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Crop Postharvest Loss Reduction Interventions in sub-Saharan Africa and South Asia

Systematic Scoping Review Update 2024

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About the report

This report, *Crop Postharvest Loss Reduction Interventions in sub-Saharan Africa and South Asia: Systematic Scoping Review Update 2024*, provides an update to an earlier systematic scoping review of literature on interventions to improve food security and livelihoods by reducing postharvest losses in sub-Saharan Africa and South Asia. The authors of this report are Tanya Stathers (Natural Resources Institute (NRI), University of Greenwich) and Deirdre Holcroft (Holcroft Postharvest Consulting), with screening assistance from Mark Engelbert (3ie), Zafeer Ravat (3ie), and Pierre Marion (3ie). The authors bear sole responsibility for the content of this report, and any errors and omissions are the authors' sole responsibility. Please direct any comments or queries to the corresponding author, Tanya Stathers, at t.e.stathers@greenwich.ac.uk.

Review process

This report was reviewed by two external reviewers, Aine McGown and colleagues (Food & Agriculture R&D Adviser and colleagues, FCDO), Mark Engelbert (Senior Evaluation Specialist, 3ie), and Dina Kiwan (Academic Director, RCC and Professor of Comparative Education, University of Birmingham).

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About the Research Commissioning Centre

The Foreign, Commonwealth and Development Office (FCDO) Research Commissioning Centre (RCC) has been established to commission and manage research to enhance development and foreign policy impact. Led by the International Initiative for Impact Evaluation (3ie), the University of Birmingham, and an unmatched consortium of UK and global research partners, the RCC aims to commission different types of high-quality research in FCDO's key priority areas.

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EXECUTIVE SUMMARY

Reducing postharvest losses (PHLs) of food crops is an integral part of helping to create more sustainable and resilient food systems, while simultaneously optimising agricultural productivity and increasing incomes of small-scale producers. Stathers et al. (2020) conducted a systematic scoping review on PHL reduction interventions for 22 crops across 57 countries in sub-Saharan Africa (SSA) and South Asia from the 1970s to 2019. This study updated that review with the aim of providing FCDO with synthesized information on research and innovation gaps for postharvest food loss to support evidence-based investments under their new business case, 'Innovation to Unlock a Sustainable Food Secure Future'.

Using the existing search strings an additional 4,009 studies were identified from October 2019 to January 2024. A double-blind screening process of these using the inclusion/exclusion criteria from the earlier review resulted in an additional 123 included studies, bringing the total number of studies to 457 and increasing the number of interventions studied to 2,187. Data were extracted and synthesis was conducted at both the study and the intervention levels to provide an overview of what interventions have been studied by crop, country and postharvest stage, and to compare the efficacy of the different interventions in reducing PHLs.

Technology/tool/equipment interventions dominated. Accounting for 87.8% of the interventions evaluated, handling practice changes 10.1%, training/extension for skill development 0.5%, combinations of training + technology or handling practice change 1.3%, infrastructure 0.2% and markets 0.1%.

Cereals, particularly maize, continued to dominate the evidence base with the most PHL reduction interventions (42.4 % and 26.3 %, respectively). The dominance of maize was mostly in SSA (25.3 %) and for storage. For cereal and legume crops hermetic bags alone and in combination with other storage insect pest management methods were widely studied. The evidence-base on mechanised threshing and solar energy drying had expanded and new evidence on postharvest training in combination with different bundles of technologies particularly for aflatoxin management was reported. Fruit was the second most studied crop group (20.8 %), particularly citrus (8.5 %) and mango (8.1 %) mainly in India. Storage protectants were the most widely studied category in fruits, particularly waxes or coatings on citrus and mango. Root and tuber crops accounted for 17.0 % of the interventions, principally potato in India. The vegetable interventions (11.4 %) focused on onion, particularly in India, and tomato, mainly in SSA. Legumes had the fewest interventions studied (8.4 %).

India had the most studies (28.0%) and the most interventions (29.2%), with a focus on potato, citrus, onion, mango, rice, wheat, banana, and tomato. Nigeria had the second highest number of studies (8.3%). Pakistan, Ethiopia, Tanzania, and Bangladesh accounted for a greater percent of the studies in 2024 than in 2019. Twenty-three countries had no studies that met the inclusions criteria. Geographically, SSA accounted for 57.8 % of the interventions studied.

This updated analysis continues to indicate an urgent need for a systematic assessment of interventions across the entire value chain over multiple seasons and sites, targeting stakeholders beyond farmers. The lack of studies on training, finance, infrastructure, policy and market interventions highlights the need for evidence on interventions beyond technologies or handling practice changes. Additionally, more studies are needed connecting the impact of PHL reductions to social, economic and environmental outcomes. This analysis provides decision makers with updated data for informing policy formulation and prioritization of investments in PHL reduction.

List of acronyms

AU	African Union
BCR	Benefit Cost Ratio
CAADP	Comprehensive Africa Agriculture Development Programme
CDC	Collapsible Grain Dryer
CFB	Cardboard Fibre Box
DRC	Democratic Republic of Congo
EU	European Union
FAO	Food and Agriculture Organisation of the United Nations
FCDO	Foreign and Commonwealth Development Office (UK)
HS	Hermetic storage
INR	Indian Rupee
LMICs	Low-and Middle-Income Countries
MRR	Marginal Rate of Return
MS	Metal silo
NS	no storage
ODA	Overseas Development Assistance
PE	polyethylene
PH	Postharvest
PHL	Postharvest Loss
PICS	Purdue Improved Crop Storage (hermetic bag brand)
PP	polypropylene (woven bags)
PRISMA	Preferred Reporting Items for Systematic Reviews and Meta-Analyses
R&D	Research and Development
RPC	Returnable Plastic Crates
Rwf	Rwandan Franc
SDG	Sustainable Development Goal
SGB	Super Grain Bag (hermetic bag brand)
SPICE	Setting, Perspective, Intervention, Comparison and Evaluation framework
SSA	Sub Saharan Africa
SSR	Systematic Scoping Review
TSP	typical storage practice
UN	United Nations
UNDESA	United Nations Department of Economic and Social Affairs
US	United States of America
USAID	United States Agency for International Development
USD	United States of America Dollar
WFLO	World Food Logistics Organisation
WHO	World Health Organization
WTP	Willingness to pay
ZECC	Zero Energy Cool Chamber

1. Introduction

The human population is projected to reach 9.7 billion people by 2050 (UNDESA, 2022). To meet the expanded and changed food demands of a range of plausible socio-economic futures, projections suggest global food consumption will need to have increased by 35 to 56 % between 2010 and 2050, or by 30 to 62 % if the uncertainty related to climate change is also taken into account (van Dijk et al., 2021). In response, major investments are being made to increase the productivity of farming systems and to close yield gaps, with the aim of simultaneously meeting this demand while reducing the detrimental impacts of using more land to produce extra food. However, a substantial portion of the food that is produced is lost at or after harvest (WFLO, 2010; World Bank et al., 2011; Gustavsson et al., 2011; Nanda et al., 2012; Hodges et al., 2014; AGRA, 2014; Loada et al., 2015; Kitinoja et al., 2016; Kitinoja and Dandago, 2017; Kitinoja and Odeyemi, 2017; Kitinoja et al., 2018). Such postharvest loss (PHL) is not only a loss of valuable food, but also of the inputs (land, labour, water, seed, fertilisers etc.) used to produce it (World Bank et al., 2011).

Food crises, climate-related events and economic shocks re-focus attention on the importance of preventing food that is produced using valuable resources from then being lost at or after harvest. Following such events, PHL reduction receives increased attention and investment. However, the research and investments are often poorly coordinated, done at a small scale with little follow-up and involve a heavy focus on tangible technologies/ equipment as opposed to accompanying investments in training, monitoring and learning, institutionalisation and the development of the necessary supporting services such as financial credit, distribution networks, quality standards, improved infrastructure, and advisory and information services. Reliable and regular synthesis of the rapidly expanding body of research and development work on PHL reduction interventions that can help small-scale producers and associated value-chain actors to reduce PHLs is a vital part of the evidence required for informed decision-making.

Between 713 and 757 million people in the world were estimated to be undernourished in 2023. This is particularly prevalent in parts of sub-Saharan Africa and South Asia, where 20.4 % and 8.1 % of the overall populations are facing hunger (FAO et al., 2024a). The adoption of interventions that reduce PHLs of food crops would help in reducing these figures and suffering.

Targets to reduce food losses have been set. In the 2014 Malabo Declaration, African Union member states committed to ending hunger by 2025. To achieve this, they resolved to cut their existing levels of PHLs in half (AU, 2014). Sustainable Development Goal (SDG) 12.3 is to “by 2030, halve per capita global food waste at the retail and consumer levels, and reduce food losses along production and supply chains, including PHLs” (UN, 2015). Reducing postharvest food loss can also contribute to many other SDGs related to food systems, and socio-economic and environmental outcomes. The reduction of postharvest food loss is a priority focus in three of the strategic objectives of CAADP’s post-Malabo (2026-2035) strategy and action plan towards a vision of “sustainable and resilient agri-food systems for a healthy and prosperous Africa” (CAADP, 2024).

Reducing PHL of food crops is an integral part of increasing agricultural productivity. This is particularly the case for small-scale producers and their associated value chain actors, as significant amounts of food crops are either: left in the field or damaged by poor handling at harvest; spilt or damaged during transport; scattered or lost during peeling or threshing;

attacked by insects, rodents, fungi or bacteria during storage; or left to rot in the field due to seasonal production gluts or limited market linkages, information systems or crop handling or processing knowledge. The causes of and stages at which postharvest losses can happen are numerous and complex, leading to reductions in the quantity and quality of food available and the crop sales-related income opportunities of small-scale food producers and other value chain actors. In many small-scale producer-dominated and traditional food systems women are responsible for many of the postharvest activities. Well-targeted PHL reduction interventions have the potential to empower women alongside improving food and nutrition security and food safety.

This project updated the earlier systematic scoping review of interventions for crop PHL reduction in sub-Saharan Africa and South Asia which was published by Stathers et al. (2020). The original systematic scoping review screened and collated original research in peer-reviewed and grey literature to identify the range of interventions that have been field-tested to help small-scale producers and their associated value chain actors (e.g. aggregators; packers; operators of driers, threshers, chippers etc.; transporters; processors; traders; other service providers (e.g. trainers, finance, information systems)) in sub-Saharan Africa and South Asia reduce PHLs along food crop value chains.

This update review adds research reported between October 2019 and January 2024 to the findings from our earlier scoping review. We have updated the evidence on both the range and effectiveness of PHL reduction interventions for improving small-scale producers' food and nutrition security, incomes, gendered and environmental impacts and productivity. PHL reduction interventions cover a diverse range of aspects (from tangible technologies and equipment, through training and education, financial services, institutional and policy changes, and infrastructural investments) and typically multiple simultaneous interventions are required to bring about sustainable loss reduction behavioural changes at scale. We have overlaid our findings onto a postharvest activity stage framework for the different crop groups. These results provide a synthesis of the existing contextual evidence from sub-Saharan Africa and South Asia on interventions that small-scale producers and associated value chain actors can adopt or adapt to reduce PHLs along food crop value chains in their focal food systems. It can be used by a wide range of actors including governments, development partners, investors, researchers and trainers for informing decisions and actions. We also use the findings to identify gaps in the literature and evidence to support the planning and commissioning of future PHL reduction research and field-based trials.

The UK FCDO's Food and Agriculture Research team are interested in exploring research and innovation gaps for postharvest food loss reduction, as a priority area for investment under a new business case, titled 'Innovation to Unlock a Sustainable Food Secure Future'. They have supported this update review and a consultation on the perspectives and experiences of postharvest key informants in different sub-Saharan Africa countries to i) inform the design of future ODA R&D investments in PHL research and technology development and ii) help guide the investment of wider stakeholders, including other FCDO teams, who are supporting interventions along agri-food value chains in diverse low- and middle-income countries (LMIC) country contexts.

The objective of this systematic scoping review was to synthesise the available research evidence on interventions small-scale producers and their associated value chain actors in low- and middle-income countries (LMIC) in sub-Saharan Africa and South Asia can adopt or adapt to reduce PHLs along food crop value chains. This updates the 2019 review of this topic.

2. Methods

2.1 Objectives

The objective of this systematic scoping review (SSR) was to synthesise the available evidence on interventions small-scale producers and associated value chain actors in LMIC countries in sub-Saharan Africa and South Asia can adopt or adapt to reduce postharvest losses along food crop value chains[1]. This synthesis provides an updated overview of the earlier evidence mapping on this topic which was conducted in 2019[2].

The method used for updating this SSR closely followed that of the original SSR.

2.2 Research question

The research was guided by the main question: what are the interventions small-scale producers and associated value chain actors in sub-Saharan African and South Asian countries can adopt or adapt to reduce postharvest losses along food crop value chains? A secondary research question was: what are the associated barriers and facilitators for adoption of the interventions?

The geographical focus of this analysis was sub-Saharan African and South Asian countries, two regions with large populations of small-scale producers dependent on local food systems, where PHLs and the incidence of poverty are relatively high. Interventions applicable to small-scale food producers and/or their associated value chain actors such as aggregators; packers; operators of driers, threshers, chippers etc.; transporters; processors; traders; and other service providers (e.g. trainers, extension, financial and market information services) were targeted to meet the food demands in these regions. Narrowing the focus to 22 key food crops from five different crop groups (cereals–maize, rice, sorghum, wheat; legumes–beans, cowpeas, pigeon peas, chickpeas, groundnuts; roots and tubers–cassava, potato, sweetpotato, yam, fruits–plantain, banana, mango, papaya, all citrus fruits including orange, lemon, lime, mandarin; and vegetables–cabbage, onion, tomato, leafy vegetable) allowed for a deeper analysis. There were no prior specifications of the types of interventions, as any interventions that apply to PHL reduction in food crop value chains are relevant, including training, information, handling practices, skills, institutional changes, financial interventions, policies, postharvest infrastructure, tangible technologies and any combinations of these.

To measure the effectiveness of the interventions, comparisons included those between different interventions, or between users and non-users, or pre- and post-use of an intervention. The comparisons could be vis-à-vis their technical, economic, environmental or social efficacy and outcomes. Intervention efficacy was evaluated by the level of PHL that occurred as well as the reduction in PHL compared with the traditional practice or untreated control in each study.

To ensure consistency during screening, key terms such as ‘postharvest’, ‘loss’, ‘adopt’, ‘intervention’, ‘field-tested postharvest interventions’, ‘small-scale food producers’ associated

[1] See Supplementary Table S1 for definitions of terms: postharvest, loss, adopt, intervention, field-tested postharvest interventions, small-scale producers, small-scale food producers’ associated value chain actors, food crop value chain and low and middle-income countries (LMIC).
[2] The original study was published as Stathers et al., 2020 https://www.nature.com/articles/s41893-020-00622-1

value chain actors', and 'food crop value chain' were defined. The definitions are given in Supplementary Table S1. An overview of the SPICE (Setting, Perspective, Intervention, Comparator, Evaluation) framing of our SSR is shown in Table 1.

Table 1. Crop Postharvest Loss Reduction in sub-Saharan Africa and South Asia Systematic Scoping Review SPICE framework

Setting	Low and Middle-Income Countries in Sub-Saharan Africa and South Asia[3]
Perspective	Small-scale food producers and their associated value chain actors (e.g. aggregators; packers; operators of driers, threshers, chippers etc.; transporters; processors; traders; other service providers (e.g. trainers, financial services, market information services))[4] Food crops[5]
Intervention/ Exposure	Open, all that apply to PHL reduction in food crop value chains, may include multiple interventions[6]
Comparator	Comparison may be between the identified interventions or with small-scale farmers or other value chain actors' normal practice, in terms of their technical, economic, environmental and social efficacy and outcomes. AND/ OR between those adopting and those not adopting the identified intervention/s - if sufficient data AND/ OR pre and post adoption of the identified intervention/s - if sufficient data
Evaluation	PHL percentage reduction and scale of reduction

2.3 Search strategy

The updated systematic scoping review used the comprehensive search strategy developed and used in the original scoping study to identify all relevant published and grey literature. Search terms include variations of the key concepts in the research question: PHLs in quantity or quality, PH activity stages, PHL causing factors, focal food crops and focal countries. The search strings used are shown in Appendix A1. The CAB Abstracts, Web of Science and Scopus online databases of peer-reviewed publications were sequentially searched on 30 January 2024 using the date coverage period 1 January 2019 – 30 January 2024. These searches returned 3,120 records, 805 records, and 258 records, respectively. Searches were not limited by language. However, the search terms were done only in English. In the original scoping study

[3] The focus was on LMICs in sub-Saharan Africa and Southern Asia
[4] Coding and filtering were used if data provides sufficient detail to allow disaggregation of producers or their associated value chain actors by gender or income/well-being group, or agro-ecological zones
[5] Search results were coded by crop type and crop groups; we are focused on the following food crops: [Cereals]: maize, rice, sorghum, wheat; [Legumes]: beans, cowpeas, pigeon peas, chickpeas, groundnuts; [Root and Tuber]: cassava, potato, sweetpotato, yam; [Fruit]: plantain, banana, mango, papaya, citrus (all citrus fruits including orange, lemon, lime and mandarin); [Vegetable]: cabbage, onion, tomato, leafy vegetable. Crops grown as cash crops were not included, but food crops which are also sold are included
[6] Our definition of interventions includes training, information, skills, institutional change, financial, policy, postharvest infrastructure as well as tangible technologies – and combinations of these

the comprehensiveness of the search strategy was assessed using the eight benchmark articles (Supplementary Appendix A2). In addition, the 47 electronic database and grey literature sources identified by the PH team members for the original review were searched (Supplementary Table S2).

These grey literature searches involved various combinations of the following terms: 'post-harvest', 'post-harvest loss', 'post harvest losses', 'post harvest', 'postharvest', 'value chain', 'crops' and 'food'. During the update review these searches returned 713 records, which were combined with the 4,183 from the databases resulting in 4,896 search hits in total. CAB Abstracts was the priority source of record. In contrast to the PHL review in six SSA countries by Affognon et al. (2015), where grey literature physically acquired through national teams made up 57.3 % of the documents, the original and this updated reviews digital search strategy captured relatively few PhD/MSc theses, working papers or project reports.

The bibliographic details for each of the resulting 4,896 peer-reviewed and grey literature documents were exported into EPPI. Records were then de-duplicated using EPPI-Reviewer's de-duplication function. This function compares all records across all metadata fields and creates groups of candidate duplicates. Each candidate duplicate is given a score between 0 and 1 indicating its overall similarity, across all metadata fields, to the "master" record of the group. We automatically marked as duplicates all items with similarity scores of 1 (i.e., identical metadata across all fields). We manually reviewed all other candidate duplicates and marked them as "Duplicate" or "Not a duplicate" as applicable.

We attempted to use machine learning tools to accelerate the screening process, but our testing suggested that we could not use these tools safely to exclude any records, so all records were manually screened (details of the classifier development and testing process are available in Supplementary Information Appendix A4). This highlights the importance of careful testing of machine learning and other automation tools in each use case before deploying them at scale in a review process.

2.4 Study inclusion and exclusion criteria:

The following exclusion criteria were applied at the title and abstract and the full-text review stages.

- *Irrelevant crop*: study does not include a PHL reduction intervention for one of the 22 focal food crops.
- *Irrelevant geographical area*: study does not take place in the target geographical area of sub-Saharan Africa and South Asia.
- *Irrelevant target actor*: study is not relevant to PHL reduction by small-scale producers or their associated value chain actors.
- *Irrelevant study type*: study is a review or does not contain original research or contains insufficient details on the original research to make an evidence-based decision about the intervention's efficacy.
- *Irrelevant data output*: study does not report the effect of an intervention on PHL.
- *Irrelevant scale of study*: study reports the effect of an intervention that was not tested at field-level or in a real-world context. For example, the intervention was tested only at small-scale in a laboratory, or tested in the field or on-station but with a treatment replicate size too small to provide reliable data on which to base investment decisions.

In the studies of the durable crops, interventions on maize using less than 50 kg per treatment replicate were excluded, while for sorghum, rice and wheat studies those with less than 25 kg per treatment replicate were excluded. For the five legume crops studies with less than 10 kg per treatment replicate were excluded. Additionally, interventions were excluded where stored crops were artificially infested with insects, fungi or bacteria, or where crops were frozen prior to study to disinfest them. If the study had crops that had been fumigated before the intervention and met all other inclusion criteria, the study would be included. The fumigation aspect was then added to the intervention's description.

In the studies of the perishable crops, those with less than 20 kg per treatment for roots and tubers and less than 10 kg per treatment for fruits and vegetables were excluded. For studies where the fruit number was stated but the weight was not, we used a typical weight for that produce type to determine inclusion. Studies that failed to state the size used in the treatments and where the size could not be inferred from the data were excluded. For some studies, in which the interventions were evaluated on a range of different grades or varieties, the results were averaged to achieve the weight expectations required for inclusion.

- *Language*: studies written in a language other than English or French were excluded.
- *Date*: for the update review, the date restrictions were 1 January 2019 – 30 January 2024.

2.5 Title and abstract screening

The titles and abstracts of the search outputs were screened in EPPI Reviewer. Using the prioritisation identified by the EPPI classifier - studies with the highest likelihood of being included were screened first – and following their division into crop groups (cereals, legumes, root and tuber crops and fruits and vegetables) sets of studies were distributed among the five screeners. For each of the 4,009 studies the title and abstract were screened independently in EPPI reviewer by two members of the screening team, one of whom was the PH expert with experience of the specific crop group that those studies focused on (e.g., cereals and legumes (TS), fruit and vegetables (DH), root and tubers were covered by either of the PH experts) and one systematic review expert. The eligibility criteria were used to decide which of the studies to include, and for excluded studies the reasons were captured. In cases where there was insufficient information in the title or abstract to exclude the study, the study was included so that the decision could be made at the full-text-screening stage. Where the two independent reviewers scoring disagreed, a third member of the screening team screened the study and organised reconciliation. There were many irrelevant studies in the initial library (for example, studies on carbon storage, cocoa or coffee beans, silage or soil; plastic replacements, reviews; and studies from other countries and languages).

2.6 Full-text article screening

A total of 1,540 of the initial 4,009 studies in the update review were selected for full-text article screening. The full text pdf copies of these 1,540 studies were accessed electronically and imported into EPPI Reviewer and divided among the team for independent screening by two members of the screening team, one of whom was the PH expert with experience of the specific crop group and one systematic review expert. The inclusion or exclusion decision was recorded in EPPI Reviewer and exclusions reasons were captured. Where two independent reviewers' scoring disagreed, a third member of the team screened and organised reconciliation. To develop consistency, 20 studies were screened by all five members of the screening team.

2.7 Data extraction

For each of the 123 studies included at full text in the update review, the relevant data was extracted by one of the two postharvest experts in the team. The perishable crop PH expert handled the studies on perishable crops and the durable crop PH expert handled those for the durable crops. The coding framework from the protocol of the original review registered on the Open Science Framework at https://osf.io/6zc92/ and the MS Excel database developed for the original review were used with some adaptations.

In addition to its bibliographic information, the researchers extracted data for each article using a two-part coding framework (Supplementary Appendix A3). Part I data comprised the following: geographic locations (country, region and village), focal crops, crop form (fresh, dried, shelled or on the cob), focal postharvest activities (harvesting, handling, field drying, transport to homestead, curing, cooling, further drying, threshing/shelling, milling, packing, storing dry, storing fresh, transport to market and wholesale market), targeted postharvest actors (small-scale producers/point of production; packers and processors; service providers of harvesting, drying, milling, storage and transport; and traders, middlemen or collectors), type of study (field or on-farm trial, on-station trial or survey), study method (quantitative, qualitative, survey or mixed), study design (comparison with traditional practices, other types of intervention, non-adopters or pre- and post-adoption) and funding source.

The classification of the interventions was based on a four-tier hierarchical system, with the first tier being the intervention type (technology/tool/equipment, handling practice change, training/extension, finance, policy, markets, support or infrastructure or combinations of these). These were further divided into a second tier, intervention stage, where the interventions were grouped into typical PH stages (for example, harvesting, drying and storage). Tier 3 consisted of specific interventions (for example, zero-energy cool chamber and traditional granary plus synthetic chemical) (Supplementary Table S3). Detailed descriptions of the intervention were then provided in tier 4 (for example, name and application rate of the agricultural chemical, size of the box or specific details of the traditional granary). Tier 4 was included for reference but not used in the data synthesis.

In Part II, the following were captured: the PHL measurements of quantity or quality; facilitators and barriers for adoption; study design, duration and scale; intervention cost; and any assessment of any social, economic or environmental outcomes associated with the interventions. In the original review, the database build only enabled one quantity loss and one quality loss metric per intervention to be recorded, but it was recognised as a weakness by the team. In this update review, data extraction was done directly into MS Excel, and we expanded the datasheet to enable data for up to three types of quantity and three types of quality loss metrics from each study to be entered if such data had been collected during the study. However, we could not retrospectively do this for the 334 previously included studies.

The study design of each included full-text article was assessed as part of the coding. If a study had unsound methodology (e.g. insufficient detail, incorrect measurement, no replication of treatments), or did not meet the criteria for size it was excluded.

2.8 Data synthesis

A series of pivot tables were used to examine the different data fields in the synthesis. This synthesis analysis was conducted at both the study level and the intervention level. A few studies covered multiple crops, multiple countries or multiple postharvest activity stages. Each study reported on at least 2 and as many as 24 interventions. In the analysis the means, medians and ranges of the quantity and quality loss figures for the interventions (tier 3) were calculated, and the data were presented within the relevant tier 1, 2 and 3 categories. For storage method interventions for durable crops (that is, dried cereals and legumes), data for the quantity loss metric (% weight loss) and the quality loss metric (% damaged grain) were adjusted to a standardized storage time of 6 months for cereals and 4.5 months for legumes to facilitate comparisons and represent typical storage durations for these crops in these geographical regions. The data on storage methods for perishable crops were presented without adjusting for storage time. Temperature is the most important factor affecting the storage life of perishable crops, and its effects are not linear. The wide range in treatment temperatures used in the studies (from <5 °C to >38 °C) made standardization by storage time for perishable crops inappropriate, even for ambient conditions.

3. Results

3.1 General results section

In the earlier scoping review by Stathers et al. (2020), 334 (2.6 %) of the 12,907 studies identified for the 22 food crops across 57 countries of SSA and South Asia met the inclusion criteria. In this update review, 125 (3.1%) of the 4,009 studies identified met the inclusion criteria, of which 123 were unique studies bringing the total number of included studies from which data was extracted to 457 (Fig. 1).

During this update review, we screened the titles and abstracts of 4,009 studies to remove irrelevant records, this led to the exclusion of 2,469 articles (61.6 %). The main exclusion reasons at this screening stage were irrelevant crop or no crop (32.2 %), not a PHL reduction intervention (27.7 %) and irrelevant geographical area (15.4 %). The full texts of the remaining 1,540 studies were then screened and 91.9 % of them were then excluded. The main exclusion reasons at full text screening stage were irrelevant country (41.2 %), not meeting the size criteria (24.9 %), not a PHL reduction intervention or contained no PHL data (11.9 %) (Fig. 1). Data from each of the 123 additional unique included studies were coded and entered into a MS Excel database containing the data from the original 334 included studies to create a dataset from the 457 included studies.

3.2 Outline of the evidence

The earliest articles in our dataset on PHL reduction interventions were published in 1971 with a steady increase in publications this century (Fig. 2a). In the first decade of the study (1970-1979) 4.4 % of the included articles were published with 6.1 %, 12.5 %, 19.3 %, and 33.7 % in each subsequent decade. The increasing interest in and generation of evidence occurring on PHL reduction interventions in the focal countries is illustrated by the fact 24.1 % of the 457 included studies were published from 2020-2023. India accounted for 28.0 % of the articles, followed by Nigeria (8.3 %), Pakistan (7.2 %) and Ghana (7.0 %). Pakistan, Ethiopia, Tanzania, and Bangladesh accounted for a greater percent of the studies by 2024 than in 2019. Senegal and Rwanda had their first studies included in the database in the recent update (Fig. 2b and 3).

Studies on maize continued to dominate (26.0 %) (Fig. 2c), followed by mango (9.2 %). Mango, maize, tomato, chickpea, groundnut and papaya accounted for a greater percent of the studies by 2024 than in 2019. There were still no included studies for plantain. When aggregated by crop group the majority of the studies involved cereals (41.8 %), followed by fruits (20.1 %), roots and tubers (17.9 %), vegetables (12.7 %) and legumes (9.2 %) (Fig. 2 d). Twenty one of the 457 studies included more than one crop, with seven of these covering a cereal and a legume crop, one covering a fruit and a vegetable crop and another covering a root and tuber and a vegetable crop. When grouped by PH activity stages, studies on storage interventions for dry and fresh forms of the crops still dominated, accounting for 42.5 % and 40.5 % of the studies, respectively (Fig. 2e). The proportion of studies covering threshing/shelling and further drying had increased since the original 2019 review. Most of the studies (92.8 %) focused on PH interventions that small-scale producers could use to reduce losses. Studies of PHL reduction interventions for use by traders, transporters or other food-system actors and service providers were limited. On-station trials made up 55.4 % of the studies, on-farm/field trials 35.2 %, surveys 9.2 % and 0.2 % (a single study) had both a field and an on-station component. In only 20.6 % of the studies had the interventions been studied over multiple seasons.

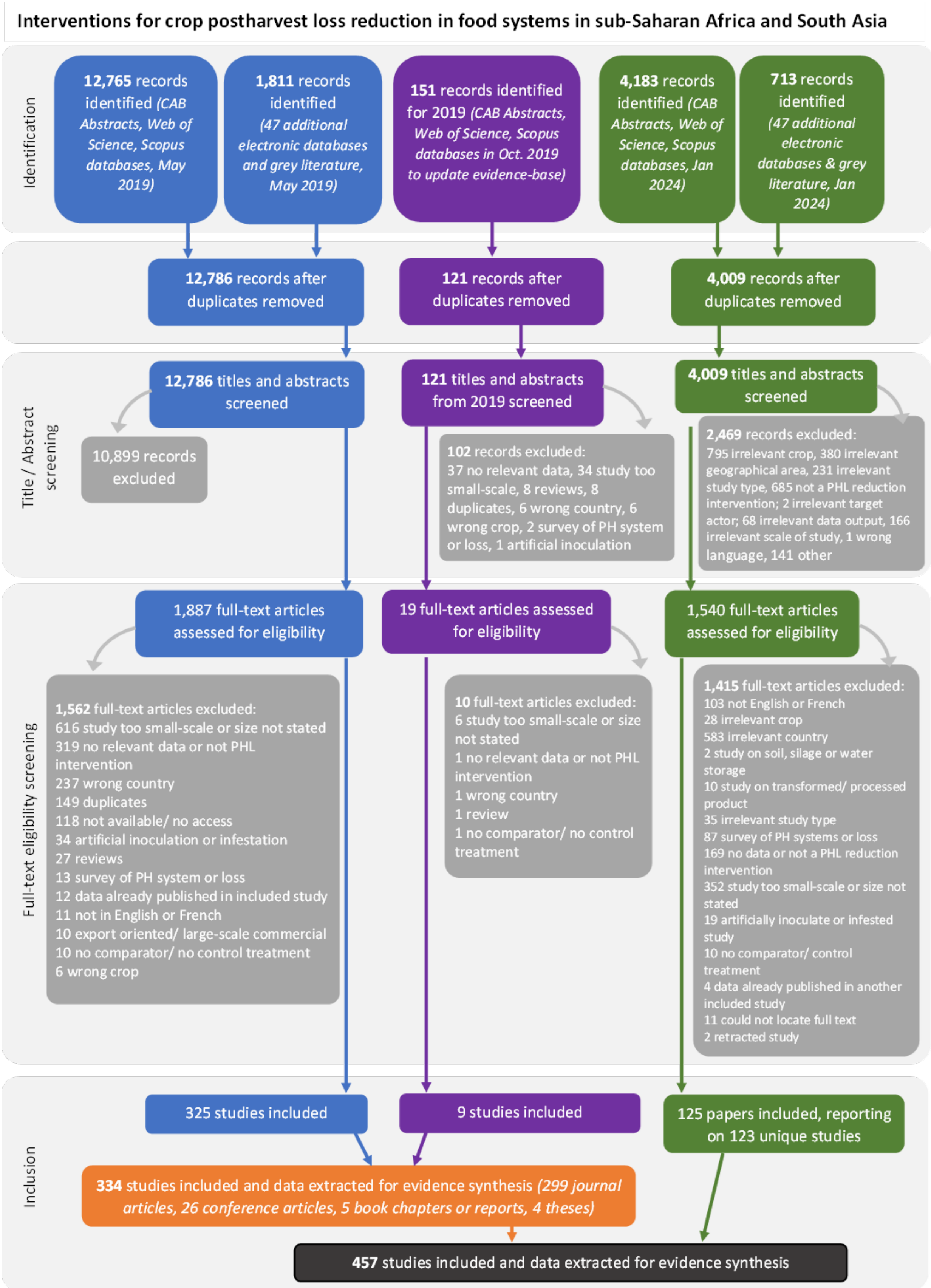

Fig. 1 PRISMA flowchart. The number of articles that were retrieved in the searches and passed each subsequent stage of screening is shown. The green and grey cells on the far right describe the screening results of the update review

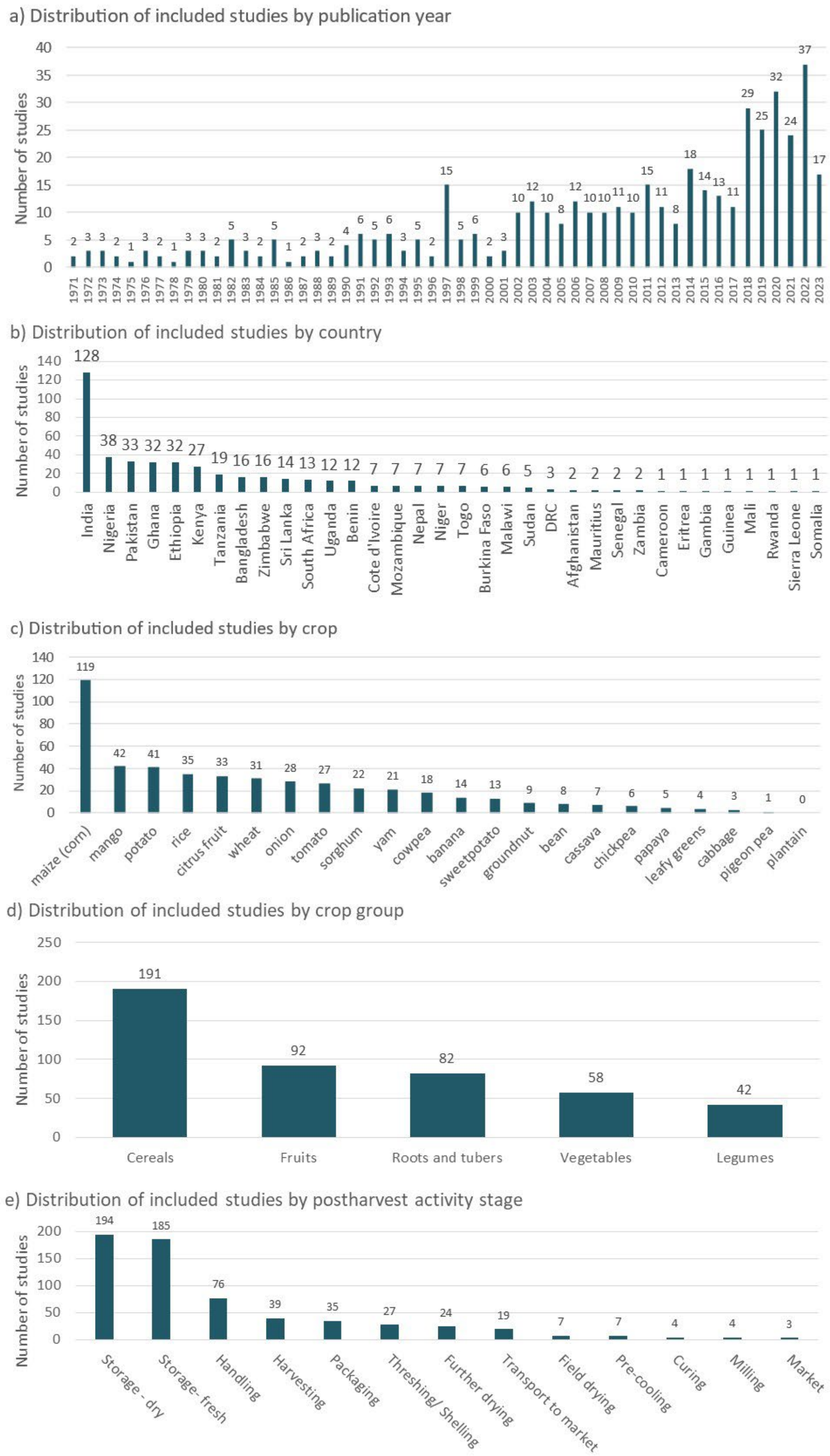

Fig. 2 a-e Profile of the 457 PHL reduction intervention studies. The number of studies by year (**a**), country (**b**), crop (**c**), crop group (**d**) and postharvest activity stage (**e**).

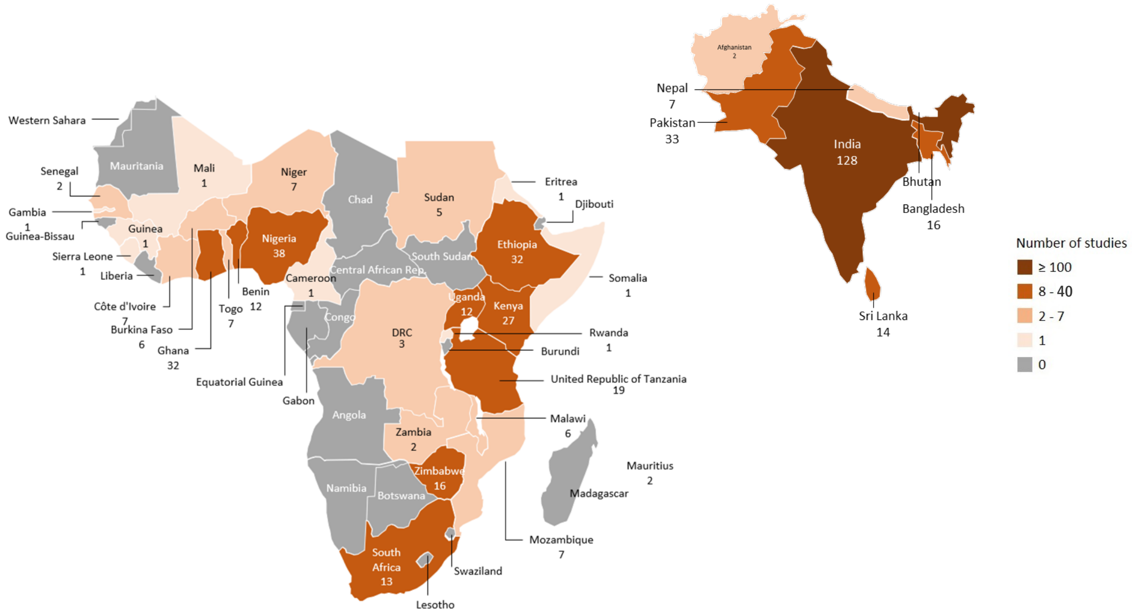

Fig. 3 Distribution of the 457 PHL reduction intervention studies.

3.3 Overview of postharvest interventions studied

Cereals, particularly maize, continued to dominate the evidence with the most PHL reduction interventions (42.4 % and 26.3 %, respectively) (Table 2). The dominance of maize interventions was mostly in SSA where it accounted for 25.3 % of all interventions, predominantly for storage (Tables 2 & 3). Fruits followed (20.8 %), particularly citrus (8.5 %) and mango (8.1 %) interventions mainly from India. Root and tuber crops accounted for 17.0 % of the interventions, principally potato in India. The vegetable interventions (11.4 %) focused on onion, particularly in India, and tomato, mainly in SSA. Legumes had the fewest interventions studied (8.4 %).

Of the 2187 studies of interventions, 1921 (87.8 %) were studies of technologies/tools/ equipment and particularly focused on loss reduction during storage. For the cereals, 75.2 % of studied interventions were focused on storage methods, and for the legumes 81 %. For the root and tubers, fruits, and vegetables 68.8 %, 66.6 % and 62.2 % of studied interventions were on storage protectants, structures or containers. For the focal 22 crops there has been comparatively little or no study of technologies/tools or equipment for reducing losses during other activity stages such as harvesting, drying, threshing/shelling, packaging (Table 3).

There has also been much less reported study of handling practice changes (221 studied interventions), which accounted for just 10.1 % (94) of cereal interventions, and for 6.0 % (11) of legumes, 18.6 % (69) of root and tubers, 4.6 % (21) of fruits, and 19.4 % (26) of vegetable studied interventions. Only 0.5 % (10) of the reported studied interventions were on training interventions, 0.2 % (5) on road infrastructure, 0.1 % (2) on market access and 1.3 % (28) on combined training plus technology use or handling practice.

Geographically, SSA accounted for 57.8 % of the interventions studied. The most interventions had been studied in India (29.2 %), with a focus on potato, citrus, onion, mango, rice, wheat, banana, and tomato. Within SSA, 54.1 % of the interventions were on cereals, 15.9 % on root and tuber crops, 13.4 % on legumes, 8.4 % on vegetables and 8.2 % on fruit. While within South Asia, 38.0 % of the interventions were on fruits, 26.3 % on cereals, 18.5 % on root and tuber crops, 15.5 % on vegetables, and just 1.6 % on legumes (Table 2).

The PHL reduction interventions studied were aggregated using a four-tier hierarchical system, with the first tier being the intervention type (technology/tool/equipment, handling practice change, training/extension, finance, policy, markets, support/organisation, or infrastructure). The second tier was the intervention stage, grouped into typical postharvest stages (such as harvesting, drying and storage), and tier 3 was the specific interventions (such as zero-energy cool chamber or traditional granary plus synthetic chemical; for the full list, see Supplementary Table S3). The details of each intervention were provided in tier 4 (for example, the name and application rate of the agricultural chemical or the size of the box). The analysis of the 457 studies by intervention type (tier 1) highlights the dominance of studies on tangible technologies, tools or equipment (85.2 % of studies, 87.8 % of the interventions studied). There were far fewer studies on handling practices (12.5 %, 10.1 %), training (1.3 %, 0.5 %), infrastructure (0.4 %, 0.2 %), markets (0.2 %; 0.1 %) and combinations of training, handling practices, technology (0.8 %, 0.1.3 %) (Table 3). While training-type interventions represented a tiny proportion (1.8 %) of the interventions studied, this was an increase from the 0.3 % in the original review. There were no studies on policy, finance, or support/organisation type PHL reduction interventions.

Table 2 Number of PHL reduction interventions studied by crop, crop group, country and region. Derived from the dataset of 457 studies, the numbers in each cell specify the number of interventions studied for each specific crop and country combination. The darkest orange cells identify the crop–country combinations with the most data. The blank cells represent zeroes/ gaps. The blue rows at the end of the table show the total numbers and percentages of interventions studied by crop, crop group and region (SSA, South Asia (SAsia) and the geographical regions of SSA (WAfrica, West Africa; EAfrica, East Africa; SAfrica, Southern Africa; CAfrica, Central Africa)).

	Cereals				Legumes					Roots and Tubers				Fruits					Vegetables					
	maize (corn)	rice	sorghum	wheat	bean	cowpea	chickpea	pigeon pea	groundnut	cassava	potato	sweetpotato	yam	plantain	banana	mango	papaya	citrus	cabbage	onion	tomato	leafy vegetable	Country total	Country (%)
Afghanistan				2																2			**4**	0.2
Bangladesh		15		4							6	4			6	16		16	2	12		2	**83**	3.8
Benin	50					8				2													**60**	2.7
Burkina Faso	6	2	4			5																	**17**	0.8
Cameroon													12										**12**	0.5
Cote d'Ivoire	3									4			18			4							**29**	1.3
DRC		2								4	7										7		**20**	0.9
Eritrea			5				6																**11**	0.5
Ethiopia	71		18	19	3		12				2	2			2	9	10	3		6	8		**165**	7.5
Gambia									3														**3**	0.1
Ghana	48	24				20			10	2		22	19			8					9	3	**165**	7.5
Guinea									2														**2**	0.1
India	16	67	4	59			7		3		138	3	7		35	74	6	114	2	78	21	4	**638**	29.2
Kenya	84		2		2			2			14	2			6	3				8			**123**	5.6
Malawi	31		2						14														**47**	2.1
Mali			3																				**3**	0.1
Mauritius											3										3		**6**	0.3
Mozambique	5	8				4						8										2	**27**	1.2
Nepal	3			5							4	5						5			10		**32**	1.5
Niger		2				19			4											3			**28**	1.3
Nigeria	39	4				8				17	6	3	32			5		3		6	15		**138**	6.3
Pakistan	3	3		39					3		4				4	36	6	17		3	4		**122**	5.6
Rwanda																					4		**4**	0.2
Senegal	10																						**10**	0.5
Sierra Leone		3																					**3**	0.1
Somalia			4																				**4**	0.2
South Africa											2				4	8	6	28			16		**64**	2.9
Sri Lanka		23			2										7	9			3				**44**	2.0
Sudan			6													2				7			**15**	0.7
Tanzania	66		7		19							4				3					9		**108**	4.9
Togo	25					3																	**28**	1.3
Uganda	39				4						7	9											**59**	2.7
Zambia	8																						**8**	0.4
Zimbabwe	68		16			21																	**105**	4.8
Crop Total	**575**	**153**	**71**	**128**	**30**	**88**	**25**	**2**	**39**	**29**	**193**	**62**	**88**	**0**	**64**	**177**	**28**	**186**	**7**	**125**	**106**	**11**	**2187**	
Crop (%)	26.3	7.0	3.2	5.9	1.4	4.0	1.1	0.1	1.8	1.3	8.8	2.8	4.0	0.0	2.9	8.1	1.3	8.5	0.3	5.7	4.8	0.5	100	
Crop Group Total	**927**				**184**					**372**				**455**					**249**				**2187**	
Crop Group (%)	42.4				8.4					17.0				20.8					11.4				100	
SSA Crop Total	**553**	**45**	**67**	**19**	**28**	**88**	**18**	**2**	**33**	**29**	**41**	**50**	**81**	**0**	**12**	**42**	**16**	**34**	**0**	**30**	**71**	**5**	**1264**	
SSA Crop (%)	25.3	2.1	3.1	0.9	1.3	4.0	0.8	0.1	1.5	1.3	1.9	2.3	3.7	0.0	0.5	1.9	0.7	1.6	0.0	1.4	3.2	0.2	57.8	
Crop % within SSA	43.8	3.6	5.3	1.5	2.2	7.0	1.4	0.2	2.6	2.3	3.2	4.0	6.4	0.0	0.9	3.3	1.3	2.7	0.0	2.4	5.6	0.4	100	
SAsia Crop Total	**22**	**108**	**4**	**109**	**2**	**0**	**7**	**0**	**6**	**0**	**152**	**12**	**7**	**0**	**52**	**135**	**12**	**152**	**7**	**95**	**35**	**6**	**923**	
SAsia Crop (%)	1.0	4.9	0.2	5.0	0.1	0.0	0.3	0.0	0.3	0.0	7.0	0.5	0.3	0.0	2.4	6.2	0.5	7.0	0.3	4.3	1.6	0.3	42.2	
Crop % within SAsia	2.4	11.7	0.4	11.8	0.2	0.0	0.8	0.0	0.7	0.0	16.5	1.3	0.8	0.0	5.6	14.6	1.3	16.5	0.8	10.3	3.8	0.7	100	
WAfrica Crop Total	**181**	**35**	**7**	**0**	**0**	**63**	**0**	**0**	**17**	**25**	**6**	**25**	**69**	**0**	**0**	**17**	**0**	**3**	**0**	**9**	**24**	**3**	**484**	
WAfrica Crop % within SSA	32.7	77.8	10.4	0.0	0.0	71.6	0.0	0.0	51.5	86.2	14.6	50.0	85.2	0.0	0.0	40.5	0.0	8.8	0.0	30.0	0.0	60.0	38.3	
EAfrica Crop Total	**260**	**0**	**42**	**19**	**28**	**0**	**18**	**2**	**0**	**0**	**26**	**17**	**0**	**0**	**8**	**17**	**10**	**3**	**0**	**21**	**24**	**0**	**495**	
EAfrica Crop % within SSA	47.0	0.0	62.7	100	100	0.0	100	100	0.0	0.0	63.4	34.0	0.0	0.0	0.0	40.5	62.5	8.8	0.0	70.0	0.0	0.0	39.2	
SAfrica Crop Total	**112**	**8**	**18**	**0**	**0**	**25**	**0**	**0**	**14**	**0**	**2**	**8**	**0**	**0**	**4**	**8**	**6**	**28**	**0**	**0**	**16**	**2**	**251**	
SAfrica Crop % within SSA	20.3	17.8	26.9	0.0	0.0	28.4	0.0	0.0	42.4	0.0	4.9	16.0	0.0	0.0	0.0	19.0	37.5	82.4	0.0	0.0	0.0	40.0	19.9	
CAfrica Crop Total	**0**	**2**	**0**	**0**	**0**	**0**	**0**	**0**	**2**	**4**	**7**	**0**	**12**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**7**	**0**	**34**	
CAfrica Crop % within SSA	0.0	4.4	0.0	0.0	0.0	0.0	0.0	0.0	6.1	13.8	17.1	0.0	14.8	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	2.7	
Crop Group SSA Total	**684**				**169**					**201**				**104**					**106**				**1264**	
Crop Group % within SSA	54.1				13.4					15.9				8.2					8.4				100	
Crop Group SAsia Total	**243**				**15**					**171**				**351**					**143**				**923**	
Crop Group % within SAsia	26.3				1.6					18.5				38.0					15.5				100	
WAfrica Crop Group Total	**223**				**80**					**125**				**20**					**36**				**484**	
EAfrica Crop Group Total	**321**				**48**					**43**				**38**					**45**				**495**	
SAfrica Crop Group Total	**138**				**39**					**10**				**46**					**18**				**251**	
CAfrica Crop Group Total	**2**				**2**					**23**				**0**					**7**				**34**	

Table 3 Overview of the number of PHL reduction interventions studied by type (tier 1) and stage (tier 2) and by crop and crop group. Derived from the dataset of 457 studies, the numbers in each cell specify the number of interventions studied for each specific crop and intervention stage combination. The darkest orange cells identify the crop–intervention stage combinations with the most data. The blank cells represent zeroes. The blue cells at the end of the table show the total number and percent of interventions studied by crop and crop group, and in the two rightmost columns by intervention type and stage.

	Cereals				Legumes					Roots and Tubers				Fruits				Vegetables					
Intervention type (tier 1), and intervention stage (tier 2)	maize (corn)	rice	sorghum	wheat	bean	cowpea	chickpea	pigeon pea	groundnut	cassava	potato	sweetpotato	yam	banana	mango	papaya	citrus	cabbage	onion	tomato	leafy vegetable	Intervention Total	Intervention (%)
Technology/tool/equipment use (TTE)	**487**	**125**	**69**	**119**	**24**	**88**	**25**	**2**	**27**	**16**	**171**	**41**	**73**	**64**	**156**	**28**	**186**	**4**	**105**	**100**	**11**	**1921**	**87.8**
Harvesting		20		2					3	2					21		13					59	2.7
Precooling														9	13							22	1
Packaging (perishables)					2					7	16	12		15	18		40	2	9	37	2	160	7.3
Storage protectant										6	65	7	44	19	74	18	106		42	12		393	18
Storage structure or container										1	90	14	29	19	30	10	27	2	49	43	7	321	15
Ripening/senescence														2						3		5	0.2
Drying	25								12			8							5	5	2	57	2.6
Threshing or Shelling or De-husking	17	26	2																			45	2.1
Storage method (durables)	445	68	67	117	22	88	25	2	12													846	39
Processing		11																				11	0.5
Handling practice change (HPC)	**57**	**28**		**9**	**6**				**5**	**13**	**20**	**21**	**15**		**21**			**3**	**20**	**3**		**221**	**10.1**
Handling pre and or after harvest	43	20		6	6				5	4	9	6	3						20			122	5.6
Harvest	14	8		3						4	9	15	12		11			3		3		82	3.7
Harvest and handling										5	2				10							17	0.8
Training/extension	**4**		**2**						**4**													**10**	**0.5**
Expert advice	2																					2	0.1
Training	2		2						4													8	0.4
Infrastructure											**2**									**3**		**5**	**0.2**
Road transport											2									3		5	0.2
Markets	**2**																					**2**	**0.1**
Market access	2																					2	0.1
Training/extension + TTE and/or HPC	**25**								**3**													**28**	**1.3**
Training + handling practice change									3													3	0.1
Training + technology	25																					25	1.1
Grand Total	**575**	**153**	**71**	**128**	**30**	**88**	**25**	**2**	**39**	**29**	**193**	**62**	**88**	**64**	**177**	**28**	**186**	**7**	**125**	**106**	**11**	**2187**	**100**
Crop Group Total	927				184					372				455				249					
Crop Group (%)	42.4				8.4					17.0				20.8				11.4					

3.4 Measurement of PHL

PHLs are multidimensional and can be measured in different ways, both quantitatively (physical loss) and qualitatively (for example, increased damage, decay, breakage, contamination with toxins, reduced seed viability and deterioration in the nutrient content or economic value of a product) (World Bank et al., 2011; FAO, 2019). These losses can be assessed using a range of metrics depending on the focus of the research or intended use of the crop. For each intervention studied, data for up to three quantitative and up to three qualitative loss metrics were included in the update review depending on the evidence presented in the respective study, while in the original review data for only up to one quantitative and one qualitative loss metric was included. To support the comparative efficacy analyses, the different loss measurements were aggregated into groups (Supplementary Tables S4 and S5).

3.5 PHL reduction interventions and their efficacy

Most of the interventions studied were tangible technologies for reducing losses during storage, while a few studies focused on changes in handling practices or training (Table 3). A comparison of the loss in quantity or quality for the different interventions can provide an overview of their efficacy. Since the studies were conducted in different years, seasons, locations and contexts, using different varieties and by different research teams, comparisons beyond those within a single study provide only an indication of the relative efficacy of the different interventions and their stability in different contexts.

3.5.1 Cereals

For cereals, the focus (75.2 % of the cereal interventions studied) has primarily been on storage technologies (Table 3), and most of these storage interventions have been studied on maize (63.8 %). A wide range of storage technologies have been covered (Supplementary Table S3), including those which aim to create a modified atmosphere (e.g., reduced oxygen and increased carbon dioxide levels) within the storage container such as, air-tight (hermetic) high density polyethylene liner bags inside woven polypropylene sacks, air-tight plastic and metal drums, silos and jerry cans, or large cocoons, or the use of nitrogen gas in silos. A wide range of interventions admixing grain with pesticidal products (e.g., commercially available synthetic grain protectant chemicals, plant materials (botanicals), various types of inert dusts), or adding fumigant products, a few where biological control organisms (e.g. predatory insects, bacteria) or pheromone traps had been introduced. Combinations of these technologies had also been studied. Only 15 of the 163 cereal storage studies (9.2 %) targeted traders or other storage service providers. Six of these studied large-scale storage interventions such as metal silos or hermetic cocoons of seven-tonne capacity or above, one study tested a one tonne capacity hermetic bag and the remainder studied large bag stacks in warehouses.

Studies on changes in handling practices focused on harvest maturity, timing or weather conditions and their combination with other postharvest handling practices or technologies (e.g., threshers, tarpaulin or plastic sheet or mat use during drying, grain moisture measurement tools, de-husking of cobs, winnowing). Some studies evaluated the effects of sorting or field-drying or store hygiene methods.

Simple tools (e.g., sickles) and a range of mechanised harvesting machines were compared with manual practices. Drying technologies studied included different structures and heat sources (e.g. solar, charcoal, firewood), as well as use of different barriers to prevent the crop from contacting the ground during sun-drying versus drying it directly on the ground, along with the effect of different thicknesses of grain layers during drying. Threshing, shelling or de-husking studies compared manual or oxen/buffalo/tractor trampling methods, simple tools (e.g., stick, bambam, drum) and mechanized threshing often in combination with different grain moisture contents. Just four studies investigated the effect of different milling equipment on PHLs, all on rice in Ghana, India or Bangladesh. One study in Uganda analysed the effect of quality sensitive markets plus PH training (Bold et al., 2022). Six recent studies (Chegere et al., 2020 (with additional data in Chegere et al., 2022); Leavens et al., 2021; Bauchet et al., 2021; Vandercasteelen and Christiaensen, 2020; Pretari et al., 2019; Anitha et al., 2019) investigated the effect of training on PH management or aflatoxin management for farmers, five of them with various combinations of plastic drying sheets, grain driers and/or hermetic storage bags.

Maize

For the analysis of quantity loss for different maize storage interventions (tier 3), directly measured percentage weight loss data were used. For quality loss, the percentage of damaged grains was the main metric reported, although other quality loss measurements were recorded in some of the maize studies, such as % germination, % grain moisture content and concentration of aflatoxin (ppb) and fumonisin (ppm) (Supplementary Table S5). As the studies presented loss data from different storage durations (ranging from 1 to 12 months), the data for a standardized storage period of six months were used to facilitate comparison. Of the 90 studies on maize storage methods, 85 were from SSA and 5 were from South Asia (India (4) and Nepal (1)). The storage method included details of both the facility in which the crop was stored, and any protectant used. The heterogeneity between the studies and the small number of cases (that is, n = 1 or 2) available for comparison for many of the interventions must be noted.

Storage method. In the earlier scoping review (Stathers et al., 2020), the aggregated data indicated that several air-tight/hermetic facilities, the admixture of grain with diatomaceous earth (DE) or cooking oils, and a fumigated and insecticide-sprayed bag stack kept quantity loss below 2 % during six months of storage. From the additional studies available since 2019 (Fig. 4a), fumigation alone and in combination with botanicals, hermetic bags, synthetic chemicals or inert dust, and the combination of a sack with a hermetic liner with a pesticide incorporated into it or a hermetic liner inside a polypropylene bag that has a pesticide incorporated into it, and hermetic bag interventions (n=13) kept grain weight loss below 2 % during six months storage. When the % weight loss data from all the available maize storage intervention studies were compared fifteen interventions kept weight loss below 2 %, although several of these interventions had only been studied once or twice (n=1 or 2) within the dataset (Fig. 5a). Those interventions which had been studied two or more times and kept median % weight loss below 2% were PP bags + diatomaceous earth, hermetic cocoons, stacks of bags of grain treated with synthetic chemical and then fumigated or fumigated grain then treated with synthetic chemical protectant and stored in bags, plastic drums, fumigated and non-fumigated grain stored in hermetic bags, metal silo, grain admixed with vegetable oils, grain that had been fumigated and then stored in a bag with pesticide incorporated into the fabric (Fig. 5a). Differences in the types, efficacy, stability and application rates of synthetic chemicals, varietal susceptibility, environmental conditions, time between harvest and store loading, level of insect infestation at start of storage and number of occurrences of the interventions help explain the high variability. For example, the most studied synthetic chemical intervention, ‘polypropylene bag + synthetic chemical’ (n = 25), had a median weight loss of 2.8 % with a range from 0 to 44.0 %. The ‘metal silo’ (n=12) had a median weight loss of 1.2 % with a range from 0.2 to 29.7 %, the ‘hermetic bag’ intervention (n=28) had a median weight loss was 1.2 % with a range from 0 to 9.7 %.

Trends between interventions for losses in quality in terms of the % damaged grain metric were similar to those for the quantity loss data (Fig. 4a&b & 5a&b). This is because much of the grain damage and weight loss was due to insect pest attack of the grain during storage, so the relationship between this quantity and this quality loss metric was expected. For example, for maize when 20 % of grains show damage by insects this typically equates to ~5 % weight loss (Holst et al., 2000), as only part of the weight of each damaged grain has been removed due to insect feeding or boring. As mentioned, different studies and research teams collect data on different loss metrics, so for some interventions there is only % damage data and not % damage and % weight loss data etc. Grain stored untreated without a protectant in bags that were not hermetic or grain stored in store rooms, warehouses or traditional or improved granaries typically suffered high median levels of grain damage (9.8-100%) during a six-month storage period, although variability was high between studies. Hermetic bags and cocoons alone and in combination with other treatments or handling practices kept grain damage low (<10 %). One recent Ethiopian on-farm study found that even the addition of a hermetic liner to traditional granaries filled with dried unshelled maize cobs, kept grain damage below 10 % during a six-month storage period, while in the non-lined traditional granary grain damage reached 47.3 % (Tola et al., 2020). When diatomaceous earth was admixed with maize grain the median damage was below 2 %, although across studies the range went from 0.3% to 9.9 %. Most of the interventions that combined fumigation with other pest management treatments kept grain damage below 10 % (Fig. 5b).

Most of the maize storage studies since 2019 have studied the effect of storage in various hermetic bags or drums or admixture with different types and application rates of diatomaceous earths or other inert dusts (e.g., Triplex or filter cake powder), or grain dried to different moisture contents and then manually or mechanically shelled and placed in different storage containers. The levels of loss occurring in these methods were compared to maize stored in the commonly used woven PP bags or farmers' practices that involve admixing various plant materials or admixture of the recommended commercially available grain protectant synthetic chemical dusts. Comparison of the reduction in % weight loss and % damage that these interventions resulted in versus that which occurred when using farmers' traditional storage practices or in untreated stored grain, reveals how comparatively effective treatments were, including those that did not keep % weight loss below 2 % or % grain damage below 10 % but did result in large reductions in weight loss and damage compared to leaving grain untreated or using farmers typical practices (Fig. 6a&b and Supplementary Fig. S1a&b).

Data on the effect of the interventions in studies added since 2019 on % germination was available for two studies. Data on the effect on % grain moisture content (mc) was available for eight of the update review studies added since 2019. While the overall mean % moisture content (mc) reported for each of the intervention types (tier 3) was within the recommended 12.5 % mc for safe storage of maize grain, the underlying data showed several studies where moisture content was just above 13 % including in some studies of hermetic bags. Further exploration of these studies could determine whether at loading the grain was above the recommended % mc or whether the % mc increased during the storage period.

In the studies added since 2019, one maize, one rice and one wheat study reported specifically on the effect of a storage intervention on rodent damage. The maize study found a 9-percentage point reduction in the likelihood of rodent damage in hermetic bags versus in jute sacks plus fumigant treatment (Shukla et al., 2023). However, exploration of farmers' store hygiene practices in Kenya led Makinya et al. (2021) to remark on the many rodent damaged hermetic bags they had encountered. An earlier Tanzanian included study (Mdangi et al., 2013) showed that sealing of traditional granaries could reduce rodent consumption of stored maize grain, and closing of sacks and protecting them with a metal mesh proofing could eliminate it.

Four of the maize storage studies included since 2019, reported the concentration of aflatoxin measured in parts per billion (ppb) in the maize grain from the different storage methods they evaluated. One of these studies also reported on the concentration of another mycotoxin, fumonisin. In one study in Nigeria (Nwaubani et al., 2020), the grain had been fumigated prior to setting up the trial and very low levels of weight loss, damage, and aflatoxin (<2 ppb) occurred in all the treatments including the grain that was then stored in a PP bag with no further protection. Using fumigation and then also applying a further grain protectant method, in the way some researchers do in technical studies, would increase the cost of storage protection for farmers. Additionally in most countries it is illegal for anyone who is not a licensed fumigator to use fumigants, although they are widely used by farmers. In the other three studies (Opuku et al., 2023; Worku et al., 2022; Nyarko et al., 2021) which were in Ethiopia and Ghana the maize grain had not been fumigated prior to set up, and the aflatoxin levels were lower in grain that had been stored in hermetic bags as opposed to in PP bags plus synthetic chemicals, or untreated in either PP bags or metal silos following six months of storage for two of the studies, and 12 months for the other study. A similar effect was seen for fumonisin concentration. Where recorded in these studies, insect damage to grain and % weight loss were also lower in the hermetic bag treatments similar to the trends seen for the mycotoxin incidence data.

Four maize studies of training or training combined with other interventions also reported the mycotoxins levels following their different interventions.

An overview of all the loss data for the **non-storage stage interventions** studied on maize is presented in Table 4. Due to different types of loss metrics being reported in the different studies it is not simple to directly compare effects of specific interventions between studies.

For **maize drying interventions**, the data from studies in Uganda, Tanzania, Ghana shows higher weight loss and aflatoxin concentrations or odds ratios occur in maize grain dried directly on the bare ground as compared to when it is protected from having direct contact with the soil through drying it on plastic sheets/mats/tarpaulins or using raised drying racks (Kamala et al., 2016; Kaaya & Kyamuhangire, 2010; Mwebaze & Mugisha, 2011; Bosomtwe et al., 2019) (Table 4). Whether drying using sun-drying, protected solar bubble driers or solar cabinets, drying in a thin as opposed to a thick layer of grain led to lower weight loss and less reduction of % germination during subsequent storage in an Ethiopian study (Asemu et al., 2020).

For **maize threshing interventions**, opposing results were obtained from different studies with some showing higher breakage rates of grains when machine as opposed to manual or stick beating methods were used, and others lower breakage rates (Table 4). Factors such as the type of machine, the flow rates and other settings, labour, variety and grain moisture content may also influence grain breakage rates.

There were 16 studies on maize which compared different **handling practices and/or the effect of PH training** (Tables 5 and 6). This included study of the effects of harvesting the crop early or late, selecting cobs, drying cobs husked or de-husked, combinations of these practices plus protecting the maize from contacting the ground during drying and different methods of applying a grain protectant. Work in Kenya in the 1970s showed that for cob storage, selecting cobs with tightly closed as opposed to open or loose husks reduced insect damage to grain (Giles et al., 1971) (Table 5). While a study in Benin found the tightness of the husk made no difference to subsequent weight loss during storage unless the cobs with good husk cover were also fumigated prior to storage (Borgemeister et al., 1994) (Table 5). The data available also shows that the maturity stage at harvesting matters. Harvesting later than at the recommended stage of physiological maturity increases grain weight loss and damage during storage (Borgemeister et al., 1998; Jonsson et al., 1987) and can increase aflatoxin concentration in the grain (Kaaya et al., 2005). Harvesting early can lead to higher incidence of mouldy, diseased or discoloured grains (Borgemeister et al., 1998). In northern Tanzania, Mutungi et al. (2019) found early harvesting, de-husking of cobs and drying them on a tarpaulin before shelling as opposed to leaving them in heaps on the ground to dry led to lower subsequent grain damage and weight loss, while leaving the cobs husked during drying appeared to lead to lower % broken grains than the other treatments. However, when their statistical analysis compared each of the different factors, late as opposed to early harvesting led to lower weight loss, grain damage and mouldy grains, as did de-husking the cobs before as opposed to after drying. The effect of late harvesting leading to lower weight loss and damage in their study contrasts to the findings in the earlier studies. Compared to farmers' ordinary practices, following a set of improved PH practices (harvest timing, off-ground drying, threshing, winnowing, air-tight storage) led to lower weight loss and grain damage during storage while mouldy grain incidence remained similar (Mutungi et al., 2022a). Another Tanzanian study based on farmers' perceptions of loss levels as opposed to measured losses, found harvesting late, leaving the crop drying for too long, delaying shelling, not sorting grain and not disinfesting stores or using grain protectant led to higher levels of perceived loss than when improved handling and storage practices were followed (Chegere et al., 2018).

In a study in Ghana, leaving the cobs to dry on standing plants in the field, as opposed to heaping them in a pile led to reduced grain weight loss and lower aflatoxin concentrations (Manu et al., 2019) (Table 5). Work from Nigeria showed that poor storage hygiene and no monitoring led to higher weight loss and a slight increase in aflatoxin concentration (Otitodun et al., 2018). Mutambuki et al. (2010) showed that just changing the method and/or tool that farmers used to apply/admix their grain protectant could significantly reduce grain damage during maize storage in Kenya.

The impact of different combinations of a package of PH technologies (training, plastic sheet for drying, grain dryer use, hermetic bag use) on aflatoxin contamination of maize was assessed with farmers in 30 maize-growing villages in Meru and Tharaka-Nithi counties in Kenya. The interventions reduced aflatoxin contamination by over 50%, most of this reduction appeared to be due to training and the use of drying sheets (Pretari et al., 2019) (Table 6). A large-scale study with >1,500 farmers in Senegal aimed at reducing the levels of aflatoxins in stored maize, found additive effects of bundling PH training, measurement of moisture content during drying, off ground sun-drying and hermetic bag storage in terms of leading to lower incidences of grain contaminated with over 10 or 20 ppb of aflatoxin (Bauchet et al., 2021) (Table 6). Work by Leavens et al. (2021) with 2,000 farmers two years following their participation in the trial reported on by Bauchet et al. (2021), confirmed the continuing additive effect of each input in the bundle when combining training, a moisture meter, and a tarpaulin. However, the additive effect of hermetic bag use had not persisted due to supply chain issues rendering it difficult for the famers to access and replace their bags (Table 6). A study in Malawi found training in aflatoxin and PH management led to a lower incidence of these farmers' maize (and sorghum and groundnut) samples containing aflatoxin concentrations >20 ppb (Anitha et al., 2019). Two studies in Tanzania which analysed how farmers perceptions of the level of losses in their stored maize changed after they had received PH training, reported that their losses had reduced (Chegere et al., 2020; Vandercasteelen & Christiaensen, 2022). One of these studies found that bundling the provision of a hermetic bag with the training further reduced perceived levels of loss, the other study showed a slight increase in perceived loss level when a metal silo was purchased with a 70% discount. An overview of the mycotoxin and mould-related data from all the handling practice and training studies for cereals and legumes is given in Supplementary Table S6.

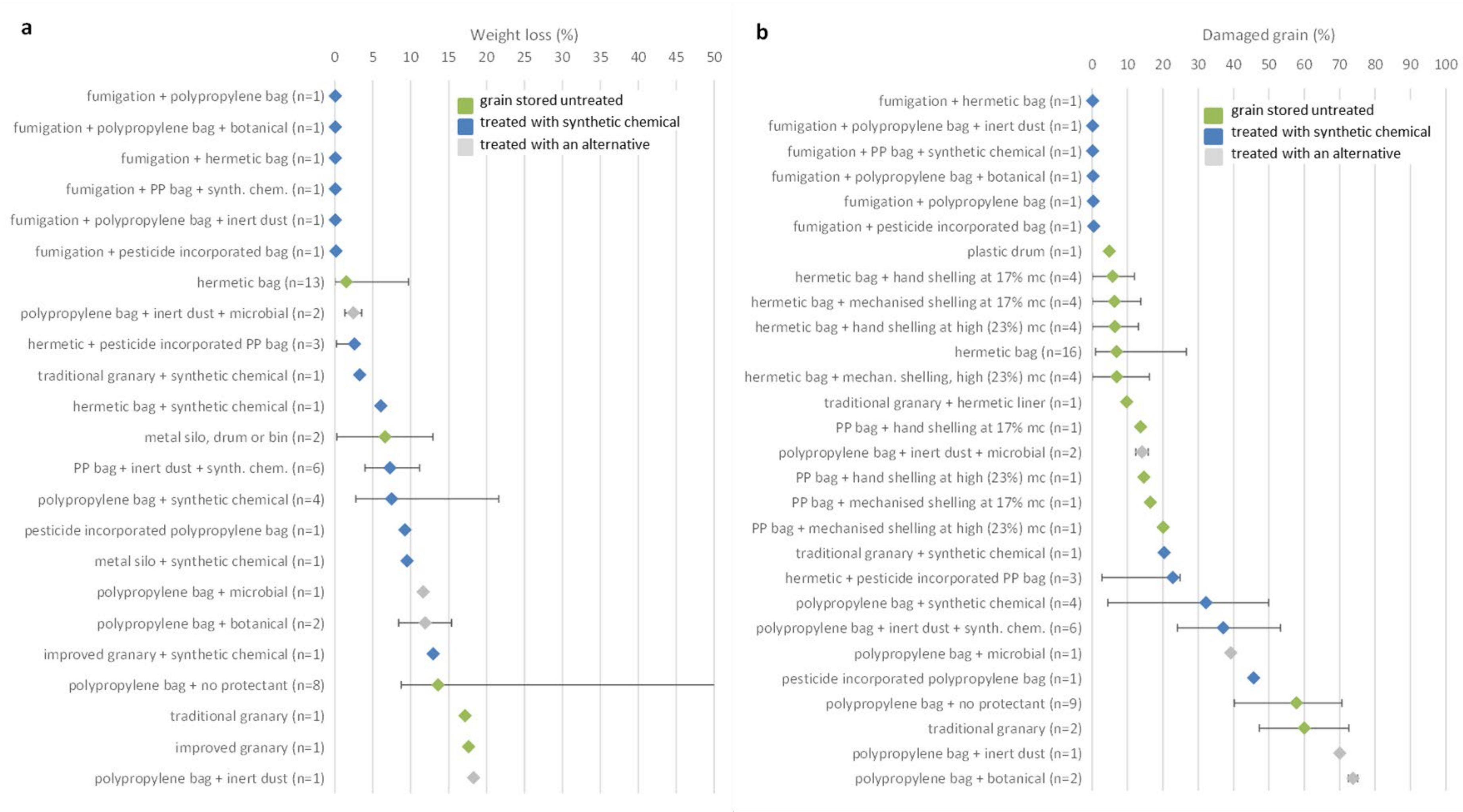

Fig. 4a & b Quantity loss (% weight loss) (a) and quality loss (% damaged grain) (b) of maize stored for 6 months using different storage interventions. The median, range and n values (that is, the number of times this intervention was found in the 123 studies of the update review) are presented. The loss levels are dependent on numerous factors including the conditions during the study, which can result in high heterogeneity between studies. The loss levels for each intervention need to be interpreted with caution particularly where the n value is low. Interventions in which the grain was stored untreated are shown as green symbols. The blue symbols indicate grain treated with a synthetic chemical. The grey symbols indicate grain treated with an alternative method.

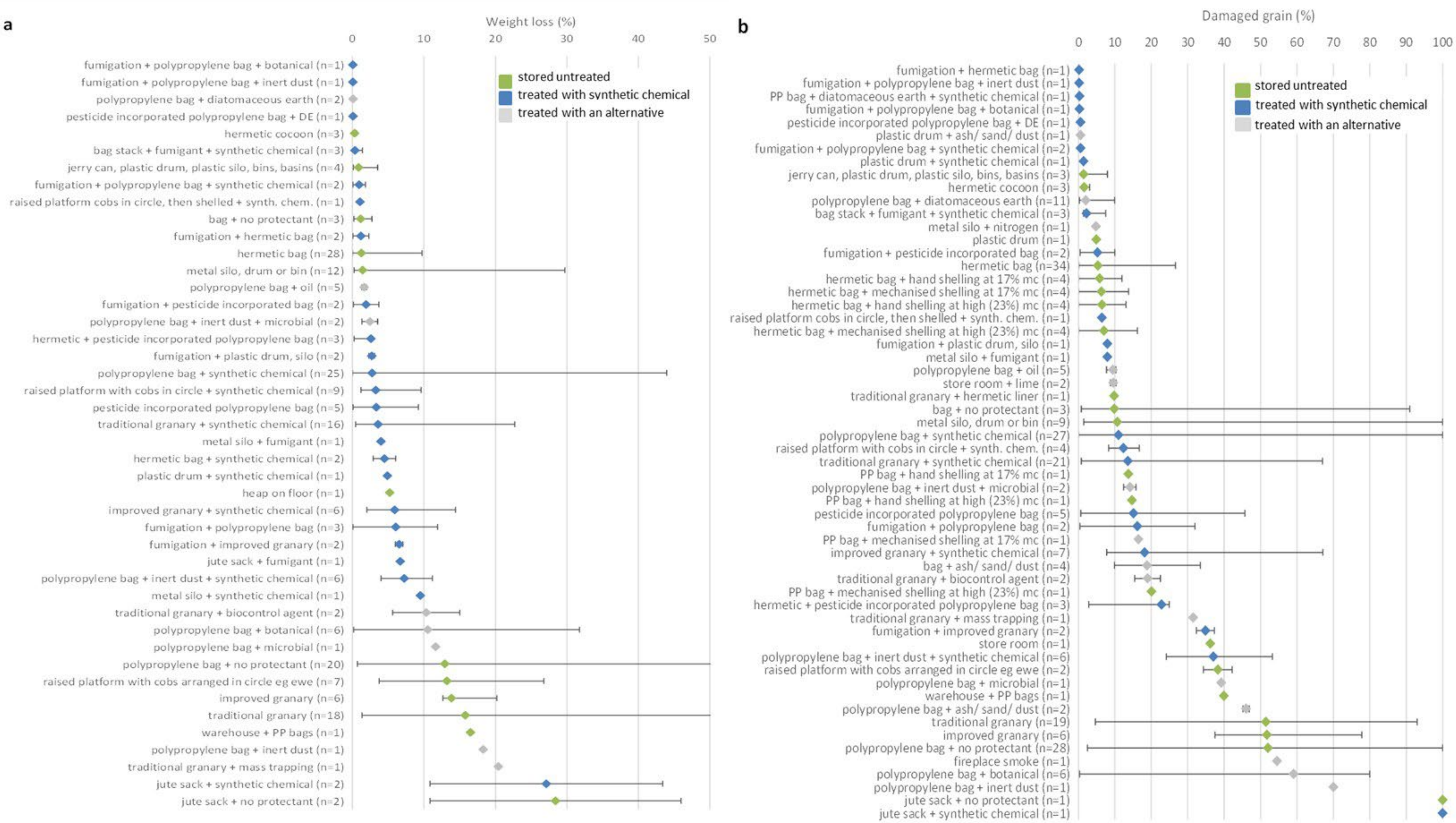

Fig. 5a & b Quantity loss (% weight loss) (a) and quality loss (% damaged grain) (b) of maize stored for 6 months using different storage interventions. The median, range, and n values (that is, the number of times this intervention was found in the 457 studies) are presented. Note: where n=1 the loss value reported from that one study is shown.

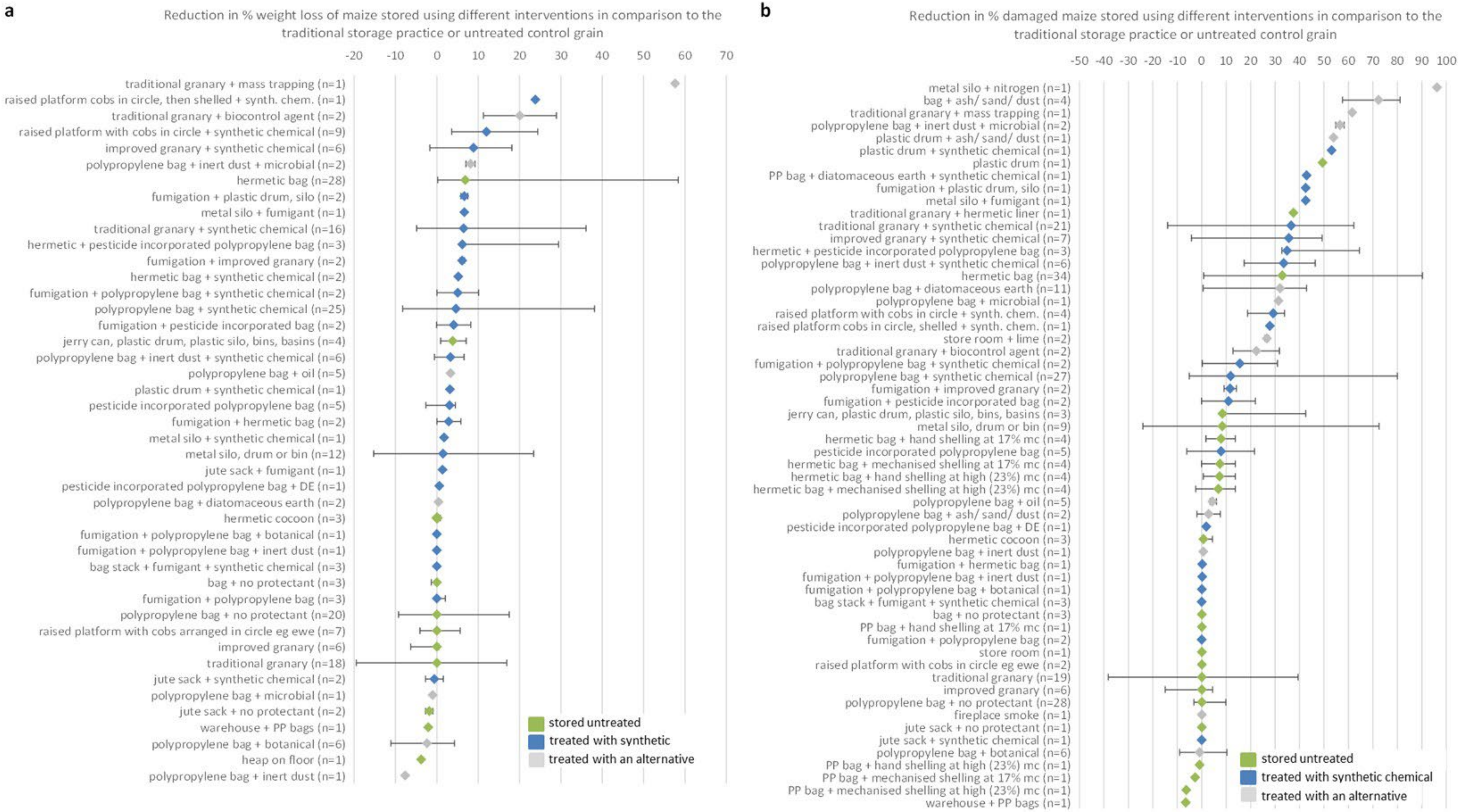

Fig. 6a & b Reduction in quantity loss (% weight loss) (a) and quality loss (% damaged grain) (b) loss of maize stored for 6 months using different interventions compared to the traditional storage practice or the untreated control. The median, range and n values (that is, the number of times this intervention was found in the 457 studies) are presented. Note: where n=1 the loss value from that one study is shown.

Table 4. Comparison of loss levels and metrics recorded in non-storage stage technology interventions (tier 3) for maize, bean and groundnuts

Crop - Non-Storage Stage Technology/tool/equipment Interventions (Tier 2 and 3)	n	Weight loss (%)	Damaged grains (%)	Germination (%)	Moisture content (%)	Protein content (%)	Aflatoxin (ppb)	Aflatoxin associated odds ratio	Broken grains (%)	Milling yield (%)	Mouldy/ diseased/ discoloured grains (%)	Perceived loss (%)	kg/ha	bulk density (%)	% loss (unspecified)	Threshing efficiency (%)	% collected pods	% loss of uncut plants	Thousand seed weight (g)	Visual Insect Dam Score	Study ID
MAIZE (CORN)																					
Drying																					
outside (unassisted solar) on bare ground	1							2.80													979
outside (unassisted solar) protected from contact with ground	1							1.00													979
heat source - nonrenewable energy	2						5.03													0.56	1168
outside (unassisted solar) on bare ground	2						17.96													1.52	1168
improved drying crib + mechanised shelling	1	1.00																			1807
traditional drying on ground + stick beating shelling	1	19.00																			1807
heat source - firewood	1								6.70												2285
outside (unassisted solar) protected from contact with ground	1								3.30												2285
outside (unassisted solar) on bare ground	1	3.04					2.30														95579932
outside (unassisted solar) on raised rack	1	0.43					1.15														95579932
outside (unassisted solar) protected from contact with ground	1	1.56					1.48														95579932
thick grain layer + outside (unassisted solar) protected from contact with ground + polyproylene bag	1	3.62	38.21	95.00		7.85								13.69					344.67		95580081
thick grain layer + protected solar bubble drier + polypropylene bag	1	4.90	43.31	96.67		7.43								15.89					341.58		95580081
thick grain layer + solar cabinet indirect drier + polypropylene bag	1	5.32	47.63	90.00		8.13								13.47					335.73		95580081
thick grain layer + solar cabinet mixer drier + polypropylene bag	1	4.86	37.37	90.00		8.30								13.39					363.99		95580081
thin grain layer + outside (unassisted solar) protected from contact with ground + polyproylene bag	1	3.40	32.41	97.50		8.25								12.77					359.02		95580081
thin grain layer + protected solar bubble drier + polypropylene bag	1	1.27	33.07	96.67		8.60								13.41					377.08		95580081
thin grain layer + solar cabinet indirect drier + polypropylene bag	1	1.49	35.92	99.17		8.37								13.86					385.03		95580081
thin grain layer + solar cabinet mixer drier + polypropylene bag	1	0.97	37.58	96.67		8.13								11.46					385.52		95580081
Threshing or Shelling or De-husking																					
mechanised	1							1.00													979
stick or simple tool	1							1.00													979
mechanised	3	4.12	3.35																		1449
by hand/manually	2								10.15												95580896
mechanised	2								31.40												95580896
mechanised	1												6450.00								95580902
stick or simple tool	1												6483.30								95580902
mechanised	1								0.50												95582032
stick or simple tool	1								2.90												95582032
mechanised	2								4.55												95582183
mechanised	1	3.68																			98339856
stick or simple tool	1	0.05																			98339856
BEAN																					
Packaging (perishables)																					
bags (all) (perishables)	1	17.40																			2022
plastic crates incl. RPC	1	15.50																			2022
GROUNDNUT																					
Harvesting																					
mechanised pod collector	3		1.40														89.83				95580060
Drying																					
A-frame	3				8.30		0.73				9.50										97944440
Drying rack	3				8.13		1.27				9.30										97944440
Mandela cock	3				6.17		1.03				10.03										97944440
outside (unassisted solar) on bare ground	3				9.57		4.80				27.83										97944440

Table 5. Comparison of loss levels and metrics recorded for different maize handling practice type interventions (tier 3) for maize

Crop - Handling Practice Change Interventions (Tier 2 and 3)	n	Weight loss (%)	n	Standardised weight loss (%)	n	Damaged grains (%)	n	Standardised damaged grains (%)	n	Mouldy/ diseased/ discoloured grains (%)	n	Broken grains (%)	n	Milling yield (%)	n	Aflatoxin (ppb)	n	% over 10ppb Aflatoxin	n	% over 20 ppb Aflatoxin	n	Perceived loss (%)	Storage duration (days)	Study ID
MAIZE (CORN)																								
Handling pre and or after harvest																								
changed method of grain protectant application					2	7.05	2	5.69															124	9740
typical method of grain protectant application					1	14.00	1	11.29															124	9740
tool used for grain protectant application					1	3.15	1	2.54															124	9740
no grain protectant application					11	58.60	1	47.26															124	9740
extra day of drying																					1	10.65		2960
harvest at physiological maturity/ recommended time																					1	7.30		2960
harvest late, delayed handling, no sorting, no store disinfestation or protectant use																					1	10.70		2960
improved handling practices																					1	7.40		2960
protectant use																					1	8.10		2960
sorting																					1	9.60		2960
store disinfestation																					1	7.60		2960
improved handling and storage	1	0.17	1	0.10											1	1.45							310	10262
poor hygiene and no monitoring	1	0.50	1	0.30											1	1.95							310	10262
cob selection - open husk					1	20.00																		3854
cob selection - loose husk					1	13.00																		3854
cob selection - tightly closed husk					1	1.00																		3854
field drying	1	0.20													1	13.10								201917
heaping cobs on ground	1	0.40													1	25.10								201917
cob selection	1	58.00	1	38.67																			279	1924
cob selection and protectant use	1	18.00	1	12.00																			279	1924
no cob selection	1	58.00	1	38.67																			279	1924
protectant use	1	30.00	1	20.00																			279	1924
fumigation + integrated pest management	1	0.20			1	1.30	1	0.78							1	1.90							310	95579937
fumigation + traditional storage practice	1	0.50			1	2.30	1	1.38							1	1.40							310	95579937
storage in granary																					1	8.12		95581786
storage in room in house																					1	8.58		95581786
early harvest, de-husk cobs, dry on tarpaulin, shell	1	6.75			1	0.18			1	10.75	1	1.40												95582037
early harvest, de-husk cobs, heap on the ground to dry, shell	1	7.50			1	0.43			1	10.00	1	1.50												95582037
early harvest, de-husk cobs, shell	1	5.85			1	0.20			1	5.38	1	1.40												95582037
early harvest, dry cobs with husks on tarpaulin, husk cobs, shell	1	9.35			1	0.73			1	10.75	1	0.80												95582037
early harvest, dry cobs with husks on the ground, husk cobs, shell	1	9.75			1	0.38			1	14.50	1	0.85												95582037
late harvest, de-husk cobs, dry on tarpaulin, shell	1	5.65			1	0.30			1	11.50	1	2.60												95582037
late harvest, de-husk cobs, shell	1	9.25			1	0.20			1	11.50	1	0.85												95582037
early harvested stored grain	1	27.00	1	29.89	1	67.00	1	74.18	1	12.50													168	95582037
grain dehusked after drying	1	32.50	1	35.98	1	65.00	1	71.96	1	12.20													168	95582037
grain dehusked before drying	1	23.00	1	25.46	1	58.00	1	64.21	1	9.00													168	95582037
late harvested stored grain	1	21.00	1	23.25	1	43.00	1	47.61	1	10.00													168	95582037
improved PH practices (harvest timing, off-ground drying, threshing, winnowing, air-tight storage	1	5.00	1	4.29	1	2.00	1	1.71	1	1.80													217	95582039
ordinary practices	1	26.00	1	22.29	1	48.00	1	41.14	1	1.70													217	95582039
Harvest																								
harvest at physiological maturity/ recommended time															1	0.66								6932
harvest later/more mature															4	2.56								6932
harvest at physiological maturity/ recommended time	1	7.20	1	5.40					1	7.00													248	5690
harvest earlier/less mature	1	5.50	1	4.13					1	18.00													248	5690
harvest later/more mature	1	16.40	1	12.30					1	4.00													248	5690
harvest earlier/less mature	2	2.00			2	7.00																		5001
harvest later/more mature	2	12.20			2	16.30																		5001

Table 6. Comparison of loss levels and metrics recorded for different training type interventions (tier 3) for cereals and legumes

Crop - Training Interventions (Tier 2 and 3)	n	Weight loss (%)	n	Aflatoxin (ppb)	n	% over 10 ppb Aflatoxin	n	% over 20 ppb Aflatoxin	n	Perceived loss (%)	Citation/ *Country*
MAIZE (CORN)											
Training											
no training									1	11.80	Chegere et al., 2020
postharvest training									1	8.90	*Tanzania*
postharvest training + hermetic bags									1	5.40	
no training									1	1.02	Vandercasteelen & Christiaensen, 2022
training in PH management									1	0.86	*Tanzania*
training in PH management and purchase of silo with 70% discount									1	1.34	
no training							1	44.80			Anitha et al., 2019
training in aflatoxin and PH management							1	31.90			*Malawi*
Training + technology access											
traditional practices			1	17.61	1	24.35					Leavens et al., 2021
traditional practices + grain PH training			1	16.18	1	24.30					*Senegal*
traditional practices + grain PH training + moisture measurement			1	17.42	1	23.83					
grain PH training + moisture measurement + off-ground drying + traditional storage			1	12.79	1	18.46					
grain PH training + moisture measurement + off-ground drying + hermetic bag			1	13.25	1	20.23					
traditional practices					1	31.00	1	27.00			Bauchet et al., 2021
traditional practices + grain PH training					1	25.00	1	21.00			*Senegal*
traditional practices + grain PH training + moisture measurement					1	25.00	1	22.00			
grain PH training + moisture measurement + off-ground drying + traditional storage					1	27.00	1	23.00			
grain PH training + moisture measurement + off-ground drying + hermetic bag					1	20.00	1	15.00			
no intervention			1	18.50							Pretari et al., 2019
training on aflatoxin management			1	10.90							*Kenya*
training on aflatoxin management + used grain dryer			1	5.00							
training on aflatoxin management + used grain dryer + used hermetic bag			1	1.10							
training on aflatoxin management + used hermetic bag			1	29.30							
training on aflatoxin management + used plastic sheet + used hermetic bag			1	13.20							
training on aflatoxin management + used plastic sheet for drying			1	3.90							
training on aflatoxin management + used plastic sheet for drying + grain dryer			1	7.50							
training on aflatoxin management + used plastic sheet for drying + grain dryer + used hermetic bag			1	0.60							
SORGHUM											
Training											
no training							1	50.90			Anitha et al., 2019
training in aflatoxin and PH management							1	32.50			*Malawi*
GROUNDNUT											
Training											
baseline sample prior to training	1	0.00	1	112.50							Xu et al., 2017
training then sorting of groundnuts	1	1.90	1	0.28							*Gambia*
training, sorting groundnuts, then roasting	1	1.00	1	0.17							
no training							1	39.60			Anitha et al., 2019
training in aflatoxin and PH management							1	29.60			*Malawi*

Rice, Sorghum and Wheat

During storage of paddy rice, a number of interventions kept grain weight loss below 2 % and / or grain damage below 6 % during 6 months of storage (Fig. 7a&b). These included: hermetic bags and cocoons, plastic drums and metal bins; untreated grain stored in an improved granary; and fumigation plus the use of a metal silo or a bag with pesticide incorporated into its fabric; and a new intervention where a bag wrapped in fish netting was found to help reduce rodent attack during storage (Htwe et al., 2021). One study in Ghana, Burkina Faso and Niger (Baoua et al., 2016) found that just storing paddy rice untreated in polypropylene bags kept damage below 6 %. Although other studies found that untreated paddy rice stored in jute or another unspecified type of sack, or in store rooms or traditional granaries, or even when treated with synthetic chemicals experienced higher grain damage levels of above 13 %. These rice storage studies came from Sri Lanka, Mozambique, India, Ghana, Burkina Faso and Niger. A comparison of the reduction in % weight loss and % damage that these interventions resulted in versus that which occurred when using farmers' traditional storage practices or in untreated stored grain is shown in Supplementary Fig. S2a&b.

Sorghum grain experienced less than 2 % weight loss during six months of storage when kept untreated in hermetic bags, improved underground pits or metal silos, or in bags following fumigation and admixture with synthetic chemicals, or in a traditional granary admixed with wood ash. Even without these interventions, weight loss was relatively low (3.5–7.7 %) (Fig. 7a). Less than 10% damage occurred when sorghum was fumigated, treated with synthetic chemicals, and stored in bags; or admixed with wood ash, synthetic chemicals or DE and stored in a traditional granary; or stored untreated in hermetic bags or an improved granary (Fig 7b). However, untreated grain stored in bags or store rooms, or in traditional granaries with or without botanical preparations, or admixed with synthetic chemicals, or in a polypropylene bag with pesticide incorporated into its fabric sustained between 14.1 % and 45.4 % damage (Fig 7b). These sorghum storage studies were in Eritrea, Ethiopia, Sudan, Kenya, Tanzania, Zimbabwe, Burkina Faso and Mali.

During wheat storage, weight loss exceeded 2 % only when the grain was stored untreated in clay pots, heaps on the floor, traditional granaries and polypropylene or jute sacks (Fig 7a). Hermetic bag use, the admixture of botanicals or synthetic chemicals or filter cake by-product from an aluminium sulphate factory, the use of improved granaries or metal silos or drums, and fumigation and use of synthetic chemical dust or spray treatments kept weight loss below 2 %, as did underground pit storage in India. These treatments along with sealing of the grain in a concrete bin also kept grain damage during six months storage at levels below 5 % (Fig. 7b). All the wheat storage studies were from India, Pakistan, Nepal, Bangladesh, Afghanistan or Ethiopia. One recent Indian study explored the effect of applying a repellent on three different materials on the number and area of holes gnawed by rodents in sacks stacked in a small warehouse.

Harvesting rice at the recommended time resulted in lower weight loss (0-1.2 %) and fewer broken grains (8.5-10.0 %) than either earlier or later harvesting (4.4–20.3 % weight loss and 18.7–32.4 % broken grains) (Table 7). Results comparing improved harvest and handling practice, and mechanised harvesting with the use of simple harvest tools such as sickles varied, but in most of the studies mechanised harvesting reduced weight loss or number of uncut plants left in the field (Table 8). Loss reduction varied in studies for rice comparing mechanised threshing to simple tool use or bullock treading threshing methods (Table 8). A recent study in Nigeria (Castelein et al., 2022) calculated higher losses when rice was threshed with sticks as opposed to mechanically. Modern milling equipment reduced rice weight loss and increased milling yields compared to locally made or traditional milling equipment (Table 8). A recent sorghum study in Malawi of training on aflatoxin and PH management showed reduced incidence of aflatoxin >20 ppb in the subsequent grain samples from farmers who had received training (Anitha et al., 2019).

3.5.2 Legumes

Legumes remain the least studied of the five crops groups, accounting for just 9.2 % of the 457 included studies, and 8.4 % (184) of the 2187 studies of interventions (Table 3). The interventions studied were predominantly focused on storage methods of dried legumes (81.0 %) (Table 3). The update review brought in more evidence on the comparative efficacy of hermetic bags versus traditional storage methods for cowpea, chickpea and bean.

Cowpea storage accounted for almost half of the legume interventions studied (47.8 %). Storage loss was generally higher in legumes than in cereals, despite the shorter standardized storage duration of 4.5 months that was used. For example, when cowpeas or beans were stored in jute or PP bags with no protectant, grain damage ranged from 25.2 % to 100 %, and mean weight loss ranged from 4.5 % to 32.3 % (Fig. 8a&b).

The storage methods investigated included the effect of admixing pesticides (botanicals, synthetic chemicals, DEs or ashes) or a biocontrol agent (*Beauveria bassiana*) with grain legumes stored in bags (with and without air-tight liners), clay pots, plastic or metal containers, or traditional granaries.

Most of the legume loss data were for non-synthetic chemical interventions, such as cowpea storage in hermetic bags or with alternative treatment (Fig. 8a&b). Hermetic bags were clearly effective in reducing weight loss and damage in cowpeas, groundnuts and beans, when compared with traditionally used practices or untreated controls within the same studies (Fig. 9a&b). This remained the case with re-used hermetic bags for cowpeas (Fig. 8b). Other interventions that kept the grain damage levels at least 20 percentage points lower than the untreated control included mixing synthetic chemicals, botanicals or DEs with cowpeas or beans before storing them in sacks (Fig. 9b). The storage of cowpeas in clay pots, or plastic drums reduced storage losses, but not as effectively as hermetic bags or synthetic chemicals. The protective effect of storing unshelled cowpeas was illustrated in one very early study in Nigeria (Caswell, 1975).

Only four legume studies compared handling practices (Table 7). Early work found simple handling practice changes, such as weekly sunning or sieving of beans, reduced storage damage to 3.6–4.1 %, compared with 37.7 % in the untreated control (Nahdy et al., 1992). Recent work in Tanzania (Mutungi et al., 2022a) showed that in comparison to farmers’ ordinary practices the use of a combination of improved PH handling practices (harvest timing, off-ground drying, threshing, winnowing, air-tight storage) reduced weight loss in beans from 14.5 % to 4.5 % and damage from 29.7 % to 6.5 %. Careful sorting and drying of groundnuts led to a striking reduction in aflatoxin B1 content (from 55 ppb to 17 ppb), although still beyond the safe limits of most standards (Turner et al., 2005). Harvesting groundnuts in the rain and slow drying, as opposed to rapid drying, increased fungal incidence on pods from 19.4–24.5 % to 32.5–38.9 % (Palanisami et al., 1990).

In a Gambian study, baseline samples of groundnuts had an average aflatoxin B1 content of 112.5 ppb and a median level of 0.49 ppb (Xu et al., 2017) (Table 6). After 25 women were trained in sorting and removing any mouldy groundnuts, the resulting weight loss was 1.9 %, and the remaining groundnuts had an average aflatoxin B1 concentration of 0.28 ppb. A study in Malawi found training on aflatoxin and postharvest management resulted in reduced percentage of groundnut samples with >20 ppb aflatoxin in the stocks of those farmers who had received training (Anitha et al., 2019). No other study of PH training interventions for legumes was identified. A recent study in Malawi (Dambolachepa et al., 2019) of different methods for drying groundnut plants after harvesting, reported lower aflatoxin levels and incidence of % mouldy kernels in groundnuts dried using an A-frame, a drying rack or the Mandela cock method than in those sun-dried directly on the ground (Table 4).

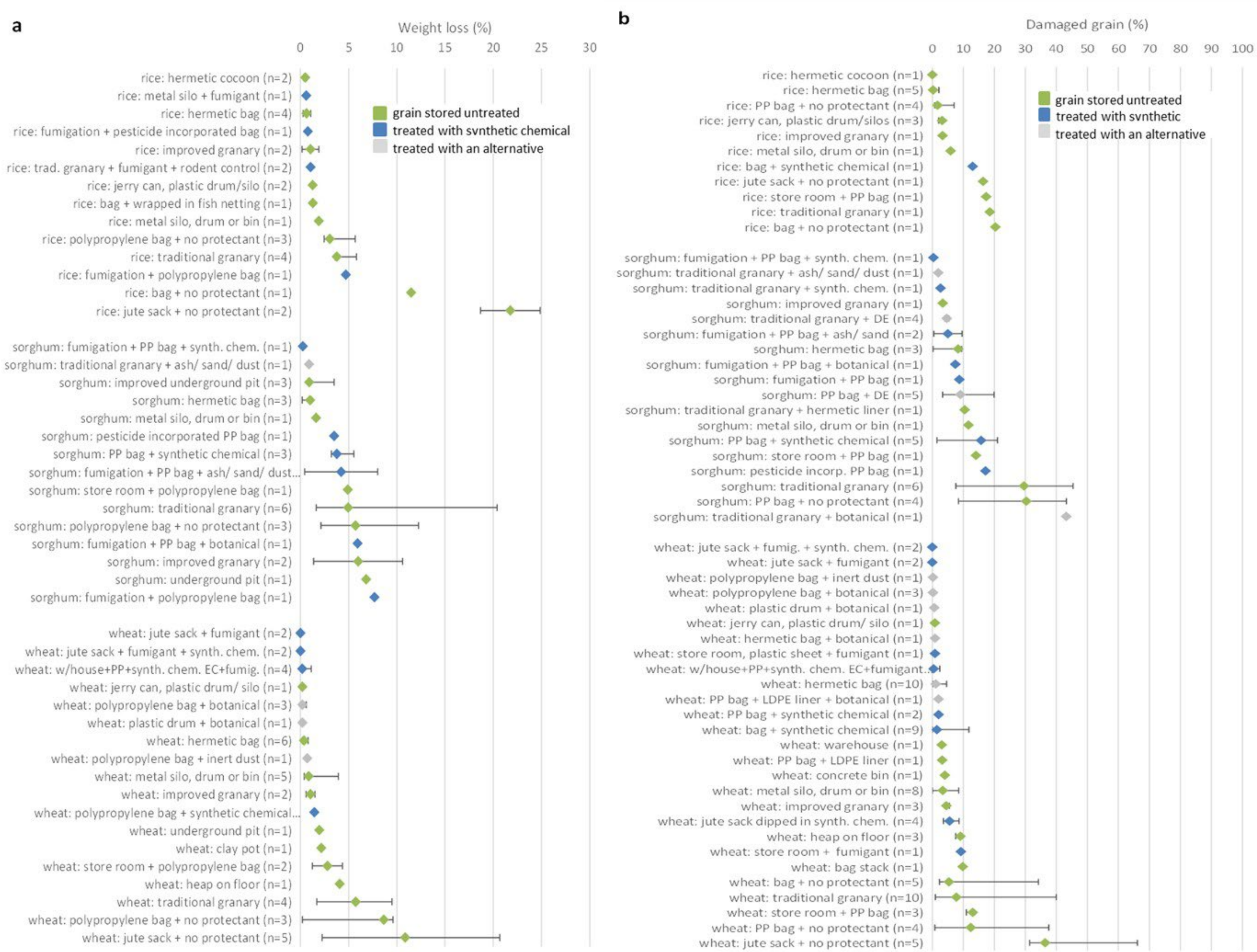

Fig 7a & b Quantity loss (% weight loss) (a) and quality loss (% damaged grain) (b) of rice, sorghum and wheat stored for 6 months using different storage interventions. The median, range and n values (that is, the number of times this intervention was found in the 457 studies) are presented. Note: where n=1 the loss value from that one study is shown.

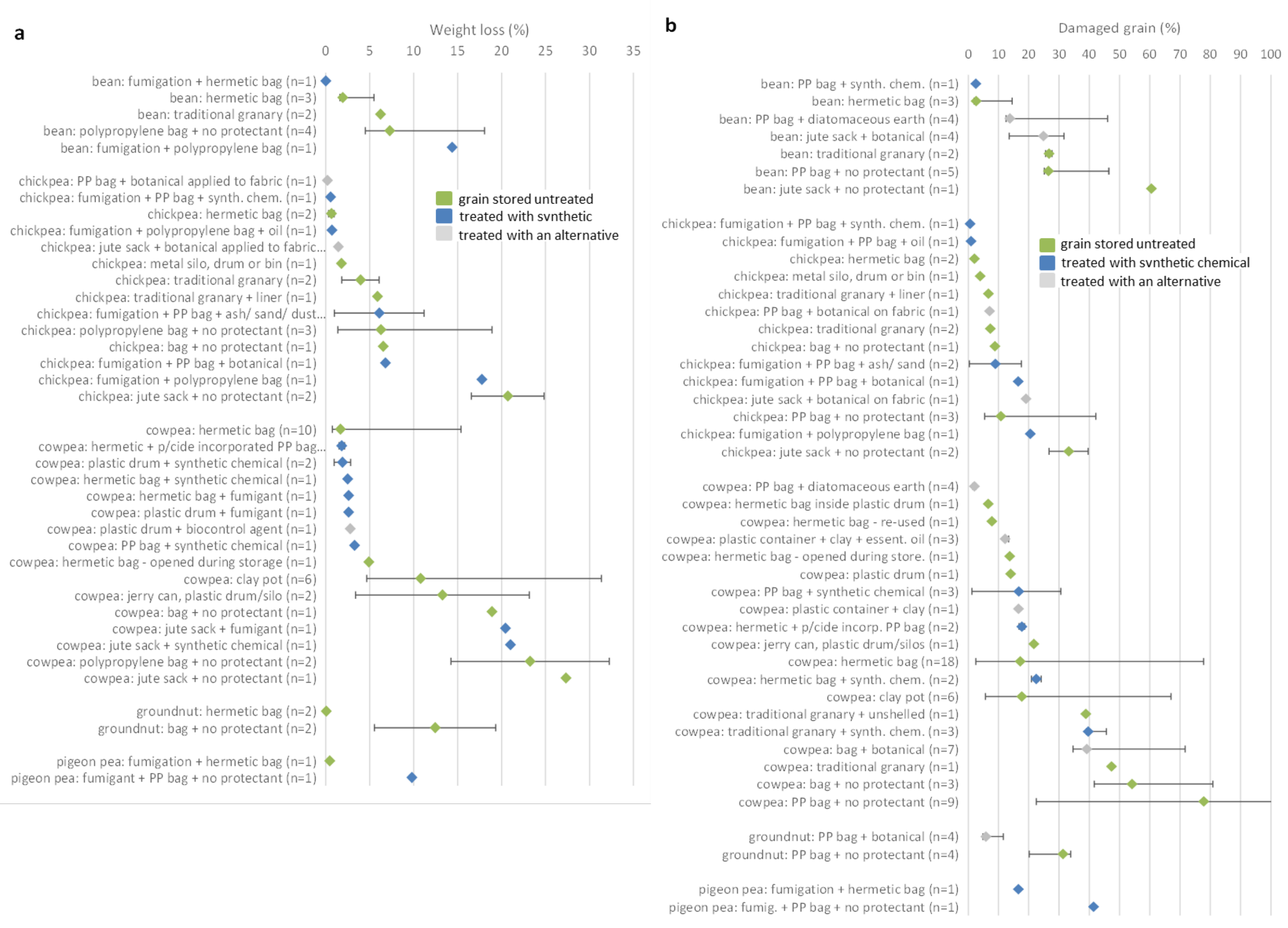

Fig 8a & b. Quantity loss (% weight loss) (a) and quality loss (% damaged grain) (b) of beans, chickpea, cowpea, groundnut and pigeon pea stored for 4.5 months using different storage interventions. The median, range and n values (that is, the number of times this intervention was found in the 457 studies) are presented. Note: where n=1 the loss value from that one study is shown.

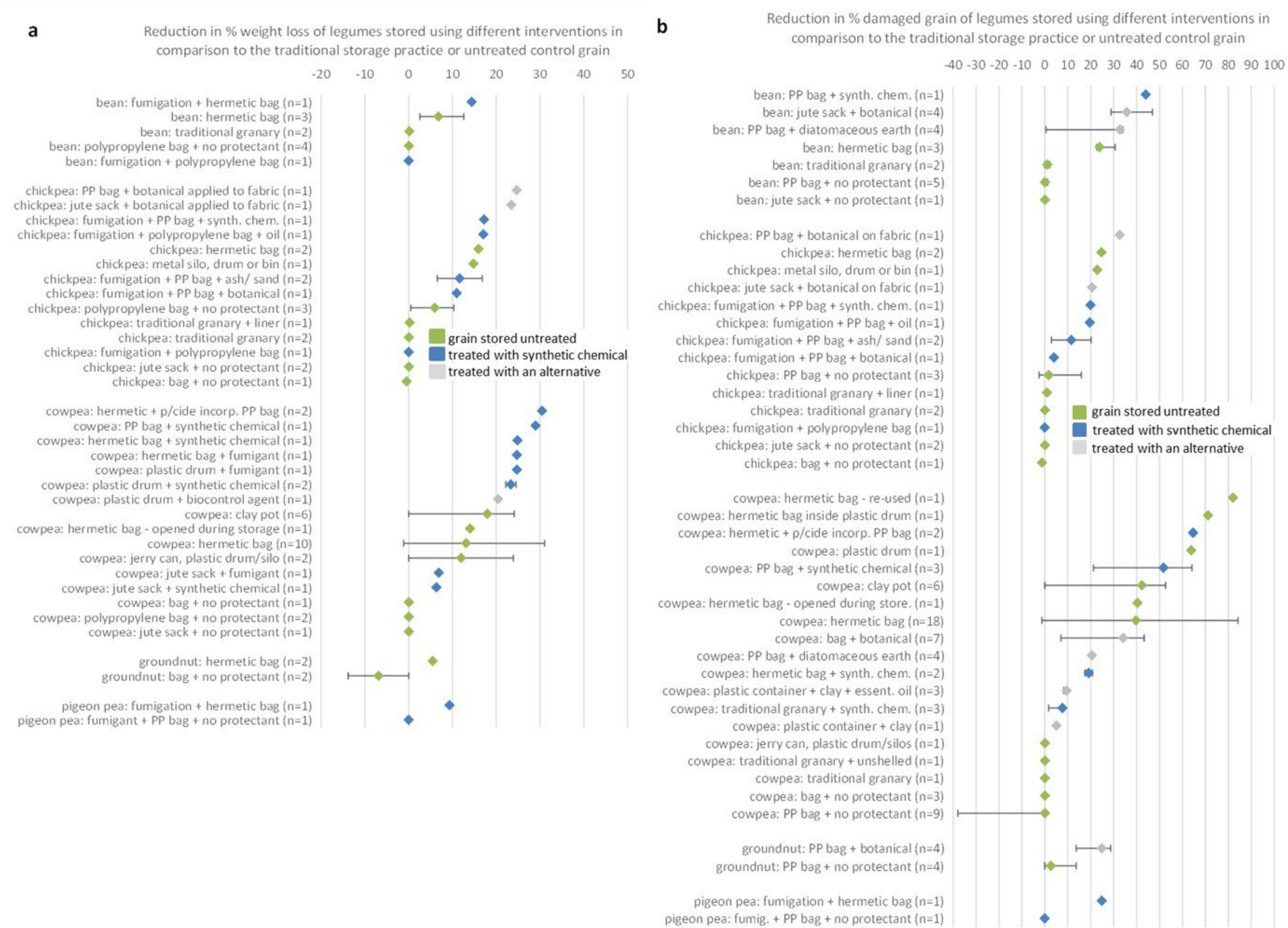

Fig 9a & b. Reduction in quantity loss (% weight loss) (a) and quality loss (% damaged grain) (b) of legumes stored for 6 months using different interventions compared to the traditional storage practice or untreated control grain. The median, range and n values (that is, the number of times this intervention was found in the 457 studies) are presented. Note: where n=1 the loss value from that one study is shown.

Table 7. Comparison of loss levels and metrics recorded for different handling practice type interventions (tier 3) for cereals and legumes

Crop - Handling Practice Change Interventions (Tier 2 and 3)	n	Weight loss (%)	n	Standardised weight loss (%)	n	Damaged grains (%)	n	Standardised damaged grains (%)	n	Mouldy/ diseased/ discoloured grains (%)	n	Broken grains (%)	n	Milling yield (%)	n	Aflatoxin (ppb)	n	% over 10ppb Aflatoxin	n	% over 20 ppb Aflatoxin	n	Perceived loss (%)	Storage duration (days)	Study ID
RICE																								
Handling pre and or after harvest																								
field drying	2	4.56									2	16.68												5488
field drying + stacking	4	16.78									4	26.81												5488
no field drying or stacking	2	0.56									2	10.18												5488
field drying											2	13.14												5488
field drying + stacking											5	25.17												5488
no field drying or stacking											1	8.81												5488
field drying	1	70.10											1	70.10	1	15.00								4758
field drying + stacking	1	66.30											1	66.30	1	28.00								4758
no field drying or stacking	2	71.50											2	71.50	2	1.00								4758
WHEAT																								
Handling pre and or after harvest																								
mechanised threshing during the day	3	0.94																						7227
mechanised threshing during the night	3	1.09																						7227
BEAN																								
Handling pre and or after harvest																								
corn oil					1	8.19	1	10.92															105	5537
no sunning or sieving or oil					1	37.67	1	50.23															105	5537
sieving					1	4.10	1	5.47															105	5537
sunning					1	3.64	1	4.85															105	5537
improved PH practices (harvest timing, off-ground drying, threshing, winnowing, air-tight storage	1	4.50	1	2.90	1	10.00	1	6.45	1	1.90													217	95582039
ordinary practices	1	14.50	1	9.35	1	46.00	1	29.68	1	1.70													217	95582039
GROUNDNUT																								
Handling pre and or after harvest																								
no sorting															1	55.00							155	12179
sorting, off-ground drying and storage															1	17.00							155	12179
dry at harvest + rapid drying									1	21.95														5110
rain at harvest + heap drying medium speed									1	38.90														5110
rain at harvest + heap drying slow speed									1	32.50														5110
RICE																								
Harvest																								
harvest at physiological maturity/ recommended time	1	1.24									1	9.97												4341
harvest later/more mature	2	4.40									2	18.76												4341
harvest at physiological maturity/ recommended time	1	0.00									1	8.75												5317
harvest earlier/less mature	2	20.25									2	32.38												5317
harvest later/more mature	2	7.50									2	29.28												5317
WHEAT																								
Harvest																								
harvest earlier/less mature	1	0.21									1	1.11												95582176
harvest later/more mature	1	0.22									1	1.19												95582176
harvest mid	1	0.16									1	0.80												95582176

Table 8. Comparison of loss levels and metrics recorded in non-storage stage technology interventions (tier 3) for rice, sorghum and wheat

Crop - Non-Storage Stage Technology/tool/equipment Interventions (Tier 2 and 3)	n	Weight loss (%)	Damaged grains (%)	Germination (%)	Moisture content (%)	Protein content (%)	Aflatoxin (ppb)	Aflatoxin associated odds ratio	Broken grains (%)	Milling yield (%)	Mouldy/ diseased/ discoloured grains (%)	Perceived loss (%)	kg/ha	bulk density (%)	% loss (unspecified)	Threshing efficiency (%)	% collected pods	% loss of uncut plants	Thousand seed weight (g)	Visual Insect Dam Score	Study ID
RICE																					
Harvesting																					
improved harvest + handling	1											13.00									958
mechanised harvesting	1											7.50									958
improved harvest + handling	1	1.39																			1281
simple harvest tools or aids	1	2.94																			1281
improved harvest + handling	2												5355.00								1605
mechanised harvesting	1												5820.00								1605
improved harvest + handling	1														1.39						2072
simple harvest tools or aids	1														2.93						2072
mechanised harvesting	3														1.52						2106
simple harvest tools or aids	1														1.40						2106
mechanised harvesting	1	0.93																			95580337
simple harvest tools or aids	1	9.55																			95580337
mechanised harvesting	1																	1.35			95581929
simple harvest tools or aids	1																	7.84			95581929
mechanised harvest reaper + trolley transport + close drum thresher & winnower	1	2.94																			95582074
mechanised harvesting	1	1.25																			95582074
simple harvest tools or aids + head load + beating threshing + manual winnowing	1	3.09																			95582074
Threshing or Shelling or De-husking																					
mechanised	3												276.75								1164
stick or simple tool	1												306.40								1164
stick or simple tool	2	4.30																			1281
by hand/manually	2	9.08																			1726
stick or simple tool	4	11.98																			1726
stick or simple tool	2														4.30						2072
pestle & mortar	3	6.05																			2257
bullock treading	1	2.54																			3009
manual + bullock treading	2	1.03																			3009
pedal thresher	2	2.66																			3009
mechanised	1															33.10					95580337
stick or simple tool	1															31.10					95580337
mechanised	1	22.20							50.00												98339854
stick or simple tool	1	11.30							79.90												98339854
Processing																					
milling equipment - locally made	1	3.97																			1281
milling equipment - one-pass type	2	0.65																			1281
milling equipment - modern	1								2.00	63.00											1450
milling equipment - traditional	1								10.20	58.70											1450
milling equipment	3								45.13	65.53											2072
mechanised huller mill	2									70.91											3009
pedal pounder	1									72.02											3009
SORGHUM																					
Threshing or Shelling or De-husking																					
mechanised	1	0.60																			98339856
stick or simple tool	1	0.73																			98339856
WHEAT																					
Harvesting																					
mechanised harvesting	1											6.28									97709383
simple harvest tools or aids	1											21.25									97709383

3.5.3 Roots and Tubers

For the full scoping review (the original plus the 2024 update), 51.9 % of the root and tuber crop interventions were on potato, followed by yam (23.7 %), sweetpotato (16.7 %) and cassava (7.8 %) (Table 3). The majority (80.9 %) of these interventions were technologies/tools/equipment while handling practices changes accounted for 18.5 %, and infrastructure 0.5 %. In the update review (2019-2024), 65.6 % of the interventions were for potato, followed by sweetpotato and cassava (both with 14.8 %), and yam (4.9 %). Yam and cassava had a single new study each. Of the interventions in the update review, 68.9 % were in the category of technology/tool/equipment with the remaining being handling practice changes.

For the 82 studies on roots and tubers, the main quantity loss metrics studied were weight loss and overall loss (%). Several quality attributes were also analysed (Supplementary Table S5), these included percentage decay, damage, and sprouting. Measurements of nutrient loss, namely starch and total carotenoid, were conducted in very few experiments of large enough scale to qualify for inclusion.

The major areas of research for roots and tubers were the use of storage structures or containers, storage protectants, and packaging (Table 9). The sample size (n) (i.e., the number of interventions from all the included studies) tended to be small for the interventions evaluated on roots and tubers. Storage structures that were cooler than ambient conditions resulted in less quantity loss, decay, and sprouting. Cold-rooms were the most effective storage structures, followed by evaporatively cooled structures and pits or trenches. Ambient conditions and heaps/piles resulted in higher quantitative and qualitative losses as shown in the data synthesis for potato and yam in Table 10.

Storage protectants included pesticides, growth regulators (particularly anti-sprouting compounds), botanicals/essential oils, heat treatments and radiation. Using growth regulators reduced sprouting in potatoes by 49.5 % when compared to no protectants. There was no equivalent reported data on cassava, sweetpotato and yam. One study assessed the impact on postharvest physiological deterioration (PPD) of storing freshly harvested cassava roots in bags made from different materials, but found no significant difference between PPD score for roots kept in woven PP bags, tarpaulin bags or jute bags or roots kept loose and not in a bag. Rotting was lower on roots in tarpaulin or jute bags than the other treatments for the first 8 days. Roots with significant mechanical damage had a shorted shelf-life in a PP bag compared to whole roots and roots with retained stalk (peduncle).

Some handling practice changes reduced quantity and quality losses (Table 9). For example, harvesting cassava from moist soil reduced damage by 23.0 % compared to cassava harvested from dry soil. Soaking cassava chips in water before sun-drying or smoke-drying resulted in 23.9 % weight loss during a six-month storage period versus 96.4 % weight loss for unsoaked chips. Storing harvested potato in heaps in the shade versus in the sun reduced quantitative losses by 15.2 % and decay by 6.0 %. Harvesting sweetpotato later (after 6-9 months) reduced loss in quantity compared to earlier harvests (after 4-5 months), however, no data on decay levels was presented in the study. Selecting only undamaged yams for long term storage (6 months) resulted in less quantity loss and no decay, whereas yams with slight or severe wounds had higher quantity losses and 80.0 % and 100.0 % decay, respectively. The number of handling practice interventions evaluated was low.

A single study on infrastructure showed a 2.6 % reduction in quantity loss when improved versus poor roads were compared for transporting potato (Table 9).

Storage duration in the focal roots and tubers ranged from 30 to 330 days (Table 9).

Table 9 Quantity loss and quality losses (% decay, sprouting and mechanical damage) **of the focal root and tuber crops (potato, cassava, sweetpotato and yam) for different interventions.** The data is arranged by crop and intervention tier showing the number of times the intervention was found in the 457 studies (n), the mean and range for the different loss metrics, and the storage period. Note: where n=1 the loss value from that one study is shown.

Crop, Intervention type, stage and description	n	Quantity loss (%)		n	Decay (%)		n	Sprouting (%)		n	Damage (%)		n	Storage (days)	
POTATO															
Technology/tool/equipment use															
Storage structure or container															
ambient storage	6	26.2	(15.4-53)	6	29.2	(1.9-80.0)							6	106	(84-150)
cold room	10	3.7	(0.32-8)	6	0.9	(0.0-2.5)	3	38.3	(0.0-100)				11	98	(45-150)
cold room + CIPC	2	4.3	(3.7-4.9)	2	0.4	(0.2-0.7)							2	90	
evap cooled structure + chemical	1	6.9					1	5.9					1	112	
evap cooled structure/container	12	13.8	(3.6-22.5)	9	3.4	(0.0-8.0)	2	60.2	(20.3-100)				12	112	(75-133)
heap + chemical	2	12.2	(9-15.3)				2	22.1	(11.4-32.7)				2	112	
heap/pile/clamp	15	15.6	(2.3-24.2)	10	2.9	(0.0-6.0)	1	100					15	97	(90-120)
improved pit	3	2.8	(2.4-3.2)										3	196	
pit + chemical	3	6.1	(5.1-8.2)				3	6.9	(2.7-13.4)				3	110	(105-112)
pit + ventilation	1	14.4		1	2.4								1	120	
pit/trench	13	19.6	(2.4-100)	3	10.7	(5.4-13.9)	2	100					13	147	(90-210)
shaded structure (thatch, net etc)	6	15.5	(9-28.8)	1	25.7		2	100					7	92	(60-120)
shaded structure + chemical	1	7.5					1	2.0					1	105	
store room + dark	2	14.4	(5.6-23.1)										2	60	(30-90)
store room + light	5	16.1	(0-55.6)										5	66	(30-90)
store room or warehouse	2	10.8	(6.2-15.4)	1	8.2								2	120	(119-120)
structure with forced air ventilation	2	14.8	(9.2-20.4)	1	4.8								2	105	(90-120)
traditional structure	1	31.1		1	30.0								1	75	
Storage protectant															
biocontrol / BT							1	12.0		1	20.0		2	128	(76-180)
botanicals, essential oils etc							2	4.5	(2.0-7.0)	2	26.8	(24.2-29.3)	4	128	(76-180)
growth regulators	3	9.9	(8.7-11)				3	24.5	(3.6-50.0)				6	78	(45-90)
irradiation	7	25.8	(4.8-69.2)	4	22.7	(1.2-47.8)							7	149	(95-190)
no protectant (control)	5	12.6	(3-28)	2	7.6	(6.6-8.6)	2	74.0	(48.0-100)	2	77.4	(73.3-81.5)	11	112	(21-190)
no protectant at ambient	3	67.5	(52.7-75.8)	3	36.5	(22.4-44.3)							3	118	(95-130)
no protectant; cool storage	3	14.3	(4.6-23)	3	5.4	(1.0-8.2)							3	127	(120-130)
pesticide				9	3.2	(2.4-4.6)	1	33.0		5	39.7	(29.0-49.5)	15	55	(21-180)
Packaging (perishables)															
bags (all)	2	39.8	(34.6-44.9)	7	10.2	(0.0-36.1)							7	76	(35-180)
baskets (all)	1	43.5		1	31.9								1	180	
modified atmosphere packaging (MAP)				2	38.9	(17.8-60.0)							2	35	
not packed	2	47.9	(47.6-48.2)	3	15.4	(0.0-25.8)							3	132	(35-180)
wooden box/bulk bin	1	50.3		1	20.2								1	180	
Handling practice change															
Handling pre and or after harvest															
heap/pile/clamp	3	36.6	(34.6-40.3)	3	11.8	(9.3-14.1)							3	90	
heap/pile/clamp + shade	3	21.4	(18.3-23.6)	3	5.8	(5.0-7.2)							3	90	
manual desprouting	1	6.0		1	2.2								1	140	
no desprouting	1	7.5		1	2.0								1	140	
Harvest															
de-haulming + harvest earlier/less mature	1	17.5		1	11.0								1	120	
de-haulming + harvest later/more mature	2	16.8	(16-17.5)	2	8.2	(6.5-9.8)							2	120	
harvest earlier/less mature	1	23.5		1	17.5								1	120	
harvest later/more mature	2	20.0	(20-20)	2	12.5	(12.0-13.0)							2	120	
one-time harvest + storage in shaded structure	1	37.1													
piecemeal harvest	1	11.3													
Infrastructure e.g. warehouses, packhouses															
Road transport															
improved roads	1	15.3	(15.3-15.3)										1	30	
poor roads	1	17.9											1	30	

Table 9 *continued*

Crop, Intervention type, stage and description	n	Quantity loss (%)		n	Decay (%)		n	Sprouting (%)		n	Damage (%)		n	Storage (days)	
CASSAVA															
Technology/tool/equipment use															
Storage protectant															
biocontrol / BT	1	41.0											1	150	
botanicals, essential oils etc	2	7.9	(7.6-8.1)	2	19.9	(10.7-29.0)							2	49	
no protectant (control)	2	31.7	(13.3-50)	1	44.6								2	100	(49-150)
pesticide	1	9.0		1	25.0								1	49	
Harvesting															
automated/harvesters/mechanical										2	12.5	(10.8-14.3)			
Handling practice change															
Handling pre and or after harvest															
soaked + processing into chips	3	23.9	(13.6-39.1)										3	180	
not soaked + processed into chips	1	96.4											1	180	
Harvest															
harvest when soil is dry and compacted										1	44.6				
harvest when soil is moist and less compacted										3	21.6	(10.7-29.0)			
SWEETPOTATO															
Technology/tool/equipment use															
Storage structure or container															
clay pot	3	14.7	(9.1-24.6)	3	15.8	(0.0-45.0)							3	50	
crate	1	70.2		1	71.0								1	84	
in dry sand in a crate	1	50.2		1	48.7								1	84	
in sawdust in a crate	1	62.9		1	69.0								1	84	
natural mud pot	1	65.2		1	76.5								1	84	
thin jute sack	1	63.4		1	76.7								1	84	
Storage protectant															
growth regulators	2	16.9	(11.9-21.9)	2	9.8	(8.6-10.9)							2	56	
no protectant (control)	2	15.7	(11.0-20.5)	2	7.8	(7.8-7.8)							2	56	
Packaging (perishables)															
bags (all)										9	15.9	(4.2-25.0)			
wooden box/bulk bin										3	11.0	(5.0-14.8)			
Handling practice change															
Handling pre and or after harvest															
assemblers + brokers + wholesalers	1	13.0													
farmer groups, cooperatives, associations	1	10.0													
Harvest															
1x harvest after 4 months	1	85.0													
1x harvest after 5 months	1	68.0													
1x harvest after 6 months	1	47.0													
1x harvest after 7 months	1	43.0													
1x harvest after 8 months	1	40.0													
1x harvest after 9 months	1	36.0													
harvest at maturity	1	5.0		1	6.4								1	56	
harvest earlier/less mature	3	4.2	(3.9-4.6)	3	5.6	(5.5-5.7)							3	56	
harvest at recommended time										1	19.1				
harvest later/more mature										1	59.5				
one time harvest										1	31.6				
piecemeal harvest										1	22.7				
piecemeal harvest (6x over 9 months)	1	49.0													

Table 9 *continued*

Crop, Intervention type, stage and description	n	Quantity loss (%)		n	Decay (%)		n	Sprouting (%)		n	Damage (%)		n	Storage (days)	
YAM															
Technology/tool/equipment use															
Storage structure or container															
heap/pile/clamp	2	11.2	(10.5-12)	1	26.7		1	97.0					2	135	(90-180)
pit/trench	3	17.0	(10-24)	1	12.0		2	35.0	(0.0-70.0)				3	97	(70-150)
shaded structure (thatch, net etc)	5	18.4	(3-36.2)	2	55.7	(53.3-58.1)				1	27.0		6	143	(90-180)
store room or warehouse	1	5.0								1	0.0		2	160	(140-180)
structure with forced air ventilation	6	22.4	(15.7-33)	1	1.9								6	253	(180-308)
traditional structure	9	39.2	(1.5-100)	3	19.0	(12.0-27.0)	2	99.5	(99.0-100)	1	17.0		10	178	(70-308)
Storage protectant															
biocontrol / BT	3	13.7	(11.7-17.2)	3	16.7	(14.0-18.0)							1	330	
botanicals, essential oils etc	4	6.1	(5-7.5)	2	12.0	(12.0-12.0)							6	80	(60-120)
curing + irradiation				1	10.0								1	120	
curing + irradiation + physical barrier				1	10.7								1	120	
curing + irradiation + synthetic chemical				1	14.0								1	120	
curing + no protectant				1	24.7								1	120	
curing + physical barrier				1	13.3								1	120	
curing + synthetic chemical				1	10.7								1	120	
growth regulators	9	37.4	(22.9-49.3)										9	150	
heat treatments	1	17.5		4	36.3	(5.0-100)							5	156	(60-180)
irradiation	2	12.1	(2.3-22)				2	11.8	(5.6-18.0)				2	180	
no protectant (control)	3	44.0	(27-65)	5	23.3	(1.9-53.3)				1	8.1		7	160	(60-330)
pesticide	2	29.0	(16-42)	2	22.2	(15.6-28.9)				1	1.0		4	117	(60-210)
Handling practice change															
Handling pre and or after harvest															
selected undamaged yams only	1	74.2		1	0.0								1	252	
selected yams with severe cuts only	1	84.0		1	100								1	252	
selected yams with slights cuts only	1	74.8		1	80.0								1	252	
Harvest															
harvest earlier/less mature	6	39.7	(20.4-66.9)										6	119	
harvest later/more mature	6	47.5	(28.1-65.7)										6	119	

Table 10 Quantity loss and quality losses (% decay and sprouting) **of potato and yam stored in structures that result in different storage temperature conditions.** The data is arranged by crop and storage structure types showing the number of times the intervention was found in the 457 studies (n), the mean and range for the different loss metrics, and the storage period. Note: where n=1 the loss value from that one study is shown.

Crop/ Storage structure	n	Quantity loss (%)		n	Decay (%)		n	Sprouting (%)		n	Storage (days)	
POTATO												
ambient	25	18.0	(0.0-55.6)	10	24.4	(1.9-80.0)	3	67.3	(2.0-100)	27	88	(15-150)
heap/pile/clamp	17	15.2	(2.3-24.2)	10	2.9	(0.0-6.0)	3	48.0	(11.4-100)	17	99	(90-120)
pit/trench	20	14.8	(2.4-100)	4	8.7	(2.4-13.9)	5	44.1	(2.7-100)	20	147	(90-210)
evap cooled	13	13.2	(3.6-22.5)	9	3.4	(0.0-8.0)	3	42.1	(5.9-100)	13	112	(75-133)
coldroom	12	3.8	(0.3-8.0)	8	0.8	(0.0-2.5)	3	38.3	(0.0-100)	13	97	(45-150)
YAM												
ambient	21	27.8	(1.5-100)	6	28.4	(1.9-58.1)	2	99.5	(99.0-100)	24	186	(70-308)
pit/trench	3	17.0	(10.0-24.0)	1	12.0	(12.0-12.0)	2	35.0	(0.0-70.0)	3	97	(70-150)
heap/pile/clamp	2	11.2	(10.5-12.0)	1	26.7	(26.7-26.7)	1	97.0	(97.0-97.0)	2	135	(90-180)

3.5.4 Fruits

The majority of the PHL interventions which have been studied on fruit crops have been on mango (41.8 %), followed by citrus (38.0 %), banana (14.1 %), and papaya (6.2 %) (Table 3). The category technology/tools/equipment accounted for 95.4 % of the interventions, while handling practice changes were 4.6 %, and these were limited to mango. In the update review (2019-2024), 54.5 % of the fruit crop interventions were on mango, 26.0 % on citrus, 11.7 % on banana and 7.8 % on papaya. Technology/tools/equipment accounted for 96.1 % of the interventions.

The main quantity loss metrics reported in fruits were weight loss and overall loss (%). Several quality attributes were measured (Supplementary Table S5), these included decay, fruit flesh firmness, vitamin C content, and percentage of fruit that were not marketable. Firmness of the flesh of fruit, which is a good indicator of ripening, varies between fruit types, varieties within a fruit type, stage of ripeness and the equipment used to measure firmness, so it is not a good attribute to include in comparisons.

Overall, for the fruit crops, storage protectant use accounted for 47.7 % of the interventions, while storage structures and packaging accounted for 18.9 % and 16.0 %, respectively. While in the update review (2019-2024), 71.4 % of the interventions were on storage protectants, 20.1 % on storage structures/containers, and just 2.6 % on packaging. Waxes or coating agents applied on their own or in combination with fungicides, botanical products or growth regulators formed the largest group of storage protectants studied on the fruit crops in the full (original + update) review. They accounted for 40.6 % of all storage protectant interventions tested, followed by fungicides, growth regulators, botanicals and heat treatments.

Designed to decrease water loss (quantity loss), waxes or coating agents also reduced decay and increased the proportion of marketable stored fruit in this review (Tables 11 & 12). When banana, mango and citrus fruits treated with wax or coatings - with or without other storage protectants - were compared to untreated control fruits (Table 12), quantity loss and decay were consistently lower, and shelf life was longer. The vitamin C content of mango and citrus was higher in fruit treated with waxes or coating agents than in untreated controls. However, these studies were conducted on-station. No large-scale pilot studies under real-world conditions are reported in the literature.

The evaluation of different storage structures demonstrated their impact on temperature. Structures providing conditions colder than ambient storage resulted in less quantity loss and decay, more marketable fruit, and longer shelf life. When the effect of structures that resulted in ambient conditions, evaporatively cooled structures, or cold-rooms (including CoolBots which are insulated rooms cooled with a modification to an air conditioner) were compared across all four focal fruit crops (Table 13), quantity loss decreased from an average of 21.4 % under ambient conditions to 8.4 % and 6.5 % for evaporatively cooled structures and cold-rooms, respectively. Fruit decay was reduced on average by 17.5 % in bananas, and 6.0 % in mango when stored in cold-rooms versus ambient structures. Shelf life increased by 9.9 days in banana and 12.0 days in mango when stored in cold-rooms versus ambient structures. It increased by 24.3 days in citrus and 7.4 days in papaya when stored in evaporatively cooled versus ambient structures. The percent of papaya fruit that were considered ‘not marketable’ decreased by 45.5 % in evaporatively cooled versus ambient structures. Evaporatively cooled versus ambient structures also reduced fruit decay in citrus and mango. Use of shade netting reduced quantity loss in mango, and use of cellar stores reduced quantity loss and decay in citrus. Storage duration in these studies on these focal fruits ranged from 0 to 231 days.

Precooling, (i.e., rapidly removing the field heat from fruit before placing in storage) was evaluated on mango and banana. In mango, it reduced quantity loss by about 10 % when compared to no precooling. Hydrocooling of mango (i.e., precooling with cold water) reduced decay on average by 42.9 %).

There are very few studies on the use of plastic crates in fruits, probably because more fruit are packed in cardboard/fibreboard cartons or wooden boxes. Cartons are superior to wooden boxes for packaging the focal fruits, especially in terms of decay incidence. The use of liners (whether plastic, paper, or natural products) in the boxes, cartons or baskets reduces quantity loss. For example, citrus packed in cartons had an average quantity loss of 12.6 %. The inclusion of liners in cartons reduced quantity loss to 8.1 %, but increased decay by 1.3 %. Plastic liners can increase condensation which favours decay.

Handling practice changes affected both quantity and quality losses in mango. Traditional handling practices were associated with an average quantity loss of 27.9 % and 68.3 % decay, while improved handling conditions (i.e., more selective picking, leaving a stalk or pedicel, removing latex before packing), had an average quantity loss of 9.8 %, 22.5 % decay, and extended the shelf life by 1.5 days. While manual plucking of mango fruits or tree shaking harvesting methods resulted in 28.5 % decay, the use of improved mango harvesting tools resulted in between 0 and 18.5 % decay.

Table 11 Quantity loss and quality losses (% decay, vitamin C content) **for the focal fruit crops with different interventions.** The data is arranged by crop and intervention tier showing the number of times the intervention was found in the 457 studies (n), the mean for the different loss metrics, shelf life (SL[7]) and the storage period. Note: where n=1 the loss value from that one study is shown.

Crop, Intervention type, stage, description	**n**	**Quantity loss** (%)		**n**	**Decay** (%)		**n**	**Vit C** (mg/100ml)		**n**	**SL** (days)		**n**	**Storage** (days)	
CITRUS FRUIT															
Technology/tool/equipment use															
Harvesting															
harvest tools or aids e.g. poles				4	7.0	(1.6-16.8)							4	52.5	(0-70.0)
improved harvest + handling				4	1.9	(0-6.0)							4	52.5	(0.70.0)
Packaging															
baskets (all)	1	5.3											1	15.0	
baskets (all) + liner	4	12.2	(8.7-14.0)	4	19.0	(7.0-33.8)							4	14.0	(14.0-14.0)
cardboard/fibreboard cartons + liner	5	8.1	(3.6-20.6)	4	13.1	(7.5-21.0)							5	43.4	(21.0-77.0)
cardboard/fibreboard cartons/bulk bins	7	12.6	(1.4-20.01)	4	11.8	(9.2-18.5)							8	72.8	(15.0-231.0)
modified atmosphere packaging MAP	2	5.0	(4.9-5.1)	2	8.4	(8.3-8.4)							2	77.0	(77.0-77.0)
not packed	2	12.0	(1.1-22.9)	1	0.0								1	40.0	
plastic crates incl. RPC	1	0.3													
shrink wrap	4	7.5	(2.94-19.8)	4	5.6	(0-12.5)							4	58.5	(40.0-77.0)
wooden box + liner	5	10.1	(7.0-12.9)	4	27.6	(8.0-37.5)							5	15.4	(14.0-21.0)
wooden box/bulk bin	4	10.2	(1.4-17.5)	2	11.4	(8.9-13.9)							4	72.0	(15.0-231.0)
bags (all)	2	6.3	(5.9-6.6)										1	15.0	
Storage protectant															
botanicals, essential oils etc.	6	12.7	(6.5-19.2)	3	0.7	(0-1.0)	3	3.8	(3.6-4.0)	3	30.0	(30.0-30.0)	6	33.5	(30.0-37.0)
fungicide	1	14.0		11	14.1	(2.3-35.6)	1	38.2					11	37.9	(21.0-90.0)
growth regulators	5	20.3	(7.76-36.2)	5	24.2	(11.7-34.4)	1	3.6					5	47.2	(28.0-60.0)
no protectant (control)	12	22.7	(1.0-50.1)	11	34.8	(12.1-53.0)	4	10.5	(2.6-21.4)	1	17.0		17	44.6	(3.0-120.0)
wax + fungicide	19	11.7	(5.6-21.0)	3	1.6	(0-4.7)							19	23.2	(21.0-37.0)
wax/coating	23	8.0	(0.1-27.4)	21	11.2	(0-30.0)	9	24.7	(4.0-40.6)				31	58.7	(3.0-120.0)
wax/coating + botanicals/essential oils	5	6.5	(0.1-8.5)	5	0.2	(0-1.0)							5	39.6	(37.0-50.0)
wax/coating + growth regulator	1	5.1		1	2.0		1	2.6					1	60.0	
wax/coating + synthetic chemical	1	6.0		1	9.0								1	28.0	
Storage structure or container															
ambient storage	7	30.3	(9.0-54.0)	2	11.8	(10-13.5)	2	29.0	(25.0-33.0)	5	9.7	(4.5-12.5)	7	26.9	(14.0-30.0)
cold room	4	10.7	(8.5-16.2)	4	6.9	(0.5-25.3)							4	82.5	(60.0-90.0)
evap cooled structure/container	10	7.1	(1.5-16.2)	5	5.8	(1.0-8.6)	2	34.0	(30.0-38.0)	8	35.1	(23.0-45.0)	10	22.4	(12.0-30.0)
heap/pile/clamp	1	52.3		1	43.0								1	60.0	
shaded structure (thatch, net etc)	1	13.2		1	8.2					1	16.0		1	12.0	
store room or warehouse	4	11.2	(8.3-13.8)	4	4.7	(3.0-7.3)							4	60.0	(60.0-60.0)

Key: RPC = returnable plastic crates

[7] Shelf life is the number of days of remaining life on removal from storage and transfer to warmer temperatures during display and ripening of fruit. This is an important measurement because some treatments can result in a very long storage life, but the fruit never ripen to eating quality and would then contribute to loss and waste. This differs from storage life which is the number of days that fresh produce is held during storage, usually under low temperature conditions.

Table 11 *continued*

Crop, Intervention type, stage, description	n	Quantity loss (%)		n	Decay (%)		n	Vit C (mg/100ml)		n	SL (days)		n	Storage (days)	
MANGO															
Handling practice change															
Harvest															
harvest earlier/less mature	3	4.5	(3.5-5.5)										3	13.0	
harvest later/more mature	3	3.8	(3.0-4.5)										3	13.0	
harvest mature	3	2.9	(1.8-4.0)										3	13.0	
harvest with stalk (pedicel)				1	9.7								1	10.0	
harvest without stalk				1	24.7								1	10.0	
Harvest and handling															
improved harvest + handling	4	9.8	(6.2-16.0)	1	22.5					2	7.5	(6.0-9.0)	5	5.8	(5.0-9.0)
traditional harvest + handling	4	27.9	(10-39.6)	1	68.3					2	6.0	(4.0-8.0)	5	5.8	(5.0-9.0)
Technology/tool/equipment use															
Harvesting															
harvest tools or aids e.g. poles	6	13.0	(2.7-24)	9	8.1	(0-28.0)				9	12.3	(6.5-15.0)			
improved harvest + handling	1	17.2		1	21.8										
manual harvest (control)				2	28.5	(26.0-31.0)				2	6.0	(5.2-6.8)			
Packaging															
baskets (all)				1	83.0										
cardboard/fibreboard cartons/bulk bins	2	6.2	(5.5-6.9)	1	90.0								2	28.0	(21.0-35.0)
modified atmosphere packaging MAP	3	7.6	(3.5-15.0)										3	18.7	(14.0-21.0)
not packed	1	35.0		1	90.0								1	10.0	
plastic crates incl. RPC				1	79.0										
protective biodegradable sleeve	1	9.0											1	21.0	
protective styrofoam sleeve	1	9.8											1	21.0	
shrink wrap	3	1.5	(1.4-1.7)										3	35.0	
bags (all)	2	39.9	(9.8-70.0)	1	85.2					1	10.0		2	13.5	(12.0-15.0)
bags (all) + growth regulator	1	10.5		1	74.1					1	11.7		1	12.0	
Precooling															
hydrocooling	4	16.1	(10.9-26.0)	4	22.6	(0-68.0)				3	12.7	(11.5-14.3)	4	13.5	(9.0-15.0)
hydrocooling + fungicide	6	16.4	(10.9-19.9)	6	17.3	(0-42.0)				4	14.3	(13.0-15.3)	6	15.0	
no cooling	1	26.0		2	65.6	(31.1-100)				2	9.9	(9.2-10.7)	1	15.0	
Storage protectant															
ash	1	100.0											1	15.0	
biocontrol / BT				2	26.0	(12.0-40.0)							1	7.0	
botanicals/ essential oils etc.	1	12.5		1	92.6					1	9.3		1	12.0	
fungicide	1	11.2		15	16.1	(5.0-31.0)				2	15.5	(15.0-16.0)	14	13.3	(9.0-33.0)
fungicide + biocontrol				1	25.0										
growth regulators	15	10.8	(7.2-28.3)	2	7.4	(2.9-11.8)	1	28.3					15	26.6	(7.0-28.0)
heat treatments	7	12.5	(10.0-14.5)	2	47.2	(13.0-81.5)	3	8.8	(6.7-10.3)	1	11.3		8	10.6	(6.0-17.0)
integrated treatment				1	20.0								1	7.0	
no protectant (control)	15	17.0	(6.1-51.4)	12	35.9	(8.0-91.0)	3	19.2	(7.0-26.7)	2	11.0	(8.0-14.0)	19	16.5	(6.0-33.0)
wax + fungicide				1	30.0								1	7.0	
wax/coating	16	11.5	(5.2-20.5)	10	18.7	(6.0-85.2)	4	25.9	(24.9-26.8)	6	19.6	(10.7-24.0)	17	17.4	(9.0-28.0)
wax/coating + botanicals/ess. oils etc.	1	9.3		2	7.2	(6.8-7.5)							2	30.5	(2.0-30.5)
Storage structure or container															
ambient storage	5	20.4	(4.1-80.0)	4	35.9	(15.4-76.0)	3	16.1	(13.4-18.2)	8	12.1	(9.5-15.0)	10	10.0	(5.0-15.0)
cold + pesticide				2	15.5	(9.0-22.0)				2	26.0	(26.0-26.0)	2	25.0	(25.0-25.0)
cold room	4	2.8	(2.3-3.3)	1	44.0					5	24.6	(22.0-26.0)	5	25.8	(25.0-26.0)
Coolbot													2	23.5	(12.0-35.0)
evap cooled structure/container	1	50.0		3	15.5	(10.3-25.5)	3	18.1	(14.6-20.6)	3	19.0	(18.0-20.0)	4	13.5	(12.0-15.0)
heap/pile/clamp	1	15.1													
shaded structure (thatch, net etc)	2	8.2	(7.1-9.3)												
traditional structure	1	90.0		3	24.5	(19.9-31.5)	3	17.0	(14.8-18.7)	3	15.3	(14.0-17.0)	4	13.0	(12.0-15.0)

Table 11 *continued*

Crop, Intervention type, stage, description	**n**	**Quantity loss** (%)		**n**	**Decay** (%)		**n**	**Vit C** (mg/100ml)			**SL** (days)		**n**	**Storage** (days)	
BANANA															
Technology/tool/equipment use															
Packaging															
cardboard/fibreboard cartons/bulk bins	1	7.9											2	6.0	(5.0-7.0)
modified atmosphere packaging MAP	2	6.4	(6.2-6.5)										2	28.0	(21.0-35.0)
not packed	2	16.8	(9.5-24.0)										2	10.0	(5.0-15.0)
protective padding	5	7.2	(6.1-9.0)										5	5.0	(5.0-5.0)
bags (all)	1	4.0											1	30.0	
Precooling															
forced air cooling	3	17.3	(7.6-22.3)	3	14.3	(13.0-17.0)				3	17.7	(10.0-24.0)	3	17.7	(10.0-24.0)
hydrocooling	6	18.3	(7.9-30.3)	6	14.3	(0-29.0)				6	17.2	(10.0-24.0)	6	17.2	(10.0-24.0)
Ripening/senescence															
low tech. ripening	2	6.7	(5.0-8.3)										2	5.0	(5.0-5.0)
Storage protectant															
botanicals, essential oils etc.	3	18.2	(17.0-20.0)	3	34.7	(32.0-40.0)				3	26.3	(25.0-28.0)	3	30.0	(30.0-30.0)
heat treatments				1	65.0					1	13.0		1	12.0	(12.0-12.0)
no protectant (control)	3	19.0	(17.5-19.8)	2	69.5	(39.0-100)				1	9.5		4	16.8	(12.0-20.0)
wax/coating	11	13.5	(5.4-24.2)	7	7.6	(0-24.0)				4	20.8	(10.0-30.0)	11	18.9	(10.0-30.0)
Storage structure or container															
ambient storage	5	17.0	(5.0-37.0)	1	21.2					3	14.3	(5.0-30.0)	5	25.4	(8.0-45.0)
cold room	5	6.1	(0-21.3)	2	9.5	(0-19.0)				4	23.3	(9.0-41.0)	5	26.4	(8.0-45.0)
evap cooled structure/container	7	8.0	(4.5-13.7)	5	30.6	(0-53.0)				5	12.4	(9.0-16.0)	7	13.1	(8.0-16.0)
shaded structure (thatch, net etc)	1	18.6		1	31.7					1	14.0		1	12.0	
store room or warehouse	1	23.1		1	28.0					1	10.0		1	10.0	
PAPAYA															
Technology/tool/equipment use															
Storage protectant															
botanicals/essential oils etc.	5	14.2	(12.2-15.5)	5	5.7	(5.2-6.0)	5	15.3	(15.2-15.5)				5	12.0	(12.0-12.0)
growth regulators	4	8.6	(4.6-11.0)	4	7.2	(2.1-10.2)	1	28.0					4	28.0	(28.0-28.0)
no protectant (control)	3	17.4	(9.1-24.0)	3	17.4	(6.1-28.9)	2	16.1	(15.1-17.0)				5	19.8	(12.0-28.0)
Storage structure or container															
ambient + box (no liner)	1	18.3								1	8.0		1	9.0	(9.0-9.0)
ambient + box + liner	2	12.9	(11.2-14.7)							2	8.0	(7.0-9.0)	2	9.0	(9.0-9.0)
ambient + box + PE liner	2	5.7	(5.3-6.2)							2	9.0	(9.0-9.0)	2	9.0	(9.0-9.0)
evap cooled structure + box + liner	2	3.8	(3.6-3.9)							2	15.0	(15.0-15.0)	2	9.0	(9.0-9.0)
evap cooled structure + box + PE liner	2	2.3	(1.9-2.8)							2	18.0	(18.0-18.0)	2	9.0	(9.0-9.0)
evap cooled structure + box no liner	1	4.4								1	13.0		1	9.0	(9.0-9.0)

Table 12 Quantity loss and quality losses (% decay, vitamin C content, % not marketable) **of citrus fruits, mango and banana treated with waxes or coating agent**, with or without additional storage protectants, compared to fruit without protectants. The data is arranged by crop and wax/ coating treatment showing the number of times the intervention was found in the 457 studies (n), the mean and range for the different loss metrics, and the shelf life (SL) and storage period. Note: where n=1 the loss value from that one study is shown.

Crop Wax/coating	n	Quantity loss (%)		n	Decay (%)		n	Vit C (mg/100 ml)		n	Not marketable (%)		n	SL (days)		n	Storage (days)	
CITRUS FRUIT																		
no protectant	14	20.2	(1.0-50.1)	13	30.3	(2.0-53.0)	5	8.9	(2.6-21.4)	3	70.0	(35-100)				19	44.5	(3-120)
wax/coating	47	9.3	(0.1-27.4)	29	8.3	(0.0-30.0)	9	24.7	(4.0-40.6)	3	34.7	(12-74)				55	44.7	(3-120)
MANGO																		
no protectant	14	17.2	(6.1-51.4)	11	35.6	(8.0-91.0)	2	25.2	(23.8-26.7)	2	42.6	(37.0-48.2)	2	11.0	(8-14)	18	16.9	(6-33)
wax/coating	17	11.4	(5.2-20.5)	13	17.8	(6.0-85.2)	4	25.9	(24.9-26.8)				6	19.6	(10.7-24)	20	18.2	(7-33)
BANANA																		
no protectant	3	19.0	(17.5-19.8)	2	69.5	(39.0-100)							1	9.5		4	16.8	(12-20)
wax/coating	8	13.9	(6.8-17.4)	4	13.3	(8.0-24.0)							1	30.0		8	19.4	(15-30)

Table 13 Quantity loss and quality losses (% decay, vitamin C content, % not marketable) **of the focal fruit crops stored in storage structures that result in different storage temperature regimes.** The data is arranged by crop and storage structure types showing the number of times the intervention was found in the 457 studies (n), the mean and range for the different loss metrics, and the shelf life (SL) and storage period. Note: where n=1 the loss value from that one study is shown.

Crop Storage structure	n	Quantity loss (%)		n	Decay (%)		n	Vit C (mg/100 ml)		n	Not marketable (%)		n	SL (days)		n	Storage (days)	
CITRUS FRUIT																		
ambient	13	24.8	(8.3-54.0)	8	11.7	(3.0-43.0)	2	29.0	(25.0-38.0)				6	10.8	(4.5-16)	13	38.5	(12-60)
evaporatively cooled	10	7.1	(1.5-16.2)	5	5.8	(1.0-8.6)	2	34.0	(30.0-38.0)				8	35.1	(23-45)	10	22.4	(12-30)
cold room/CoolBot	4	10.7	(8.5-16.2)	4	6.9	(0.5-25.3)										4	82.5	(60-90)
MANGO																		
ambient	9	24.8	(4.1-90.0)	7	31.0	(15.4-76.0)	6	16.5	(13.4-18.7)				11	13.0	(9.5-17)	14	10.9	(5-15)
evaporatively cooled	1	50.0		3	15.5	(10.3-25.5)	3	18.1	(14.6-20.6)				3	19.0	(18-20)	4	13.5	(12-15)
cold room/CoolBot	4	2.8	(2.3-3.3)	3	25.0	(9.0-44.0)							7	25.0	(22-26)	9	25.1	(12-35)
BANANA																		
ambient	7	18.1	(5.0-37.0)	3	27.0	(21.2-31.7)							5	13.4	(5-30)	7	21.1	(8-45)
evaporatively cooled	7	8.0	(4.5-13.7)	5	30.6	(0.0-53.0)							5	12.4	(9-16)	7	13.3	(8-16)
cold room/CoolBot	5	6.1	(0.0-21.3)	2	9.5	(0.0-19.0)							4	23.3	(9-41)	5	26.4	(8-45)
PAPAYA																		
ambient	5	11.1	(5.3-18.3)							5	58.9	(45.8-73.6)	5	8.4	(7-9)	5	9.0	
evaporatively cooled	5	3.3	(1.9-4.4)							5	13.4	(5.6-23.6)	5	15.8	(13-18)	5	9.0	

3.5.5 Vegetables

In the full scoping review (the original plus the 2024 update), the majority of the PHL interventions on vegetable crops were on onion (50.2 %), followed by tomato (42.6 %), leafy vegetables (amaranth, spinach, jute mallow) (4.4 %) and cabbage (2.8 %). Overall, the interventions fall into three central categories: technology/ tools/ equipment (88.4 %), handling practice changes (10.4 %), and infrastructure (1.2 %). In the update review, tomato accounted for 58.0 % of the interventions, onion 34.6 % and leafy vegetables 7.4 %. Technology/tool/equipment accounted for 82.7 %, handling practice changes 13.6 % and infrastructure 3.7 % of these interventions. There were no recent studies on cabbage that met the inclusion criteria.

Weight loss and overall loss (%) were the main metrics measured for quantity loss (Supplementary Table S4). Decay was the most frequently reported quality loss attribute in vegetables, followed by the percentage not marketable. Percent sprouting was reported for onion. Vitamin C content was measured in a few tomato and onion studies, while carotenoid content was measured only in onion.

The use of storage structures (40.6 % of interventions), storage protectants (21.7 %), and packaging (20.1 %) were the major areas of research for vegetables (Table 14). In the recent update, storage protectants accounted for slightly more of the interventions (33.3 % of the interventions, restricted to onion and tomato) than storage structures (32.1 %). Far fewer interventions were studied on cabbage (n=5) and leafy greens (n=7) than on onion (n=94) and tomato (n=82).

When the effect of storage at ambient conditions versus evaporative cooling, or mechanically cooled cold-rooms (including CoolBots), were compared across the four focal vegetable crops, reductions in quantity loss, decay and sprouting were reported (Table 15). For example, quantity loss was reduced by 25.0 % in cabbage, 35.5 % in leafy vegetables and 30.0 % in onions when stored in cold-rooms compared to ambient structures. Tomatoes had a 12.8 % reduction in quantity loss and 5.8 % reduction in decay when stored in cold-rooms versus ambient structures.

Storage protectants were only evaluated on onion and tomato (Table 14). Pesticide use reduced both quantity and quality losses in onion. Irradiation caused a reduction in decay in onion from 62 % in the untreated control to 24-59 % depending on the irradiation level and duration, and reduced sprouting incidence, however results for quantity loss varied between studies. Storage duration in these vegetable crop studies ranged from one day for transport studies to 240 days.

The number of packaging interventions evaluated was low on cabbage (n=2) and leafy greens (n=2), and none were attempted for onions. However, packaging interventions for tomatoes were subject to evaluation. The use of plastic crates reduced quantity loss and decay to 12.6 % and 8.9 %, compared to 30.3 % and 19.5 % when packaged in baskets. Quantity loss totalled 48.3 % in wooden boxes.

Some handling practice changes reduced quantity loss, but there were no data on percentage decay, and the number of interventions evaluated was low. Harvesting later, curing, and improved handling practices on average reduced quantity loss in onions by 20.0 %, 18.0 %, and 12.4 %, respectively. Delayed harvest reduced quantity loss in cabbage by 3.6 %. Harvesting less mature tomatoes reduced quantity loss by 20.0 %.

A single study on infrastructure on tomato showed slightly higher mean quantity loss with poorer roads (4.3 %) when compared to improved roads, although this varied from 7.0 % higher where 25 km of the road was bumpy to 1.4 % higher on a road where 7 km of it was bumpy.

Table 14 Quantity loss and quality losses (% decay, % sprouting (onion) and % not marketable (tomato)) **for the focal vegetable crops with different interventions.** The data is arranged by crop and intervention tier showing the number of times the intervention was found in the 457 studies (n), the mean for the different loss metrics. Note: where n=1 the value from that one study is shown.

Crop, Intervention type, stage, description	**n**	**Quantity loss** (%)		**n**	**Decay** (%)		**n**	**Sprouting** (%)		**n**	**Storage** (days)	
CABBAGE												
Handling practice change												
Harvest												
harvest earlier/less mature	1	32.0		1	26.0					1	12.0	
harvest later/more mature	2	28.4	(25.9-30.8)	2	13.0	(8.0-18.0)				2	12.0	(12-12)
Technology/tool/equipment use												
Storage structure or container												
ambient storage	1	30.0								1	21.0	
Coolbot	1	5.0								1	21.0	
LEAFY VEGETABLE												
Technology/tool/equipment use												
Storage structure or container												
ambient storage	2	56.7	(44.0-69.4)							2	5.7	(3.0-8.4)
cold room	1	21.2										
evap and solar cooled structure	1	14.8										
evap cooled structure/container	3	16.1	(5.3-36.9)							3	4.8	(3.0-8.4)
ONION												
Handling practice change												
Handling pre and or after harvest												
curing in heaps	2	31.0	(31.0-31.0)							4	105.0	(90-120)
harvest earlier/less mature	1	27.0								1	90.0	
harvest intermediate	1	22.0								1	90.0	
harvest later/more mature	1	7.0								1	90.0	
improved handling practices	8	39.3	(32.3-46.5)	8	11.1	(8.9-14.6)				9	143.0	(90-150)
no curing (control)	1	47.0								2	105.0	(90-120)
traditional handling practices	1	51.7		1	17.4					2	120.0	(90-150)
Technology/tool/equipment use												
Drying												
heat source - nonrenewable energy				1	7.3					3	38.3	(3-56)
Packaging (perishables)												
bags (all) (perishables)	7	32.6	(4.5-39.8)	7	8.2	(4.6-12.6)				7	162.9	(60.2-180)
cardboard/fibreboard cartons/bulk bins	1	8.4		1	15.4					1	60.2	
not packed	1	11.9		1	15.4					1	60.2	
Storage protectant												
biocontrol / BT	2	14.5	(14.4-14.5)	2	43.7	(35.5-51.9)				2	60.0	
growth regulators	1	22.0		1	2.8		2	6.9	(4.7-9.0)	3	160.0	(120-240)
irradiation	6	36.6	(14.5-62.1)	4	41.4	(24.3-59.0)	5	9.2	(0-25.7)	6	146.0	(120-180)
no irradiation	1	47.0										
no protectant (control)	7	29.7	(15.9-44.3)	4	54.8	(18.1-71.4)	3	26.9	(6.2-56.0)	10	129.0	(60-240)
pesticide	12	14.2	(10.7-32.3)	10	31.4	(22.7-42.9)				12	72.5	(60-135)
Storage structure or container												
ambient storage	1	17.8					1	28.7		2	88.0	(56-120)
cold room	2	10.0	(6.1-14.0)	2	5.7	(2.3-9.0)	2	8.8	(7.9-9.6)	5	81.6	(56-120)
farmers storage	1	38.5					1	3.5		1	180.0	
heap/pile/clamp	1	22.1		1	73.0					1	126.0	
improved structure+ forced air ventilation	1	33.4					1	2.5		1	180.0	
shaded structure (thatch, net etc)	14	50.5	(28.0-98.1)	6	6.5	(2.4-8.2)	2	95.7	(91.4-100)	15	150.0	(50-180)
store room or warehouse	8	33.4	(10.0-70.0)	5	13.6	(1.8-34.2)				9	129.6	(56-180)
structure with forced air ventilation	4	16.1	(9.0-23.8)	2	2.9	(2.6-3.2)	1	0.0		4	145.0	(120-180)
traditional structure	9	43.0	(11.6-70.3)	9	12.4	(2.1-43.8)				11	122.5	(50-180)

Table 14 continued

Crop, Intervention type, stage, description	n	Quantity loss (%)		n	Decay (%)		n	NOT market. (%)		n	Storage (days)	
TOMATO												
Handling practice change												
Harvest												
harvest earlier/less mature	1	10.0										
harvest mature	1	30.0										
Infrastructure e.g. warehouses, packhouses												
Road transport												
improved roads	1	1.2								1	5.0	
poor roads	2	5.5	(2.7-8.2)							2	5.0	(5-5)
Technology/tool/equipment use												
Ripening/ senescence												
low tech. ripening							2	42.5	(40.0-45.0)	2	8.0	(8-8)
natural ripening							1	80.0		1	8.0	
Drying												
heat source - solar systems										3	80.1	(8.4-116.0)
outside(sun) on bare ground	1	9.3										
outside (sun) off ground	1	8.4										
Packaging (perishables)												
baskets (all)	5	28.3	(14.0-40.0)	2	11.3	(8.3-14.3)				2	11.0	(11-11)
improved basket	1	7.9		1	3.2					1	11.0	
MAP + synthetic chemical				1	50.5					1	14.0	
modified atmosphere packaging	3	6.2	(0.3-9.8)	1	27.0					3	19.0	(14-23)
no bag (control)				1	54.0					1	14.0	
not packed										3	19.0	(14-23)
plastic crates incl. RPC	6	12.6	(0.6-40.0)							1	1.0	
plastic crates incl. RPC + liner	4	17.7	(0.5-40.0)							2	1.0	(1-1)
shrink wrap (perishables)	2	15.4	(11.9-18.8)							2	21.5	(20-23)
wooden box + liner	6	34.8	(25.0-47.0)							6	8.7	(1-24)
wooden box/bulk bin	3	48.3	(40.0-55.0)							3	8.7	(1-24)
Storage protectant												
fungicide				4	36.0	(15.0-55.0)				4	28.0	(28-28)
no protectant (control)	1	13.8		3	53.8	(40.0-65.5)				2	25.3	(20-28)
wax/coating	3	11.1	(9.25-13.75)	3	25.4	(17.9-34.5)				3	20.0	(20-20)
Storage structure or container												
ambient + basket	1	8.4								1	9.0	
ambient + box (no liner)	1	9.6								1	9.0	
ambient + CFB box	1	7.0								1	9.0	
ambient + wooden box	1	7.2								1	9.0	
ambient storage	6	28.5	(3.0-58.0)	1	68.8		1	90.1		5	21.8	(5-42)
ambient storage + harvest earlier/less mature	1	11.8					1	83.0		1	28.0	
ambient storage + harvest later/more mature	1	17.1					1	84.0		1	28.0	
cold room	2	15.4	(4.7-26)	1	23.3					2	31.0	(20-42)
cold room+ harvest earlier/less mature	1	4.9					1	43.0		1	28.0	
cold room+ harvest later/more mature	1	7.7					1	71.0		1	28.0	
Coolbot	1	5.0								1	21.0	
CoolBot + breaker	2	2.9	(2.9-3.0)				2	39.7	(37.9-41.5)	2	42.0	(42-42)
CoolBot + light red	2	2.6	(2.5-2.6)				2	52.7	(48.4-57.0)	2	42.0	(42-42)
CoolBot + mature green	2	3.0	(2.9-3.0)				2	15.7	(14.0-17.4)	2	42.0	(42-42)
evap cooled structure + basket	1	9.1								1	9.0	
evap cooled structure + CFB box	1	8.7								1	9.0	
evap cooled structure/container	12	7.5	(0.5-14.2)	3	29.6	(28.5-30.8)	1	19.1		11	23.1	(5-50)
shaded structure (thatch, net etc)	3	16.2	(10.5-21.5)	1	23.7					3	20.7	(12-30)

Key : MAP = modified atmosphere packaging, RPC = returnable plastic crate, CFB = cardboard fibre box

Table 15 Quantity loss and quality losses (% decay, % sprouting, % not marketable) **of the focal vegetable crops stored in structures that resulted in different temperature conditions.** The data is arranged by crop and storage structure types showing the number of times the intervention was found in the 457 studies (n), the mean and range for the different loss metrics, and storage duration (days). Note: where n=1 the loss value from that one study is shown.

Crop, Storage structure	**n**	**Quantity loss** (%)		**n**	**Decay** (%)		**n**	**Sprouting** (%)		**n**	**Not marketable** (%)		**n**	**Storage** (days)	
CABBAGE															
ambient	1	30.0	(30.0-30.0)										1	21	
cold room/CoolBot	1	5.0	(5.0-5.0)										1	21	
LEAFY VEGETABLE															
ambient	2	56.7	(44.0-69.4)										2	6	(3-8)
evap cooled	4	15.8	(5.3-36.9)										4	6	(3-8)
cold room/CoolBot	1	21.2	(21.2-21.2)										1	8	
ONION															
ambient	37	40.1	(9.0-98.1)	20	10.9	(1.8-43.8)	5	44.72	(0.0-100)				38	144	(56-180)
cold room/CoolBot	2	10.0	(6.1-14.0)	2	5.7	(2.3-9.0)	2	8.75	(7.9-9.6)				4	88	(56-120)
TOMATO															
ambient	15	18.7	(3.0-58.0)	2	46.3	(23.7-68.8)				3	85.7	(83.0-90.1)	14	19	(5-42)
evap cooled	14	7.7	(0.5-14.2)	3	29.6	(28.5-30.8)				1	19.1	(19.1-19.1)	13	21	(5-50)
cold room/CoolBot	11	5.9	(2.5-26.0)	1	23.3	(23.3-23.3)				8	41.28	(14.0-71.0)	11	36	(20-42)

3.6 Intervention costs

The range of costs reported in the update reviews included 123 studies for different interventions have been summarised at the tier 3 level and the values are presented in Table 16. The complete list of costs reported per specific intervention is shown in Supplementary Table S7.

In the included studies for the update review, reported costs of PHL reduction interventions for the durable crops ranged from <1 USD for different types of sacks with and without a synthetic chemical to treat 100 kg of grain to a small combine harvester costing USD 21,000. Hermetic bags ranged in cost from USD 1.20 to USD 2.50. A local hermetic bag version using a fertiliser bag with a low density polyethylene (LDPE) liner was costed at USD 0.40.

For interventions for perishable crops costs ranged from <2 USD for raffia baskets, local mango harvesting tools and materials for covering heaps of potato to evaporative cooling structures from USD 600 to USD1,200 (Table 16 and S10). Despite the inclusion of data on cold-rooms there were no data on their capital and operating costs. However, the operating costs of a CoolBot at two temperatures (13°C and 16°C) was compared.

In the earlier original review reported intervention costs ranged from less than USD 1 for harvesting tools, sacks, baskets, cartons, liners and protective padding to around USD 2,000 for cold rooms cooled evaporatively (20t capacity) or with a modified air-conditioner (8-10t capacity). The cost for a 20-t capacity hermetically sealed cocoon was USD 4,000, USD 190 for a 1,000kg-capacity hermetic bag, and USD 36,000 for a combine harvester. Prices depend on manufacturer, size of bag, country of use and exchange rate. Although the relative cost of items such hermetic bags may seem relatively low, they have a limited lifespan. A simple return on investment, or cost: benefit analysis, would be a more appropriate means of evaluating the effect of interventions than costs alone (Saran et al., 2012).

Table 16 The cost of interventions in the update review in USD organised by crop groups, intervention type, stage and group description. If the cost in USD was not provided in the paper the local currency was converted to USD based on the average exchange rate from the year of publication, cost ranges are shown where there was data for more than one intervention per group.[8]

Crop Group, Intervention type, stage, description	n	Intervention cost (USD)	
Cereals&Legumes			
Technology/tool/equipment use			
Harvesting			
mechanised harvesting	2	11525.00	(2050-21000)
Storage method (durables)			
jute sack + fumigant	1	0.15	
polypropylene bag + no protectant	1	0.22	
bag + synthetic chemical	3	0.26	(0.26-0.26)
bag + wrapped in fish netting	1	0.40	
polypropylene bag + LDPE liner	1	0.40	
polypropylene bag + LDPE liner + botanical	1	0.40	
no storage/ immediate sales	1	0.41	
hermetic + pesticide incorporated polypropylene bag	3	1.67	(1.50-2.00)
hermetic bag	15	1.88	(0.74-2.50)
hermetic bag + botanical	1	1.90	
polypropylene bag + synthetic chemical	3	2.02	(0.30-4.25)
hermetic bag + synthetic chemical	1	2.04	
improved granary	1	12.01	
improved granary + synthetic chemical	1	18.49	
metal silo, drum or bin	1	28.51	
metal silo + synthetic chemical	1	34.98	
Threshing or Shelling or De-husking			
mechanised	5	1968.40	(577.00-5793.0)
Handling practice change			
Handling pre and or after harvest			
traditional practices	2	0.00	(0.00-0.00)
traditional practices + grain PH training	2	2.71	(1.60-3.81)
traditional practices + grain PH training + moisture measurement	2	4.52	(2.73-6.31)
grain PH training + moisture measurement + off-ground drying + traditional storage	2	7.79	(6.00-9.58)
grain PH training + moisture measurement + off-ground drying + hermetic bag	2	10.20	(8.60-11.80)
Training/extension for skill development			
Training			
Training in PH management and purchase of silo with 70% discount	1	25.00	
Postharvest training	1	33.33	
Postharvest training + hermetic bags	1	57.33	
Training/extension for skill development; Handling practice change; Technology/tool/equipment use			
Training + technology access			
No intervention	1	1.70	
Training on aflatoxin management	1	1.70	
Training on aflatoxin management + used plastic sheet for drying	1	6.70	
Fruits & Vegetables			
Technology/tool/equipment use			
Harvesting			
manual harvest (control)	1	0.00	
harvest tools or aids e.g. poles	2	2.70	(1.35-4.05)
Packaging (perishables)			
baskets (all)	2	0.94	(0.94-0.94)
plastic crates incl. RPC	3	7.47	(5.90-9.00)
Storage structure or container			
farmers storage	1	0.00	
electricity usage of CoolBot + mature green over 42 days	2	15.52	(11.40-19.65)
improved structure with forced air ventilation	1	603.67	
evap cooled structure/container	2	629.89	(59.78-1200.00)
structure with forced air ventilation	1	783.63	
Handling practice change			
Harvest			
harvest mature	1	4.00	
Root & tubers			
Handling practice change			
Handling pre and or after harvest			
heap/pile/clamp	3	0.93	(0.93-0.93)
heap/pile/clamp + shade	3	1.85	(1.85-1.85)

[8] Note for Storage structure/container (perishables) for the operating cost of CoolBot at 16C or 13C, the electrical consumption of the CoolBots operating at different temperatures were provide in kWh for the 42-day storage period. The consumption was converted to electrical costs using average electricity prices in Tanzania from Cowling (2014).

3.7 Social, economic and environmental outcomes

In the original scoping review 13.1 % of the 334 studies mentioned economic, social or environmental outcomes of the interventions, either separately or combined. Economic outcomes were reported by 12.3 % of the studies, social outcomes by 3.0 % and environmental outcomes by 1.2 %. Most of the reported economic outcomes were for maize, rice and potato. Nineteen studies reported on theoretical cost–benefit analyses. Nine studies directly mentioned the actual costs and benefits of interventions.

In the update review, 23 (18.7 %) of the 123 studies included a cost benefit analysis of the interventions they focused on. Cereal studies accounted for 13 of these 23 studies, legumes for four, and root and tubers, fruits and vegetables for two studies each. A further three studies mentioned the participants' views on the prices but conducted no further calculations, five studies compared the costs of different interventions; and 15 studies mentioned economic related aspects such as price discounting for damage, or price premiums for quality etc. in their discussion but had no further economic analysis.

A total of 20 (16.3 %) of the 123 studies included in the update involved study of social outcomes of PHL interventions, an increase from just 3.0 % in the earlier scoping review. Studies on cereals accounted for 16 of these 20 studies. Four of these studies involved surveys where the responses had been disaggregated by gender, age, number of years of farming experience etc. Seven studies reported on gendered roles, views or actions in relation to PHL interventions. Six studies reported on time use and labour dimensions of PH interventions such as machines or simple tools for harvesting or threshing. Two studies reported on the impact of the PH intervention on household food security, and one study looked at the effect on dietary diversity. A further 14 did not focus directly on a social outcome but discussed social outcomes in their reports, e.g., social acceptability of interventions, hazardous use of pesticides, farmer preferences, study of traditional practices, labour shortages and PHLs. All of the 457 included studies reported on at least one quantity or quality food loss metric, the scale and type of these losses impact on outcomes such as food availability, quality, safety and/or nutrition. However, as that data is reported in section 3.5 it is not repeated here.

Just two of the 123 studies had specifically focused on environmental outcomes, both of which had also looked at social outcomes. Further details and findings of the social, economic and environmental outcomes from the 457 included studies are presented in sections 3.7.1-3.7.3.

3.7.1 Social outcomes

Only a few studies reported on social outcomes of PHL reduction interventions. These were focused on food security, gendered and labour outcomes.

Food security outcomes: More stable maize consumption through the year, reduced food insecurity, with the period of food insecurity starting 7-10 weeks later than in control households was reported for metal silo use in Kenya (Gitonga et al., 2013; 2015). In a study in Uganda by Omotilewa et al. (2018), provision of one hermetic bag per household led to maize stored for consumption being available for an extra 3 weeks. Additionally, significantly less use of and expenditure on pesticides was reported for households using either metal silos or hermetic bags (Gitonga et al., 2013; Omotilewa et al., 2018). A randomised control trial in Tanzania by Brander et al. (2021) on the effects of improved on-farm storage on seasonal food security, found the proportion of households who self-reported being severely food insecure reduced by 20.4 % among households given five hermetic bags plus three rounds of standardised PH training. In Tanzania, Chegere et al. (2020) found combining PH training and supplying of sufficient hermetic bags for 60% of the maize harvest reduced the household food insecurity score (HFIAS) by 30.9%, while the training alone reduced it by 10.8%. Another Tanzanian study calculated 29-31 more days of calories and protein sufficiency per year could be obtained for 50% of households through use of improved PH practices (Mutungi et al., 2022a). A study in India found hermetic bag use had no effect on dietary diversity, although sugar and dairy consumption increased (Shukla et al. 2023). However, the use of hermetic bag storage of maize increased the sales price received by 13 %, the likelihood of a household selling stored grains in the market by 30 %, the duration of storage by 25 %, the consumption of grain from their own stocks by 20 % and decreased consumption from market sources by 8 %, and led to a significant increase in the share and quantity of output stored by the household after harvest.

Gendered outcomes*:* Few studies analysed gendered outcomes. One study in Senegal of PH training either alone or bundled with combinations of other PH technologies (e.g., tarpaulin, hygrometer, hermetic bag), found households in which a woman attended the training with their husbands plus received a hygrometer and a tarpaulin were 20-30 % less likely to have aflatoxins over the EU limit (10 ppb), than those where only males attended the training (Leavens et al., 2021). However, this was not the case for incidence of aflatoxins over the 20 ppb US threshold suggesting there may be a Type I error. While a study in Malawi by Anitha et al. (2019) found that although farmers' understanding of aflatoxin risks increased following training they would still consume and sell grains they graded out due to the grade outs accounting for 10 to 20% of their profit. Also, they did not adequately practice the better drying methods learnt due to space limitations at their homesteads and fear of theft if done in the field.

A maize study in Tanzania (Mutungi et al., 2022b) that explored a range of PH interventions (collapsible dryer, mechanised thresher, hermetic storage bags) versus farmers normal practice found the mechanised sheller saved time and labour – the sheller achieved a throughput of 690 kg/hour versus 68.5 kg/hour by one person's manual shelling. Manual shelling and cleaning of grain was mainly done by women in the trial districts, and it was suggested this 10-fold improvement in work rate could free up time to use for other income-generating activities. The study discusses how introduction of such mechanisation leads to gendered shifts in responsibilities, although manual shelling is mostly done by women and children, mechanised shelling is typically taken over by men. During the village-level training the study found when men and women were taught together the women started to disappear when the time to touch the shelling machine arrived. However, when the female agricultural engineering extensionist worked separately with the women on use of the sheller they found the confidence and capability to use the machine. One Kenyan study (Makinya et al., 2021) found women-managed grain household stores were associated with significantly lower losses by 2.8 percentage points than stores managed by men, and that farmers with over twenty years maize farming experience incurred significantly lower losses by 4.3 percentage points than those with less experience, and that grain storage training did not significantly affect loss levels. Farmers who bagged and stored the grain in the bedroom or living room experienced lower losses than those who stored in granaries by 2.8 and 4.6 percentage points, respectively, while storage in the kitchen was associated with higher losses than in granaries. Storage in woven PP bags or hermetic bags or silos resulted in similar loss levels, storing maize together with other food or non-food items results in higher losses, and farmers' who received a higher store hygiene score had significantly lower losses.

A loading tracking PH loss assessment study in Burkina Faso (FAO, 2019a) highlighted issues around women's heavy workloads impacting on the timely completion of activities and application of good practices and the limited decision-making power and control over resources by women and young people. Women explained that despite their responsibility for many agricultural activities, they often have no control over the management of food stocks and are often unaware of how the income from the sales of these agricultural products is then used. The women had tried reacting to these unequal gender relations through refusing to harvest cowpeas or lead the maize farming activities, but it had not brought successful changes. A PHL assessment in DRC listed the inequality in the division of tasks between men and women, the limited access for women to equipment, credit, technical information and training, and women's limited decision-making power regarding PH tasks, stock control and income allocation as causes of PHLs (FAO, 2019b).

A study on farmers' potato storage in Uganda reported a significantly lower proportion of female headed than male headed households had access to information on ware potato, on potato harvest and PH handling, and on potato storage (Wauters et al., 2022). With female headed households being more likely to report that they did not store ware potato for later sales because they did not have enough potato to store.

Labour-related outcomes: A study on the effect of introducing a quality sensitive market buyer into some villages in Uganda alongside extension training, found farmers in the treatment group then reduced the use of family labour and instead hired more labour, producing employment opportunities in areas where they were otherwise scarce (Bold et al., 2022).

The labour requirements of different rice harvesting and threshing methods were compared in studies in India, Sri Lanka and Bangladesh with mechanised harvesting significantly reducing the labour hours required per ha (Basavarajappa et al., 2013; Mahrouf and Rafeek, 2003; Nath et al., 2022). Farmers in one Indian study said modified reaper and manual sickle rice harvesting were gender neutral methods, with the reaper being time-saving while the sickle risks causing injuries (Mishra and Satapathy, 2021). A study from Nigeria reported that in Nasarawa state youth were being trained to operate harvesting and threshing machinery purchased by cooperatives with fees being charged to those using the services (Castelein et al., 2022). Harvesting and threshing activities would usually be done manually by women, so the machines had resulted in time saving, with the women reportedly spending that saved time working in warehouses, on quality assurance and cultivation of other crops, and on social and family matters. The study suggests labour shortages exist during harvesting in Nasarawa so unemployment risks due to mechanisation are not observed and small machine workshops offering spart parts, maintenance and repair services have begun to appear.

For the fruits, vegetables and root and tuber crops social outcomes of PHL reduction interventions received little attention in the included studies. A handful of studies from India report on harvesting rates and labour requirements alongside fruit damage levels for different mango harvesting tools versus manual plucking or tree shaking methods (Savita et al., 2010; Srinivasappa et al., 2015; Aparna et al., 2020). The improved mango harvesting tools were reported to reduce drudgery and fatigue typically associated with mango harvesting. In the Aparna et al. (2020) study manual plucking had a higher drudgery score[9] (72%) and required 30 people per day per ha, while the IIHR harvesting tool with a pole frame net and blade had a drudgery score of 43% and required 18 people per day per ha, and the local harvesting tool had a drudgery score of 65%.

[9] Drudgery index score of ≥70 = maximum drudgery, between 50-70 = moderate drudgery, ≤50 = minimum drudgery

3.7.2 Economic outcomes

The set of studies reporting on economic outcomes covered a range of PH interventions used for reducing PHLs at different activity stages, but particularly for maize, rice and wheat. Examples from the findings of these studies are presented.

Several studies focused on the economics of maize grain storage technologies. In Benin, Gbenou et al. (2021) tracked 25 producers for 2 years and made detailed calculations of the benefit cost ratio (BCR) for storage of maize grain (including purchase and construction costs, storage labour, protectant cost, monthly maize grain sales prices, interest rates, lifespan of facility) for 6 months using a range of different facilities with and without the addition of the grain protectant dust (Actellic Super dust applied at 50g/100kg which reduced % weight loss by ~3% in all facilities). The BCR of the different treatments were: polypropylene (PP) bag 7.7 (*5.9 with grain protectant*); hermetic PICS bag 9.1 (*6.1*); metal silo of 250-1000kg capacity 4.4 (4.4); improved clay granaries (up to 1000kg capacity) 6.8 (5.4). Their analysis illustrates how reductions in the selling price of maize lead to treatments becoming less profitable and requiring storage of larger quantities of grain to break-even. While a study in Kenya (Ndegwa et al., 2016), found that if farmers store their maize for four months, they can break even with the cost of the hermetic bags after three seasons (i.e., marginal rate of return (MRR) becomes positive (0.34)), although MRR >1 only occurs after four seasons of use. But if farmers store their maize for six months' then the MRR for the hermetic bag reaches >1 (2.01) after three seasons.

An Ethiopian study (Kalsa et al., 2020) compared farmers immediate maize grain sales with no storage (NS), with storage in hermetic PICS bag (a 100kg capacity PICS bag cost USD 1.73) and with farmers typical storage practice (TSP) of treatment of grain with pesticides before storage (the PP bag and pesticide cost USD 3.84 for storage of 100kg of grain). They found the hermetic PICS bag had the highest net gross margin (USD 19.31/100 kg), followed by NS (USD 15.89/100 kg) and TSP (USD 10.83/ 100 kg). These treatments ran for different storage periods (TSP 5.4 months; PICS 9.6 months). They calculated the difference in gross margin if a household changes from NS to TSP (USD –4.36 /100kg) or to PICS (USD 5.87/100kg), and for changing from TSP to PICS (USD 10.23/100 kg).

In India a study found maize stored in hermetic bags (Super Grain Bag (SGB)) received, on average, 13 percent higher prices than that stored in traditional bags (jute sack + fumigant) (Shukla et al, 2023). The study also found that the SGB hermetic bags users experienced a 30 % increase in likelihood of selling grains in the market compared to the control group. The hermetic bag users also had a 25 % and 16 % increase in consumption of rice and wheat from their own stocks, respectively. Their cost benefit analysis if grain were sold after two months or consumed, demonstrates a high return with the use of improved storage technology relative to farmers current methods. They also commented on, but did not monetize, the health benefits of the lower aflatoxin grain. During their survey, >95% of the farmers were reusing the hermetic bags for a fourth season. A study in Uganda by Omotilewa et al. (2018) found households that received one hermetic bag stored maize for longer periods for both consumption and marketed sales (3 and 0.7 weeks, respectively), were 4% less likely to use chemical insecticides on their stored maize, reduced average self-reported storage losses by 61-70%, and were 10% more likely to cultivate improved maize varieties that are higher-yielding but more susceptible to storage insect pests than traditional maize varieties.

In a Tanzanian study, the net benefit of a PH training plus receipt of 12 hermetic bags per farmer was USD 37.2, the PH training cost USD 4,000 for 120 farmers per farmer, and the 12 hermetic bags USD 24, giving an initial investment of USD 57.3 per farmer and assuming net benefits are constant per season a discounted payback period of slightly less than 2 years (Chegere et al., 2022). The authors explain that if the intervention has no effect on maize prices, the total net benefit reduces to

USD 22.23 per farmer and a discount payback period of slightly more than 3 years. Their calculations imply that if the hermetic bags last for at least 3 seasons, they are profitable even if there is no positive effect on prices, they show if the training effects last beyond 4 years it is economically effective.

For metal silos, a Kenyan study by Gitonga et al. (2013), found metal silo users lost on average just 3 kg of maize grain in storage, valued at KSh153 (USD 2), while those control households not using metal silos, lost on average 157–198 kg (worth USD 104–132). Metal silo use saved grain equivalent to the annual consumption of two people, or 4 months consumption by a family of six, and also reduced the number of households using pesticides and expenditure on pesticides.

In a large-scale storage study using cocoons in Zimbabwe, the BCR of storing maize grain with a market price of USD 390/t using a 20 t GrainPro Cocoon that cost USD 4,000 and has an assumed 15 year life-span versus storing the grain in standard bag stacks with fumigation was 0.51 (Chigoverah et al., 2018). If import tariffs were to be removed reducing the cost of the cocoon to USD 2,995 the BCR increases to 1.11; if the factory price of the cocoon in the Philippines were used (USD 2,570) the BCR increases to 2.23.

Study of the effect of introducing a quality sensitive market buyer alongside extension training into villages in Uganda saw farmers with access to a high quality market receive USD 2.40 or 11% more per bag of maize (Bold et al., 2022). The price increase together with the productivity effect on quantity increase increased the value of farmers harvest by USD 7.87 or 30 % per season. Farmers in the treatment group earned on average USD 63 or 36 % more per season than farmers in the control group. With access to a market for high quality maize the share of farmers who engaged in improved PH practices nearly doubled: 60 % dried their maize properly (a difference of 24 percentage points, $p = .001$), 27 % sorted the maize (a difference of 14pp, $p = .001$) and 34 % winnowed it (a difference of 15pp, $p = .036$). Consistent with this, spending on harvest and post-harvest activities rose by 20 % ($p = .255$, control mean USD 30), an increase mainly driven by higher expenses on hired labour (a difference of 40 %, $p = .144$, control mean USD 15.6).

Regarding maize shelling, one Ethiopian study by Getachew et al. (2022), found in unimodal areas a multi-crop thresher had a negative (-6%) internal rate of return (IRR) and a 0.87 BCR, but in areas with a double cropping season the thresher had a 36% IRR and BCR of 1.21. They also report positive BCRs of 3.51 and 1.45 for the Bako-model maize sheller, and the maize dehusker-sheller machine, respectively. Analysis of farmers budgets found threshing machine use reduced threshing costs by USD 158.2 (51.9%) per ha of land compared to the traditional threshing method of oxen trampling. Analysis of a commercially available maize sheller in Uganda with a fixed cost of USD 577, found it had a BCR of 1.07 and a payback period of 1.37 years (Nsubuga et al., 2020). A willingness-to-pay study in Tanzania found 80% of farmers would potentially adopt mechanised shelling if it was available as a rental service (Mutungi et al., 2022b). No gender difference existed in willingness to pay for mechanised shelling rental service or group purchase models, but the percentage of women interested in private ownership of the machines was significantly lower than that of men.

In rice systems in Nigeria switching to mechanised harvesting and threshing was found to be profitable for farmers (Castelein et al., 2022). The financial results show a 16.1 % increase of 75,871 Naira per ha, and 144 hours per ha labour saved for harvesting and 59 hours for threshing. Switching to mechanised threshing and mechanised harvesting increases the profit of a farmer per ha (all else equal) by ~USD 68 and ~USD 190, respectively. Mechanised threshing is more expensive than manual threshing as the cost of renting the thresher is equal to the total labour costs of manual threshing, but the authors suggest the improved threshing efficiency and reduced losses of the threshing machine increase the total by enough to make the intervention worthwhile. In Bangladesh, study of a small-scale combine harvester found manual and semi-mechanised harvesting costs were 2.5 and 1.84 times higher than those of the combine harvester, respectively (Nath et al., 2022). However, the authors highlight that the benefits may not be significant to outweigh the capital cost (~USD 21,000) and operational expenses.

In Kenya, the effect of combining farmer training on aflatoxin management with full price or subsidised access to PH technologies was studied, the use of plastic drying sheets (which cost USD 5 per farmer) led to 79 % lower aflatoxin concentration which the authors suggest makes this a simple and relatively low-cost technology (Pretari et al., 2019). They calculate the training costs at USD 1.70 per farmer. The authors suggest this USD 6.70 cost per farmer (which covers the drying sheet plus training) is cost effective compared to other methods such as Aflasafe KE01 which costs USD 8.40 per farmer (based on a cost of USD 16 per ha) without including training on how to correctly apply the product at the correct time and rate. Work in Gambia with a suite of PH interventions (PH training, woven drying mat, jute bags, pallets, and insecticide) which cost USD 50 per farmer and led to a 59% reduction in aflatoxin levels of stored groundnuts (Turner et al., 2005; Wu and Khlangwiset, 2010). In Senegal, a study with 2000 households on the effect of different combinations of four interventions (training (USD 1.60/household), hygrometer (USD 1.13 each), tarpaulin (USD3.27 per 10m^2 each), hermetic bag (USD 2.60 each)) on aflatoxin levels in stored maize suggests training plus a tarpaulin is a cost-effective intervention at USD 1.01 per ppb of aflatoxins reduced and explain the cost would likely decrease given tarpaulins last for longer than one year. Using World Health Organisation (WHO) cost-effectiveness guidelines for public health interventions[10], they calculate the total annual equivalent costs per person of providing training plus tarpaulin to be USD 0.11, which is less than USD 0.15, the value of 3 times the per-person total DALY averted multiplied by GDP per capita. They state this likely underestimates the true benefits as the WHO only provides aflatoxins-related disease data for just one condition, liver cancer. Nevertheless, our findings suggest that providing training and a tarp is moderately cost-efficient based solely on reductions in morbidity and mortality of aflatoxin-induced liver cancer.

For harvesting of perishable crops, two studies in India (Srinivasappa et al., 2015, Savita et al., 2010) compared different improved mango harvesting tools (poles with net and cutting blades) with traditional harvesting practices (i.e., manual plucking or shaking the tree). In comparison to manual harvesting, the improved harvesting tools which ranged in cost from INR 100 to 250 (~USD 2-5.5) led to savings of 27-45%, while the use of a local harvesting stick with a cutter led to 18% savings. A recent study in India by Aparna et al. (2020) found the improved harvesting tool (IIHR harvester) led to more mango fruit being harvested per hour 354/h versus 290/h and 250/h for the local harvesting tool or manual plucking, respectively – and it also caused less damage to the fruit. The IIHR harvester saved INR 2,100/ha/day compared to manual plucking as less labour was required per ha and reduced the drudgery index score (43%), compared to the local harvester (65%) or manual plucking (72 %). In a Rwandan study improved PH practice of harvesting tomatoes at turning stage reduced PHL to 10% as the tomatoes were firmer and better adjusted to handling during transportation and marketing (Odeyemi et al., 2022). The per kilogram price of tomato increased from 200 Rwf (USD 0.25) to 400 Rwf (USD 0.50) because the tomato were better protected from mechanical injury during handling which led to a relative profit of USD 170 for each 1000 kg load.

For packaging, a study in Bangladesh of different packaging options found that in comparison to the use of bamboo baskets, cardboard cartons (CFB), plastic crates or wooden boxes increased profit for mango, but for banana the increase in profit does not justify use of CFB in local markets and plastic crates were recommended (Roy, 2005). Replacing the large traditional woven baskets used

[10] Under WHO guidelines, a project is considered highly cost efficient if the total cost of the intervention is smaller than the averted loss of disability adjusted life years (DALYs), a measure of disease burden, times the GDP per capita of the relevant country. A project is considered moderately cost efficient if the total cost of the intervention is less than three times the GDP per capita times the DALYs averted (Sachs, 2001).

for transporting tomatoes to market in Nigeria and Rwanda with returnable plastic crates (RPCs) reduced losses from 30 % to 10 % in Rwanda with increased relative profit of USD 9, and from 40 % to 5 % in Nigeria with a relative profit of USD 76 (Odeyemi et al., 2022). In Rwanda, utilizing the plastic crates over 10 times will pay for the plastic crates and subsequently generate an additional USD 9 per 100 kg load of tomato. In Nigeria, utilizing the crates over five times will pay for the plastic crates with an additional USD 76 per 100 kg load.

For cool storage, detailed economic calculations by Ishaque et al. (2022) of citrus fruits storage at ambient versus in a ZECC, found the economic return for storing citrus in a ZECC for 35 days is USD 693. Compared to a conventional refrigeration system, the lower upfront costs of a ZECC, and the water but no electricity requirements make it more economical and efficient. When a cellar storage system for citrus was tested for farmers in Nepal, the profit varied between locations, but the added gross income was about 300 % of the initial price of the fruit due to farmers being able to sell later in the season after the market glut (Subedi et al., 1995). In Nigeria, the cost of constructing a ZECC with storing capacity for 250 kg of tomato was USD 1,200 (Odeyemi et al., 2022). Compared with the current practice of immediate sales of harvested produce with a 30 % loss, use of the ZECC reduced loss to 5 %. This loss reduction provided a relative profit of USD 55 per 1,000 kg of tomato in comparison to the traditional practice of handling and temporary storage of the fruit at ambient temperature. The study reported that 22 uses will pay for the ZECC and plastic crates; then subsequent earnings will be USD 209/1000 kg load versus USD 154 for current practice. Under typical market conditions the market price may be higher for the ZECC stored produce which has a fresher appearance and less physical damage.

For wax coatings, a positive BCR was reported for treatment of citrus fruits with a wax coating in India, leading to a profit of INR 448 for 1000 fruits versus INR 300 for untreated fruit (Zade et al., 2005).

3.7.3 Environmental outcomes

Just two of the 123 studies in the update review had specifically focused on environmental outcomes, both of which had also looked at social outcomes. One of these studies (Castelein et al., 2022), had calculated the loss reduction associated greenhouse gas emissions avoided by mechanising rice harvesting, suggesting if all the rice farmers in Nigeria (3.2 million ha) harvested mechanically this would avoid 5.4 million tonnes of CO_2eq. The other study (Mutungi et al., 2022b) calculated the environmental outcome by converting the quantity of food saved by different combinations of grain PHL reduction interventions to the equivalent area of agricultural land that could be saved. They suggest the collapsible grain dryer (CDC) they tested could save 5-6% of the agricultural land area used, the mechanised sheller (MS) 6-8%, hermetic storage (HS) 8-17%. They calculate combining the CDC and MS would save 8-11%, the HS and MS 19-28%, and the CDC + MS + HS 21-32%. Many of the studies of grain protection methods which avoid or reduce the use of chemical control for rodents or insect pests discuss environmental outcomes. However, there has been limited exploration of this area. A study in Kenya by Gitonga et al. (2013) confirmed that use of a metal silo by households to store maize grain led to significantly reduced numbers of them using grain storage pesticides and reduced expenditure on these pesticides. Work in Uganda by Omotilewa et al. (2018), which gave households one hermetic bag each found these households were 4 % less likely to use storage chemicals, which this figure expected to increase if they used further hermetic bags to store the rest of their grain stocks.

For perishable crops, one study from Ghana (Abu et al., 2020) discussed how during export some varieties of mango (e.g., Kent and Keitt) can be shipped by sea while other varieties (e.g., Haden and

Palmer) need to be airfreighted due to their shorter shelf-life. Another study discussed environmental benefits of use of renewable energy and low energy cooling stores.

Other environmental aspects of PH interventions discussed by studies included pest management methods that reduced or avoided the use of synthetic chemical pesticides or fumigants, low efficacy pesticides leading to repeated applications of the chemicals, recycling of and reusability of hermetic bags alongside methods for prolonging their lifespan, locally available grain protectants (e.g., botanicals, diatomite), the need to alternate the use of grain protection methods with different modes of action as part of a resistance management strategy, the climate resilience of small grains compared to maize, energy sources and usage of different cool storage systems, and rechargeable batteries in equipment such as reapers.

4. Discussion

Overview of the current evidence base: This study updated the earlier systematic scoping review by Stathers et al. (2020) which investigated PHL reduction interventions for 22 crops across 57 countries of SSA and South Asia from the 1970s to January 2024. The identification of just 457 studies – 334 of which were from the 1970s to 2019 and 123 from October 2019 to January 2024 – highlights the limitations of this evidence-base, particularly as one country, India, accounted for 38.3 % of these studies (and 29.2% of all the studied interventions). It is notable that for 23 of the 57 countries, not a single study for any of the 22 focal food crops was identified since the records began in the 1970s. The synthesised findings of these studies of interventions for different PH activity stages and crops provide important opportunities for cross-learning between countries given the apparent array of evidence gaps in most countries.

Interventions for reducing PHLs in cereals, particularly maize, dominated, whereas vegetables and legumes have received much less attention. The rapidly increasing trend in the overall number of studies during the past two decades might be indicative of growing recognition of the need for PHL reduction. Most of the studies from the original review and this update review focused on the effect of a technology/ tool/ piece of equipment during farm-level storage. While interventions to reduce storage losses are crucial, a better understanding of losses during non-storage stages (e.g., harvesting, handling, packaging and transport, threshing/shelling, drying and at the market), and interventions that can reduce these losses is also needed. PHLs are the cumulative result of a sequence of actions (or inactions) and conditions along the value chain. While the update identified seven studies (six of them on maize, and one on maize, sorghum and groundnuts) on the effect of training in postharvest management and sometimes aflatoxin management, as well as combinations of training plus access to a bundle of technologies (such as plastic sheets for drying crops on, grain driers, moisture measurement, hermetic bags), the continued lack of studies on training, finance, infrastructure, policy and market interventions highlights the persisting need for more evidence on interventions beyond technology or handling practice changes.

Supporting PHL reduction by value chain actors beyond farmers: Given the rapid transformation of food systems in SSA and South Asia—linked to population growth, urbanization, changing dietary choices and climate variability, among other drivers—there is an urgent need for evidence on interventions that support other value-chain actors beyond farmers in reducing PHLs, and not only during the storage stage. For perishable crops, for example, this would require studies that include maturity assessment, harvest method, handling, cooling, packing/packaging, transportation, storage and drying or processing. However, greater understanding is first needed of what these other value chain actors, often viewed as the ‘hidden middle’ are already doing or not doing to reduce PHLs and why (Stathers et al., 2024; de Steenhuijsen, 2022). The anticipated increased purchasing of food, lengthening of supply chains, and the associated emissions contributions underscores the urgency of this evidence-need (Stathers et al., 2024; FAO, 2024)

Comparisons with existing PHL reduction practices: Most storage studies included a traditional practice or untreated control as a comparator. In reality, traditional practices may be more dynamic than researchers recognize (Ndegwa et al., 2016). As emphasized by Ng’ang’a et al. (2016), “*farmers, unlike scientists do not wait for 35 weeks to see their storage losses go up to 79.6 %*”. Lack of sufficient understanding by researchers of how farmers manage their traditional practices during the storage season may be biasing a realistic comparison between ‘improved’ practices and farmers’ traditional practices, with important implications for further use of these technologies. Additionally, there is limited published evidence on common-sense good practices, such as careful handling of perishable crops or of cleaning or disinfesting a grain store before use. Although one newly included study by Makinya et al. (2021) explores the importance of farm-level store hygiene practices for maize storage.

Evaluating and comparing interventions across multiple dimensions of PHL: A sound evaluation of PH interventions requires a more complete assessment of their efficacy in reducing losses in several of the multiple dimensions of both quantity and quality. A large number of different metrics are used by researchers to study loss (Supplementary Tables S4 and S5), and farmers and traders may use additional characteristics that have not been well studied. Future PHL reduction research, and the evidence syntheses that draw on it, would benefit from employing more systematic and uniform collection methods of a wider array of data, where resources and skills allow. It is also worth noting that some PH interventions, such as mechanized shellers or threshers, save farmers' time and reduce drudgery but may increase quality and/or quantity losses. This highlights the trade-offs which may surround PHL reduction interventions and the importance of understanding the socio-economic context within which they operate or are being explored.

In our original study, the data entry database's design allowed the extraction of a maximum of one quantity loss metric and one quality loss metric per intervention. However, a wide range of metrics are used to analyse postharvest quantity and quality losses in our focal crops, and so during this update review we entered up to three quantity loss and three quality loss metrics per intervention where such data had been presented in the study. For the 123 studies included in the update study, this enabled us to analyse and compare the efficacy of the interventions on the different kinds of postharvest loss that occur, although for the original 334 studies only one quantity and one quality loss metric were available in our dataset which limited comparisons. Inclusion of a wider range of loss metrics provides a more complete overview of the efficacy of different interventions, and we recommend this approach for any similar future studies.

Drawing robust conclusions on the technical efficacy of many of the interventions is difficult because there are relatively few studies of each intervention for each crop, and there is considerable heterogeneity as they vary in scale, duration, type of loss data collected, location and context. However, this is not unusual for evidence syntheses that bring together and synthesise findings from diverse studies.

Perishable produce has an additional challenge because storage temperature and duration have a very strong effect on storage and shelf life. Perishable produce continues to respire after harvest, and the respiration rate directly affects produce perishability. Each 10°C rise in temperature causes the rate of respiration to increase 2-5 times (Kader, 2011). Only the general conditions of storage (e.g., in a shaded area, in a building, or in evaporatively or mechanically cooled structures), and not the storage temperature, were recorded in most of the articles reviewed. Combined with the different storage durations and the genetic variation in varieties (in the case of citrus and leafy greens, even a distinct species), this complicates the interpretation. The variation in storage duration between studies further complicated comparisons for interventions on perishables. While for the dried cereal and legume grains, given the relatively long storage durations required to ensure stocks of staple foods between harvests, studies tend to take samples every month or two, we used a common smallholder grain storage duration of 6 months for cereals and 4.5 months for legumes to extract standardised data and support comparisons between studies.

Scale of studies on PHL reduction interventions: Many studies were excluded during screening because they used very small quantities of the crops, were conducted only in the laboratory or did not replicate the interventions. Studies that met the minimum size requirement of 20 kg per treatment for roots and tubers and 10 kg per treatment for fruits and vegetables could still end up being excluded, often because the key PHL metric, e.g., weight loss or decay incidence, was then conducted on just 5-10 individual produce items. For example, a study with 60 mangoes per treatment (> 10 kg/treatment) used only three mangoes from three replicates, i.e., nine fruit per evaluation date to measure quality, making the data extremely unreliable. Fruit-to-fruit firmness variation is high, and sample sizes should be greater. Holcroft (2022) recommends that four replicates of at least one marketable unit are assessed. For example, if tomatoes are sold in 10 kg cartons, then 10 kg would be a decent size for a replicate, and 4 x 10 kg boxes should be used for each treatment at each evaluation date. Holcroft (2022) also recommended using preliminary experiments with higher numbers of treatments and smaller replicates to eliminate low performing treatments. The experiment would then be repeated with less treatments, ideally a control and a treatment, and more replication. Typically, studies testing new treatments, e.g., waxes and coating agents, did not report on using preliminary testing to determine a suitable concentration range. However, there were exceptions, for example, Ali et al. (2023) and Ali et al. (2022). In addition, discussion on the need to scale up studies under real-world conditions before more widely promoting the interventions was extremely limited. Studies on pre-harvest aspects such as varietal or fertiliser effect on PHLs were excluded as the intervention did not occur postharvest.

Several studies did not acknowledge all the treatment details. For example, the additional cost and effect of prior fumigation on grain storage interventions was rarely recognized, nor the fact that in most countries it is illegal for fumigants to be used by anyone who is not an officially trained and certified fumigator. The concentrations and application rates of active ingredients of protectants were not always stated, even though these details are important for efficacy comparisons, as well as compliance with national product registration and safety regulations. Some grain storage trial durations were very short. The efficacy of the tested interventions may be different during the longer storage durations (six to ten months) required by many small-scale producers to ensure the availability of their staple grains between harvests and in response to increasingly unpredictable climate (Mvumi et al., 1995; Stathers et al., 2008; Waongo et al., 2013; Stathers et al., 2013; Gitonga et al., 2013; Abass et al., 2014; Affognon et al., 2015; Baoua et al., 2015). Such issues highlight opportunities to support improvements to PHL reduction research systems, methods, data analyses and interpretation. Recent initiatives and funders' forums set up to ensure value in medical research may offer prospects for cross-learning for other research fields (Glasziou et al., 2018).

Use of participatory research approaches: A large proportion (65%) of the 457 included studies involved only researchers without any participation from farmers or other community members. Their participation could have provided experiential learning opportunities and built ownership. Even if technically effective in researcher-managed trials, such interventions may not be as effective in real life and may not be acceptable to or affordable for farmers (Stathers et al., 2020; Mutungi et al., 2022a). In the 123 studies identified during the update review, a lower proportion (49 %) had involved only researchers, and among the 65 durable crop (cereal or legume) studies in the update review just 16 % involved only researchers. In general, far less of the research on perishable fruit and vegetable crops included in this overall review was conducted in 'field' trials (21 %) compared to for durable crops (51 %). Instead, most of the perishable crop research was conducted in laboratory/ on-station type trials, meaning there is limited understanding of the interventions tested for perishable crop PHL reduction under real-world conditions. Additionally, more data from multi-season and multi-location/site testing of interventions are required to provide a critical understanding of their replicability and degree of variation. While loosening the inclusion criteria would increase the number of studies, it would compromise the value and quality of evidence on which the synthesis was based.

Perishable crop PHL reduction trends: Technologies such as waxes and coatings have been widely evaluated on mango, citrus and tomato in the included studies, but not beyond on-station trials. While these technologies are used in large-scale commercial systems, particularly on citrus and tomato, they may be more difficult to adapt by small-scale producers. Most produce is washed before being waxed or coated. Washing is used to improve the cosmetic appearance and removes dirt or latex. However, experience in commercial conditions has demonstrated that this increases the risk of spreading decay organisms, e.g., fungal spores, and human pathogens, e.g., *E. coli* bacteria. Zagory (2013) stated that "*washing fresh produce is not an opportunity to clean it…it is an opportunity to contaminate it!*". Used carefully, wash water sanitisers can prevent cross-contamination, but they cannot completely clean produce (defined at a log five reduction in microbial load) (Zagory, 2013; Gombas et al., 2017). Formulations for coatings and waxes must work at ambient or warmer conditions without causing excessive modification of the internal atmospheres in the fruit. Anaerobic conditions (low oxygen and/or high carbon dioxide) can increase quantity and quality losses (Bai & Plotto, 2011).

The recent update of this review showed more testing of cold-rooms as opposed to evaporatively cooled structures. However, more substantial studies including cost-benefit and socio-economic analyses of building cold storage versus renting cold storage would be beneficial to address the gaps in knowledge and evaluate investment and operational costs. Just one study (Tadesse et al., 2022) in the recent update explored the impact of poor roads on perishable produce, although another interesting study (Diwakar et al., 2020) which did not meet the inclusion criteria studied the impact of a rope pulley system to smoothly and quickly transport fresh produce down from mountain-based small-scale producers in Nepal.

Storage protectants need to be registered and approved for use in the country of production, as well as being readily available and affordable. Registration costs limit the number of products available in the countries included in this study.

Durable crop PHL reduction trends: For cereal and legume crops, the update review found hermetic bags alone and in combination with other storage insect pest management methods have continued to be widely studied, the evidence-base on mechanised threshing/ shelling and harvesting and on solar energy drying has expanded and new evidence on postharvest training in combination with different bundles of technologies was reported on. These training studies provide opportunities to better understand and to disentangle the effects of training and of technologies which can be useful for informing policies and programmes (Brander et al., 2021).

Limitations of our review process: Although a separate quality assessment scoring exercise and score for each included study was not recorded, the review's inclusion criteria covered many of the elements in quality assessment tools that have been used for this literature. For example, an included study needed to contain original data that focused on loss reduction postharvest; that compared data for different interventions or data from before and after the use of an intervention, or between adopters and non-adopters; the intervention needed to have been tested at a specified scale with appropriate quantity criteria set in advance for each of the 22 crops; the method used in the comparison needed to be rigorous, appropriate and clearly explained to ensure sufficient details were presented to make an evidence-based decision about the interventions efficacy. Therefore, the degree of quality variation in the studies included in this review is likely to be smaller than in other reviews that have been more lenient in their inclusion criteria but then assessed some studies as "low quality". Such "low quality studies" would have been excluded in our review. Additionally, during data extraction the coding fields such as number of seasons or sites an intervention was studied at, whether work was done on-station or on-farm, how many people were involved in testing the intervention, the specific method used (e.g., direct, indirect) for assessing the loss levels, the range of different types of loss metrics studied (e.g., different types of quantitative and qualitative loss metrics), could be used as further quality assessment criteria. Suggestions for improving the quality of studies on PHL reduction interventions are discussed. Inclusion of a specific quality assessment scoring exercise of all included studies could add value to future reviews of PHL reduction interventions.

An earlier review of PHL studies in six African countries for seven commodity categories by Affognon et al. (2015) used methodological appropriateness for assessing the quality of the studies. They screened out articles with serious methodological weaknesses (e.g., studies needed to include actual data, use a credible methodology for data collection and analysis, specifically the use of an appropriate sampling technique, and of suitable statistical techniques during analysis, and where no actual data was collected they established whether sources of secondary data were accurately disclosed). Using these methodological needs each article was assigned an overall rating of suitability and only articles with satisfactory or higher ratings were selected. Our screening method only allowed inclusion of studies containing original data, which used a suitable experimental design and method, which were done at an appropriate scale, and where the data was clearly and correctly analysed and reported on.

A further limitation of our study was that the data extraction for each study was done by one of the postharvest experts only as opposed to both. The resources and timeframe available did not allow for dual independent data extraction. This study was to update the original review during which only one postharvest expert extracted the data per study. However, discussion between the postharvest experts during the data extraction process occurred to compare method and all the postharvest experts extracted data for a set of 10 studies at the beginning and then compared and discussed it to align practice.

Despite the systematic approach used and the recognition of the four principles (inclusive, rigorous, transparent and accessible) for synthesizing evidence for policymakers as identified by Donnelly et al. (2018), the present evidence-base is subject to non-publication bias, as results from less effective interventions may not be as widely shared. This practice reduces overall research efficiency by limiting the opportunities for shared learning about what does not work and why, which can result in repetition of studies of interventions that are ineffective, or unacceptable to target users. Furthermore, where there is no requirement for PhD or MSc theses or project reports to be registered in public databases, digital search strategies do not always identify these important sources of evidence.

Exploration beyond technical outcomes to understand the social, economic and environmental dimensions: Well-designed, multidisciplinary, participatory field studies that include objective measurements of technical efficacy dimensions of the PHL reduction interventions should also analyse the links between the use of interventions and reductions in different types of loss, and their social, economic and environmental outcomes. This will support better understanding for informing co-development of PHL reduction interventions – in their various forms, such as technologies, policies, training, infrastructure and combinations of these – which can support transitions to more sustainable, equitable and productive food systems. Understanding of these aspects could inform discussions on whether a significant proportion of the food loss and waste that occurs is an unaccounted and unintended trade-off of the use of production and productivity outcomes for measuring food system performance, as opposed to use of socio-economic, food security, nutrition and environmental outcomes (Snel, 2022).

Although only a limited number of our included studies explored social, economic or environmental outcomes of PHL interventions, there are other studies which have focused on these outcomes but as they did not also report the effect of an intervention on PHL they could not be included in our evidence-base. Taking hermetic storage as an example, a few studies have explored the gender dimensions. These include the impact of hermetic storage bag use on perceived stress and coping by pregnant women in small-scale farming households (Eichenauer et al., 2023), whether women benefit from metal silos (Farnworth et al., 2021), transforming gender relations through the use of hermetic technology (Nyanga et al., 2020), adoption of cowpea hermetic storage by women in West Africa (Ibro et al., 2014). Other studies (Lelea et al., 2022; Manda & Mvumi, 2008) have explored gendered PH roles. Food security outcomes have also been studied. For example, during the COVID-19 pandemic a study in Kenya by Huss et al. (2021) found receipt of five hermetic storage bags per household would have reduced the increased number of food-insecure people from 117,000 to 54,000 in the 30 days following COVID-19 restrictions in one Kenyan county alone. They state that this is of comparable magnitude to the effects of direct cash transfers to smallholder farmers reported by Banerjee et al. (2020), although the cost of the cash transfer interventions were substantially higher than the hermetic storage bags plus training which cost about USD 20 per household.

The willingness-to-pay (WTP) for hermetic bags has been explored in other studies (e.g., Channa et al., 2019; Schwab & Yu, 2022; Shukla et al., 2022), findings showed an increase in the WTP for the technology if credit is made available, or after gaining experience of using the hermetic bag for a year. Dijkink et al. (2022) found that for home consumption hermetic bags were only economical for storage durations of over 100 days, and for grain for sale it depended largely on the rate of seasonal price fluctuation. Grain prices fluctuate during the year in low-income countries and on average generally increase after harvest as food becomes scarcer which contributes to seasonal hunger (Gilbert et al., 2017; Dercon & Krishnan, 2000; Khandker, 2012; Kaminski et al., 2016) but also provides opportunities for farmers to store grain in order to sell it when the price rises. However, a recent analysis of 20 years of maize price data from retail markets in 30 African countries found the lean season price failed to rise above the harvest season price 16.3 % of the time on average in countries with a single maize season and between 15.9 % and 24.9 % on average in countries with two maize seasons (Cardell and Michelson, 2022). This highlights the further complexity for farmers in predicting returns to storage and PH management even where credit access is available. This issue is exemplified by a recent study (Channa et al., 2022) in Tanzania which reported that the estimated magnitude of the impact of an intervention which provided two hermetic storage bags, was attenuated as prices did not rise that year in the way they had in the previous 17 years where the average intraseasonal price rise had been 40% in December-February following harvest in June. They suggest this was possibly due to an export ban imposed at harvest to try and avoid a repeat of the 80 % price differential that had occurred between the previous year's harvest and subsequent lean season, and/or a bumper harvest in the neighbouring country. Despite the uncertainty caused by the lower maize prices during the intervention year, the partner offering farmers credit viewed hermetic bag storage of collateralised maize as lowering their risk, as if the grain needed to be repossessed it would still be good quality. The subsequent year the credit provider offered farmers credit collateralised with 200 kg of common beans stored in hermetic bags, as they viewed intervention in bean market prices as less likely.

Focusing on environmental outcomes, net greenhouse gas emissions of hermetic bag use were calculated by Dijkink et al. (2022). As reducing PHLs leaves more food available for consumption and sale while reducing emission intensity, it can contribute to decoupling trajectories of economic growth and GHG emissions (Galford et al., 2020). However, analysis of a set of USAID projects highlighted the context specific nature of this. While they found on average emissions reduced by 63% across the nine maize food loss and waste reduction intervention projects, this ranged widely from a reduction of 231% of emissions to an increase of 106% (Galford et al., 2020). A recent consultation worked with stakeholders in 10 Near East and North African countries in identifying PHL reduction technologies which they perceived to be environmentally-friendly as well as affordable, reliable and easy-to-use (FAO et al., 2024b). It is also important that the impacts of environmental regulations such as bans on plastic bags on PHLs are monitored over time and across different contexts.

Food safety dimensions of PHLs: Another important aspect of postharvest food loss is the degradation of food safety. Consumers in Kenya were found to generally prefer maize that they have grown themselves, due to perceptions of superior drying or storage practices and more careful sorting, and the absence of chemical additives (Hoffman and Gatobu, 2014; Hoffman et al., 2021). Farmers in Benin were found to be less likely to use storage insecticides on maize stored for home consumption than that which they intend to sell (Kadjo et al., 2020). The invisibility of food safety makes it both difficult for value chain actors to address food safety losses and limits their economic incentive to do so. But if correlated with more observable attributes of food quality, markets may penalise these, and consumers may be able to divert contaminated food to uses that reduce health risks or process it in ways that reduce the risk (Hoffman et al., 2021). For example, maize with no broken kernels contains roughly half the level of aflatoxin as maize in which over 10% of kernels have a damaged hull (Hoffman et al., 2021). If consumers were aware that maize with significant breakage in the outer layer of the grain is likely to be contaminated with aflatoxin it could increase consumers' attention to this attribute and reduce aflatoxin exposure significantly. Given the higher breakage rate of maize grains reported in some studies when it is mechanically versus manually shelled (e.g., 31.4% vs 10.5% (Geremew et al., 2023)), and the expected increase in use of mechanised threshing in many locations, greater awareness about the associated increased aflatoxin risks with broken grains is needed. This is important as findings suggest maize consumers are currently more likely to be sorting out discoloured grains than broken grains (Hoffman et al., 2021). Greater understanding of the complex economic, health and environmental trade-offs associated with reducing the different types of losses is required to support PHL reduction at scale.

Factors affecting the use of PHL reduction interventions: There is also a need to understand the factors that facilitate or constrain use of PHL reduction interventions. We reviewed the small body of literature which existed on this for our original review (Stathers et al., 2020), although much of it was focused on the adoption of relatively expensive interventions (Mwebaze et al., 2011; Bokusheva et al., 2012; Villane et al., 2012; Moussa et al., 2014; Kitinoja & Barrett, 2015; Mujuka et al., 2019). Cost, access, ease of use and reuse, cultural acceptability, one-time subsidies, willingness to pay, scale, awareness and demonstrations, and training are just some of the factors influencing the uptake of PHL reduction interventions along with technical efficacy (Compton et al., 1993; Baributsa et al., 2010; Adegbola et al., 2011; Kitinoja, 2013; Baributsa et al., 2014; Affognon et al., 2015; de Groote et al., 2016; Ricker-Gilbert & Jones, 2015; Jones et al., 2016; Ndegwa et al., 2016; Walker et al., 2018; Dijkink et al., 2019; Govereh et al., 2019; Omotilewa et al., 2019; Darfour & Rosentrater, 2020). Since our original review, a systematic literature review of the major barriers to adoption of improved postharvest technologies among smallholder farmers in sub-Saharan Africa and South Asia has been completed by Bisheko & Rejikumar (2023). Their review confirms key barriers were high cost, local unavailability and limited awareness about improved PH technologies, alongside limited information about adoption constraints pertaining to policy, regulations and behavioural aspects, and the dominance of technology type interventions for storage, particularly of maize in their dataset. Most of their evidence came from Nigeria, followed by Kenya and India and their recommendations include the need for future research into adoption barriers of PH interventions to widen its focus beyond hermetic technologies. A recent study in Tanzania on factors affecting adoption of grain PH technologies found labour issues for mechanised shelling, product quality and quantity concerns for drying tarpaulins and airtight storage, larger farm sizes, being in high production potential zones, and neighbours' use of technologies were drivers for adoption (Mutungi et al., 2023).

Key findings and gaps: Notwithstanding the still limited size of the evidence-base, the many critical gaps and the dominance of storage technologies in it, particularly those which have been tested on maize, the efficacy of a number of interventions in reducing PHLs was recognized. These were summarised in our original review and have not changed as a result of our updated review, which has strengthened the evidence on many of them (e.g., hermetic grain storage bags, mechanised shellers/threshers, solar energy driers, cold stores, storage protectants including waxes and coatings), and added a small but valuable body of evidence on the efficacy of postharvest and aflatoxin management training bundled with different interventions on grain weight loss, damage and aflatoxin incidence. An important study by Leavens et al. (2021) questions the existing knowledge around the sustainability of many interventions and longer-term impacts from development projects. Their study involving 2,000 farmers analyses the comparative efficacy of postharvest training with different bundled technologies on aflatoxin contamination in farmers grain two years after the end of the project, then contrasts these findings with those obtained during the project. Analysis of the efficacy of interventions with end users several years after interventions have received attention and promotion through public, private systems or projects can provide important learning concerning the durability and metamorphosing of interventions and the associated decisions and investments.

A summary of notable technically effective PHL reduction interventions and critical knowledge gaps in the evidence-base is presented in Table 17, followed by a set of policy and investment recommendations (Box 1). These are almost identical to those in the original review as although the evidence-base has expanded in the last four years, the expansion has predominantly added volume and depth to areas where there was existing evidence while the critical gaps remain.

Findings of this review can support future decision-making around PHL reduction research, development actions and investments by different stakeholders. A large number of different technology/tool/equipment type interventions which are technically effective in reducing PHLs in quantity and/ or quality were identified in the review. However, to support the real-world use of these and other PHL reduction interventions it is crucial to gain a deeper understanding of the social, economic and environmental outcomes and trade-offs alongside the technical outcomes. These can be explored through work by multi-disciplinary research teams in partnership with famers or other focal value chain actors (for example, traders, transporters, cool storage or threshing service providers) and stakeholders. There is a need for the evidence-base to be expanded to include a more diverse range of food systems actors, food crops and postharvest activity stages. There is a gap in the included evidence around the study of and efficacy of training, market linkage, farmer organisation, financial access, infrastructure, policy etc. interventions and combinations of them and when combined with technologies and/or handling practice changes. Work on these evidence gaps would support more informed decision-making, policy and investments for PHL reduction to contribute to transitions towards more sustainable, equitable and productive food systems.

Table 17 Summary of the PHL reduction interventions evidence-base for SSA and South Asia

<table>
<tr><th rowspan="2">Crop group</th><th colspan="2">Technically effective interventions</th><th rowspan="2">Critical gaps in the evidence-base</th></tr>
<tr><th>Technologies/ tools/ equipment</th><th>Handling practices</th></tr>
<tr><td>Cereals (maize, rice, sorghum, wheat)</td><td>Maize storage: in hermetic containers, or admixed with some synthetic chemical insecticides or diatomaceous earths (and combinations of these)

Wheat, rice, sorghum storage: in hermetic containers, underground pits, or admixed with some synthetic chemical insecticides, botanicals or diatomaceous earths

Wheat, rice harvesting: mechanised harvesters</td><td>Timely harvesting, protecting crop from direct ground contact while drying combined with postharvest and aflatoxin management training</td><td rowspan="5">• Interventions for loss reduction in the non-storage activity stages
• Evaluation of policy, training infrastructure, finance interventions on loss reduction
• Effect of sanitation, grain-cleaning, and timing of activities on subsequent losses
• Socio-economic, and environmental outcomes and trade-offs of uptake of different postharvest loss reduction interventions at any scale
• Factors facilitating and constraining the adoption and use of postharvest loss reduction interventions at different scales
• Stakeholder participation in the design and study of interventions to facilitate co-innovation and co-learning, and the need for more real-world scale on-farm participatory studies
• Standardised loss measurement metrics
• Consistency of intervention results confirmed through multi-season and multi-location studies</td></tr>
<tr><td>Legumes (bean, cowpea, chickpea, pigeon pea, groundnut)</td><td>Storage in hermetic containers, or admixed with synthetic chemicals, botanicals, diatomaceous earths or edible oil</td><td>Protecting crop from direct ground contact while drying; sorting to remove mouldy grains</td></tr>
<tr><td>Root and tubers (yam, cassava, potato, sweetpotato)</td><td>Use of improved storage containers, ventilated storage, evaporative cool storage, cold storage, sprout suppressants and some pesticides</td><td>Piecemeal harvesting, curing, sorting to remove damaged roots or tubers, avoidance of rough handling, use of maturity indices</td></tr>
<tr><td>Fruits (mango, banana, plantain, papaya, citrus)</td><td>Harvesting poles/pickers, use of improved packaging, waxing (alone or with fungicides or botanicals), hot-water treatments, evaporative cool storage, cold storage, ripening treatments, some fungicides</td><td>Use of maturity indices, gentle harvesting and handling, sorting to remove damaged fruits</td></tr>
<tr><td>Vegetables (cabbage, onion, tomato, leafy vegetable)</td><td>Use of improved packaging, evaporative cool storage, ventilated storage (onions), cold storage</td><td>Gentle handling, curing (onions)</td></tr>
</table>

The interventions for which sufficient evidence existed of their efficacy in reducing PHLs are listed for each crop group. These interventions were either of the technologies/tools/equipment type or of the handling practices type, and they predominantly focused on reducing losses during crop storage. Critical gaps identified in the evidence base for all crop groups are listed in the final column.

Box 1 Policy and practice investment recommendations

- Studies should be conducted to increase the available data on PHL reduction interventions, particularly for legumes, small grains, root and tuber crops, fruits, and vegetables. Notably effective PHL reduction interventions, along with critical gaps in the evidence-base, are presented in Table 17.
- Future studies should include the non-storage activities in the value chain and the key actors (such as farmers, traders, transporters and wholesalers), because to date the focus has been predominantly on tangible technical interventions to reduce losses during farmer-level storage.
- The limited evidence on PHL reduction interventions can be extrapolated to similar crops within each crop group, with participatory field-level studies to confirm and expand the evidence.
- The effects of training, finance, policy and infrastructure interventions on PHL reduction need to be studied to guide investments.
- More evidence is needed regarding verified socio-economic and environmental outcomes of PHL reduction interventions, because to date the focus has been on their technical efficacy and actual use will be determined by their acceptability, affordability, availability and efficacy.
- More evidence is needed on the efficacy of PHL reduction interventions, particularly when technologies are combined with interventions such as training, changes in handling practices, access to finance and policies.
- More follow-up is needed with participants of PHL reduction investments, because understanding and assessment of longer-term benefits and challenges, sustainability and cost-effectiveness of interventions is needed to guide investments.
- Future studies would benefit from collecting a wider array of data using uniform and more systematic methods to capture the quantitative, qualitative and socio-economic aspects of PHLs.
- For improved postharvest management and loss reduction, there is a need for:
    1. Greater efforts to raise the awareness of stakeholders of the ability to reduce losses and the benefits of doing so
    2. Recognition that all technologies have strengths and weaknesses and that due to the heterogeneity between households, agro-ecologies and crops, one-size-fits-all solutions are unlikely to be successful
    3. Technical solutions to be simultaneously promoted alongside good postharvest training and management to build understanding of why losses are occurring, how the technologies can best be used and the local costs and expected benefits of interventions
    4. More study of how national policies, financial access and infrastructure investments affect PHL reduction
    5. Implementation of policies that support quality-sensitive markets to provide incentives for PHL reduction
    6. Multi-stakeholder postharvest platforms or institutions to promote co-learning and co-innovation, support access to information, and support multi-location and multi-season studies with active participation of stakeholders along the commodity value chains
- Targeting of the aforementioned recommendations may be needed depending on limitations of financial resources and information, and whether the main objective for reducing PHLs is improved food security and nutrition or lower environmental impacts.

5. References

Note: References for the full list of studies included in the update review is shown in Supplementary Table S11, and for the full list of studies from the original review in Supplementary Table S12.

Abass, A. B., Ndunguru, G., Mamiro, P., Alenkhe, B., Mlingi, N., & Bekunda, M. (2014). Post-harvest food losses in a maize-based farming system of semi-arid savannah area of Tanzania. *Journal of Stored Products Research*, *57*, 49-57.

Abu M, Olympio N S, Darko J O. (2020). Effects of different storage temperature conditions on ripening quality and shelf life of mango (Mangifera indica) fruits in Ghana. *Journal of Horticulture and Postharvest Research,* 3, 245-255.

Adegbola, P. Y., Arouna, A. & Ahoyo, N. R. A. (2011). Analyse des facteurs affectant l'adoption des greniers améliorés pour le stockage du maïs au Sud-Bénin. Bull. Rech. Agron. Bénin 2, 43–50.

Affognon, H., Mutungi, C., Sanginga, P., Borgemeister, C. (2015). Unpacking postharvest losses in sub-Saharan Africa: a meta-analysis. World Dev. 66, 49–68.

AU (African Union) (2014), Malabo declaration on Accelerated Growth and Transformation for Shared Prosperity and Improved Livelihoods. 12pp.

AGRA. (2014). Establishing the status of post-harvest losses and storage for major staple crops in eleven African countries (Phase 2). AGRA: Nairobi, Kenya. Alliance for a Green Revolution in Africa (AGRA).

Ali, S., Anjum, M. A., Khan, A. S., Nawaz, A., Ejaz, S., Khaliq, G., Iqbal, S., Ullah, S., Ur Rehman, R.N., Ali, M., Saleem, M. S. (2022). Carboxymethyl cellulose coating delays ripening of harvested mango fruits by regulating softening enzymes activities. Food Chemistry, 380, 131804.

Ali, S., Khan, A. S., Nawaz, A., Naz, S., Ejaz, S., Shah, A. A., & Haider, M. W. (2023). The combined application of Arabic gum coating and γ-aminobutyric acid mitigates chilling injury and maintains eating quality of 'Kinnow'mandarin fruits. *International Journal of Biological Macromolecules*, *236*, 123966.

Anitha, S., Tsusaka, T. W., Njoroge, S. M., Kumwenda, N., Kachulu, L., Maruwo, J., Machinjiri, N., Botha, R., Msere, H.W., Masumba, J., Tavares, A., Heinrich, G.M., Siambi, M., Okori, P. (2019). Knowledge, attitude and practice of Malawian farmers on pre-and post-harvest crop management to mitigate aflatoxin contamination in groundnut, maize and sorghum—implication for behavioral change. *Toxins*, *11*(12), 716.

Aparna, P., Babu, G.P., Chaithanya, B.H. (2020). Assesment of IIHR mango harvester for drudgery reduction over conventional practice. Asian Journal of Home Science 15, 273-275 (2020).

Asemu, A. M., Habtu, N. G., Subramanyam, B., Delele, M. A., Kalsa, K. K., Alavi, S. (2020). Effects of grain drying methods on postharvest insect infestation and physicochemical characteristics of maize grain. *Journal of Food Process Engineering*, *43*(7), e13423.

Bai, J. & Plotto, A. (2011). Coatings for fresh fruits and vegetables. In: Edible Coatings and Films to Improve Food Quality. Eds. Baldwin, E.A., Hagenmaier, R. & Bai, J. 2nd ed. CRC Press, Boca Raton. https://doi.org/10.1201/b11082 Campbell Library. (n.d.). Retrieved March 6, 2019, from https://campbellcollaboration.org/library/campbell-systematic-review-templates.html

Banerjee, A., Faye, M., Krueger, A., Niehaus, P., & Suri, T. (2020). Effects of a Universal Basic Income during the pandemic. *Innovations for Poverty Action Working Paper*.

Baoua, I. B., Amadou, L., Abdourahmane, M., Bakoye, O., Baributsa, D., Murdock, L. L. (2015). Grain storage and insect pests of stored grain in rural Niger. *Journal of Stored Products Research*, *64*, 8-12.

Baoua, I.B., Amadou, L., Bakoye, O., Baributsa, D., Murdock, L.L. (2016). Triple bagging hermetic technology for post-harvest preservation of paddy rice *Oryza sativa* L. in the Sahel of West Africa. *Journal of Stored Products Research* 68, 73-79.

Baributsa, D., Lowenberg-DeBoer, J. & Djibo, A. K. (2010). Cell phone videos for communicating hermetic cowpea storage skills. In Proc. 5th World Cowpea Research Conference (eds Boukar, O. et al.) (IITA, 2010).

Baributsa, D., Abdoulaye, T., Lowenberg-DeBoer, J., Dabiré, C., Moussa, B., Coulibaly, O., & Baoua, I. (2014). Market building for post-harvest technology through large-scale extension efforts. *Journal of Stored Products Research*, *58*, 59-66.

Bauchet J, Prieto S, Ricker-Gilbert J. (2021). Improved Drying and Storage Practices that Reduce Aflatoxins in Stored Maize: Experimental Evidence from Smallholders in SenegaUEL codes American Journal of Agricultural Economics 103, 296-316.

Basavarajappa, D.N., Chinnappa, B., Sannathimmappa, H.G. (2013). Farm machinery: the economics of paddy harvesting. *International Journal of Agricultural Engineering* 6, 240-243.

Bisheko, M.J., Rejikumar, G., (2023). Major barriers to adoption of improved postharvest technologies among smallholder farmers in sub-Saharan Africa and South Asia: A systematic literature review. World Development Sustainability, 2, 100070.

Bokusheva, R. et al. (2012). Factors determining the adoption and impact of a postharvest storage technology. Food Secur. 4, 279–293.

Bold T, Ghisolfi S, Nsonzi F, Svensson J. Market Access and Quality Upgrading: Evidence from Four Field Experiments American Economic Review 112, 2518-2552 (2022).

Borgemeister, C., Adda, C., Djomamou, B., Degbey, P., Agbaka, A., Djossou, F., Meikle, W.G., Markham, R.H. (1994). The effect of maize cob selection and the impact of field infestation on stored maize losses by the larger grain borer (*Prostephanus truncatus* (Horn) Col., Bostrichidae) and associated storage pests. Proceedings of the 6th International Working Conference on Stored-Product Protection, 906-909.

Borgemeister, C., Adda, C., Setamou, M., Hell, K., Djomamou, B., Markham, R.H., Cardwell, K.F. (1998). Timing of harvest in maize: effects on post harvest losses due to insects and fungi in central Benin, with particular reference to (*Prostephanus truncatus* (Horn) (Coleoptera: Bostrichidae). *Agriculture, Ecosystems and Environment* 69, 233-242.

Bosomtwe, A., Danso, J.K., Osekre, E.A., Opit, G.P., Mbata, G.N., Armstrong, P.R., Arthur, F.H., Campbell, J.F., Manu, N., McNeill, S.G., Akowuah, J.O. (2019). Effectiveness of the solar biomass hybrid dryer for drying and disinfestation of maize. *Journal of Stored Products Research* 83, 66-72.

Brander, M., Bernauer, T., Huss, M. (2021). Improved on-farm storage reduces seasonal food insecurity of smallholder farmer households–Evidence from a randomized control trial in Tanzania. *Food Policy*, *98*, 101891.

CAADP (2024). CAADP Strategy and Action Plan: 2026-2035. Building Resilient Agri-Food Systems in Africa. 68pp.

Cardell, L., & Michelson, H. (2023). Price risk and small farmer maize storage in Sub-Saharan Africa: New insights into a long-standing puzzle. *American Journal of Agricultural Economics*, *105*(3), 737-759.

Castelein, R. B., Broeze, J. J., Kok, M. M., Axmann, H. H., Guo, X. X., Soethoudt, J. H. (2022). Mechanization in rice farming reduces greenhouse gas emissions, food losses, and constitutes a positive business case for smallholder farmers–Results from a controlled experiment in Nigeria. *Cleaner Engineering and Technology*, *8*, 100487.

Caswell, G.H. (1975). The development and extension of nonchemical control techniques for stored cowpeas in Nigeria. Proceedings of the First International Working Conference on Stored-Product Entomology, Savannah, Georgia, USA, October 7-11, 1974, 63-67.

Channa, H., Chen, A. Z., Pina, P., Ricker-Gilbert, J., Stein, D. (2019). What drives smallholder farmers' willingness to pay for a new farm technology? Evidence from an experimental auction in Kenya. *Food policy*, *85*, 64-71.

Chegere, M.J. (2018). Post-harvest losses reduction by small-scale maize farmers: the role of handling practices. *Food Policy* 77, 103-115.

Chegere, M. J., Lokina, R., Mwakaje, A. G. (2020). The impact of hermetic storage bag supply and training on food security in Tanzania. *Food Security,* 12, 1299-1316.

Chegere, M. J., Eggert, H., & Söderbom, M. (2022). The effects of storage technology and training on postharvest losses, practices, and sales: evidence from small-scale farms in Tanzania. *Economic Development and Cultural Change*, *70*(2), 729-761.

Chigoverah, A.A., Mvumi, B.M., Muchechemera, C., Dator, J.V. (2018). Are GrainPro Cocoons™ an effective alternative to conventional phosphine fumigation in large-scale control of stored-maize insect pests? *Journal of Pest Science* 91, 1393-1406 (2018).

Compton, J. A. F., Tyler, P. S., Hindmarsh, P. S., Golob, P., Boxall, R. A., Haines, C. P. (1993). Reducing losses in small farm grain storage in the tropics. Trop. Sci. 33, 283–318.

Cowling, N. (2024). Average electricity prices in Tanzania 2015-2020 by sector. Statistica. https://www.statista.com/statistics/1296782/average-electricity-prices-in-tanzania-by-sector/

Dambolachepa, H.B., Muthomi, J.W., Mutitu, E.W., Njoroge, S.M. (2019). Effects of postharvest handling practices on quality of groundnuts and aflatoxin contamination. *Novel Research in Microbiology Journal*, *3*(3), 396-414.

Darfour, B. & Rosentrater, K. A. (2020). Cost assessment of five different maize grain handling techniques to reduce postharvest losses from insect contamination. Insects 11, 50.

de Groote, H., Narrod, C., Kimenju, S. C., Bett, C., Scott, R. P., Tiongco, M. M., Gitonga, Z. M. (2016). Measuring rural consumers' willingness to pay for quality labels using experimental auctions: the case of aflatoxin-free maize in Kenya. *Agricultural Economics*, *47*(1), 33-45.

de Steenhuijsen Piters, B. (2022). Chapter 12. Mobilising information midstream businesses. In: A journey into the world's food systems in search of losses, waste and ways to solve them. (Eds: Stroosnijder, S., Hetterscheid, B., Castelein, B.). Wageningen University and Research. 79pp. https://edepot.wur.nl/571395

Dercon, S., Krishnan, P. (2000). Vulnerability, seasonality and poverty in Ethiopia. *The Journal of Development Studies*, *36*(6), 25-53.

Dijkink, B., Broeze, J., Axmann, H. & Vollebregt, M. (2019). Hermetic Bag for the Storage of Maize: Economic Perspective in Different Sub-Saharan African Countries, Food Security and Greenhouse Gas Emissions Working Paper No. 291 (CGIAR Research Program on Climate Change, Agriculture and Food Security).

Dijkink, B., Broeze, J., & Vollebregt, M. (2022). Hermetic bags for the storage of maize: perspectives on economics, food security and greenhouse gas emissions in different sub-saharan African Countries. *Frontiers in Sustainable Food Systems*, *6*, 767089.

Diwakar, K.C., Maraseni, T., Jamir, C., Magar, R.T., Tuladhar, F. (2020). Effectiveness of gravity goods ropeways in market participation of smallholder farmers in uplands. Transportation, *47*, 1393-1414.

Donnelly, C. A., Boyd, I., Campbell, P., Craig, C., Vallance, P., Walport, M., Whitty, C.J.M., Woods, E., Wormald, C. (2018). Four principles to make evidence synthesis more useful for policy. *Nature*, 558, 361–364.

Eichenauer, H., Huss, M., Brander, M., Bernauer, T., Ehlert, U. (2023). Effects of improved on-farm crop storage on perceived stress and perceived coping in pregnant women—Evidence from a cluster-randomized controlled trial in Kenya. *Plos one*, *18*(7), e0288446.

FAO, (2019). The State of Food and Agriculture 2019: Moving Forward on Food Loss and Waste Reduction http://www.fao.org/3/ca6030en/ca6030en.pdf

FAO, (2024). Greenhouse gas emissions from agrifood systems – Global, regional and country trends, 2000–2022. FAOSTAT Analytical Brief Series, No. 94. Rome. https://openknowledge.fao.org/handle/20.500.14283/cd3167en

FAO, WFP, IFAD. (2019a). Food loss analysis: causes and solutions – Case studies on sorghum, maize and cowpea in Burkina Faso. 242 pp. Rome.

FAO, WFP and IFAD. (2019b). Food loss analysis: causes and solutions - Case studies on maize and rice in the Democratic Republic of Congo. 192pp. Rome.

FAO, IFAD, UNICEF, WFP, WHO. (2017). The State of Food Security and Nutrition in the World 2017: Building resilience for Peace and Food Security http://www.fao.org/3/a-i7695e.pdf

FAO, IFAD, UNICEF, WFP, WHO. (2024a). The State of Food Security and Nutrition in the World 2024 – Financing to end hunger, food insecurity and malnutrition in all its forms. Rome. https://doi.org/10.4060/cd1254en Accessed: 20/11/2024

FAO, IFAD, IsDB. (2024b). Mapping affordable and transferable climate-smart technologies for smallholder farmers. Cairo. https://doi.org/10.4060/cd2799en

Farnworth, C.R., Badstule, L.B., de Groote, H., Gitonga, Z. (2021). Do metal grain silos benefit women in Kenya, Malawi, Zambia and Zimbabwe? *Journal of Stored Products Research*, *93*, 101734.

Galford, G. L., Peña, O., Sullivan, A. K., Nash, J., Gurwick, N., Pirolli, G., Richards, M., White, J., Wollenberg, E. (2020). Agricultural development addresses food loss and waste while reducing greenhouse gas emissions. *Science of The Total Environment*, *699*, 134318.

Gbenou E S, Adegbola Y P, Hessavi P M, Zossou S R. C, Biaou G. (2021). On-farm assessment of maize storage and conservation technologies in the central and northern republic of Benin *Agriculture*, *11*(1), 32.

Geremew M, Molla A, Gabbiye N, Harvey J, Mahroof R, Abay F. (2023). Effects of threshing and storage conditions on post-harvest insect infestation and physical characteristics of maize grain *Journal of Stored Products Research*, *103*, 102131.

Getachew M, Fentahun M, Fikadu C. (2022). Economic analysis of threshing and shelling machine service provision to reduce post-harvest loss in Ethiopia African *Journal of Food, Agriculture, Nutrition and Development,* 22(6), 20701-20720.

Gilbert, C. L., Christiaensen, L., Kaminski, J. (2017). Food price seasonality in Africa: Measurement and extent. *Food Policy*, *67*, 119-132.

Giles, P.H., Ashman, F. (1971). A study of pre-harvest infestation of maize by *Sitophilus zeamais* Motsch. (Coleoptera, Curculionidae) in the Kenya highlands. *Journal of Stored Products Research,* 7, 69-83.

Gitonga, Z. M., de Groote, H., Kassie, M. & Tefera, T. (2013). Impact of metal silos on households' maize storage, storage losses and food security: an application of a propensity score matching. *Food Policy,* 43, 44–55.

Gitonga, Z., de Groote, H., Tefera, T. (2015). Metal silo grain storage technology and household food security in Kenya. *Journal of Development and Agricultural Economics* 7, 222-230.

Glasziou, P., Chalmers, I. (2018). Research waste is still a scandal—an essay by Paul Glasziou and Iain Chalmers. BMJ 363, k4645.

Gombas D, Luo Y, Brennan J, Shergill G, Petran R, Walsh R, Hau H, Khurana K, Zomorodi B, Rosen J, Varley R, Deng K. (2017). Guidelines To Validate Control of Cross-Contamination during Washing of Fresh-Cut Leafy Vegetables. *Journal of Food Protection,* 80(2):312-330. doi: 10.4315/0362-028X.JFP-16-258. PMID: 28221982.

Govereh, J., Muchetu, R. G., Mvumi, B. M. & Chuma, T. (2019). Analysis of distribution systems for supply of synthetic grain protectants to maize smallholder farmers in Zimbabwe: implications for hermetic grain storage bag distribution. *Journal of Stored Products Research,* 84, 101520.

Gustavsson, J., Cedeberg, C., Sonesson, U., van Otterdijk, R., and Meybeck, A. (2011). Global food losses and food waste: extent, causes and prevention. FAO, Rome. 37pp.

Hodges, R., Bernard, M., Rembold, F., (2014). APHLIS – Postharvest cereal losses in Sub-Saharan Africa, their estimation, assessment and reduction. JRC Technical Reports, European Commission. 177pp.

Hoffmann, V., & Gatobu, K. M. (2014). Growing their own: Unobservable quality and the value of self-provisioning. *Journal of Development Economics*, *106*, 168-178.

Hoffmann, V., Mutiga, S. K., Harvey, J. W., Nelson, R. J., & Milgroom, M. G. (2021). Observability of food safety losses in maize: evidence from Kenya. *Food Policy*, *98*, 101895.

Holcroft, D. 2022. Design improvements for applied postharvest studies. PEF White Paper 22-01. https://postharvest.org/wp-content/uploads/2023/12/PEF_White_Paper_22-01_Holcroft-Experimental-Designs.pdf

Holst, N., Meikle, W.G., Markham, R.H. (2000). Grain injury models for *Prostephanus truncatus* (Coleoptera: Bostrichidae) and *Sitophilus zeamais* (Coleoptera: Curculionidae) in rural maize stores in West Africa. *J. Econ. Entomol.* **93**, 1338–1346.

Htwe N M, Sarathchandra S R, Sluydts V, Nugaliyadde L, Singleton G R, Jacob J. (2021). Small mammal communities, associated damage to rice and damage prevention in smallholder rice storage facilities in Sri Lanka. *Crop Protection* 145, 105638.

Huss, M., Brander, M., Kassie, M., Ehlert, U., & Bernauer, T. (2021). Improved storage mitigates vulnerability to food-supply shocks in smallholder agriculture during the COVID-19 pandemic. *Global Food Security*, *28*, 100468.

Ibro, G., Sorgho, M. C., Idris, A. A., Moussa, B., Baributsa, D., & Lowenberg-DeBoer, J. (2014). Adoption of cowpea hermetic storage by women in Nigeria, Niger and Burkina Faso. *Journal of Stored Products Research*, *58*, 87-96.

Jones, M., Alexander, C., Olynk Widmar, N., Ricker-Gilbert, J. & Lowenberg-DeBoer, J. M. (2016). Do insect and mold damage affect maize prices in Africa? Evidence from Malawi. Mod. Econ. 7, 1168–1185.

Jonsson, L.O., Kashweka, K. (1987). Relationship between drying, harvesting and storage losses, production and consumption of maize for a rural household in Zambia. Proceedings of FAO-SIDA Seminar on Increased Food Production through Lowcost Food Crops Technology. 2-17 March 1987. Harare, Zimbabwe, 475-482.

Kaaya, A.N., Warren, H.L., Kyamanywa, S., Kyamuhangire, W. (2005). The effect of delayed harvest on moisture content, insect damage, moulds and aflatoxin contamination of maize in Mayuge district of Uganda. *Journal of the Science of Food and Agriculture* 85, 2595-2599.

Kader, A.A. (2011). Postharvest biology and technology: An overview (Ch. 4). In: AA Kader (ed). Postharvest Technology of Horticultural Crops. 3rd Ed. University of California Agriculture and Natural Resources. Publication 3529.

Kadjo, D., Ricker-Gilbert, J., Shively, G., & Abdoulaye, T. (2020). Food safety and adverse selection in rural maize markets. *Journal of Agricultural Economics*, *71*(2), 412-438.

Kalsa, K. K., Subramanyam, B., Demisse, G., Worku, A., Workneh, S., & Gabbiye, N. (2020). On-farm performance and assessment of farmers' perceptions of hermetic bags for farm-stored wheat and maize in northwestern Ethiopia. In *Advances of Science and Technology: 7th EAI International Conference, ICAST 2019, Bahir Dar, Ethiopia, August 2–4, 2019, Proceedings 7* (pp. 98-109). Springer International Publishing.

Kamala, A., Kimanya, M., Haesaert, G., Tiisekwa, B., Madege, R., Degraeve, S., Cyprian, C., De Meulenaer, B. (2016). Local post-harvest practices associated with aflatoxin and fumonisin contamination of maize in three agro ecological zones of Tanzania. *Food Additives and Contaminants* A 33, 551-559.

Kaminski, J., Christiaensen, L., & Gilbert, C. L. (2016). Seasonality in local food markets and consumption: Evidence from Tanzania. *Oxford Economic Papers*, *68*(3), 736-757.

Khandker, S. R. (2012). Seasonality of income and poverty in Bangladesh. *Journal of Development Economics*, *97*(2), 244-256.

Kitinoja, L, Hell, K., Chahine-Tsouvalakis, H., Brondy, A. (2016). Reducing On-Farm Food Losses in the OIC Member Countries. Standing Committee for Economic and Social Cooperation (COMCEC) for the Organization of Islamic Cooperation – Ankara.

Kitinoja, L. & Barrett, D. M. (2015). Extension of small-scale postharvest horticulture technologies—a model training and services centre. Agriculture 5, 441–455.

Kitinoja, L. (2013). Innovative small-scale postharvest technologies for reducing losses in horticultural crops. Ethiopian J. Appl. Sci. Technol. 1, 9–15.

Kitinoja, L., Dandago, M.A. (2017). Maize CSAM Studies Report for the ABA World Bank Postharvest Project Rwanda, Nigeria and India Combined Report. WBG / Agribusiness Associates Inc.

Kitinoja, L., Odeyemi, O. (2017). Tomato CSAM Studies Report for the ABA World Bank Postharvest Project Rwanda, Nigeria and India Combined Report. WBG / Agribusiness Associates Inc.

Kitinoja, L., Tokala, V.Y., Brondy, A., (2018). A review of global postharvest loss assessments in plant-based food crops: Recent findings and measurement gaps. Journal of Postharvest Technology, 06(4): 1-15.

Kaaya, A. N., & Kyamuhangire, W. (2010). Drying maize using biomass-heated natural convection dryer improves grain quality during storage. *Journal of Applied Sciences*, *11*, 967-974.

Leavens, L., Bauchet, J., Ricker-Gilbert, J. (2021). After the project is over: measuring longer-term impacts of a food safety intervention in Senegal. *World Development*, *141*, 105414.

Lelea, M.A., Garbaba, C.A., Guluma, A., Hensel, O. (2022). Gendering post-harvest loss research: responsibilities of women and men to manage maize after harvest in southwestern Ethiopia. Food Security, 14(4), 951-963.

Loada, M.S., Ouedraogo, S.J., Diop, A.D., Sangare, S.K., Ouedraogo, S.N., (2015). Pertes post-recolte et securite alimentair dans les pays du Sahel et de l'Afrique de l'ouest: cas du Burkina Faso, du Ghana et du Senegal: Rapport de synthese. CILSS INSAH Report No. 27. 170pp.

Mahrouf, A.R.M., Rafeek, M.I.M. (2003). Mechanization of paddy harvesting: the economic perspective. *Annals of the Sri Lanka Department of Agriculture* 5, 161-172.

Makinya, K. J., Wagacha, J. M., Odhiambo, J. A., Likhayo, P., Edoh-Ognakossan, K., Tefera, T., Abass, A., Mutungi, C. M. (2021). The importance of store hygiene for reducing post-harvest losses in smallholder farmers' stores: Evidence from a maize-based farming system in Kenya. *Journal of Stored Products Research*, *90*, 101757.

Manda, J., Mvumi, B. M. (2010). Gender relations in household grain storage management and marketing: The case of Binga District, Zimbabwe. *Agriculture and Human Values*, *27*(1), 85-103.

Manu, N., Osekre, E.A., Opit, G.P., Arthur, F.H., Mbata, G.N., Armstrong, P.R., Danso, J.K., McNeill, S.G., Campbell, J. (2019). Moisture content, insect pests and mycotoxin levels of maize on farms in Tamale environs in the northern region of Ghana. *Journal of Stored Products Research* 83, 153-160.

Mdangi, M., Mulungu, L.S., Massawe, A.W., Eiseb, S.J., Tutjavi, V., Kirsten, F., Mahlaba, T., Malebane, P., von Maltitz, E., Monadjem, A., Dlamini, N., Makundi, R.H., Belmain, S.R. (2013). Assessment of rodent damage to stored maize (*Zea mays* L.) on smallholder farms in Tanzania. *International Journal of Pest Management* 59, 55-62.

Mishra, D., Satapathy, S. (2021). Technology adoption to reduce the harvesting losses and wastes in agriculture. *Clean Technologies and Environmental Policy* 23, 1947-1963.

Moussa, B., Abdoulaye, T., Coulibaly, O., Baributsa, D., Lowenberg-DeBoer, J. (2014). Adoption of on-farm hermetic storage for cowpea in West and Central Africa in 2012. *Journal of Stored Products Research*, *58*, 77-86.

Mwebaze, P., Mugisha, J. (2011). Adoption, utilisation and economic impacts of improved post-harvest technologies in maize production in Kapchorwa District, Uganda. *International Journal of Postharvest Technology and Innovation*, *2*(3), 301-327.

Mujuka, E., Mburu, J., Ogutu, A. & Ambuko, J. (2019). Returns to investment in postharvest loss reduction technologies among mango farmers in Embu County, Kenya. Food Energy Secur. 00, e195.

Mutambuki, K., Ngatia, C.M., Mbugua, J.N. (2010). Post-harvest technology transfer to reduce on farm grain losses in Kitui district, Kenya. Proceedings of the 10th International Working Conference on Stored Product Protection, Estoril, Portugal, 27 June-2 July, 2010, 984-990 (2010).

Mutungi, C, Abass, A, Fischer, G, Kotu, B. (2022b). Improved technologies for reducing post-harvest losses. Sustainable agricultural intensification: a handbook for practitioners in East and Southern Africa , 91-105.

Mutungi, C, Muthoni, F, Bekunda, M, Gaspar, A, Kabula, E, Abass, A. (2019). Physical quality of maize grain harvested and stored by smallholder farmers in the Northern highlands of Tanzania: effects of harvesting and pre-storage handling practices in two marginally contrasting agro-locations. *Journal of Stored Products Research,* 84, 101517.

Mutungi, C., Tungu, J., Amri, J., Gaspar, A., & Abass, A. (2022a). Nutritional benefits of improved post-harvest handling practices for maize and common beans in Northern Tanzania: A quantitative farm-level assessment. *Journal of Stored Products Research*, *95*, 101918.

Mutungi, C., Manda, J., Feleke, S., Abass, A., Bekunda, M., Hoschle-Zeledon, I., & Fischer, G. (2023). Adoption and impacts of improved post-harvest technologies on food security and welfare of maize-farming households in Tanzania: a comparative assessment. *Food Security*, *15*(4), 1007-1023.

Mvumi, B. M., Giga, D. P. & Chiuswa, D. V. (1995). The maize (Zea mays L.) post-production practices of smallholder farmers in Zimbabwe: findings from surveys. J. Appl. Sci. South. Afr. 1, 115–130.

Mwebaze, P. & Mugisha, J. (2011). Adoption, utilisation and economic impacts of improved post-harvest technologies in maize production in Kapchorwa district, Uganda. Int. J. Postharvest Technol. Innov. 2, 301–327.

Nahdy, S., Agona, A. (1992). Studies on the control of the bean bruchids *Acanthoscelides obtectus* (Say) and *Zabrotes subfasciatus* (Boheman) (Coleoptera: Bruchidae) in the East African region. CIAT African workshop series (CIAT).

Nanda, S.K., Vishwakarma, R.K., Bathla, H.V.L, Rai, A., and Chandra, P. (2012). Harvest and Post-Harvest Losses of Major Crops and Livestock Produce in India. ICAR, Ludhiana. Peters, M.D.J., Godfrey, C., McInerney, P., Baldini-Soares, C., Khalil, H., Parker, D. (2017). Chapter 11: Scoping reviews. In: Aromataris E, Munn Z (Editors). Joanna Briggs Institute Reviewer's Manual. The Joanna Briggs Institute. Available from https://reviewersmanual.joannabriggs.org/

Nath, B. C., Paul, S., Huda, M. D., Hossen, M. A., Bhuiyan, M. G. K., Islam, A. S. (2022). Combine Harvester: Small Machine Solves Big Rice Harvesting Problem of Bangladesh. *Agricultural Sciences*, *13*(2), 201-220.

Ndegwa, M. K., de Groote, H., Gitonga, Z. M. Bruce, A. Y. (2016). Effectiveness and economics of hermetic bags for maize storage: results of a randomized controlled trial in Kenya. Crop Prot. 90, 17–26.

Ng'ang'a, J., Mutungi, C., Imathiu, S. M. & Affognon, H. (2016). Low permeability triple-layer plastic bags prevent losses of maize caused by insect in rural on-farm stores. Food Secur. 8, 621–633.

Nsubuga D, Kabenge I, Zziwa A, Kiggundu N, Wanyama J, Banadda N. (2020). Performance evaluation and optimization of the maize shelling operation of the multi-purpose farm vehicle Agricultural Engineering International: CIGR Journal 22, 174-183.

Nwaubani, S. I., Otitodun, G. O., Ajao, S. K., Opit, G. P., Ala, A. A., Omobowale, M. O., Ogwumike, J. C., Abel, G.I., Ogundare, M.O., Braimah, J.A., Gbenga, B.S., Olenloa, A.E., Kolayemi, O.R., McNeill, S.G., Ileleji, K.E. (2020). Assessing efficacies of insect pest management methods for stored bagged maize preservation in storehouses located in Nigerian markets. *Journal of Stored Products Research*, *86*, 101566.

Nyanga, L. K., Chahwanda, S., Nigaru, M., Dembedza, M. P., Manema, L., & Ambali, C. P. (2020). Transforming gender relations through the use of hermetic technology. IDRC, CULTIAF 4pp. https://idl-bnc-idrc.dspacedirect.org/server/api/core/bitstreams/e2d7acf1-f1fb-445a-8c6e-e92d553c7e4e/content

Nyarko, S.K., Akyereko, Y.G., Akowuah, J.O., Wireko-Manu, F.D. (2021). Comparative studies on grain quality and pesticide residues in maize stored in hermetic and polypropylene storage bags. *Agriculture*, *11*(8), 772.

Odeyemi, O. M., Kitinoja, L., Dubey, N., Musanase, S., & Gill, G. S. (2022). Preliminary study on improved postharvest practices for tomato loss reduction in Nigeria, Rwanda and India. *African Journal of Science, Technology, Innovation and Development*, *14*(6), 1500-1505.

Omotilewa, O.J., Ricker-Gilbert, J., Ainembabazi, J.H., Shively, G.E. (2018). Does improved storage technology promote modern input use and food security? Evidence from a randomized trial in Uganda. *Journal of Development Economics* 135, 176-198.

Omotilewa, O. J., Ricker-Gilbert, J. Ainembabazi, J. H. (2019). Subsidies for agricultural technology adoption: evidence from a randomised experiment with improved grain storage bags in Uganda. Am. J. Agric. Econ. 101, 753–772.

Opoku, B., Osekre, E. A., Opit, G., Bosomtwe, A., Bingham, G. V. (2023). Evaluation of hermetic storage bags for the preservation of yellow maize in poultry farms in Dormaa Ahenkro, Ghana. *Insects*, *14*(2), 141.

Otitodun, G., Ala, A., Nwaubani, S., Omobowale, M., Ogundare, M., Abel, G., Ajao, K., Braimah, J., Olenloa, A., Kolayemi, O., Ogwumike, J., Opit, G., Ileleji, K., McNeill, S.G. (2018). Evaluation of five storage technologies to preserve quality composition of maize in Nigerian markets. Proceedings of the 12th International Working Conference on Stored Product Protection (IWCSPP), Berlin, Germany, 7-11 October, 2018, 900-909.

Palanisami, A., Manickam, A., Neelakantan, S. Fungal flora and aflatoxin production in relation to post-harvest practices in groundnut. *Madras Agricultural Journal* 77, 26-31 (1990).

Pretari A, Hoffmann V, Tian L. (2019). Post-harvest practices for aflatoxin control: evidence from Kenya Journal of stored products research 82, 31-39.

Ricker-Gilbert, J. Jones, M. (2015). Does storage technology affect adoption of improved maize varieties in Africa? Insights from Malawi's input subsidy program. *Food Policy*, 50, 92–100.

Roy, K. (2005). Postharvest handling of mango and banana to minimize losses: a case study in Bangladesh. Proceedings of the International Conference on Postharvest Technology and Quality Management in Arid Tropics, Sultanate of Oman, 31 January-2 February 2005, 83-87 (2005).

Sachs, J., & WHO (Eds.). (2001). Macroeconomics and health: Investing in health for economic development; Report of the Commission on Macroeconomics and Health. Geneva: World Health Organization.

Saran, S., Roy, S. K., & Kitinoja, L. (2012). Appropriate postharvest technologies for improving market access and incomes for small horticultural farmers in Sub-Saharan Africa and South Asia. Part 2: Field trial results and identification of research needs for selected crops. Acta Horticulturae, 934(2), 41-52.

Savita, S.M., Srinivasappa, K.N., Suresha, S.V., Vasanthi, B.G., Anand, G.M., Sujith, G.M. (2010). Drudgery reduction using scientifically designed mango harvesters over conventional methods. *Journal of Dairying, Foods and Home Sciences* 29, 222-226.

Schwab, B., & Yu, J. (2024). Guaranteed storage? Risk and credit constraints in the demand for postharvest technology. *Oxford Economic Papers*, gpae027.

Shukla, P., Pullabhotla, H. K., & Baylis, K. (2023). The economics of reducing food losses: Experimental evidence from improved storage technology in India. *Food Policy*, *117*, 102442.

Snel, H. (2022). Chapter 11. Beyond technology: key ingredients for FLW reduction strategies.

In: A journey into the world's food systems in search of losses, waste and ways to solve them. (Eds: Stroosnijder, S., Hetterscheid, B., Castelein, B.). Wageningen University and Research. 79pp. https://edepot.wur.nl/571395

Srinivasappa, K.N., Savita, S.M., Rajanna, N. (2015). Evaluation on efficacy of farmer friendly mango harvesters. *Mysore Journal of Agricultural Sciences* 49, 484-491.

Stathers, T.E., Riwa, W., Mvumi, B.M., Mosha, R., Kitandu, L., Mngara, K., Kaoneka, B., Morris, M. (2008). Do diatomaceous earths have potential as grain protectants for small-holder farmers in sub-Saharan Africa? the case of Tanzania. *Crop Protection* 27, 44-70.

Stathers, T., Holcroft, D., Kitinoja, L., Mvumi, B. M., English, A., Omotilewa, O., Kocher, M., Ault, J., Torero, M. (2020). A scoping review of interventions for crop postharvest loss reduction in sub-Saharan Africa and South Asia. Nature Sustainability, 3(10), 821-835. https://www.nature.com/articles/s41893-020-00622-1

Stathers, T., Onumah, G., Lamboll, R. (2024). Postharvest loss reduction interventions in sub-Saharan Africa: experiences and perspectives. 127pp. Natural Resources Institute (NRI), Chatham, UK.

Stathers, T., Lamboll, R. Mvumi, B. M. (2013). Postharvest agriculture in changing climates: its importance to African smallholder farmers. Food Secur. 5, 361–392.

Subedi, P.P., Bhattarai, S.P. (1995). The effects of a low cost cellar structure upon the storage of mandarin oranges in the sub-tropics. Postharvest physiology, pathology and technologies for horticultural commodities: recent advances. Proceedings of an International Symposium held at Agadir, Morocco, 16-21 January 1994, 137-151.

Tadesse, E. E., Assaye, H., Delele, M. A., Fanta, S. W., Huluka, D. F., Alemayehu, M., Alemayehu G, Adgo, E. (2022). Assessing tomato postharvest loss through the supply chain using load tracking technique in Northwest Ethiopia. *International Journal of Postharvest Technology and Innovation*, *8*(4), 360-381.

Tola Y B, Muleta O D, Hofacker W C. (2020). Low-cost modified-atmosphere hermetic storage structures to reduce storage losses of maize (Zea mays L.) cobs and sorghum (Sorghum bicolor L.) heads Journal of the Science of Food and Agriculture 100, 1132-1141.

Turner, P.C., Sylla, A., Gong, Y.Y., Diallo, M.S., Sutcliffe, A.E., Hall, A.J., Wild, C.P. (2005). Reduction in exposure to carcinogenic aflatoxins by postharvest intervention measures in west Africa: a community-based intervention study. *Lancet (British edition)* 365, 1950-1956.

United Nations Department of Economic and Social Affairs (UNDESA). (2022). World population prospects 2022. Accessed: 26/01/2024

United Nations, (2015). United Nations Sustainable Development Goals https://sustainabledevelopment.un.org/topics/sustainabledevelopmentgoals#

Vandercasteelen J, Christiaensen L. (2020). Breaking down silos - on post-harvest loss interventions in Tanzania. (No. 653201). KU Leuven, Faculty of Economics and Business (FEB), LICOS-Centre for Institutions and Economic Performance. 43pp.

Van Dijk, M., Morley, T., Rau, M. L., & Saghai, Y. (2021). A meta-analysis of projected global food demand and population at risk of hunger for the period 2010–2050. Nature Food, 2(7), 494-501.

Villane, B. R. T., Shongwe, M. I., Motsa, N. M. & Shongwe, V. D. (2012). Adoption of postharvest technologies used by smallholder farmers in Swaziland. Afr. J. Agric. Res. 7, 4983–4995.

Walker, S., Jaime, R., Kagot, V. & Probst, C. Comparative effects of hermetic and traditional storage devices on maize grain: mycotoxin development, insect infestation and grain quality. J. Stored Prod. Res. 77, 34–44 (2018).

Waongo, A., Yamkoulga, M., Dabire-Binso, C. L., Ba, M. N. & Sanon, A. (2013). Conservation post-recolte des cereals en zone sud-soudanienne du Burkina Faso: perception paysanne et evaluation des stocks. Int. J. Biol. Chem. Sci. 7, 1157–1167.

Wauters, P., Naziri, D., Turinawe, A., Akello, R., & Parker, M. L. (2022). Economic analysis of alternative ware potato storage technologies in Uganda. *American Journal of Potato Research*, *99*(3), 217-228.

World Bank, NRI and FAO. (2011), Missing Food: the case of postharvest grain losses in sub-Saharan Africa. The World Bank, Washington, US, Report No: 60371-AFR. 116pp. http://siteresources.worldbank.org/INTARD/Resources/MissingFoods10_web.pdf Accessed 20/11/2024

World Bank. (2019). World Bank Country and Lending Groups. Accessed 30 May 2019: https://datahelpdesk.worldbank.org/knowledgebase/articles/906519

World Food Logistics Organization (WFLO). 2010. Identification of Appropriate Postharvest Technologies for Improving Market Access and Incomes for Small Horticultural Farmers in Sub-Saharan Africa and South Asia. Bill and Melinda Gates Foundation, World Food Logistics Organization Grant No. 52198.

Worku, A. F., Kalsa, K. K., Abera, M., Tenagashaw, M. W., Habtu, N. G. (2022). Evaluation of various maize storage techniques on total aflatoxins prevalence and nutrient preservation. *Journal of Stored Products Research*, *95*, 101913.

Wu, F., Khlangwiset, P. (2010). Health economic impacts and cost-effectiveness of aflatoxin-reduction strategies in Africa: case studies in biocontrol and postharvest interventions. Food Addit. Contam. 27 (4), 496e509. https://doi.org/10.1080/19440040903437865.

Xu, Y., Doel, A., Watson, S., Routledge, M.N., Elliett, C.T., Moore, S.E., Gong, Y. (2017). Study of an Educational Hand Sorting Intervention for Reducing Aflatoxin B in Groundnuts in Rural Gambia. *Journal of Food Protection* 80, 44-49.

Zade, V.R., Babhulkar, V.P., Paslawar, A.N., Pardey, V.P. (2005). Extension of storage life of fungicidal waxol dip treated Nagpur mandarin under ambient conditions. *Annals of Plant Physiology* 19, 150-153.

Zagory, D. (2013). Wash water sanitation and validation. Center for Produce Safety seminar. https://fpsc-anz.com/wp-content/uploads/2013/02/devon-zagory-ppt-washwaterworkshopcps-jan-2013.pdf