

Preharvest Fungicide Timing Improves Postharvest Seed Quality and Storage Stability by Suppressing Grain Mould in Sorghum (*Sorghum bicolor* (L.) Moench)

John Mbugri Azasiba

jazasiba@gmail.com

¹ Council for Scientific and Industrial Research – Savanna Agricultural Research Institute (CSIR-SARI),
P.O. Box 52, Tamale, Ghana

Francis Kusi

¹ Council for Scientific and Industrial Research – Savanna Agricultural Research Institute (CSIR-SARI),
P.O. Box 52, Tamale, Ghana

Peter Anabire Asungre

¹ Council for Scientific and Industrial Research – Savanna Agricultural Research Institute (CSIR-SARI),
P.O. Box 52, Tamale, Ghana

Francis Appiah

²Kwame Nkrumah University of Science and Technology (KNUST), P.O. Box PMB, Kumasi, Ghana

Eli Gaveh

²Kwame Nkrumah University of Science and Technology (KNUST), P.O. Box PMB, Kumasi, Ghana

Salim Lamini

¹ Council for Scientific and Industrial Research – Savanna Agricultural Research Institute (CSIR-SARI),
P.O. Box 52, Tamale, Ghana

Patrick Attamah

¹ Council for Scientific and Industrial Research – Savanna Agricultural Research Institute (CSIR-SARI),
P.O. Box 52, Tamale, Ghana

Mustapha M. Suraj

¹ Council for Scientific and Industrial Research – Savanna Agricultural Research Institute (CSIR-SARI),
P.O. Box 52, Tamale, Ghana

Emmanuel Asibi Aziiba

¹ Council for Scientific and Industrial Research – Savanna Agricultural Research Institute (CSIR-SARI),
P.O. Box 52, Tamale, Ghana

Issah Sugri

Research Article

Keywords: Grain mould suppression, integrated disease management, postharvest seed quality, seed physiological quality, storage stability, tropical production systems

Posted Date: September 21st, 2026

DOI: <https://doi.org/10.21203/rs.3.rs-10631230/v1>

License:  This work is licensed under a Creative Commons Attribution 4.0 International License.
[Read Full License](#)

Additional Declarations: No competing interests reported.

Abstract

Grain mould is a major constraint to sorghum production, reducing grain quality, seed viability, and storage potential under humid tropical conditions. Although fungicides are widely used to suppress grain mould before harvest, little is known about how the timing of fungicide application influences subsequent seed quality and storage performance. This study investigated whether preharvest fungicide timing affects postharvest seed quality and storage stability through effective grain mould suppression. A $2 \times 2 \times 3$ factorial experiment arranged in a randomised complete block design was conducted during the 2024 cropping season in northern Ghana using two sorghum genotypes, two fungicides, three application stages (flowering, milking, and dough), and untreated controls. Grain mould incidence and severity, seed germination, seedling vigour, fungal pathogen incidence, moisture loss, and insect damage were assessed over six months of ambient storage. Fungicide application timing significantly affected grain mould development and postharvest seed quality ($P < 0.001$). Flowering-stage application consistently produced the lowest grain mould incidence (1.93%) and severity (1.23) and maintained the highest germination after six months of storage (83.67%). In contrast, untreated controls exhibited greater disease severity, higher fungal incidence, increased moisture loss and insect damage, and the lowest germination (26.33%). *Fusarium* spp. and *Curvularia* spp. were the predominant storage fungi, while grain mould incidence and severity were strongly negatively correlated with seed germination ($\rho = -0.956$ to -0.989). These findings demonstrate that preharvest fungicide timing has measurable carry-over effects on postharvest seed quality and storage stability by suppressing grain mould, providing new evidence that the timing of preharvest disease management influences postharvest seed physiological quality and storage stability in sorghum under tropical production systems.

1. Introduction

Sorghum (*Sorghum bicolor* (L.) Moench) is one of the world's most important cereal crops, providing food, animal feed, and income for millions of people, particularly in arid and semi-arid regions where its tolerance to drought, high temperatures, and low-input production systems makes it an essential component of climate-resilient agriculture [1, 2]. In sub-Saharan Africa, sorghum plays a critical role in sustaining rural livelihoods, especially where climatic variability constrains the productivity of maize and other cereals. Beyond its traditional use as a staple food, sorghum is increasingly utilised in brewing, livestock feed, bio-industrial products, and formal seed systems, making the preservation of grain quality fundamental to food security, market value, seed viability, and sustainable value chains.

Among the most important biotic constraints limiting sorghum productivity and grain quality, grain mould remains one of the most destructive diseases in humid and sub-humid environments. The disease results from infection by a complex of fungal pathogens, predominantly *Fusarium*, *Curvularia*, *Aspergillus*, *Penicillium*, and *Macrophomina* species, which colonise developing grains from flowering through physiological maturity under conditions of prolonged rainfall, high relative humidity, and extended panicle wetness [3–5]. Grain mould reduces grain quality through kernel discolouration, deterioration, reduced grain weight, poor germination, and loss of seed viability, thereby diminishing both commercial value and

planting quality. In addition, several grain mould-associated fungi produce mycotoxins that threaten food safety, livestock productivity, and international grain trade [6, 7]. Consequently, integrated disease management remains the most sustainable approach for reducing grain mould-associated losses in sorghum production [8].

The consequences of grain mould extend beyond field infection into the postharvest phase, where preharvest fungal establishment continues to influence seed physiological quality and storage performance. Fungal infections frequently persist during storage, accelerating seed deterioration, reducing germination and seed vigour, increasing susceptibility to insect infestation, and promoting further fungal colonisation under favourable storage conditions [9, 10]. Recent studies have further demonstrated that fungi infecting sorghum before harvest remain prevalent during storage and continue to compromise grain quality where temperature and moisture conditions favour fungal development [11]. These observations highlight the close relationship between field disease management and postharvest quality preservation and emphasise the need for integrated strategies capable of protecting grain throughout the production, storage continuum.

Several complementary approaches have been developed to manage sorghum grain mould, including host resistance, improved agronomic practices, timely harvesting, and fungicide application [12, 13]. Among these, fungicides remain an important component of integrated grain mould management when environmental conditions favour pathogen infection. However, effective disease management depends not only on fungicide efficacy but also on synchronising fungicide application with crop developmental stages that coincide with the highest risk of infection. Sorghum panicles are particularly susceptible during anthesis because exposed floral tissues and developing kernels provide favourable sites for pathogen establishment [4]. Consequently, fungicide application during flowering is expected to provide greater protection than applications delayed until the milking or dough stages, when pathogen colonisation has already progressed. Recent reviews likewise emphasise that integrating timely fungicide application with resistant cultivars and sound agronomic practices offers the most sustainable strategy for managing sorghum fungal diseases under changing climatic conditions [8].

Although fungicides have been shown to reduce grain mould under field conditions, comparatively little attention has been given to whether the timing of preharvest disease management influences the physiological quality of seed during subsequent storage. Most previous studies have focused on disease suppression before harvest, whereas the carry-over effects of preharvest disease management on seed viability, seedling vigour, fungal persistence, insect damage, and storage stability remain poorly understood, particularly under tropical production systems. This knowledge gap limits the development of integrated disease management strategies capable of protecting grain quality throughout the production, storage continuum.

To our knowledge, no previous study has comprehensively evaluated how fungicide application timing influences both field suppression of grain mould and subsequent postharvest seed physiological quality under tropical production conditions. Previous investigations have largely concentrated on fungicide efficacy, host resistance, or field disease suppression, with limited attention to the carry-over effects of

preharvest disease management on fungal persistence, seed quality, and storage stability. Unlike previous studies that primarily evaluated the field efficacy of fungicides against sorghum grain mould, the present study investigates how the timing of preharvest fungicide application influences subsequent seed physiological quality and storage stability, thereby extending the concept of grain mould management from disease suppression to postharvest quality preservation. By integrating field disease management with postharvest quality assessment, this study provides new evidence linking preharvest disease management with postharvest seed physiological quality and storage stability in sorghum.

We hypothesised that fungicide application at the flowering stage would provide greater suppression of grain mould than applications at the milking or dough stages and would consequently improve postharvest seed quality and storage performance. Accordingly, this study evaluated the effects of fungicide type and application timing on grain mould suppression and their subsequent influence on seed quality, fungal pathogen incidence, and storage performance under ambient tropical storage conditions. Grain mould incidence and severity, seed germination, seedling vigour, moisture loss, insect damage, and the incidence of major grain mould pathogens were assessed to determine the carry-over effects of preharvest disease management on postharvest grain quality. The findings provide new insights into the role of preharvest disease management in maintaining seed physiological quality during storage and contribute to the development of integrated grain mould management strategies for sustainable sorghum production.

2. Materials and Methods

2.1 Study Area

The field experiment was conducted during the 2024 major cropping season at the CSIR–Savanna Agricultural Research Institute (CSIR–SARI), Manga Agricultural Research Station, located in the Binduri District of the Upper East Region of Ghana (11°01' N, 00°16' W; 249 m above sea level). The site lies within the Guinea Savannah agroecological zone, characterised by a unimodal rainfall pattern extending from May to October, with peak rainfall occurring between July and August. During the cropping season, mean monthly temperatures ranged from 25 to 30°C, while relative humidity reached approximately 84% during the peak rainfall period (Fig. 1). These warm and humid conditions favour the development of sorghum grain mould pathogens and provide a suitable environment for evaluating fungicide application strategies under natural disease pressure. The experimental soil is classified as a Plinthic Lixisol derived from granite [14]. Baseline soil physical and chemical properties previously reported by Kanton et al. [15] are presented to characterise the experimental site. The surface soil (0–15 cm) has a loamy-sand texture comprising 80.4% sand, 16.0% silt, and 3.6% clay. The soil is strongly acidic (pH 4.64), with low organic carbon (0.35%) and total nitrogen (0.06%) contents but adequate available phosphorus (13.6 mg kg⁻¹). The cation exchange capacity is relatively low (3.28 cmol(+) kg⁻¹), reflecting the limited nutrient retention capacity typical of this soil type [15].

2.2 Plant Materials

Two sorghum (*Sorghum bicolor* (L.) Moench) genotypes with contrasting genetic backgrounds were used in this study. Kapaala is an improved open-pollinated variety widely cultivated in northern Ghana because of its adaptation to the Guinea Savannah agroecology and stable grain yield. ADV23012 is a high-yielding advanced breeding line currently undergoing multi-location evaluation by the CSIR–Savanna Agricultural Research Institute (CSIR–SARI) for agronomic performance and disease response. Seed of both genotypes was obtained from the CSIR–SARI sorghum breeding programme at the Manga Agricultural Research Station. The two genotypes were selected to represent a released cultivar and an advanced breeding line, thereby enabling the evaluation of genotype-dependent responses to fungicide type and application timing under natural grain mould pressure. Their principal agronomic characteristics are summarised in Table 1.

Table 1 Register of Sorghum Entries Used in the Study					
Entry Name	Type	Origin	Maturity Period	Yield Potential	Remarks
Kapaala	Cultivar	Ghana (CSIR-SARI)	100–110 days	2.0–3.0 t/ha	Open-pollinated; early maturing, compact panicle
ADV23012	Advanced breeding line	Ghana (CSIR-SARI)	90–100 days	3.5–5.0 t/ha	Experimental, high yield potential, early maturing, compact panicle
Note: Yield potential and maturity periods are based on CSIR-SARI trials under Guinea Savannah conditions. ADV23012 is currently under multi-location evaluation and has not yet been officially released for commercial cultivation in Ghana.					

2.3 Experimental Design and Treatments

The experiment was arranged as a 2 × 2 × 3 factorial within a randomised complete block design (RCBD) with three replications. The treatment factors comprised two sorghum genotypes (Kapaala and ADV23012), two fungicides [Adepa (organic) and Guardian Xtra (synthetic)], and three application stages (flowering, milking, and dough). In addition, an untreated control was included for each genotype, resulting in 14 treatment combinations per replication and 42 experimental plots in total. Treatments were randomly assigned within each block.

Each experimental plot consisted of four rows, each 3 m long, with an inter-row spacing of 0.75 m and an intra-row spacing of 0.25 m. Recommended agronomic practices for sorghum production in northern Ghana were followed throughout the experiment. To ensure fungicide application at comparable phenological stages, Kapaala was planted on 1 July 2024, whereas ADV23012 was planted on 10 July 2024 to account for differences in maturity between the two genotypes.

2.4 Fungicide Application

Adepa (organic fungicide) and Guardian Xtra (synthetic fungicide) were applied once according to the assigned treatment using separate calibrated knapsack sprayers to prevent cross-contamination. Adepa

was applied at a rate of 100 mL per 15 L of water, whereas Guardian Xtra was applied at 300 g per 16 L of water following the manufacturers' recommendations. A spray volume of 500 L ha⁻¹ was maintained to ensure uniform coverage of the sorghum panicles. Fungicide applications were carried out during the early morning or late afternoon to minimise spray drift and evaporation and to maximise fungicide deposition on the panicles [13]. Applications were made at the flowering (anthesis), milking, or dough stage according to the assigned treatment, whereas untreated control plots received no fungicide application.

2.5 Field Data Collection

Data were collected from the two central rows of each plot to minimise border effects.

Grain mould assessment

Grain mould incidence (%) was assessed using 10 randomly selected panicles per plot and expressed as the percentage of panicles exhibiting visible grain mould symptoms. Grain mould severity was evaluated on the same panicles using the 1–9 visual rating scale described by Bandyopadhyay et al. [4], where 1 indicates no visible infection and 9 represents severe fungal colonisation accompanied by extensive grain discolouration.

Agronomic traits

Agronomic traits recorded included plant population at three weeks after planting (WAP), days to 50% flowering, plant height (cm), panicle number, dry panicle weight (g), grain yield (kg ha⁻¹), and 100-grain weight (g). Dry panicle weight and grain yield were measured using a digital balance, whereas 100-grain weight was determined using an analytical balance (0.01 g precision).

Insect assessment

Populations of ear-head bugs (*Calocoris angustatus*) and sorghum midge larvae were assessed on the same 10 randomly selected panicles per plot following the procedure described by Sharma et al. [16].

2.6 Seed Quality and Storage Evaluation

Following harvest, seeds from each treatment were dried to a safe storage moisture content, cleaned manually, and stored in Purdue Improved Crop Storage (PICS) bags under ambient laboratory conditions. Seed quality was evaluated immediately after harvest (0 months after storage) and after 3 and 6 months of storage [17, 18]. Additional postharvest assessments of storage characteristics were conducted after 30, 60, 90, 150, and 180 days of storage.

Seed germination (%) was determined using 100 seeds per replicate, placed on moistened paper towels and incubated at 25–30°C for seven days according to the International Seed Testing Association (ISTA) procedures [19]. Seedling vigour was assessed using the 1–9 rating scale of Abdul-Baki and Anderson [20], consistent with ISTA guidelines [21], where **1** represents highly vigorous seedlings and **9** represents weak or abnormal seedlings.

Grain moisture content (%) was measured using a calibrated Damiński TwistGrain Pro® moisture meter (Damiński S.A., Olsztyn, Poland). Moisture loss (%) was calculated relative to the initial seed moisture content at the commencement of storage. Grain damage (%) was determined from 200 g grain samples by quantifying insect exit holes according to Boxall [22]. Live and dead storage insects were manually separated and counted from the same samples.

2.7 Pathogen Isolation and Identification

Seed health was assessed using the standard blotter method according to the International Seed Testing Association (ISTA) procedures [19]. For each experimental plot, three replicates of 20 seeds were randomly selected, placed on moistened sterile blotter paper in Petri dishes, and incubated at $22 \pm 2^\circ\text{C}$ under a 12 h light/12 h dark photoperiod for seven days. Emerging fungal colonies were examined under a stereomicroscope and identified based on colony morphology, pigmentation, and microscopic spore characteristics following Leslie and Summerell [23] and ISTA procedures [19]. Pathogen incidence (%) was calculated as the percentage of infected seeds, with particular emphasis on *Fusarium* spp., *Curvularia* spp., *Aspergillus flavus*, and *Macrophomina phaseolina*.

2.8 Statistical Analysis

Data were analysed using R version 4.4.1 [24]. The experimental plot was considered the experimental unit for all analyses. Continuous variables were analysed using factorial analysis of variance (ANOVA) appropriate for a randomised complete block design (RCBD). Prior to analysis, model residuals were assessed for normality and homogeneity of variance. Count data were log-transformed using $\log(x + 1)$ where necessary to satisfy model assumptions. Statistical analyses were performed on transformed data where applicable, whereas treatment means are presented on the original measurement scale for ease of interpretation. Ordinal response variables, including grain mould severity and seedling vigour, were analysed using the aligned rank transform (ART) ANOVA, followed by ART-C pairwise comparisons [25]. Where ANOVA indicated significant treatment effects, treatment means were separated using Fisher's least significant difference (LSD) test at $P \leq 0.05$. Relationships among grain mould incidence, grain mould severity, fungal pathogen incidence, and seed quality parameters were evaluated using Spearman's rank correlation coefficient (ρ).

3. Results

3.1 Effects of Fungicide Type and Application Timing on Grain Mould Incidence and Severity

Grain mould incidence and severity were significantly influenced by fungicide type and application stage (Fig. 2a,b). Across both sorghum genotypes, fungicide application at the flowering stage consistently produced the lowest grain mould incidence and severity. Disease levels increased progressively when applications were delayed to the milking and dough stages and were highest in the untreated controls. Among all treatment combinations, Kapaala treated with Adepa at the flowering stage recorded the

lowest grain mould incidence (1.93%) and severity score (1.23), whereas the untreated ADV23012 plots exhibited the highest incidence (44.45%) and severity score (7.40) (Fig. 2a,b).

3.2 Effects of Fungicide Application Timing on Seed Germination During Storage

Seed germination declined progressively throughout the storage period across all fungicide treatments, sorghum genotypes, and application stages (Fig. 3A–D). However, fungicide application at the flowering stage consistently maintained higher germination percentages than applications at the milking or dough stages and the untreated controls. Under both Adepa and Guardian Xtra, flowering-stage application maintained higher germination throughout storage in both genotypes, with Kapaala consistently exhibiting greater germination than ADV23012, particularly following flowering- and milking-stage applications (Fig. 3A–D). By six months of storage, the lowest germination percentages were generally observed following dough-stage applications and in the untreated controls, with the poorest performance occurring in untreated or late-treated ADV23012, particularly under Guardian Xtra (Fig. 3A–D).

Fig. 3A–D Germination (%) of sorghum seeds during six months of storage as influenced by variety, fungicide type, and application timing

3.3 Effects of Fungicide Type and Application Timing on Seed Quality and Storage Performance

Seed quality and storage performance after six months of storage were significantly influenced by fungicide type and application stage (Table 2). Across both sorghum genotypes, fungicide application at the flowering stage generally maintained higher germination percentages and superior seedling vigour than applications at the milking or dough stages and the untreated controls. Among all treatment combinations, Kapaala treated with Adepa at the flowering stage recorded the highest germination (83.67%), whereas untreated ADV23012 recorded the lowest germination (26.33%) together with the poorest seedling vigour (vigour score = 8.67). Grain damage and moisture loss were generally lower following flowering- and milking-stage applications than following dough-stage applications or in the untreated controls. The highest moisture loss (12.66%) occurred in untreated ADV23012, whereas the lowest moisture loss (7.59%) was observed in Kapaala treated with Adepa at the milking stage. Across all treatments, Kapaala generally maintained higher germination and lower grain damage than ADV23012, indicating superior storage performance after six months of storage (Table 2).

Table 2

Effects of fungicide type and application timing on seed quality and storage performance of two sorghum genotypes after six months of storage.

Variety	Fungicide	Application timing	Germination (%) (6 MAS)	Seedling vigour (1–9) (6 MAS)	Grain damage (%) (180 DAS)	Live insects (no.) (180 DAS)	Moisture loss (%) (180 DAS)
ADV23012	Adepa	Flowering	77.67b	3.67d	12.67d	3.67a	9.64d
		Milking	60.00c	5.33c	16.00c	4.00a	8.27e
		Dough	35.33e	7.00b	18.00c	3.33b	10.86c
	Guardian Xtra	Flowering	62.33c	5.17c	16.00c	3.33b	10.07d
		Milking	19.33g	5.50c	17.67c	3.33b	10.03d
		Dough	24.67f	7.67a	28.67a	3.67a	11.45b
	Control	—	26.33f	8.67a	32.00a	4.00a	12.66a
Kapaala	Adepa	Flowering	83.67a	3.33d	9.67d	5.33a	9.77d
		Milking	73.00b	5.33c	13.00c	3.33b	7.59f
		Dough	31.67e	7.50a	16.33c	5.00a	10.46c
	Guardian Xtra	Flowering	81.00a	5.33c	13.00c	3.67a	10.57c
		Milking	43.67d	6.67b	16.00c	2.00b	8.75e
		Dough	26.67f	8.00a	24.33b	3.67a	10.25c
	Control	—	35.67e	7.33b	30.67a	4.00a	11.90b
Grand mean			48.64	6.18	18.86	3.74	10.16
CV (%)			6.06	11.96	16.15	28.44	4.08
LSD (0.05)			4.95	1.24	5.11	1.78	0.70
Note: Values are treatment means (n = 3). Means within a column followed by different lowercase letters differ significantly according to Fisher's LSD test at $P \leq 0.05$. MAS = months after storage; DAS = days after storage.							

3.4 Incidence of Fungal Pathogens in Stored Sorghum Grain

The incidence of fungal pathogens in stored sorghum grain was significantly affected by fungicide type and application stage (Table 3). Across all treatments, *Fusarium* spp. and *Curvularia* spp. were the predominant pathogens, whereas *Macrophomina phaseolina* and *Aspergillus flavus* occurred at lower incidences. Flowering-stage fungicide application generally resulted in lower pathogen incidence than

dough-stage application and the untreated controls. Kapaala treated with Adepa at the flowering stage recorded low incidences of *Curvularia* spp. (2.33%) and *Fusarium* spp. (6.00%), whereas untreated ADV23012 and dough-stage applications generally recorded higher pathogen incidences. The highest *Fusarium* spp. incidence (12.67%) occurred in ADV23012 treated with Guardian Xtra at the dough stage, while the highest *Aspergillus flavus* incidence (9.67%) was recorded in Kapaala treated with Adepa at the dough stage (Table 3).

Table 3
Incidence (%) of major fungal pathogens associated with sorghum grain under different fungicide application timings.

Variety	Fungicide	Spray Regime	<i>Macrophomina phaseolina</i>	<i>Aspergillus flavus</i>	<i>Curvularia</i> spp	<i>Fusarium</i> spp
ADV23012	Adepa	flowering	2.67h	0.00b	5.00i	8.67h
		milking	2.00e	2.67a	6.33e	9.67f
		dough	2.67g	2.33a	6.00g	6.00j
	Control	—	3.67k	3.33a	7.00c	11.67c
	Guardian Xtra	flowering	1.00b	2.67a	2.33m	11.33d
		milking	3.00i	2.67a	5.00j	10.00e
		dough	3.67l	3.33a	5.33h	12.67a
Kapaala	Adepa	flowering	1.00c	2.67a	2.33n	6.00j
		milking	1.67d	3.00a	5.00k	8.00i
		dough	5.00e	9.67a	6.67d	12.33b
	Control	—	2.33f	3.00a	6.33f	9.00g
	Guardian Xtra	flowering	0.67a	9.33a	9.00a	4.00k
		milking	3.00j	4.00a	3.67l	6.00j
		dough	4.00b	2.00a	7.67b	9.00g
Variety			0.519ns	0.026*	0.298ns	0.818ns
Fungicide			0.014*	0.001***	0.036*	< 0.001***
Spray Regime			0.381ns	0.001***	0.161ns	0.005**
Variety × Fungicide			0.243ns	0.028*	0.065ns	< 0.001***
Variety × Spray Regime			0.005**	0.026*	0.605ns	< 0.001***
Fungicide × Spray Regime			0.064ns	0.042*	0.466ns	< 0.001***
Variety × Fungicide × Spray Regime			0.196ns	0.017*	0.014*	< 0.001***
Note: Values are treatment means (n = 3). Means within a column followed by different lowercase letters are significantly different according to Fisher's LSD test (P ≤ 0.05). ns = not significant; *P < 0.05; **P < 0.01; ***P < 0.001.						

Variety	Fungicide	Spray Regime	<i>Macrophomina phaseolina</i>	<i>Aspergillus flavus</i>	<i>Curvularia</i> spp	<i>Fusarium</i> spp
Grand Mean			2.60	3.62	5.55	8.88
CV (%)			55.84	93.35	34.04	19.73
LSD (0.05)			1.57	4.40	3.70	2.93
Note: Values are treatment means (n = 3). Means within a column followed by different lowercase letters are significantly different according to Fisher's LSD test ($P \leq 0.05$). ns = not significant; *$P < 0.05$; **$P < 0.01$; ***$P < 0.001$.						

3.5 Correlation Between Grain Mould Traits and Seed Quality Parameters

Grain mould incidence and severity were strongly associated with seed quality parameters throughout storage (Fig. 4). Both traits were strongly and negatively correlated with seed germination immediately after harvest (0 months after storage) and after three and six months of storage ($\rho = -0.96$ to -0.99). In contrast, grain mould incidence and severity were strongly and positively correlated with seedling vigour scores ($\rho = 0.93$ – 0.96) across all storage periods.

4. Discussion

4.1 Fungicide Application Timing and Suppression of Grain Mould

Flowering-stage fungicide application consistently provided the greatest suppression of grain mould, confirming that the timing of disease intervention is a critical determinant of successful grain mould management in sorghum. Anthesis represents the primary infection window because exposed floral tissues and developing kernels are highly susceptible to colonisation by grain mould pathogens under conditions of high humidity and prolonged panicle wetness. Protecting panicles during this stage likely reduced primary pathogen establishment, thereby limiting subsequent fungal colonisation and disease development throughout grain filling. These observations agree with previous studies demonstrating that fungicide applications are most effective when synchronised with flowering, before extensive pathogen invasion of developing grains occurs [3, 4, 8, 26].

The progressive increase in grain mould incidence and severity following fungicide application at the milking and dough stages further emphasises that successful grain mould management depends on preventing pathogen establishment rather than suppressing established infections. Grain mould pathogens, including *Fusarium*, *Curvularia*, *Aspergillus*, and *Macrophomina* species, typically initiate infection during flowering and early grain development, after which favourable environmental conditions promote rapid colonisation of developing kernels [3, 5, 12]. Consequently, fungicides function predominantly as protective interventions, with substantially reduced effectiveness once fungal

colonisation has progressed. These findings reinforce the importance of aligning fungicide application with host phenology and pathogen infection dynamics as fundamental components of integrated grain mould management.

Although flowering-stage application of both fungicides substantially reduced grain mould, Adepa consistently achieved greater suppression, particularly in Kapaala. This response probably reflects the combined influence of fungicide efficacy and genotype-dependent characteristics, including panicle architecture and inherent disease tolerance, which collectively reduced opportunities for pathogen establishment and subsequent disease development [4, 8]. Similar interactions between host genotype and disease management have been reported in cereal pathosystems, where varietal characteristics influence both disease susceptibility and treatment effectiveness. However, the present study extends these observations by demonstrating that the benefits of timely fungicide application are not confined to field disease suppression but have measurable implications for subsequent seed quality and storage performance.

Unlike previous studies that primarily evaluated fungicide efficacy based on reductions in grain mould incidence and severity before harvest, the present study demonstrates that the timing of fungicide application determines the extent to which preharvest disease suppression is translated into improved postharvest grain quality. This finding broadens the current understanding of grain mould management by identifying flowering-stage fungicide application as a key intervention linking field disease control with postharvest quality preservation. Consequently, integrating timely fungicide application with less susceptible cultivars represents a practical strategy for enhancing grain quality, maintaining seed viability, and reducing postharvest losses in sorghum production systems under humid tropical conditions.

4.2 Effects of Fungicide Application Timing on Seed Quality Preservation During Storage

The superior germination and seedling vigour observed following flowering-stage fungicide application indicate that effective suppression of grain mould before harvest contributed to the preservation of seed physiological quality during storage. By limiting pathogen establishment during grain development, timely fungicide application likely protected developing embryos and seed reserves from fungal invasion, thereby maintaining higher seed viability and vigour throughout the six-month storage period. Similar relationships between effective preharvest disease management and improved postharvest seed quality have been reported in sorghum and other cereals [9, 11].

The strong negative correlation between grain mould severity and germination further demonstrates the detrimental effects of fungal infection on seed viability. Grain mould pathogens invade developing kernels, impair embryo integrity, and accelerate physiological deterioration through membrane disruption and depletion of seed reserves, resulting in reduced germination and poorer seedling performance during storage [27, 7]. Consequently, the higher seedling vigour scores recorded following dough-stage application and in the untreated controls reflect greater seed deterioration associated with increased disease pressure and prolonged fungal colonisation.

Kapaala consistently maintained better seed quality during storage than ADV23012, suggesting that varietal characteristics complemented fungicide protection in preserving seed viability. Importantly, the present study demonstrates that the benefits of timely preharvest disease management extend beyond reducing field infection to preserving seed physiological quality during storage. This finding strengthens the concept that effective grain mould management should be viewed not only as a disease control strategy but also as an approach for maintaining postharvest seed quality and storage stability under tropical production conditions.

4.3 Storage Deterioration and Fungal Colonisation

The reduced grain damage, insect infestation, and moisture loss observed following flowering-stage fungicide application indicate that effective preharvest suppression of grain mould contributed to improved storage stability. By limiting fungal infection during grain development, timely fungicide application likely reduced the amount of fungal inoculum entering storage, thereby slowing grain deterioration and preserving postharvest quality. Similar relationships between effective preharvest disease management and improved postharvest grain quality have been reported in sorghum and other cereals stored under tropical conditions [9, 11].

The greater deterioration observed following dough-stage application and in the untreated controls further demonstrates that inadequate disease suppression before harvest predisposes grain to progressive deterioration during storage. Fungal colonisation compromises grain integrity through degradation of structural tissues and depletion of stored reserves, increasing susceptibility to insect damage, moisture fluctuations, and secondary microbial invasion [22, 10]. Consequently, delayed fungicide application provided less protection against the cumulative effects of fungal infection on grain storability.

The predominance of *Fusarium* spp. and *Curvularia* spp. across treatments further supports the biological link between field infection and subsequent storage deterioration. Their higher incidence following delayed fungicide application and in the untreated controls suggests that inadequate disease management before harvest permitted greater fungal persistence during storage. Although *Aspergillus flavus* occurred at comparatively lower incidences, its detection remains important because of its potential to proliferate under warm storage conditions and contribute to spoilage and mycotoxin contamination [6]. Collectively, these findings demonstrate that effective preharvest disease management not only suppresses grain mould in the field but also reduces fungal carry-over into storage, providing further evidence that disease management before harvest influences subsequent storage stability and grain quality.

4.4 Implications for Integrated Grain Mould Management in Sorghum

The strong relationships among grain mould incidence, grain mould severity, and seed quality demonstrate that effective preharvest disease management is fundamental to maintaining grain quality during storage. Reduced disease was consistently associated with higher germination, improved seedling

vigour, lower fungal incidence, and greater storage stability, indicating that the benefits of disease management extend beyond field protection into the postharvest phase. Similar relationships have been reported in sorghum and other cereals, where minimising preharvest fungal infection improved postharvest seed quality and reduced storage losses [9, 11].

The consistent superiority of flowering-stage fungicide application across disease suppression, seed quality preservation, pathogen incidence, and storage performance supports the hypothesis that intervention during the primary infection period provides the greatest protection against grain mould. The superior performance of Kapaala further indicates that genotypic differences in grain mould susceptibility can complement fungicide application as part of an integrated disease management strategy. Consequently, combining flowering-stage fungicide application with less susceptible cultivars and appropriate postharvest storage practices offers a practical and sustainable approach to reducing disease-related losses under humid tropical conditions.

Beyond its practical implications, the present study demonstrates that the timing of preharvest disease management determines not only the effectiveness of grain mould suppression but also the extent to which postharvest seed physiological quality and storage stability are preserved. By linking field disease management with postharvest quality preservation, these findings provide new evidence supporting a more integrated approach to grain mould management in sorghum and offer a framework for improving seed quality and reducing postharvest losses in tropical production systems.

5. Conclusion

Fungicide application timing significantly influenced grain mould development, seed quality, fungal incidence, and storage performance in sorghum. Application at the flowering stage consistently provided the greatest suppression of grain mould, resulting in higher germination, improved seedling vigour, lower fungal incidence, and enhanced storage stability compared with later applications and untreated controls. The predominance of *Fusarium* spp. and *Curvularia* spp. further emphasises the importance of protecting developing grains during the primary infection period to minimise fungal carry-over into storage.

Beyond improving field disease control, the present study demonstrates that the timing of preharvest fungicide application influences the preservation of postharvest seed physiological quality and storage stability. Although Adepa applied at the flowering stage, particularly in Kapaala, produced the best overall performance, the findings indicate that timely fungicide application, combined with less susceptible cultivars, represents an effective component of integrated grain mould management for preserving grain quality, maintaining seed viability, and reducing postharvest losses under humid tropical production systems.

Future research should validate these findings across multiple seasons, environments, and sorghum genotypes, evaluate the long-term effects of flowering-stage fungicide application on mycotoxin accumulation, and investigate its integration with resistant cultivars and complementary cultural practices to strengthen sustainable grain mould management.

Declarations

Acknowledgements

The authors acknowledge the support of the Council for Scientific and Industrial Research (CSIR)-Savanna Agricultural Research Institute (SARI) for providing research facilities and field support. We also thank the Kwame Nkrumah University of Science and Technology for academic guidance and supervision.

Author contributions

J.M.A.: Conceptualization, Methodology, Investigation, Data curation, Formal analysis, Writing—original draft. P.A.: Investigation, Data curation, Validation. M.M.S.: Data curation, Validation. S.L.: Investigation. I.S.: Conceptualization, Supervision, Project administration, Writing—review and editing. P.A.A.: Investigation, Validation, Resources. E.G.: Methodology, Writing—review and editing. F.A.: Supervision, Methodology, Writing—review and editing. E.A.A.: Writing—review and editing. F.K.: Supervision, Resources, Writing—review and editing. All authors read and approved the final manuscript.

Funding

The authors did not receive support from any organization for the submitted work.

Data availability

The datasets generated and/or analysed during the current study are available from the corresponding author on reasonable request.

Ethics approval and consent to participate

Not applicable. This study involved cultivated sorghum (*Sorghum bicolor* (L.) Moench) plant materials obtained from the CSIR–Savanna Agricultural Research Institute (CSIR–SARI) sorghum breeding programme and evaluated at the CSIR–SARI Manga Agricultural Research Station, Ghana. The use and cultivation of the plant materials complied with applicable institutional, local and national guidelines. No wild plant materials or endangered or protected plant species were collected or used in this study. No specific permissions or licences were required for the use of these cultivated experimental materials. The study did not involve human participants or animals.

Consent for publication

Not applicable.

Competing interests

The authors declare no competing interests.

References

1. Food and Agriculture Organization. FAOSTAT statistical database [Internet]. Rome: FAO. 2023 [cited 2026 Aug 7]. Available from: <https://www.fao.org/faostat/>
2. Paterson AH, Borrell AK, Mullet JE. Sorghum improvement for climate resilience and food security. *Plant Biotechnol J*. 2021;19(12):2412–24. <https://doi.org/10.1111/pbi.13675>.
3. Forbes GA, Bandyopadhyay R. The biology and epidemiology of sorghum grain mold. *Plant Dis*. 1997;81(7):715–22. <https://doi.org/10.1094/PDIS.1997.81.7.715>.
4. Bandyopadhyay R, Butler DR, Chandrashekar A, Reddy RK, Navi SS. Biology, epidemiology, and management of sorghum grain mold. In: Chandrashekar A, Bandyopadhyay R, Hall AJ, editors. Technical and institutional options for sorghum grain mold management. Patancheru (India). International Crops Research Institute for the Semi-Arid Tropics (ICRISAT); 2000. pp. 34–71.
5. Ackerman A, Wenndt A, Boyles R. The sorghum grain mold disease complex: pathogens, host responses, and the bioactive metabolites at play. *Front Plant Sci*. 2021;12:660171. <https://doi.org/10.3389/fpls.2021.660171>.
6. Khatibi PA, Wilson JP, Prom LK. Sorghum grain mold and associated mycotoxins. *Toxins (Basel)*. 2020;12(9):567. <https://doi.org/10.3390/toxins12090567>.
7. Shephard GS. Current status of mycotoxin contamination in Africa. *World Mycotoxin J*. 2018;11(2):253–61. <https://doi.org/10.3920/WMJ2017.2348>.
8. Gichile H. Review on sorghum grain mold and its sustainable management methods through host resistance. *J Agric Res Adv*. 2023;5(3):34–41.
9. Prom LK, Isakeit T, Perumal R, Rooney WL, Magill CW. Evaluation of grain mold resistance in sorghum using field and laboratory techniques. *Plant Dis*. 2011;95(5):567–72. <https://doi.org/10.1094/PDIS-09-10-0674>.
10. Wilson JP, Frederiksen RA. Grain molds. In: Frederiksen RA, Odvody GN, editors. *Compendium of sorghum diseases*. 2nd ed. St. Paul (MN): APS; 2002. pp. 35–8.
11. Ahmed Mohammed, Chala A, Dejene M, Fininsa C. Sorghum grain mold fungi: occurrence and distribution in freshly harvested and stored sorghum in Eastern Ethiopia. *J Stored Prod Postharvest Res*. 2025;16(2):24–39. <https://doi.org/10.5897/JSPPR2024.0341>.
12. Sharma R, Thakur RP, Rao VP, Reddy BVS. Grain mold resistance in sorghum: challenges and opportunities. *J SAT Agric Res*. 2010;8:1–10.
13. Thakur RP, Reddy BVS, Indira S, Rao VP, Navi SS, Yang XB, Ramesh S. Sorghum grain mold. Information Bulletin No. 72. Patancheru (India). International Crops Research Institute for the Semi-Arid Tropics (ICRISAT); 2006.
14. Food and Agriculture Organization. FAO soil classification system. Rome: FAO; 1991.
15. Kanton RAL, Prasad PVV, Ansoba EY, Abdulai AL, Bidzakin JK, Asungre PA, Denwar NN, Mahama GY. Maize-legumes rotation effects on growth and yield of maize in a semi-arid agro-ecology in Northern Ghana. *Int J Plant Soil Sci*. 2019;29:1–16. <https://doi.org/10.9734/IJPSS/2019/v29i630162>.
16. Sharma HC, Taneja SL, Leuschner K, Nwanze KF. Techniques to screen sorghum for resistance to insect pests. Patancheru (India): International Crops Research Institute for the Semi-Arid Tropics

- (ICRISAT); 1985.
17. Baributsa D, Lowenberg-DeBoer J, Murdock LL, Moussa B. Purdue Improved Crop Storage (PICS) bags for postharvest storage. *J Stored Prod Res.* 2010;46:1–5.
<https://doi.org/10.1016/j.jspr.2009.08.001>.
 18. Sudini H, Ranga Rao GV, Gowda CLL, Chandrika R, Margam V, Rathore A, Murdock LL. Purdue Improved Crop Storage (PICS) bags for safe storage of groundnut seed. *J Stored Prod Res.* 2015;64:133–8.
 19. International Seed Testing Association. International rules for seed testing. Bassersdorf (Switzerland): ISTA; 2016.
 20. Abdul-Baki AA, Anderson JD. Vigor determination in soybean seed by multiple criteria. *Crop Sci.* 1973;13(6):630–3. <https://doi.org/10.2135/cropsci1973.0011183X001300060013x>.
 21. International Seed Testing Association. Seed vigor testing handbook. Bassersdorf (Switzerland): ISTA; 2015.
 22. Boxall RA. A critical review of the methodology for assessing farm-level grain losses after harvest. London: Tropical Development and Research Institute; 1986.
 23. Leslie JF, Summerell BA. The *Fusarium* laboratory manual. Ames (IA): Blackwell Publishing; 2006.
 24. R Core Team. R: A language and environment for statistical computing [Internet]. Vienna (Austria): R Foundation for Statistical Computing. 2024. Available from: <https://www.r-project.org/>
 25. Wobbrock JO, Findlater L, Gergle D, Higgins JJ, Conference on Human Factors in Computing Systems. The aligned rank transform for nonparametric factorial analyses using only ANOVA procedures. In: Proceedings of the SIGCHI ; 2011 May 7–12; Vancouver, BC, Canada. New York (NY): Association for Computing Machinery; 2011. pp. 143–146.
<https://doi.org/10.1145/1978942.1978963>
 26. Das IK, Aruna C, Tonapi VA. Sorghum grain mold. Hyderabad (India): ICAR–Indian Institute of Millets Research; 2020.
 27. Waniska RD, Rooney LW, Bandyopadhyay R. Effects of grain mold on sorghum grain quality. In: Chandrashekar A, Bandyopadhyay R, Hall AJ, editors. Technical and institutional options for sorghum grain mold management. Patancheru (India). International Crops Research Institute for the Semi-Arid Tropics (ICRISAT); 2000. pp. 125–35.

Figures

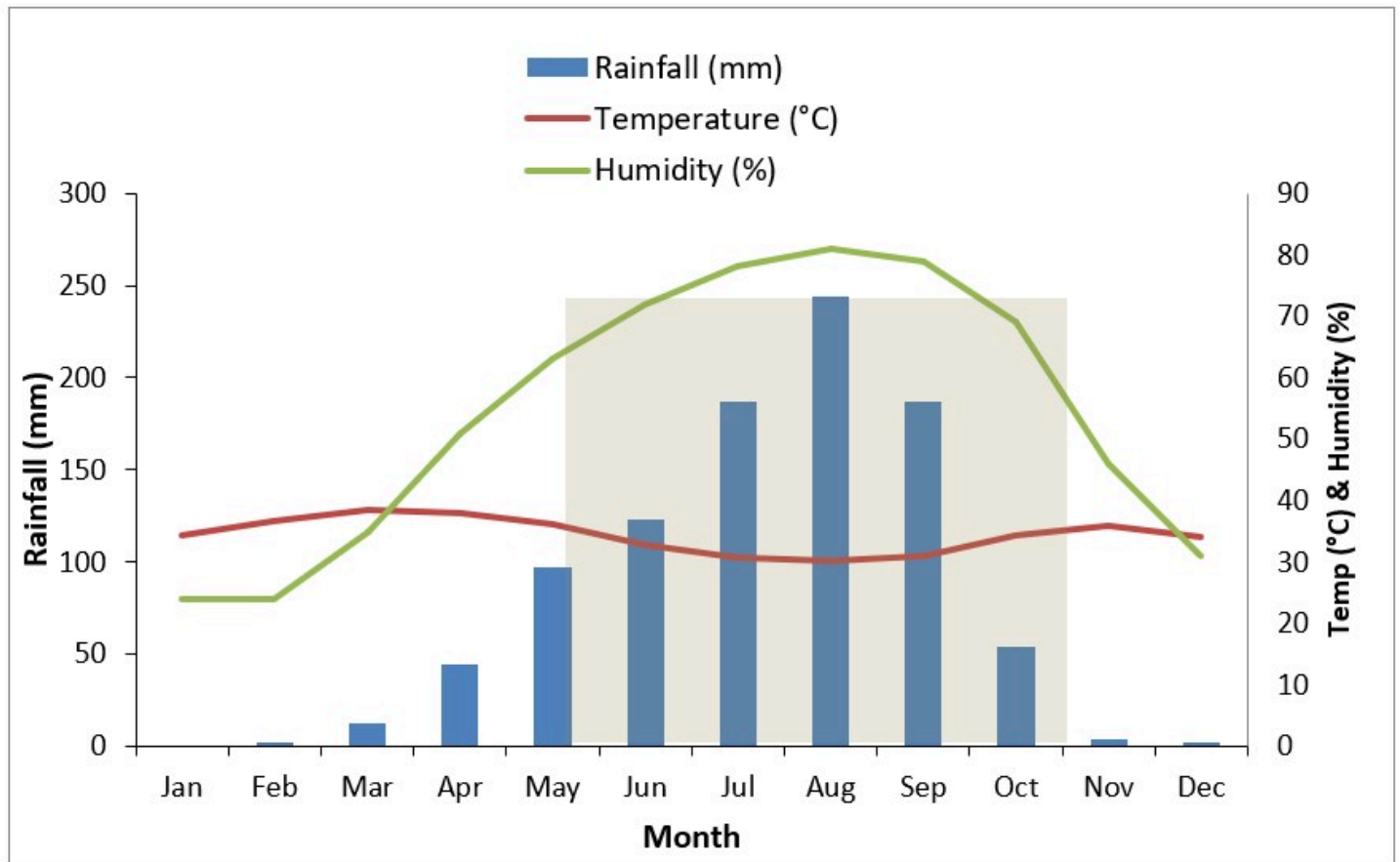


Figure 1

Fig. 1 Monthly rainfall, temperature and relative humidity trends in the Upper East Region of Ghana

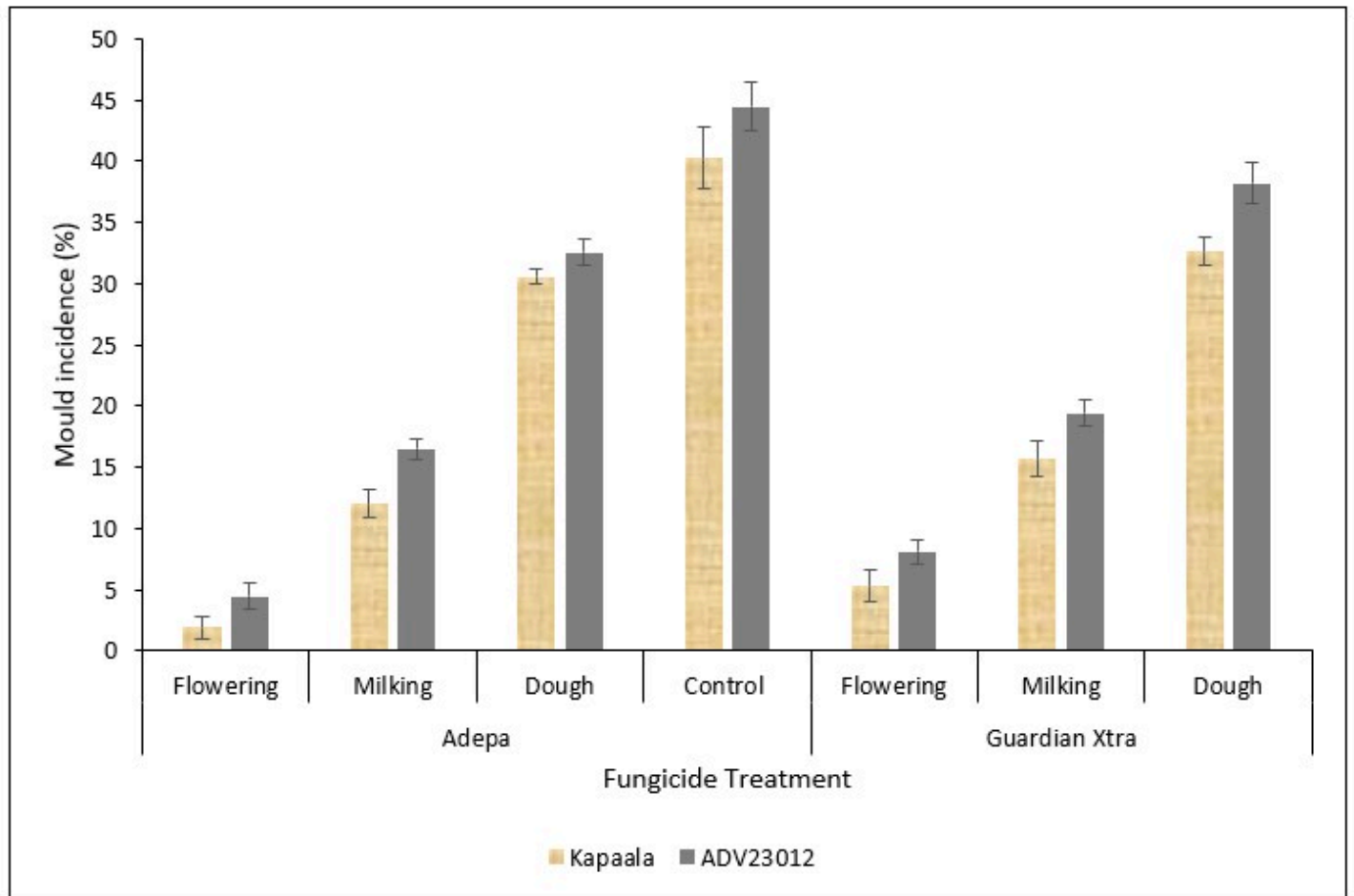


Figure 2

Fig. 2a Effect of fungicide type and application timing on grain mould incidence (%) of two sorghum genotypes. Values are means $\pm$ standard deviation (n = 3)

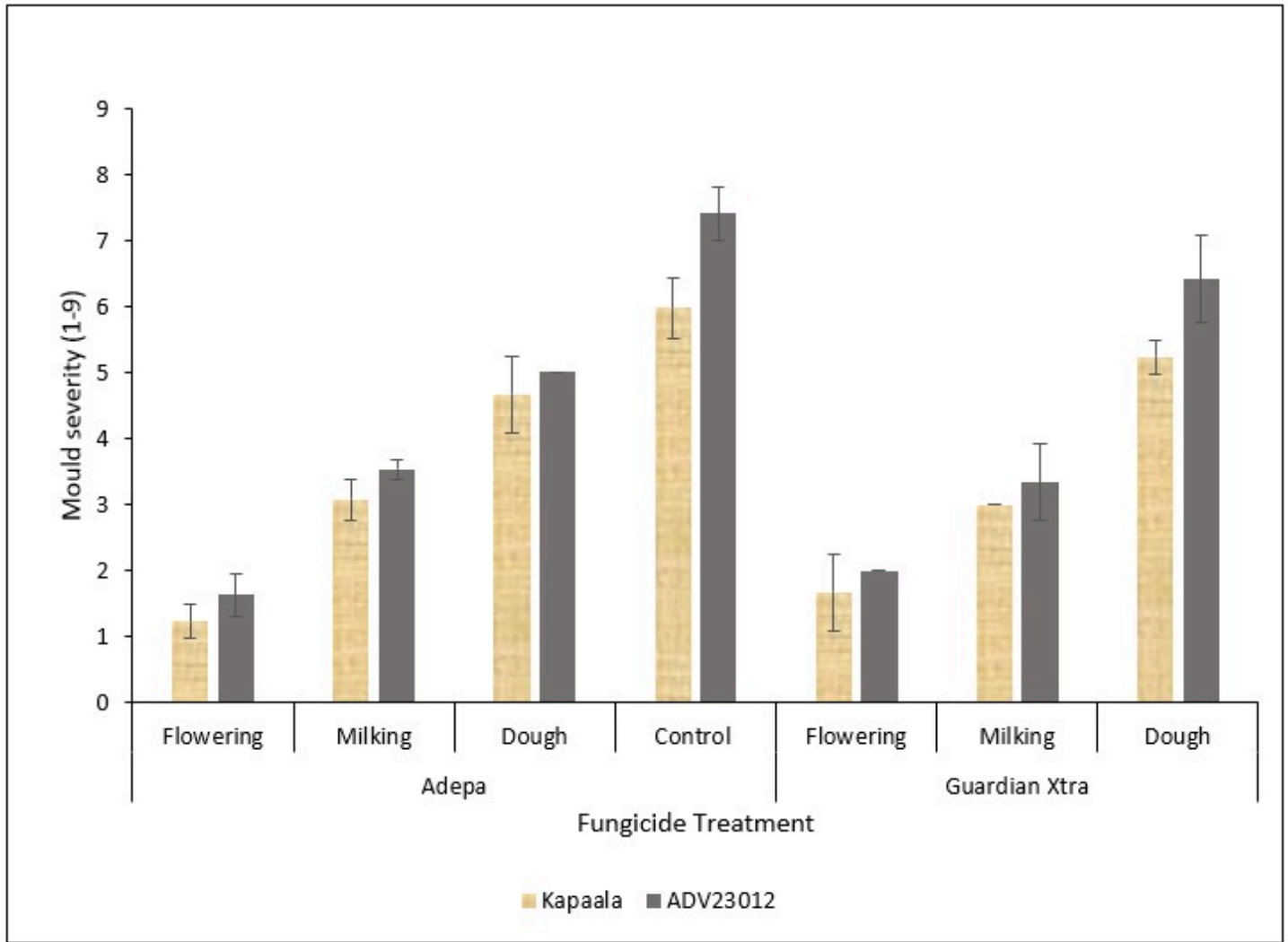


Figure 3

Fig. 2b Effect of fungicide type and application timing on grain mould severity (1–9 scale) of two sorghum genotypes. Values are means $\pm$ standard deviation (n = 3)

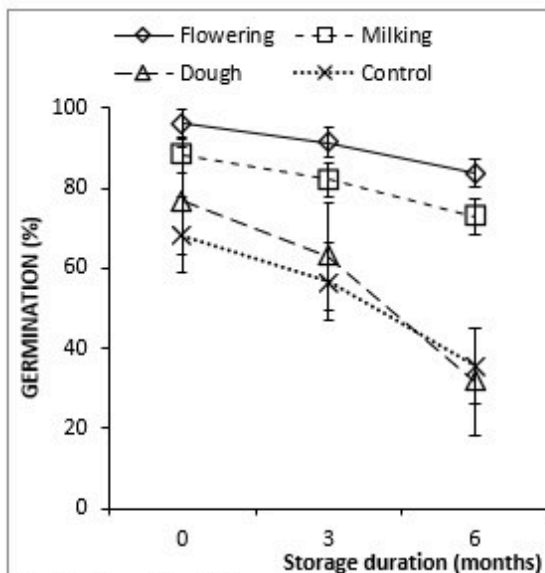


Fig. 3A. Kapaala × Adepa

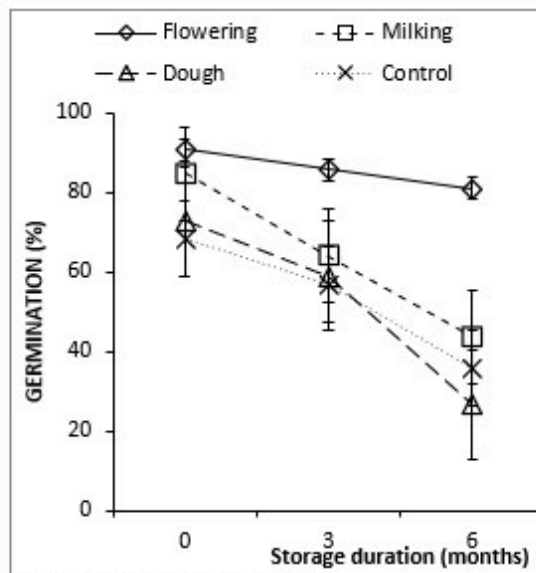


Fig. 3B. Kapaala × Guardian Xtra

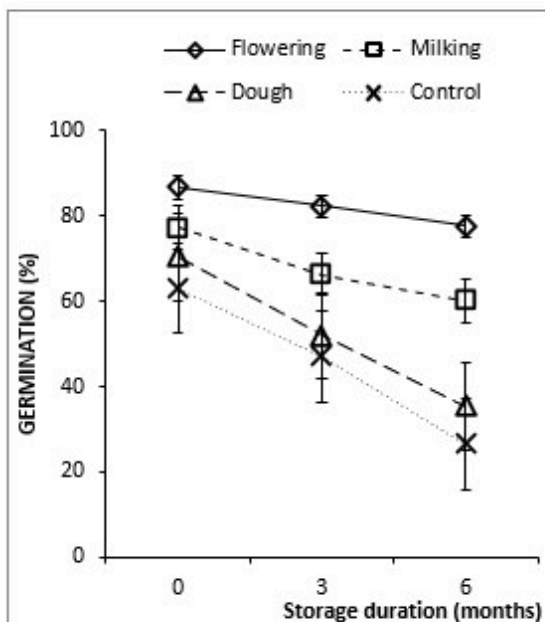


Fig. 3C. ADV23012 × Adepa

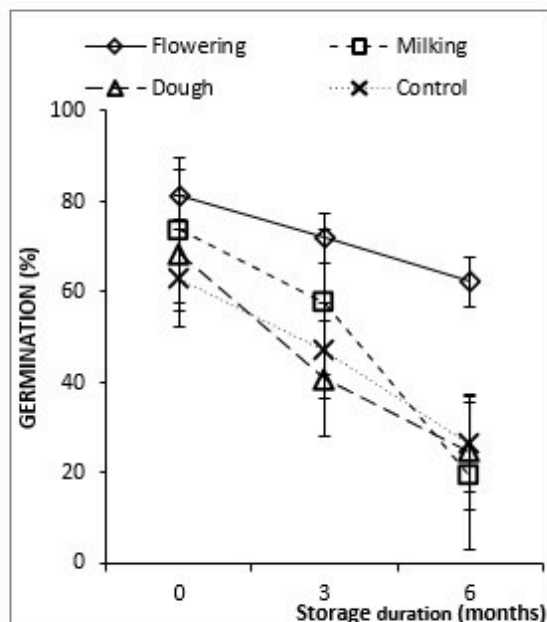


Fig. 3D. ADV23012 × Guardian Xtra

Figure 4

Fig. 3A–D Germination (%) of sorghum seeds during six months of storage as influenced by variety, fungicide type, and application timing

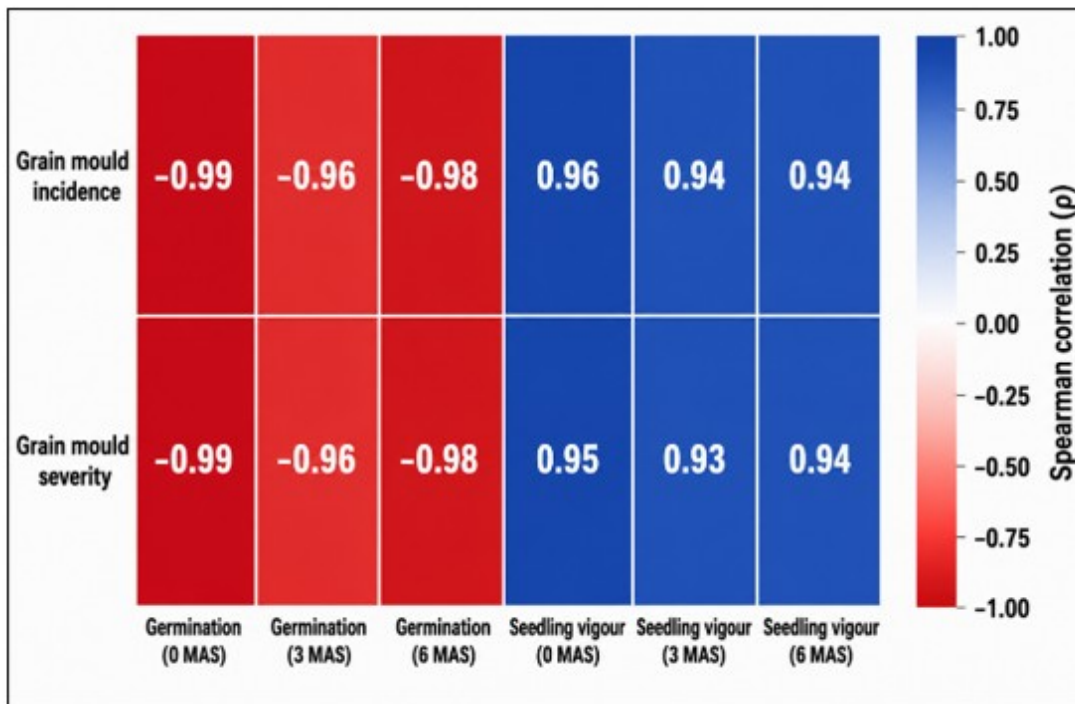


Figure 5

Fig. 4 Heatmap showing Spearman's rank correlation coefficients (ρ) between grain mould incidence, grain mould severity, and seed quality parameters measured immediately after harvest (0 MAS) and after 3 and 6 months of storage (MAS). Positive values indicate direct associations, whereas negative values indicate inverse associations. Higher seedling vigour scores represent poorer seedling performance

Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- [Tables.docx](#)
- [Highlights.docx](#)