency analysis of paddy farmers in minor/major tank areas	Efficient farmers yielded 5.1 t/ha vs 3.3 t/ha for least efficient; high postharvest losses (20–30%) mainly due to labor scarcity; scope to improve yield without raising costs
11	Hiregoudar et al., 2011	India (Raichur, Karnataka)	Artificial Neural Network (ANN) applied to assess grain losses in paddy combine harvesting	ANN predicted grain losses with RMSE of 0.1582 (cutter bar), 0.1299 (threshing), and 0.1321 (separation). ANN effectively reduced postharvest losses by identifying optimal harvesting conditions.
12	Muthukumar et al., 2020	India (Nagapattinam, Tamil Nadu)	Survey on socioeconomic and psychological factors influencing adoption of postharvest technologies	Education, farming experience, extension agency contact, information sharing, risk orientation, and innovativeness were positively correlated with adoption of postharvest practices. Accounted for 54.7% variation in adoption level.
13	Atta et al., 2023	Pakistan (Kala Shah Kaku, Punjab)	Feeding preference study of *Rhyzopertha dominica* on rice cultivars (Basmati 515, Super Basmati, Super Gold, Super Basmati 2019) across processing stages	Highest mortality on Super Basmati 2019 paddy (50.89%), highest survival on polished Basmati 515 (84.89%). Grain damage up to 80.67% and weight loss 1.58% in polished Basmati 515. Polished rice most vulnerable to infestation.
14	Atta et al., 2022	Pakistan (Kala Shah Kaku, Punjab)	Feeding preference of *Tribolium castaneum* on rice cultivars (Super Basmati, Basmati 515, Super Basmati 2019, Super Gold) and components (Paddy, Brown, Polished rice)	Maximum growth rate (64.0), grain damage (76.67%), and weight loss (5.15%) on polished Basmati 515. *T. castaneum* strongly preferred Basmati 515 components. Highlights need for resistant cultivars and better storage management.
15	Almasoud et al., 2024	Egypt (Kafrelsheikh, Alexandria, Sakha, Giza)	Evaluation of physical and engineering properties of new climate-adapted Egyptian rice variety Giza 183	Giza 183 had average length 7.50 mm, width 3.18 mm, thickness 2.19 mm, sphericity 49.9%, bulk density 572.17kg/m³, milling yield 71%, amylose content 18%. Resistant to stem borers and rice blast. Suitable for processing and storage design.
16	Mouleeshuwara pprabu et al., 2024	India (Kongu Engineering College, Tamil Nadu)	Design of mobile postharvest seed processing unit using repurposed oil barrel with fan and heating element for drying	Portable, low-cost system ensured controlled drying in wet season, reduced mould/mycotoxin risk, improved seed quality and food security. Provided sustainable alternative to traditional sun drying.
17	Krah et al., 2020	Ghana (Aveyime, Volta Region) & Indonesia (IPB University collaboration)	Comparison of threshing methods (stone, wooden box "bambam", combine harvester) on AGRA and Jasmine 85 rice varieties	Combine harvester gave highest dockage (0.41%) but lowest fissured grains (3.14%). Bambam produced cleanest grains (0.22% dockage). Jasmine 85 had higher germination (86.11%) than AGRA (63.88%). Varieties responded differently to threshing.
18	Saha et al., 2023	Bangladesh (Mymensingh, Netrokona)	Development and scaling of 12-ton BAU Recirculating Paddy Dryer for both parboiled and aromatic rice mills	Capacity utilisation of Moti Auto Rice Mill increased from 33.3% (sun drying) to 60% after dryer adoption, with potential up to 72.5%. Drying time reduced (parboiled: 15 hr, aromatic: 8 hr). Male workers' weekly income rose from USD 28.6 to 42.9. Female workers in sun drying required alternative income sources (poultry, goat rearing, cattle fattening). Dryer adoption improved mill productivity and resilience against weather dependency
19	Alam et al., 2022	Bangladesh	Hermetic storage (PICS and SuperGrain bags) from farmer to commercial scale	Reduced insect infestation, mould, and moisture fluctuation; higher grain quality and storability compared with traditional methods.
20	Htwe et al., 2016	Myanmar (Ayeyarwady Delta)	Assessment of rodent impacts on piled and stored paddy; recommendation of rodent-proofing and community management	Losses in granaries up to 14%; rodents consumed/stored ~1.4kg grain/burrow; enough losses to feed households 1.6–4 months.
21	Orge et al., 2020	Philippines	Re-engineered drying system using 500kg "drying bags" inside typhoon-resistant shelters	Integrated harvest–handling–drying; reduced handling time and losses; ensured quality even under typhoon/flood conditions; more climate-resilient.
23	Singh et al., 2023	India (Bihar)	Microwarehousing system for paddy, maize, wheat	Reduced postharvest losses (~35–40%); improved farmer access to storage/markets; attracted $20 M investment; scalable solution for smallholders.
23	Jha et al., 2020	India (Bihar)	Modelling climate-smart practices + 30% postharvest loss reduction	Combining conservation agriculture + loss reduction decreased irrigation requirement by up to 26%; mitigated climate change yield losses; improved sustainability.

AGRA – Alliance for a Green Revolution in Africa, ANN – artificial neural networks, hr – hour,kg – kilogram, M – million, Min – minutes, MC – moisture content, PICS – Purdue Improved Crop Storage, ROI – return of investments, RMSE – root mean square error, SGB – supergrain bag, USD – dollar of united states, % - percentages.

methods, airtight storage, and group efforts to manage pests is the better way to reduce grain loss to just a small percentage of rice-growing areas across Asia.

Fig. 3 and 4 show the relative scale of rice production among Asian countries. Unsurprisingly, China and India dominate the picture, together supplying well over two-thirds of the region's output. They are followed by a group of substantial producers—Indonesia, Bangladesh, Vietnam and Thailand—while smaller contributors, such as Nepal, Laos and Sri Lanka, remain more relevant at the subregional level than globally. The distribution underlines the concentration of production in just a handful of countries. This pattern is important because any disruption in these key producers, whether from weather, policy change or pest outbreaks, can be felt across international markets. It also makes clear where the adoption of improved postharvest technologies could have the greatest overall effect in reducing losses. A critical comparison of the technologies reviewed reveals that each intervention targets different bottlenecks in the postharvest chain and has distinct operational strengths and limitations. Fixed bed dryers offer relatively uniform drying but are highly sensitive to bed thickness and airflow distribution when improperly loaded; they tend to produce moisture gradients that lower downstream head rice yield. Recirculating dryers solve these problems by constantly mixing the grain, which makes the drying process faster and reduces the time needed, especially during high humidity, such as in the monsoon season. However, they need more money upfront and a steady supply of energy. On the other hand, solar bubble dryers (SBDs) are a cheaper option for small farmers, but they cannot handle large amounts of grain and have trouble drying it to 14% moisture or less during the rainy season. This can cause the grains to become wet again and lose quality. Storage methods also work differently. Traps that use attractants and air help identify insect problems and can lower insect numbers, but they do not provide the same strong protection as those used to seal grains tightly or via RF treatment. Overall, these comparisons show that one method is not enough to handle all stages of storing grain after it is harvested.

On the storage side, hermetic bags and cocoons consistently stabilise moisture, suppress live insects, and improve milling quality (more head rice and fewer brokens) under humid monsoon conditions. They also increase seed lot germination, with measured O_2/CO_2 values confirming the hypoxic mechanism (Khandai et al., 2025). When infestations must be cleared or polished rice is held, radiofrequency heating results in high insect mortality when temperature–time profiles are calibrated, and enhanced attractant/air-assisted traps improve monitoring and removal in warehouses, making both practical complements to hermetic containment (Krittigamas et al., 2012; Balingbing et al., 2025). Fig. 4 shows where postharvest losses are most frequently reported. Countries such as India, Bangladesh, Myanmar and Cambodia appear most prominently, reflecting not only their sizeable harvests but also the challenges posed by humid, monsoon-driven climates and more limited storage infrastructure. In contrast, Japan and South Korea are less conspicuous, which is consistent with their lower reported loss rates and more advanced storage and mechanisation systems. The comparison suggests that the scale of losses is influenced as much by technology and infrastructure as by production volume. This highlights the need for targeted interventions in those settings where disproportionately high levels of loss undermine large harvests.

Losses are not confined to insects. Community measurements in Myanmar document substantial rodent impacts on village granaries, indicating that household-level hermetic practices must be paired with community-scale rodent management to reduce aggregate losses (Htwe et al., 2016). Upstream, the threshing method and grain properties matter: combine-based threshing minimises fissuring relative to stone or manual approaches, and engineering properties linked to breakage underscore why quality penalties often originate before drying and milling (Krah et al., 2020; Almasoud et al., 2024). At the system level, adding mill-scale recirculating capacity increases capacity utilisation and stabilises labour income without displacing women, where sun floors remain viable in clear weather, supporting a hub-and-spoke configuration of small recirculating units at farm/coop nodes and larger units at mills (Saha et al., 2023). Finally, sensing acts as an enabler rather than a substitute: radio tomography imaging localises wet pockets in silos for targeted aeration or redrying, and maturity sensing with drones can tighten harvest windows when linked to explicit operating rules (Ramli et al., 2024; Tan et al., 2025). Together with systems modelling showing that postharvest loss reduction can ease irrigation requirements, these results connect device-level efficacy to food and water security objectives (Jha et al. 2020). With more standardised reporting and longer real-world storage trials, future syntheses can deliver prescriptive operating envelopes via agroecology, enabling policymakers to scale technologies with predictable advantages.

Fig. 5 and 6 quantify the scale of grain that never reaches consumers. Because of their enormous harvests, China and India account for the greatest absolute losses, but relative terms tell a slightly different story. Midsised producers such as Myanmar, Cambodia and Bangladesh experience considerable waste relative to their production capacity, which represents a heavy burden on both livelihoods and resources. These Fig. remind us that postharvest loss is not just a matter of wasted rice: it also reflects wasted land, water, labor and energy. Even small improvements can be transformative.

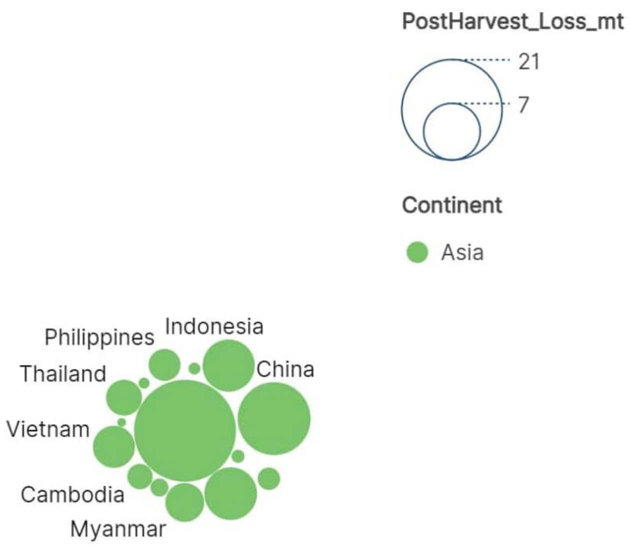

Fig. 6: Bubble Chart of Post-Harvest Loss (metric tonnes) in Asia.

For example, reducing India's postharvest losses by a single percentage point would release more rice than the total annual output of several smaller countries. In this context, investment in reliable drying, hermetic storage and community-based pest management in high-loss regions offers particularly high returns. The evidence points to a stage-specific modernisation package as the most credible route from typical double-digit postharvest losses to low single digits at the treated stages. In practice, this means pairing well-tuned mechanical threshing or combining to curb spillage and fissuring with recirculating or fixed-bed dryers run within explicit operating envelopes for bed thickness and air conditions and standardising hermetic storage as the default for grains and seeds, with targeted RF disinfestation or enhanced trapping where the risk warrants. Placing drying capacity at aggregation nodes reduces queue times and weather exposure, enables bulk handling, and provides the control needed to achieve quality targets. In contrast, micro warehousing and negotiable receipts link physical protection to liquidity, conditions that favour adoption by smallholders (Orge et al., 2020; Saha et al., 2023; Singh et al., 2023). Implementation should be governed by a minimal set of measurable indicators: share of lots reaching ≤14% moisture within 24 h, live insect counts in storage below thresholds, HRY and broken fraction at delivery, and stage-specific loss. In this way, incentives for service providers and financiers can be tied to outcomes rather than equipment uptime alone (Khandai et al., 2025; Saha et al., 2017). Because the technical paybacks for smallholder-appropriate dryers can be rapid, performance-based credit and receipt-backed storage financing are logical next steps, provided that programs explicitly preserve or transition women's roles where sun floors remain a source of income (Saha et al. 2023).

For the research agenda, the findings argue for standardised reporting that will unlock more powerful synthesis: always state moisture basis and provide convertible statistics (means/SD/N or exact CIs), report milling settings and the HRY definition used, and include sufficient cost details to allow CPI/PPP normalisation across currencies and years. Future trials should report quality outcomes with time and cost, capture weather and humidity logs, randomise at the lot level or use robust quasiexperimental designs in live supply chains, and extend storage horizons to match real seasonal practices, especially for polished rice, where susceptibility is greatest (Atta et al., 2022, 2023; Khandai et al., 2025). With such datasets, meta-regressions can quantify how initial moisture, bed thickness, air temperature, storage duration, and parboiled status modulate effects, yielding prescriptive operating envelopes by agroecology. Coupling device trials with adoption and equity metrics—capacity utilisation, queue times, labour hours, earnings by gender, and default risk on equipment loans—will help move from efficacy to scale with distributional awareness (Saha et al., 2023). Future studies should focus on creating postharvest technologies that can handle changing weather conditions. First, new drying systems need to work well even in humid areas, with sudden rain and hot temperatures. This could be accomplished by using a mix of solar and biomass energy, smart air movement control, and systems that adjust heat levels automatically. Second, storage systems that keep things airtight need better materials and stronger seals. These materials should remain sealed properly even when the temperature increases, after being handled many times, and after being kept in fields for long periods. Third, integrating IoT sensors and machine learning tools into postharvest operations could enable real-time detection of rewetting, pest outbreaks, and moisture anomalies, thereby providing farmers with climate-smart decision support. Fourth, future studies should test scalable cooperative- or mill-based service delivery models that reduce upfront costs and facilitate community-level resilience.

Limitations

Despite the promising performance of these technologies in controlled trials, several limitations remain when they are deployed under real farmer conditions. High ambient humidity during the monsoon season significantly reduces the effectiveness of solar bubble dryers and conventional fixed-bed systems, which often fail to bring moisture below 14% and are prone to rewetting, compromising grain quality. Recirculating dryers while able to overcome these constraints requires higher upfront investment, reliable power sources, and skilled operation, making them less accessible to smallholder farmers unless supported through cooperatives or mill-level service provisions. During storage, hermetic bags perform well under stable conditions but rely heavily on seal integrity; repeated opening, rough handling, or rodent damage can compromise the hypoxic environment and reduce their effectiveness. Radiofrequency (RF) disinfestation is highly efficient against insects but demands specialised equipment, technical expertise, and greater energy input, placing it beyond the financial reach of most smallholders. Attractant and air-assisted traps can improve monitoring but are insufficient as stand-alone protection methods, particularly in communities with high insect or rodent pressure where coordinated village-level management is needed.

The conclusions are bound by the limitations of the underlying evidence and our scope. The Scopus-only strategy likely reduced the yield relative to multidatabase searches; future updates should include the Web of Science and CAB abstracts. Designs, climates, comparators, and reporting conventions vary widely, constraining cross-study pooling for certain endpoints, most notably costs reported in different currencies and years. Several engineering trials lack randomisation or complete variance reporting, require conversions or exclusions, and many storage studies are shorter than real-world storage seasons or rely on laboratory conditions that do not fully capture the variability of the monsoon. Although focusing on Scopus ensured a consistent indexing standard, relevant nonindexed or gray literature may have been overlooked. Small-study effects cannot be ruled out in domains with few comparable contrasts. These constraints temper the precision of pooled estimates but do not diminish the mechanistic coherence observed across studies: thermodynamic control of drying, hypoxia-based suppression of storage insects, heightened vulnerability of polished fractions, and the need for community rodent management, which together provide a strong, actionable basis for policy and practice (Saha et al., 2017, 2018; Orge et al., 2020; Khandai et al., 2025; Htwe et al., 2016).

Conclusion

This systematic review and meta-analysis of 26 Scopus index studies revealed that the largest and most variable components of PHL can be reduced via a targeted, stage-specific modernisation package. Mechanical drying (recirculating and fixed-bed systems, including smallholder-appropriate models) consistently compresses the time to achieve safe moisture from days to hours, improves moisture uniformity, and—under wet, monsoon-affected conditions—achieves competitive or lower unit costs than does sun drying. Protected storage—anchored by hermetic bags/cocoons and complemented where needed by radio-frequency (RF) disinfestation and IPM/attractant trapping—reduces the live-insect load, damage/weight loss, and downstream quality penalties, with measurable gains in head rice yield and fewer broken kernels than in nonprotected storage. At the front end, combines/mechanical threshers reduce spillage and fissuring relative to manual practices, preventing losses that otherwise propagate into the drying and milling processes. Across Scopus index studies, engineered drying consistently compresses the time to safe moisture, and hermetic storage preserves quality relative to traditional practices. These effects are strongest under monsoon humidity and when the intakes are wet, and they are associated with improved downstream milling qualities. The results also clarify where and how the technology should be deployed. Drying capacity at aggregation nodes (co-ops, mills, and microware houses) reduces queue times and weather exposure and enables tighter control of bed thickness, air temperature/flow, and time-to-14% MC—parameters that deterministically shape grain quality and loss. In storage, hermetic containment should be the default for grains and seeds; postmilling stocks, which are more pest-susceptible than paddy/brown rice, warrant stronger safeguards (RF/IPM) or an accelerated time-to-market. Community-level rodent management must accompany household hermetic adoption in high-risk localities; otherwise, aggregate storage losses remain elevated.

For policy and practice, the most defensible path is a package: (i) improve harvest/threshing with operator training and maintenance; (ii) deploy engineered dryers sized to farm and mill nodes with predrying options (mix-dry, bag-bin) to bridge peak inflows; (iii) standardise hermetic storage with simple monitoring; and (iv) institutionalise measurement-based extension services. Programs should track a small set of KPIs—% lots ≤14% MC within 24 h, HRY (%), broken (%), storage live-insect counts, and stage-specific loss (%)—and link incentives for service providers and credits to these outcomes. Evidence of subyear paybacks for small dryers argues for performance-based finance and receipt-backed micro warehousing that couples physical protection with liquidity. Where women's incomes depend on sun floors, role transitions (e.g., quality monitoring and bag-bin operations) should be explicitly designed to avoid displacement.

Limitations of the evidence include heterogeneous designs, moisture-basis inconsistencies, short storage horizons in some trials, and mixed cost reporting, which temper the precision of pooled estimates for specific outcomes. Nonetheless, the mechanistic coherence of the findings (thermodynamics of drying, hypoxia-driven pest suppression, and process-parameter control) and the convergent direction of the effects across settings provide strong decision guidance. In practical terms, accelerated adoption of this package is a fast, scalable route to reclaim otherwise lost grain, enhancing HRY, stabilising prices, and strengthening resilience to climate variability. To convert today's promising demonstrations into system-level gains, future studies should (1) adopt standardised reporting (moisture basis, means/SD/N, milling settings, and cost normalisation); (2) extend storage trials over full seasons in humid tropics; and (3) report equity and service-model metrics (capacity utilisation, labor by sex, and default risk). With these improvements, forthcoming syntheses can deliver prescriptive operating envelopes by agroecology and scale, supporting governments and value chain actors in reliably shifting postharvest losses from ~10% to 2–3% at critical stages while safeguarding grain quality.

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