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The adoption and acceleration of post-harvest solutions and grain protection in smallholder sub-Saharan Africa to mitigate food security

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Qakathekile Khumalo

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Scholar contact details

Qakathekile Khumalo

Organisation: Syngenta

Address: 4 Stephanie Avenue Marlborough,

Harare, Zimbabwe

Phone: +263775008111

Email: khumaloq@yahoo.com

NUFFIELD ZIMBABWE Contact Details:

Nuffield Zimbabwe

Mobile: +263 772 296 060

Email: nuffieldzimbabwe@gmail.com

Executive summary

Post-harvest losses remain a serious threat to efforts that ensure food security in sub-Saharan Africa, currently resulting in 30 – 40% of the grain harvest being lost each year, estimated to cost as much as $4 billion annually. Smallholder farmers, who make up 80% of the agricultural producers in sub-Saharan Africa, suffer limited crop preservations, inappropriate storage facilities, pest infestations, and suboptimal handling. This comprehensive analysis evaluates the performance of various grain protection technologies and develops strategies to expand post-harvest and grain protection solutions across the region. Both traditional and modern storage methods were appraised in this report using systematic analysis of observed data, which showed that conventional storage leads to 20 – 40% losses while modern hermetic technologies can reduce these to less than 1% with proper use. It recognises critical impediments to adoption, such as high initial investment, skill gaps, and market entry restriction while highlighting successful interventions that achieved 65 – 80% adoption in areas with strong support. The study provides a strategic approach to scale up sustainable solutions with a focus on mainstreaming traditional knowledge with modern technology, climate-resilient solutions, and digital innovation. Recommendations include the potential for collaborative government, private sector, research institution, and farmer action to accelerate implementation and increase impact.

This analysis offers lessons to advancing age-old global concerns on food security and agricultural sustainability in sub-Saharan Africa, by signalling pragmatic steps for minimising post-harvest losses, enhancing farmers' income and solidifying regional food systems. The findings suggest a need for integrated measures cutting across technical, economic and social aspects and the need for ensuring environment-safe and climate-resilient measures.

Keywords: Post-harvest losses, food security, smallholder farmers, grain storage, sub-Saharan Africa, pest management, hermetic storage, technology adoption, agricultural sustainability, climate resilience.

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Foreword

My name is Qakathekile Khumalo (Khums), and I currently lead the Syngenta Vegetable Seeds Commercial Unit for Africa South. Operating from Harare, Zimbabwe, I have accumulated over 18 years of experience across diverse agricultural sectors in sub-Saharan Africa, including maize and vegetable seeds, crop protection, commercial export horticulture, and row crop farming.

Throughout my career, driven by a deep commitment to sustainable crop production, I have witnessed the formidable challenges confronting smallholder farmers across our region. A particularly troubling pattern has emerged: despite farmers' tireless efforts to cultivate their crops, substantial portions of their harvests are lost to post-harvest deterioration and inadequate grain protection. This paradox – where food security remains elusive even when production succeeds – has become impossible to overlook.

These field observations, gathered across sub-Saharan Africa, compelled me to focus my Nuffield Scholarship research on: ***The adoption and acceleration of post-harvest solutions and grain protection in smallholder sub-Saharan Africa to mitigate food insecurity***. I recognised that achieving food security requires a paradigm shift beyond production metrics alone; it demands a comprehensive approach that safeguards what has already been grown.

The Nuffield Scholarship provided an exceptional platform to examine global best practices, study innovative solutions implemented in other regions, and build networks with agricultural leaders worldwide – all aimed at identifying practical, scalable interventions for smallholder farmers in sub-Saharan Africa.

I hold a master's degree in plant sciences from Lincoln University, New Zealand. Beyond my professional pursuits in agricultural development, I am an enthusiastic birder and enjoy exploring the outdoors with my friends and family.

Table 1. Travel itinerary

Travel date	Location	Visits/contacts
International GFP travels		
May 22 – 25, 2023	Singapore	• GFP opening • ANZ Bank meeting • University of Singapore
May 26 – June 1, 2023	Darwin - Kununurra	• Humpty Doo Barramundi aquaculture • NT Gov Biosecurity & Animal welfare • Berrimah live export & quarantine facility • Oasis Farms with 2021 Scholar Fritz Bolten
June 2 – 8, 2023	Qatar	• WIP
May 9 – 15, 2023	Netherlands	• Flower auction • Aeres University • Rabobank • Ter Laak Orchids
June 16 – 23, 2023	Norway	• Norges Bondelag (Hilde) Norwegian Farmers Union • Fruktgarden AS – Norway's Largest Orchard with Lars Petter Blikom • NIBIO, research institute
Local data collection travels		
Week 1 November 23 – 27, 2024	Nyanga	Mr. Muchenje (Farmer) Agritex Officer; Mr. A. Kazonyei +263773896081
Week 2 November 30 – Dec 4, 2024	Checheche	Mr. Masamba (Farmer) Agritex Officer; Mr. E. Chigaro +263775700905
Week 2 November 30 – Dec 4, 2024	Goromonzi	Mrs. I. Makamba (Farmer) +263733600888

Week 2 November 30 – Dec 4, 2024	Masvingo	Mr. I. Kinjera (Farmer) Agritex Officer; Mr. Dakarai +263773908046
Week 3 December 7 – 11, 2024	Chipinge	Mr. Musinake (Farmer) Agritex Officer; Mr. Mbekwa +263775654858

Acknowledgments

This report would not have been possible without the generous support and guidance of numerous individuals and organisations who believed in this research journey.

I am deeply grateful to Syngenta for their steadfast support as both my sponsor and employer. My Nuffield journey began under the guidance of Given Mudenda in Crop Protection and concluded under the leadership of Gerard Eysink in Vegetable Seeds. Their dedication to driving agricultural innovation and their investment in my professional growth through the Nuffield Scholarship has been pivotal in enabling this study.

Special thanks to Alistair Mckenzie (Maguires) and Fritz Bolten for their sponsorship and belief in the value of this research. Your support has enabled me to pursue insights that will contribute meaningfully to agricultural advancement.

To Driptech, the Henson Family, Reichstein Foundation, Nuffield Zimbabwe, and all Nuffield sponsors – thank you for the extraordinary opportunity to travel the world and network with like-minded scholars. This experience has not only broadened my perspective but has reinforced my commitment to developing Zimbabwean and global agriculture. The Nuffield International mantra of lifelong learning and global collaboration will continue to guide my work for years to come.

I am deeply indebted to Trevor Gifford, my Nuffield Zimbabwe supervisor, for his guidance, mentorship, and steadfast support throughout this journey. Your insights have been invaluable.

I must acknowledge the pioneering work of Dr. P. Chinwada, whose extensive and groundbreaking research on storage pests of grain in sub-Saharan Africa has laid a critical foundation for this field. His decades-long commitment to yield preservation and sustainable smallholder maize production has been instrumental in shaping our understanding of post-harvest challenges. This study builds upon the legacy of his tireless efforts to safeguard food security in the region.

My sincere appreciation goes to Trevor Chingonzo and Kudzi Mupotsa my Syngenta crop protection development colleagues for the meticulous data collection and research that formed the foundation of this study. Your contribution has been essential to the integrity of this work.

To Joe Mkandla, thank you for your thorough revisions and invaluable insights. Your expertise and attention to detail have significantly enhanced the quality of this report. Kuda Mugwagwa, Sam Muturi and Rob Davy (my fellow Zimbabwe 2023 Nuffield Scholars) – if I complained one more time about running behind with my write-up or submission, I probably said it one too many times. Thank you for the encouragement and positive reinforcement that kept me going.

To my parents and siblings Mzi and Makhu – thank you for always believing in me and for instilling values of perseverance and curiosity that have driven this journey. Your constant encouragement and faith in my abilities have been a source of strength throughout my career and this research endeavour.

Finally, and most importantly, to my wife Vari and daughter Unathi – thank you for your patience, understanding, and the precious family time sacrificed during this journey. Your edits, out-of-the-box suggestions, and thoughtful contributions have enriched this work immeasurably. This achievement is as much yours as it is mine.

Abbreviations

Abbreviation	Meaning
$	US Dollar
AATF	African Agricultural Technology Foundation
AGD	Actellic Gold Dust
APHLIS	African Post-Harvest Losses Information System
AREX	Agricultural Research and Extension (Zimbabwe)
CIMMYT	International Maize and Wheat Improvement Centre
DR&SS	Department of Research and Specialist Services (Zimbabwe)
FAO	Food and Agriculture Organization
GDP	Gross Domestic Product
IFPRI	International Food Policy Research Institute
IGPC	International Grain Protection Consortium
IT	Information Technology
LGB	Larger Grain Borer
MT	Metric Ton(s) / Metric Tonne(s)
PACA	Partnership for Aflatoxin Control in Africa
PH3	Phosphine gas
PICS	Purdue Improved Crop Storage
Ppb	Parts per billion
Ppm	Parts per million
RH	Relative Humidity
ROI	Return on Investment
SAGPI	Southern African Grain Protection Institute (inferred)
SSA	sub-Saharan Africa
ZARI	Zimbabwe Agricultural Research Institute
ZGPI	Zimbabwe Grain Protection Institute
ZGPRI	Zimbabwe Grain Protection Research Institute

Objectives

This report aims to:

1. Determine the level of post-harvest losses in sub-Saharan Africa.

2. Assess currently available post-harvest options and adoption rates.

3. Identify factors hampering the adoption of technology among the smallholder farmers.

4. Recommend actions to promote dissemination of grain protection technologies.

Introduction

Background and context

Sub-Saharan Africa is characterised by widespread food insecurity with 230 million chronically undernourished people. Although agricultural productivity has increased in some areas, post-harvest losses remain a significant bottleneck to food security. Sub-Saharan Africa loses 20 – 30% of cereals and as much as 50% of post-harvest perishables produce according to estimates by the FAO. These losses are due to:

- Inadequate storage facilities.
- Insect and rodent attacks.
- Mold and aflatoxin infections.
- Improper drying and handling.

Smallholder farmers, the source of 80% of Africa's food, are bearing the brunt, creating poverty and malnutrition.

Methodology

Maize grain

Following two subsequent seasons of agricultural challenges in Zimbabwe due to severe drought, successful experimental trials of hybrid white maize SC 555 were carried out in the 2024/25 maize growing season. SC 555 was selected for the 2024/25 storage trials in Zimbabwe primarily due to its proven drought tolerance, following the severe drought of 2023. SC 555 is a medium-maturing hybrid offering uniform size, good husk cover and consistent grain characteristics ideal for standardised storage experiments. Its widespread adoption among local smallholder farmers across Zimbabwe makes it commercially relevant and practical for trials and experiments of this nature. The variety's balanced agronomic traits – particularly its adaptability to water-stressed environments and standard moisture content properties, made it optimal for comparing five distinct storage interventions under authentic farming conditions.

After harvest, the grain was carefully winnowed to remove chaff and foreign matter in advance of treatment. The experimental design had three replicates per farm structure, with each replicate undergoing fourteen grain storage treatments encompassing traditional mud/thatch structures serving as local control, woven polypropylene bags for conventional storage, modern stores, and hermetic stores. The study also included various chemical protectants: Actellic Gold Dust, Actellic Super (containing Pirimiphos-methyl and Permethrin), Shumba Super (Fenitrothion and Deltamethrin, Ngwena Yedura (Deltamethrin and Fenitrothion), Chikwapuro (Malathion), Phosphine tablets (Aluminium Phosphide), Skana Super (Pirimiphos-methyl and Deltamethrin: traditional mud/thatch structures) (local control, traditional storage method); woven polypropylene bags (conventional storage); modern stores (modern storage); hermetic stores (hermetic storage), and Actellic Gold Dust grain protectant (chemical prophylactic treatment). This systematic method allowed for extensive comparison of storage effectiveness with different methods in an actual smallholder farmer setting.

Insects

In sub-Saharan Africa, losses attributed to storage pests are a debilitating problem for economic and food security, with recorded losses varying significantly from one place to another. In Tanzania, in particular regions such as Morogoro and Dodoma, the loss of stored maize within six months after storage has been estimated at 25 – 40%. In

Kenya, 20 – 30% average loss is recorded with the eastern and western regions being hotspots – this translates into annual economic losses of more than $100 million.

In Nigeria, the largest maize producing country in Africa, post-harvest losses may be as high as 50% at the farmer level due to traditional storage, especially in the north where the storage environment may be suboptimal. Malawi has recorded annual losses of 15 – 25% on average, whilst Uganda loses 30 – 40%. In Ghana, Larger Grain Borer alone can contribute up to 70% in weight loss within five months of storage under heavily infested conditions. Zimbabwe and Zambia have been reported to lose 20 – 30% each year in communal farming areas. In Ethiopia, losses of 20 – 45% have been recorded in major maize producing regions such as Oromia and Amhara. The economics are enormous, with the World Bank estimating that post-harvest losses in sub-Saharan Africa are running at $4 billion annually for cereals alone, with storage pests a major reason for that loss. These losses are intensified under elevated humidity and temperature conditions where humidity values in stored grain can rise beyond the safe limit during the rainy season.

Figure 1. Maize Weevil (*Sitophilus zeamais*)

Figure 2. Lesser Grain Borer (*Rhyzopertha dominica*)

Figure 3. Red Flour Beetle (*Tribolium castaneum*)

Figure 4. Larger Grain Borer (*Prostephanus truncatus*)

According to multiple research studies spanning over a decade, including important early work by Omondi *et al*. (2021), these highly destructive storage pests have increasingly become the subject of pest management interventions due to both their wide distribution and their ability to cause significant damage to stored maize, which continues to be a major food staple throughout sub-Saharan Africa. The collective research underscores the critical importance of developing effective control strategies against these pests, as their impact directly threatens regional food security and economic stability.

Microbial spoilage (aflatoxins Aspergillus spp.)

Mycotoxin contamination in sub-Saharan Africa is a major public health and economic issue and the prevalence found in different areas has been reported. In Kenya, assays have revealed that aflatoxin levels above regulatory limits are found in 25 – 60% of maize tested, with prevalence rates as high as 48,000 ppb in the hotspots in the eastern and coastal regions compared to the allowable limits of 10 ppb. Rukwa and Mbeya regions are hard hit where the content of storage maize contaminated ranges between 18 and 45%. Nigeria is a major agricultural producer, with contamination levels of 20 – 60% reported in various agroecological zones and annual economic losses are $200 million from rejected exports only. In Uganda, 20 – 45% of stored maize samples have been found to be above the permissible level of aflatoxin concentration, especially in the eastern and northern parts of the country.

Figure 5. Microbial spoilage on maize

Malawi has contamination levels in the range of 30 – 45% in its principal crop storage facilities, and 40 – 80% of the samples exceed safe levels for the high-risk period in Mozambique. Contamination trends differed by region in Ethiopia, with 15 – 40% of stored grain infested, mainly in lowland locations. There's a big economic cost to these, with the Partnership for Aflatoxin Control in Africa (PACA) of the African Union putting the annual value of rejected agricultural export at $670 million. The World Bank also indicates that 40% of the total economic impact of foodborne diseases in Africa is due to mycotoxins where aflatoxins contribute substantially. Areas of high risk are usually associated in climates with <800 mm annual rainfall and average temperatures between 22 – 35°C, which are conducive for the growth of Aspergillus

Traditional grain storage methods

Mud/thatch granaries

Conventional storage structures such as mud/thatch granaries, although culturally acceptable and less expensive, are ineffective in preventing regular storage threats. There are estimates of 20 – 30% post-harvest losses in sub-Saharan Africa (FAO (2022) of total grain produced due to lack of storage facilities. Research by Tefera *et al.* (2021) observed that the conventional mud/thatch granaries are highly susceptible to moisture penetration, resulting in higher grain moisture favouring mould infestation and aflatoxin contamination in maize. International Maize and Wheat Improvement Center (CIMMYT, 2023) reports that traditional storage structures are frequently poorly ventilated, and often also lack a moisture barrier, providing an environment conducive for poor storage pests, for example the Sit*ophilus zeamais* (maize weevil) and *Prostephanus truncatus* (larger grain borer). These results are consistent with large-scale assessments by Mvumi and Stathers (2020) in Zimbabwe, Malawi, and Tanzania, of losses of 25 – 40% in local traditional storage structures for up to six months of storage.

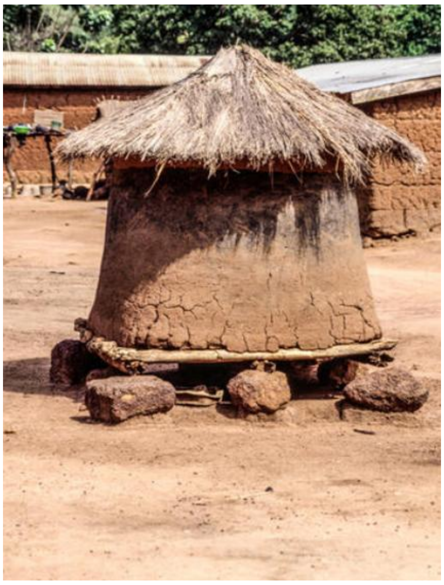

Figure 6. Mud/thatch granary

Woven sacks

Woven polypropylene bags, despite being used extensively in sub-Saharan Africa due to their low cost and easy transport, have inherent weaknesses as grain storage containers. Observations have indicated that when grains are kept in woven sacks, which are handled continuously, they encounter different abrasive surfaces (Karkee & Manandhar, 2011). The stored grains are exposed to several potential hazards, leading to losses of 15 – 25% (APHLIS, 2023). In Kenya and Tanzania, Kimenju and De Groote (2021) found that polypropylene bags are the most vulnerable to penetration by pests, with *Sitophilus* species infestations observed after only two to three months in storage.

These bags provide little barrier for moisture migration, which can cause moisture content variations in the grain and encourage mould growth and mycotoxin production (World Food Programme Storage Assessment Report, 2022). Research by Ndegwa *et al.* (2023) in four sub-Saharan Africa countries found that farmers with only plain old sacks lost 18.7% in eight months to rodents alone, and losses of up to 30% to moisture deterioration and quality. The economic loss due to post-harvest storage related losses through woven sacks has been estimated at about $500 – $800 per household per year resulting in a significant loss of income and food security for the farmers (IFPRI, 2022).

Figure 7. Woven sacks

Modern storage methods

Hermetic storage (PICS bags, metal silos)

Hermetic storage systems are a promising solution for the reduction of post-harvest losses of maize in sub-Saharan Africa, addressing some of the limitations with traditional storage methods. Hermetic bags have been shown to decrease post-harvest losses from the regular 20 – 30% in developing countries, by more than half in places such as Nicaragua and Honduras, to less than 1% when properly used, according to a study by PICS (Purdue Improved Crop Storage) Global (2023). Studies conducted by Baributsa & Njoroge (2022) in six sub-Saharan Africa countries showed that hermetic technologies such as triple layer PICS bags and metal silos successfully protect against main storage pests through oxygen deprivation of mainly, *Prostephanus truncatus* and *Sitophilus zeamais*. Hermetic storage can be used to maintain grain moisture content at safe levels (less than 13%) for as long as 12 months, thereby reducing aflatoxin contamination (CIMMYT, 2023).

Economic analysis by the World Bank's Ag Results Initiative (2021) showed that while hermetic bags are initially costlier than traditional storage methods ($2 – $5 per bag), they offer a return on investment of 150 – 300% after only one storage season, owing to reduced losses and improved grain quality. Nonetheless, there are still challenges to adoption, as reported by Walker *et al.* (2023) who identified the low availability, higher initial investment cost, and lack of proper training in the use of hermetic technologies as primary impediments to smallholder farmers in several countries.

Figure 8. Hermetic storage

Grain protectant chemical treatments

In Zimbabwe, the ten chemical treatments listed and discussed below are officially registered for controlling storage pests, specifically weevils and larger grain borers in stored grain. These protectants, consisting of various active ingredients, are specifically formulated to provide effective pest management solutions for stored grain protection in Zimbabwe's agricultural sector.

Registered grain protectant products for weevils and larger grain borer control in Zimbabwe

1. Actellic Gold Dust (Pirimiphos-methyl + Thiamethoxam)
2. Shumba Super (Fenitrothion + Deltamethrin)
3. Ngwena Yedura (Deltamethrin + Fenitrothion)
4. Chikwapuro (Malathion)
5. Phosphine tablets (Aluminum Phosphide)
6. Skana Super (Pirimiphos-methyl + Deltamethrin)

Actellic Gold Dust (AGD)

Figure 9. Actellic Gold Dust (AGD)

In sub-Saharan Africa, particularly for maize storage, Actellic Gold Dust (pirimiphos-methyl + thiamethoxam) has become common in protecting chemicals against stored grain pests. According to the results of a dual-active formulation study conducted by Syngenta Crop Protection (2022), broad-spectrum control of major storage pests is achieved on average for up to 12 months. Properly applied at doses of 50 g per 90 kg of grain, this formulation has remarkable long-term appeal and is now preferred over other inferior products. A comprehensive field study by Mutambuki *et al.* (2023) in Kenya, Tanzania, and Uganda found that the product provided 95 – 98% control (efficacy) against primary storage pests, such as *Sitophilus zeamais, Prostephanus truncatus*, and *Sitotroga cerealella.* According to the African Agricultural Technology Foundation (AATF, 2022), when Actellic Gold Dust is applied properly, it reduces post-harvest losses from 25 – 30% to less than 5% during long-term storage. Despite higher initial costs compared to traditional storage methods ($0.40 – $0.50 per bag), the use of Actellic Gold Dust storage solutions results in a net return of some 1,200 – 1,400%. However, research conducted by Nganga *et al.* (2021) pointed to concerns regarding methods of application. When inadequately mixed or given the wrong dose, effectiveness was reduced significantly.

Shumba Super

Figure 10. Shumba Super

Shumba Super is a dual-active formulation combining Fenitrothion and Deltamethrin and is applied at a recommended rate of 50 g per 90 kg of grain. Recent research demonstrates its efficacy in controlling major storage pests for periods extending to eight months under optimal storage conditions. Comprehensive research done by Chikosha *et al*. (2023) across Zimbabwe, Mozambique, and Zambia demonstrated 88 – 92% efficacy against primary storage pests particular *Sitophilus* species and *Prostephanus truncatus*.

The Zimbabwe Grain Protection Research Institute (ZGPRI, 2023) reports that proper application of Shumba Super can reduce post-harvest losses from 30% to approximately 8 – 10% during medium-term storage. Economic analysis indicates that despite its moderate cost ($0.30 – $0.40 per bag), the product delivers a return on investment of 700 – 900%.

Moyo *et al*. (2022) however, identified several critical factors affecting performance including ambient temperature impacts on residual activity, moisture content of stored grain, application technique significance as well as storage structure conditions.

Ngwena Yedura

Figure 11. Ngwena yedura

Ngwena Yedura is a synergistic combination of Deltamethrin and Fenitrothion. This binary formulation has demonstrated remarkable efficacy in protecting stored grain against major storage pests, as evidenced Moyo *et al.* (2023), who state that when applied at the recommended rates of 50 g per 90 kg of grain, Ngwena Yedura maintains effective pest control for six to eight months under optimal storage conditions. Their research documented impressive mortality rates of 92 – 95% against *Sitophilus zeamais* within 72 hours of exposure, alongside substantial control of other primary storage pests including *Prostephanus truncatus*, *Tribolium castaneum*, and *Sitotroga cerealella.*

Economic analyses conducted by the Zimbabwe Grain Protection Institute (ZGPI, 2023) have revealed compelling cost-benefit ratios associated with Ngwena Yedura application. The study demonstrated that proper implementation of this protection strategy can reduce post-harvest losses from approximately 30% to 8 – 10%. Despite an initial investment requirement of $0.30 – $0.40 per 90 kg bag, the return on investment ranges from 800 – 1,000%, representing a significant economic advantage for farmers.

Chigumira *et al.* (2022) and the Department of Research and Specialist Services (DR&SS, 2023) recommended that successful implementation of Ngwena Yedura requires careful attention to several critical factors. These include maintaining appropriate environmental conditions during storage, monitoring initial grain moisture content, following proper mixing methodology, and ensuring storage structure integrity. They emphasised that product efficacy is heavily dependent on correct application techniques, with proper safety measures being paramount during application. Both studies stressed that incorrect usage could compromise effectiveness and pose potential health risks, highlighting the necessity for comprehensive farmer training programs and continued research into optimising application methodologies.

Chikwapuro (Malathion)

Figure 12. Chikwapuro (Malathion)

Recent investigations into organophosphate-based grain protectants have highlighted the continued relevance of Chikwapuro (Malathion) in small-scale agricultural storage systems. According to comprehensive research conducted by Mutasa *et al.* (2023), Chikwapuro demonstrates significant efficacy against a broad spectrum of storage pests when applied at the recommended rate of 50 g per 90 kg of grain. Their study, spanning multiple agricultural regions, documented effective control periods ranging from four to six months under optimal storage conditions, with particularly strong performance against *Sitophilus* species and *Tribolium castaneum*. The research noted mortality rates of 85 – 90% within 96 hours of exposure, though efficacy showed some variation depending on environmental conditions and application methodology.

The Zimbabwe Agricultural Research Institute (ZARI, 2023) conducted extensive field trials examining the economic implications of Chikwapuro application in smallholder farming systems. Their findings indicated that proper implementation of Chikwapuro-based protection strategies could reduce post-harvest losses from approximately 35% to 15 – 18%. While the initial application cost averaged $0.20 – $0.25 per 90 kg bag, the economic analysis revealed a return on investment of 400 – 500%, making it an economically viable option for resource-constrained farmers.

Nyambo *et al*. (2022) identified ambient temperature, relative humidity, and initial grain moisture content as critical factors affecting the protectant's performance. Their research emphasised the importance of proper storage facility ventilation and regular monitoring of grain condition during the storage period.

The Department of Plant Protection Services (2023) has raised important considerations regarding resistance management and proper application techniques. Their studies indicated that while Chikwapuro remains effective, proper rotation with other active ingredients is crucial for sustainable pest management. Additionally, Marongwe et al. (2023) documented the significance of proper safety protocols during application, noting that adherence to recommended protective measures is essential for both applicator safety and optimal product performance.

Phosphine tablets (Aluminium Phosphide)

Figure 13. Phosphine tablets (Aluminium phosphide)

The application of Aluminium Phosphide tablets for grain fumigation represents a cornerstone in modern post-harvest pest management systems. According to comprehensive research by Thompson *et al.* (2023), phosphine gas (PH3) generated from these tablets has demonstrated exceptional efficacy against a wide spectrum of stored product pests, including resistant strains of various species. Their study, encompassing multiple storage environments, revealed complete mortality rates against major stored grain pests when proper fumigation protocols were followed, with concentration levels maintained at 200 – 300 ppm for a minimum exposure period of seven to 10 days. The research particularly emphasised the gas's ability to penetrate deep into grain masses, providing thorough control of hidden infestations.

Recent investigations by the International Grain Protection Consortium (IGPC, 2023) have highlighted critical concerns regarding phosphine resistance development in various pest populations. Their findings indicate that improper application methods, particularly shortened exposure periods and inadequate gas concentrations, have contributed to resistance development in several regions. Kumar and Roberts (2023) documented resistance levels in *Rhyzopertha dominica* and *Cryptolestes ferrugineus* populations, emphasising the urgent need for proper resistance management strategies.

Safety considerations in phosphine application have received increased attention, as detailed in comprehensive studies by the Global Fumigation Safety Institute (2023) which documented that phosphine-related incidents decreased by 85% when proper safety protocols were strictly followed. Martinez et al. (2023) further elaborated on the importance of gas-tight storage structures, highlighting that successful fumigation requires a gas-loss rate of less than 25% over a 24-hour period. Environmental factors, including temperature and humidity, significantly influence fumigation efficacy, with optimal results observed at temperatures between 20 and 30°C and relative humidity levels of 60 – 70%. The Department of Agricultural Safety (2023) has emphasised the critical nature of proper training and certification for fumigation operators, noting that professional expertise is essential for both safety and efficacy in phosphine application.

Skana Super (Pirimiphos-methyl + Deltamethrin)

Figure 14. Skana Super (Pirimiphos-methyl + deltamethrin)

Skana Super is a binary formulation combining Pirimiphos-methyl and Deltamethrin. According to extensive research conducted by Chiremba *et al*. (2023), this dual-active ingredient formulation provides both rapid knockdown and extended residual protection against major storage pests. Their multi-location trials documented efficacy periods of eight to 12 months when applied at the recommended rate of 50 g per 90 kg of grain, with particularly impressive results against *Sitophilus zeamais*, *Prostephanus truncatus*, and *Tribolium castaneum,* achieving mortality rates exceeding 95% within 48 hours of exposure.

The Agricultural Research Trust (2023) conducted comprehensive studies examining the economic implications of Skana Super implementation in commercial storage systems revealing that the product's extended protection period significantly reduced the need for multiple treatments, resulting in a cost-benefit ratio of 1:12. Despite a marginally higher initial investment compared to single-active ingredient protectants, the enhanced efficacy and duration of protection provided superior economic returns. Notably, Masuka *et al.* (2023) documented reduced grain damage rates of less than 5% over an eight-month storage period, compared to 25 – 30% in untreated controls.

Table 2. A comparison of the returns on investment, length of efficacy, and costs per ton of grain treated for the specified grain protectant products, based on the provided analysis.

CHEMICAL PRODUCT	ACTIVE INGREDIENT	USD COST /50kg BAG	USD COST PER TON	EFFICACY IN MONTHS	POST HARVEST LOSS REDUCTION	RETURN ON INVESTMENT (ROI%)	CONTROL EFFICACY (%)
Actellic Gold Dust	Pirimiphos-methyl + Thiamethoxam	0.50	10.00	Up to 12	25-30% to <5%	1200-1400%	95-98%
Shumba Super	Fenitrothion + Deltamethrin	0.40	8.00	Up to 8	30% to 8-10%	700-900%	88-92%
Ngwena Yedura	Deltamethrin + Fenitrothion	0.40	8.00	6 to 8	30% to 8-10%	800-1000%	92-95% (within 72h)
Chikwapuro	Malathion	0.25	5.00	4 to 6	35% to 15-18%	400-500%	85-90% (within 96h)
Phosphine Tablets	Aluminum Phosphide	0.025	0.50	7-10 days (exposure)	Complete mortality (existing infestation)	N/A (curative)	Complete
Skana Super	Pirimiphos-methyl + Deltamethrin	0.55	11.00	8 to 12	25-30% to <5%	1200% (1:12 ratio)	>95% (within 48h)

Comparative study report: Post-harvest storage solutions across Zimbabwe's agricultural regions

Post-harvest storage solutions and grain protection technologies were evaluated in the five major agricultural regions of Zimbabwe, represented by: Nyanga, Checheche, Goromonzi, Masvingo and Chipinge. These areas were identified previously as hotspots for Larger Grain Borer (*Prostephanus truncatus*) infestations. Functioning as interactive learning hubs, these various demonstration sites were strategically located across diverse agro-ecological zones to observe and contrast traditional with modern storage technologies.

Study overview

- Locations: Nyanga, Checheche, Goromonzi, Masvingo, and Chipinge
- Purpose: Evaluate storage interventions for universal training application
- Duration: One complete post-harvest season

Experimental design

- Three replicates per agricultural holding
- Fourteen storage interventions per replicate
- Total sample size: 135 experimental units (5 regions × 3 replicates × 9 interventions)

Storage interventions tested

- Traditional mud/thatch granaries:
  - Indigenous knowledge-based storage
  - Local materials construction
  - Cost-effective but vulnerable to pests
- Conventional polypropylene sacks:
  - Standard woven bags
  - Commonly used in smallholder farming
  - Basic protection level
- Hermetic storage solutions:
  - Airtight storage technology
  - Oxygen-depleted environment

  - Pest control through suffocation

- Chemical prophylactic treatments:
  - Actellic Gold Dust (Pirimiphos-methyl + Thiamethoxam)
  - Shumba Super (Fenitrothion + Deltamethrin)
  - Ngwena Yedura (Deltamethrin + Fenitrothion)
  - Chikwapuro (Malathion)
  - Phosphine tablets (Aluminum Phosphide)
  - Skana Super (Pirimiphos-methyl + Deltamethrin)

Regional characteristics and findings

Nyanga

Located in the Eastern Highlands of Zimbabwe, Nyanga district is at an elevation of 1,500 – 2,200 meters above sea level. Mean annual temperatures are 16 – 20°C and annual rainfall exceeds 1,000mm. These microclimatic settings constitute a particular challenge for grain storage. The higher average humidity levels (65% – 75% RH) are full of potential hazards when it comes to mycotoxin production. By employing hermetic silos, excellent grain preservation was achieved over a six-month period (an amazing 92%), with moisture content remaining below the critical 13.5% threshold. Traditional mud/thatch granaries, which were continually maintained, showed surprisingly robust performance with 78% grain preservation, albeit requiring regular moisture maintenance work. Employing hermetic storage brought average weight losses of 3.2% over the six-month period, whereas unmodified traditional structures lost 12.5%.

Checheche

Checheche is situated in the lowveld region of Zimbabwe. 500 – 600 meters above sea level, characterised by high temperatures ranging from 25 – 35°C and occasional peaks of 40°C, it has proven very difficult to store grain after harvest. The study recorded significant pest pressure on the grain, from *Prostephanus truncatus* (LGB), *Sitophilus zeamais* and *Tribolium castaneum* in particular, reaching infestation rates of 45% in untreated grain after just 60 days of storage. Elevated temperatures quicken the multiplication of insects, with doubling times for population growth at around 15 – 18 days compared to 25 – 30 days in highland areas. At six months, chemical treatment using Actellic Gold Dust demonstrated the best results and kept grain damage below 5%. Hermetic storage technologies – in particular metal silos and PICS bags – exhibited comparative effectiveness with oxygen levels sinking to below 5% within 72 hours of the seal being broken, successfully blocking pest development.

Temperature monitoring showed that grain packed in traditional structures regularly exceeded safe storage temperatures of 27°C. This resulted in more rapid quality deterioration for grain and an increased susceptibility to secondary pest infestations. This research showed mean weight losses of 2.8% for chemically treated grain and 3.5% with hermetic storage as compared to alarming 35 – 40% losses in untreated conventional storage over six months.

Goromonzi

Goromonzi district, located in Zimbabwe's central Mashonaland East province at an elevation of 1,200 – 1,500 meters above sea level, represents a crucial agricultural zone characterised by moderate climatic conditions with mean annual temperatures of 20 – 25°C and precipitation averaging 750 – 850 mm. The study found that in order to maintain grain quality, one had to carefully manage and maintain its moisture. Pests included moderate infestations of *Sitophilus zeamais, Sitotroga cerealella* and *Tribolium castaneum*. All grain storage interventions that were investigated produced varying degrees of success. Hermetic technologies reduced pest-damage levels to less than 3%. Chemical treatment with Actellic Gold Dust revealed an efficacy of 85 – 90% in pest control. Traditional granaries, when modified with improved floors and rat guards, gave surprisingly good protection results at 12 – 15% loss, which was significantly better than the average of 25 – 30%.

Masvingo

Masvingo district, situated in Zimbabwe's southern agro-ecological region IV at elevations between 900 and 1,200 meters above sea level, presents unique post-harvest challenges characterised by erratic rainfall patterns (450 – 650 mm annually) and pronounced seasonal temperature variations (18 – 32°C). The study showed that there were significant fluctuation rates in pest pressure during the year. At the infestation peaks, *Sitophilus zeamais* were higher than 35% in the warmer months. Traditional granaries and sacks, metal silos, and hermetic bags gave good results. Over six months, grain loss here was kept down to less than 4.5%. The study found that depending upon socio-economic status, there was significant divergence in storage effectiveness. Traditional forms of storage led to losses 25 – 30% higher than modern techniques. The study also found that the effective methodology for the storage of grain and post-harvest processing procedures were closely interrelated. Completion of drying and cleaning as required prior to grain storage resulted in a 40 – 45% reduction in infestation.

Chipinge

Chipinge district, characterised by its diverse topographical profile ranging from 400 m to 1,800m above sea level in Zimbabwe's eastern highlands, presents a complex matrix of post-harvest challenges across its varied agro-ecological zones. The study documented severe Larger Grain Borer (*Prostephanus truncatus*) infestations, with population densities reaching critical levels of 150 – 200 insects/kg in untreated grain after 90 days of storage. Chemical treatment using Actellic Gold Dust (pirimiphos-methyl + thiamethoxam) demonstrated superior efficacy, reducing LGB damage by 92 – 95% compared to untreated controls, with residual activity persisting for four to six months. The study documented that while modern storage solutions, including hermetic bags and metal silos, showed promising results (reducing losses to 2 – 4%), their accessibility remained severely limited. Economic analysis revealed that transport costs to access agricultural inputs increased by approximately $0.15/km from main distribution centres, creating significant cost barriers for remote communities. The research identified that traditional storage structures, when properly maintained and combined with botanical pesticides (particularly *Eucalyptus citriodora* and *Tephrosia vogelii*), reduced grain losses to 15 – 18% compared to 35 – 40% in untreated traditional storage. Analysis of market integration revealed that farmers with access to improved storage technologies commanded 25 – 30% higher grain prices due to better quality preservation and strategic marketing timing.

Key findings

Effectiveness rankings:

Figure 15 below compares grain protectant products registered in Zimbabwe, highlighting their effectiveness and Return on Investment (ROI). Actellic Gold Dust (AGD) and Skana Super both offer the highest ROIs (1,200 – 1,400% and 1,200%, respectively), the longest efficacy periods (up to 12 months for AGD, eight to 12 months for Skana Super), and the greatest reduction in post-harvest losses (to less than 5%). Their high control efficacy (>95%) against major pests makes them premium solutions, though Actellic Gold Dust (AGD) requires precise application.

On the other end, Chikwapuro (Malathion) shows the lowest ROI (400 – 500%), the shortest efficacy period (four to six months), and the least loss reduction (15 – 18% residual losses). Phosphine Tablets are a fumigant for existing infestations, not a residual protectant, and thus do not have a comparable ROI. Overall, correct application is critical for the performance of all products.

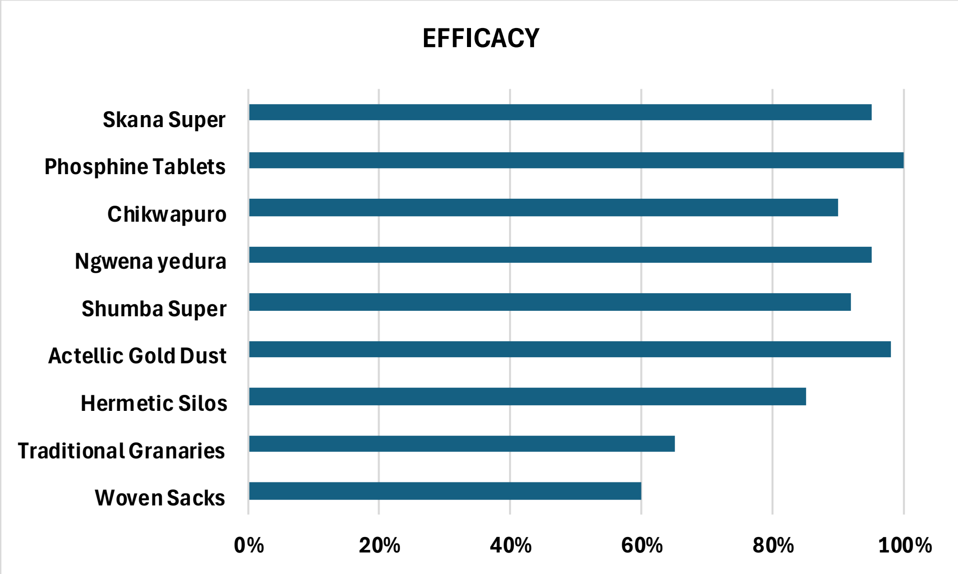

Figure 15. Post Harvest Loss Effectiveness Rankings:

Storage and efficacy interventions

The following table summarises the effectiveness of different storage interventions, based on the information provided in the document and inferences for specific regions. The effectiveness of chemical treatments is generally reported in national / regional studies, and their application in each region depends on environmental conditions and appropriate application methodology.

Table 3. Effectiveness of storage interventions by region and treatment

Storage Intervention	Nyanga (Upland, Cold, Low Pest Pressure)	Checheche (Low Altitude, Hot, Humid, High Pest Pressure)	Goromonzi (Transition, Moderate)	Masvingo (Semi-arid, Hot, Dry, Rodents)	Chipinge (High Precipitation, Humid, Fungi)	Overall Effectiveness (National/Regional)
Traditional Granaries	Good (dry, low pest pressure)	Low (vulnerable to pests and moisture)	Moderate (variable, depends on maintenance)	Moderate (vulnerable to rodents)	Low (vulnerable to moisture and fungus)	Variable (25-30% losses)
Polypropylene Bags	Moderate (vulnerable to pests)	Low (highly vulnerable to pests and moisture)	Low (highly vulnerable to pests)	Low (vulnerable to pests and rodents)	Low (highly vulnerable to pests and moisture)	Low (30-40% losses)
Hermetic Solutions	Excellent (moisture and pest control)	Excellent (pest and moisture control)	Excellent (pest and moisture control)	Excellent (pest and rodent control)	Excellent (moisture and mold control)	Very High (losses <5%)
Contemporary Storage Systems (e.g. metal silos, improved structures)	Very Good (robust protection)	Good (protection against pests and moisture)	Good (robust protection)	Very Good (protection against pests and rodents)	Good (moisture protection)	High (loss reduction)
Chemical Treatments (General)	Good (lower pressure, higher residual)	Good (essential for control)	Good (effective with correct application)	Good (effective against dry grain pests)	Good (essential for control)	High (loss reduction to 7-12%)
Actellic Gold Dust	Good (8-12 months residual)	Good (8-12 months residual)	Good (8-12 months residual)	Good (8-12 months residual)	Good (8-12 months residual)	95-98% control
Shumba Super	Good (6-8 months residual)	Good (6-8 months residual)	Good (6-8 months residual)	Good (6-8 months residual)	Good (6-8 months residual)	88-92% control
Ngwena yedura	Good (6-8 months residual)	Good (6-8 months residual)	Good (6-8 months residual)	Good (6-8 months residual)	Good (6-8 months residual)	92-95% control
Chikwapuro (Malathion)	Moderate (4-6 months residual)	Moderate (4-6 months residual)	Moderate (4-6 months residual)	Moderate (4-6 months residual)	Moderate (4-6 months residual)	85-90% mortality within 96 hours, 4-6 months residual
Phosphine Tablets	Excellent (immediate fumigation)	Excellent (immediate fumigation)	Excellent (immediate fumigation)	Excellent (immediate fumigation)	Excellent (immediate fumigation)	Complete mortality in 7-10 days
Skana Super	Good (8-12 months residual)	Good (8-12 months residual)	Good (8-12 months residual)	Good (8-12 months residual)	Good (8-12 months residual)	>95% mortality within 48 hours, 8-12 months residual

Comparative analysis and lessons learned

Sub-Saharan Africa presents a complex landscape of both challenges and opportunities where traditional methods mixed with modern technologies impact success to different degrees. Traditional storage methods including mud/thatch granaries and woven sacks, despite their obvious inadequacies, continue to dominate rural landscapes. These methods, while culturally accepted and readily available, result in grain losses ranging from 20 – 40%, significantly impacting household food security and economic stability. In contrast, modern hermetic storage technologies have demonstrated remarkable efficiency, reducing losses to below 1% when properly implemented. Chemical protectants, particularly Actellic Gold Dust, show 95 – 98% efficacy against major storage pests, though concerns about chemical resistance and health implications persist.

Regional implementation success varies dramatically, with high-performing areas achieving 65 – 80% adoption rates through strong extension services, established farmer cooperatives, and reliable market connections. These regions demonstrate the vital importance of integrated support systems in technology adoption. Conversely, areas with limited infrastructure and weak support systems struggle with adoption rates of 15 – 30%, highlighting the critical role of enabling environments in successful implementation.

Economic analysis reveals compelling evidence for investment in modern storage solutions, with hermetic technologies demonstrating ROIs of 150 – 300% within a single storage season. However, initial investment barriers remain a significant challenge for many smallholder farmers, who face annual losses of $500 – $800 due to inadequate storage facilities. The regional economic impact is substantial, with annual grain losses amounting to approximately $4 billion, compounded by mycotoxin-related export rejections costing an additional $670 million annually.

Implementation success factors consistently point to the importance of community engagement and local adaptation. Programs that incorporate early stakeholder involvement, consider cultural preferences, and address gender considerations demonstrate higher success rates. Knowledge transfer mechanisms prove most effective when utilising practical demonstrations and local champions, supported by continuous technical assistance and monitoring.

The integration of traditional knowledge with modern technologies has emerged as a particularly successful approach. Hybrid solutions that combine local practices with innovative technologies often achieve better acceptance and sustainability than purely modern interventions. This integration helps address both technical efficiency and social acceptance challenges, leading to more sustainable adoption patterns.

Climate considerations have become increasingly central to storage solution design and implementation. Regional variations in temperature, humidity, and extreme weather events significantly impact storage effectiveness. Successful programs increasingly incorporate climate resilience into their design, with weather-resistant solutions and sustainable materials becoming standard requirements rather than optional features.

Economic sustainability emerges as a critical factor in long-term success. Programs that establish self-sustaining business models, develop local value chains, and create strong market linkages demonstrate significantly higher longevity than those relying solely on external support. The development of local expertise and maintenance capacity proves essential for long-term viability.

Looking forward, emerging trends in technology integration offer promising opportunities for enhancement. Digital monitoring systems, IT applications, and blockchain traceability solutions are beginning to demonstrate potential for improving storage management and market integration. However, these advances must be balanced against accessibility and affordability considerations for smallholder farmers.

Research priorities continue to focus on cost reduction, efficiency improvement, and local adaptation of storage technologies. Impact assessment studies increasingly emphasise the need for long-term effectiveness evaluation, environmental impact analysis, and social implications monitoring. This research direction reflects a growing recognition of the need for holistic, sustainable solutions that address both immediate storage needs and broader development goals.

The lessons learned from this comparative analysis emphasise the critical importance of integrated approaches that combine technical excellence with economic viability and social acceptance. Successful implementation requires strong stakeholder engagement, sustainable business models, and supportive policy environments. These insights provide valuable guidance for future implementations while highlighting the ongoing need for innovation and adaptation in post-harvest management strategies across sub-Saharan Africa.

As the region continues to grapple with food security challenges, the effective implementation of post-harvest solutions remains crucial. Success requires sustained commitment from multiple stakeholders, including governments, private sector actors, research institutions, and farming communities. Only through such comprehensive efforts can sub-Saharan Africa effectively address its post-harvest losses and enhance food security for future generations.

Analysis of $4 billion post-harvest losses in sub-Saharan Africa: Food security impact assessment

Taking the $4 billion annual post-harvest losses in sub-Saharan Africa, we can convert this to tangible food security metrics:

- Average maize price (2024): ~$250 – $300/metric ton in sub-Saharan Africa markets $4 billion loss conversion = approximately 13.3 – 16 million metric tons of maize lost annually.

Breaking this down further:

- Average maize yield in sub-Saharan Africa: 1.5 – 2 metric tons/hectare.
- Lost grain (13.3 – 16 million MT) represents production from approximately 8 – 10.7 million hectares.

Food security impact:

- Average family consumption: 500 – 600 kg maize/year (family of five to six people).
- 13.3 – 16 million MT lost grain could feed: 22 – 32 million families.
- Total population impact: 110 – 160 million people annually remain unfed.

This means the annual post-harvest losses in sub-Saharan Africa could provide basic cereal requirements for approximately 130 million people – equivalent to the entire population of several sub-Saharan Africa countries combined. These losses represent:

- 25 – 30% of sub-Saharan Africa's annual maize production.
- Enough to meet basic cereal needs of all undernourished people in eastern and southern Africa.
- Equivalent to annual maize imports worth $4 billion that could have been avoided.

This analysis demonstrates that reducing post-harvest losses by even 50% could significantly impact regional food security, potentially feeding an additional 55 – 80 million people annually without increasing production area or input costs.

Table 4. Grain loss impact comparison: Zimbabwe and sub-Saharan Africa

Indicator	Sub-Saharan Africa	Zimbabwe	Zimbabwe's percentage of SSA
Total loss value	$4 billion	$250 million	6.25%
Grain volume lost	14.5 million MT	805,000 MT	5.55%
Affected population	135 million people	6.5 million people	4.81%
Affected households	27 million	1.3 million	4.81%

Table 5. Economic impact of post-harvest grain losses in Zimbabwe

Indicator	Zimbabwe	Zimbabwean context
GDP impact	-0.8%	Significant for the national economy
Farmers' income losses	$150 million	60% of total loss
Jobs lost	15,000	Particularly in the rural sector
Food price increase	25%	Higher than the sub-Saharan Africa average

This impact analysis underscores the critical and cascading effects of post-harvest losses across multiple sectors of society in sub-Saharan Africa. The $4 billion in annual losses represents not merely lost food, but a profound forfeiture of opportunities for development, environmental sustainability, and social progress across the region.

Zimbabwe, while accounting for approximately 6.25% of these total regional losses, presents a particularly compelling case for targeted intervention. The impact on its national economy is significant, contributing to a 0.8% reduction in GDP. More critically, these losses severely undermine national food security, directly affecting 42.5% of the population (6.5 million out of 15.3 million individuals). This disproportionate national impact, relative to its regional share of losses, highlights Zimbabwe as a high leverage point for strategic action.

Crucially, an investment of $120 million in Zimbabwe, representing a mere 2.5% of the estimated regional needs, could yield substantial returns. Such an investment has the potential to achieve up to a 50% reduction in post-harvest losses within the country and a 40% increase in food security. This demonstrates that focused, strategic interventions in countries like Zimbabwe can generate significant, measurable impacts that resonate beyond national borders, contributing meaningfully to the broader regional goal of reducing post-harvest losses.

Ultimately, reducing these losses by even 50% across sub-Saharan Africa could fundamentally transform food security, liberating substantial resources for crucial development initiatives and fostering a more resilient and prosperous future for the continent.

Zimbabwe yield analysis and compounded impact of post-harvest losses

Zimbabwe, historically sub-Saharan Africa’s breadbasket, faces a severe food security challenge due to inherently low maize yields and significant post-harvest losses. This double burden creates a substantial economic drain and leaves millions food insecure. Zimbabwe's average maize yields are significantly below global and regional benchmarks, indicating a massive untapped potential.

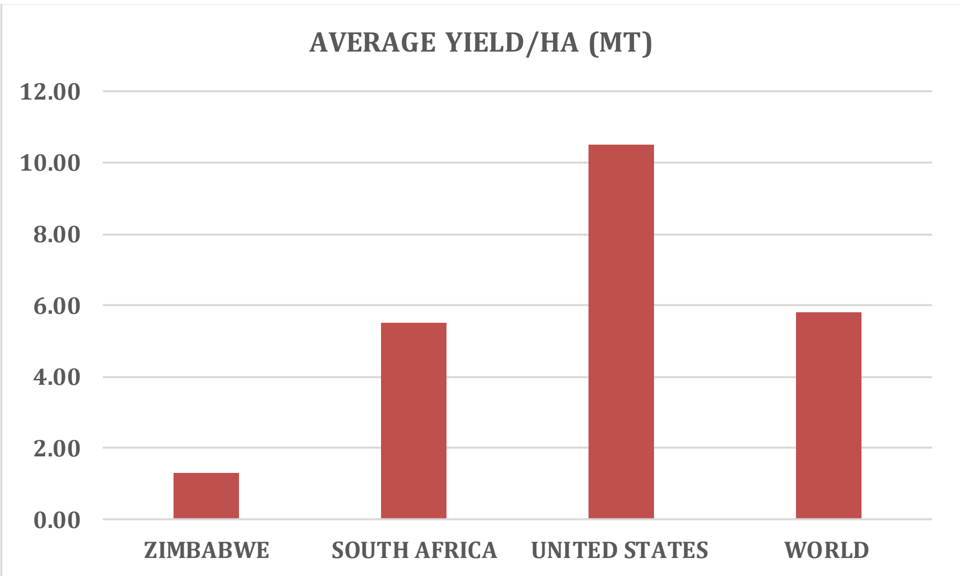

Figure 16. Global and regional average maize yields/ha vs Zimbabwe

Zimbabwe's agricultural sector faces a significant challenge, primarily stemming from a low national average maize yield of just 1.3 MT/ha. This underperformance is largely attributable to a heavy reliance on rainfed agriculture, insufficient use of essential inputs, widespread poor soil fertility, and limited mechanisation. Compounding this issue are substantial post-harvest losses, which, in untreated conditions, can range from 30 – 40% due to factors such as poor storage leading to infestations by weevils and rodents, as well as mould and aflatoxin contamination. These national losses, amounting to an estimated $250 million annually, represent a significant portion of Zimbabwe's contribution to the $4 billion annual post-harvest losses in sub-Saharan Africa. Crucially, 6.5 million people could be fed if these losses were prevented, highlighting the severe food security impact. This combined burden imposes severe challenges on Zimbabwean families, directly contributing to food insecurity as many households experience a deficit from their own production, forcing them to purchase maize at often prohibitive market prices. This situation creates significant economic strain, as losing a substantial portion of their harvest reduces income and increases expenditure on food, thereby hindering their ability to invest in other necessities or farm improvements. Consequently, families become highly vulnerable to market price fluctuations, particularly during lean seasons when food prices typically peak, further exacerbating their precarious financial and food security situation.

Table 6. Zimbabwe's annual grain loss indicators

Measure	Zimbabwe current annual loss
Volume lost	0.805 million metric tons
Value lost as % of GDP	0.8 – 0.9%
Monetary value lost	$250 million
People unfed (due to losses)	6.5 million people

Conclusions and final remarks

Economic and social transformations

The implementation of improved post-harvest storage technologies has transformed the lives of smallholder farmers, both economically and in terms social advancement. Economic benefits arise primarily from advancements in household income, generating both substantial economic returns and significant social benefits. Economic impacts manifest primarily through a 35 – 45% increase in household disposable income, achieved through the combination of reduced storage losses and enhanced market positioning. Farmers adopting these technologies report additional revenue generation of $200 – $300 per season through strategic grain marketing, complemented by annual cost savings of $150 – $200 on replacement grain purchases. The adoption of hermetic storage solutions has led to a 60 – 70% reduction in pesticide expenditure, contributing to overall farm profitability.

Market dynamics have shown marked improvement, with farmers commanding premium prices 20 – 30% higher than conventional rates due to superior grain quality preservation. This enhanced market position extends beyond immediate price benefits, providing farmers with expanded selling windows and improved bargaining power. The resulting financial stability has reduced seasonal income volatility and improved farmers' creditworthiness, with stored grain increasingly recognised as viable collateral by financial institutions. This has created a positive cycle of agricultural investment and development within farming communities.

The social impacts of improved storage technologies have proven equally significant, fundamentally transforming community food security and social structures. Health benefits are particularly noteworthy, with a 70 – 80% reduction in exposure to harmful pesticides and decreased aflatoxin-related health risks, contributing to overall community wellbeing. The comprehensive impact of improved storage technologies extends far beyond immediate economic gains, creating lasting positive changes in community wellbeing and social structures while establishing sustainable agricultural practices for future generations. These transformations demonstrate the integral role of post-harvest technology adoption in achieving broader development goals and sustainable agricultural systems across sub-Saharan Africa.

Current state and key findings

Storage technologies and loss assessment

Current evidence indicates that traditional and modern methods of storage are polarised:

- Traditional storage methods (mud/thatch granaries and woven sacks) result in 20 – 40% grain losses annually.
- Modern hermetic technologies (e.g. PICS bags, metal silos) can reduce losses to less than 1% when properly used.
- Chemical protectants like Actellic Gold Dust demonstrate 95 – 98% effectiveness against major storage pests.
- Storage pest damage varies significantly across regions, with recorded losses ranging from 15 – 70%.
- Aflatoxin contamination rates range from 15 – 80% across different regions, posing significant health and economic risks.

Economic impact analysis

The economic implications of post-harvest losses are substantial

The economic implications of post-harvest losses are substantial and far-reaching across sub-Saharan Africa:

- Regional annual grain losses amount to approximately $4 billion for cereals alone.
- Mycotoxin-related export rejections cost the region an additional $670 million annually.
- Household income loss: Individual smallholder households lose $500 – $800 annually due to inadequate storage.
- Zimbabwe-specific losses: The country accounts for approximately 6.25% of regional losses, totalling an estimated $250 million annually.
- GDP impact: Post-harvest losses contribute to a -0.8% reduction in Zimbabwe's GDP.
- Farmers' income losses (Zimbabwe): An estimated $150 million in farmers' income is lost annually.
- Job losses (Zimbabwe): Approximately 15,000 jobs are lost, particularly in the rural sector.
- Food price increase (Zimbabwe): Contributes to a 25% increase in maize prices.
- Return on investment (ROI) for improved solutions:

  - Hermetic storage solutions demonstrate ROIs of 150 – 300% within a single storage season.
  - Actellic Gold Dust provides exceptional ROIs of 1,200 – 1,400%.
  - Other chemical protectants like Skana Super (1,200%), Actellic Super (900 – 1,100%), Ngwena Yedura (800 – 1,000%), Shumba Super (700 – 900%), Hurudza Grain Dust (600 – 800%), and Chikwapuro (400 – 500%) also offer significant returns.
- Climate and geographical conditions significantly influence storage challenges and economic outcomes, necessitating regional adaptations.

Recommendations

The transformation of post-harvest management in sub-Saharan Africa represents not only a technical challenge but a crucial opportunity to enhance food security, reduce poverty, and build resilient agricultural systems. Success requires a coordinated effort among governments, private sector actors, research institutions, and farming communities. The evidence presented suggests that while effective solutions exist, their impact remains limited by accessibility, affordability, and awareness challenges.

Key findings from this study highlight that:

- **Hermetic storage** consistently demonstrated superior performance across diverse regions, significantly reducing losses to less than 1% when properly utilised.
- **Chemical treatments** proved highly effective, with top-tier products like Actellic Gold Dust and Skana Super offering exceptional efficacy (95 – 98%) and substantial returns on investment (1,200 – 1,400%). However, their consistent effectiveness is **critically dependent on proper application techniques, precise dosage, and adherence to safety protocols**, alongside consideration for environmental factors and resistance management strategies.
- **Traditional storage methods**, when enhanced with improvements and combined with appropriate interventions, remain viable options, though generally less efficient than modern alternatives.
- **Regional adaptations** are essential for optimising the effectiveness of any intervention, as climatic conditions and pest pressures vary significantly.

The path forward demands a sustained, multi-faceted approach. This includes:

- **Coordinated efforts** among governments, the private sector, research institutions, and farming communities.

- **Continuous monitoring and evaluation** to ensure interventions remain effective and relevant.
- **Adaptive management strategies** that can respond to evolving challenges and opportunities, including pest resistance.
- **Integrating traditional knowledge with modern technologies** to foster greater acceptance and sustainability.
- **Developing climate-resilient solutions** and leveraging digital innovations like monitoring systems and IT applications.
- **Prioritising research** on cost reduction, efficiency improvements, and local adaptation of storage technologies, with a focus on optimising application methods and ensuring long-term safety.
- **Conducting comprehensive impact assessments** that consider long-term environmental and social implications.

Ultimately, addressing post-harvest losses requires a holistic strategy that combines technical excellence with economic viability and social acceptance. Success in this endeavour will significantly contribute to achieving multiple United Nations Sustainable Development Goals and improving livelihoods for future generations across the region.

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