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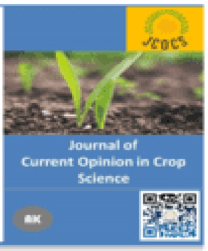

RESEARCH ARTICLE

Resistance of Common Bean (*Phaseolus vulgaris* L.) Varieties to Bruchid Infestation in Burundi

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ABSTRACT

Common beans (*Phaseolus vulgaris* L.) are essential for global food and nutritional security, but post-harvest losses caused by bruchid beetles (*Acanthoscelides obtectus* (Say)) and *Zabrotes subfasciatus* (Boheman)) significantly reduce seed quality and quantity, undermining livelihoods and incomes. This study aimed to evaluate the preference and damage of selected bean varieties to bruchid infestation under controlled and non-controlled storage conditions in Burundi. Experiments were conducted using four common bean varieties Kinure, Mukungugu, Musore, and Gasilida across three sites: ISABU Bujumbura, ISABU Murongwe, and ISABU Kayanza, with 72 treatments on all conditions. In the controlled environment, adult bruchids were introduced directly into sealed experimental jars; in the non-controlled environment, insects were allowed to infest seeds freely from the surrounding environment. A completely randomized design with three replications was used. Before storage, baseline measurements including seed moisture content and seed weight (1,000 g per lot) were recorded. Data were collected on three time points, including counts of live and dead bruchids, seed damage rates, weight loss. Results showed that Kinure consistently exhibited the highest resistance across all storage environments, with over 90% unperforated seeds and minimal weight loss, while Gasilida was the most preferred by bruchids. At ISABU Murongwe and ISABU Kayanza, Kinure maintained unperforated seed rates above 90%, whereas Gasilida recorded up to 57.7% perforation. *A. obtectus caused* less damage than *Z. subfasciatus*, and bruchid survival ranged from 60% to 79%. Overall, Kinure and Mukungugu performed best under both storage conditions, highlighting their potential for mitigating post-harvest losses in smallholder farming systems.

Keywords: Seed damage; post-harvest entomology; Common bean; Storage condition.

INTRODUCTION

Common beans, *Phaseolus vulgaris* L., are among the widely extensively cultivated and traded legumes globally, playing a central role in human nutrition and food security due to their rich protein content, affordability, and versatility in diverse diets (Ikhajiagbe et al., 2022; Odeku et al., 2024). Their global production is concentrated in Latin America, parts of Asia, and sub-Saharan Africa, with Brazil, India, Myanmar, Mexico, and the United States consistently ranking among the top producers (Siddiq et al., 2022; Mathobo & Mathobo, 2024). These nations not only fulfill substantial domestic consumption but also contribute to international markets through significant export volumes (Nchanji et al., 2023; Uebersax *et al*., 2023). On the other hand, regions with limited bean-growing capacity, such as Europe and parts of North Africa remain major importers, highlighting the crop's strategic importance in global agricultural trade (Funes et al., 2022; Islam et al., 2024). The increasing demand for plant-based protein sources has further elevated the position of common beans in international markets, reinforcing their role in sustainable food systems and cross-border supply chains (Chaudhary & Singh, 2024; Nath, 2025).

In Africa, common beans are extensively grown, particularly in the Great Lakes region, where countries such as Kenya, Uganda, Rwanda, Tanzania, and Ethiopia contribute a substantial share to the continent's total production (Blair et al., 2021; Birachi et al., 2023; Magubika et al., 2025). Beans are cultivated across diverse agroecological zones, ranging from highland to mid-altitude areas, predominantly on smallholder farms, serving both subsistence and commercial markets (Figueiredo Menezes Cavalcanti et al., 2021; Nkhata et al., 2021). The regional bean trade is dynamic, characterized by significant cross-border movements within the East African Community (EAC) and neighbouring countries, supporting food security and rural economies (Rouillé et al., 2024; Quillet et al., 2024; Magubika et al., 2025). The adoption of improved bean varieties and expansion into marginal and previously underutilized lands has led to incremental gains in production volumes (Sharma et al., 2022; Adelabu & Franke, 2023). Seasonal variations and climate variability continue to shape production and trade patterns, while emerging value chains have started to integrate beans into regional processing and export markets, contributing to enhanced livelihoods (Barua et al., 2021; Esham et al., 2025).

In Burundi, common beans are widely cultivated across the country, grown in eleven agroecological zones spanning low, medium, and high altitudes ranging from 774 to 2,670 meters (Ochieng *et al*., 2014; Amongi et al., 2025). Farmers grow a wide variety of beans, including both traditional landraces and improved cultivars, which are sold in rural and peri-urban markets (Nchanji et al., 2022; Monroy-Sais *et al*., 2024). While most of the beans produced are consumed locally, surplus quantities are traded informally to neighbouring countries such as Rwanda and the Democratic Republic of Congo, contributing to regional food supply networks (Nduwarugira et al., 2023; Marivoet, 2024). Efforts in the region focus on the selection and multiplication of diverse bean varieties adapted to local agroecological conditions (Andualem et al., 2022; Wondaferew et al., 2024).

Common beans possess substantial economic importance worldwide, acting as a major source of income for millions of smallholder farmers, particularly in developing countries (Mkuna, 2022; Muteti et al., 2022). Beyond their role as a staple food, beans contribute significantly to rural livelihoods through local sales and participation in regional and international markets (Jjagwe et al., 2022; Ma et al., 2022). Globally, bean production and trade influence commodity markets, with leading producers engaging in export activities that shape trade dynamics (Kofi, 2024; Ocran, 2024). In Africa, where beans are a dietary staple, the crop supports both subsistence and commercial farming, generating income through intra-regional trade, especially within East and Central Africa (Okodua et al., 2023; de Haas et al., 2025). In Burundi, beans represent a vital economic crop, especially in provinces, like Gitega, where production surpluses are traded informally to neighbouring countries such as Rwanda and the Democratic Republic of Congo (Douma et al., 2022; Bitama, 2023). Furthermore, beans contribute to household food security and provide opportunities for women's empowerment, as women are often primary actors in bean production, processing, and marketing (Bacon et al., 2023; Ohagwu et al., 2024). The economic significance of beans also extends to the value chain, including seed multiplication, storage, and retail, underlining the crop's multifaceted contribution to both local and national economies (Bogale, 2021).

Despite the economic significance of common beans, production and post-harvest management face challenges that can undermine yield and grain quality. Among these, the infestation of storage pests such as bruchids (*Acanthoscelides obtectus* (Say*)* and *Zabrotes subfasciatus* (Boheman) poses a significant threat, leading to seed damage, weight loss, and reduced market value (Kaplin, 2022; Mesele et al., 2022). In addition, storage conditions, including temperature and humidity, critically affect pest development and infestation levels (Uebersax et al., 2022a; Vijayaram et al., 2025). Limited access to effective storage technologies and lack of comprehensive knowledge on varietal resistance contribute to ongoing post-harvest losses (Ariong et al., 2023; Nath et al., 2024). These challenges are particularly pressing in smallholder farming systems, where reliance on traditional storage methods and informal seed systems may exacerbate bruchid infestations. Therefore, the overall objective of this study was to improve bean storage by identifying common bean varieties with enhanced resistance to storage bruchids, thereby reducing seed damage and losses during storage. Specifically, the study aims to assess the susceptibility and preference of selected common bean varieties to *A. obtectus and Z. subfasciatus* under choice and no-choice storage conditions, and to evaluate seed damage, weight loss, and bruchid survival across the different bean varieties during storage.

MATERIALS AND METHODS

Study site

The study was carried out in the laboratories of the Institute of Agronomic Sciences of Burundi (ISABU), located in the provinces of Bujumbura, Gitega, and Kayanza. Bujumbura Province lies at an altitude of 800 to 1,000 meters above sea level, with average temperatures ranging from 18 °C to 35 °C, annual precipitation below 1,100 mm, and geographical coordinates of approximately 30°22'55"S and 29°21'41"E. ISABU Murongwe in Gitega Province is situated at an altitude of 1,600 to 2,000 meters above sea level, with average annual temperatures between 18°C and 25°C, annual precipitation ranging from 1,150 to 1,500 mm, a relative humidity of 60%, and coordinates of 3°35'37"S and 29°55'29"E. Lastly, samples were collected from ISABU in Kayanza Province, where temperatures range from 15°C to 17°C, the area receives annual precipitation of 1,200 to 1,400 mm, and the geographical coordinates are 2°55'19"S and 29°37'45"E.

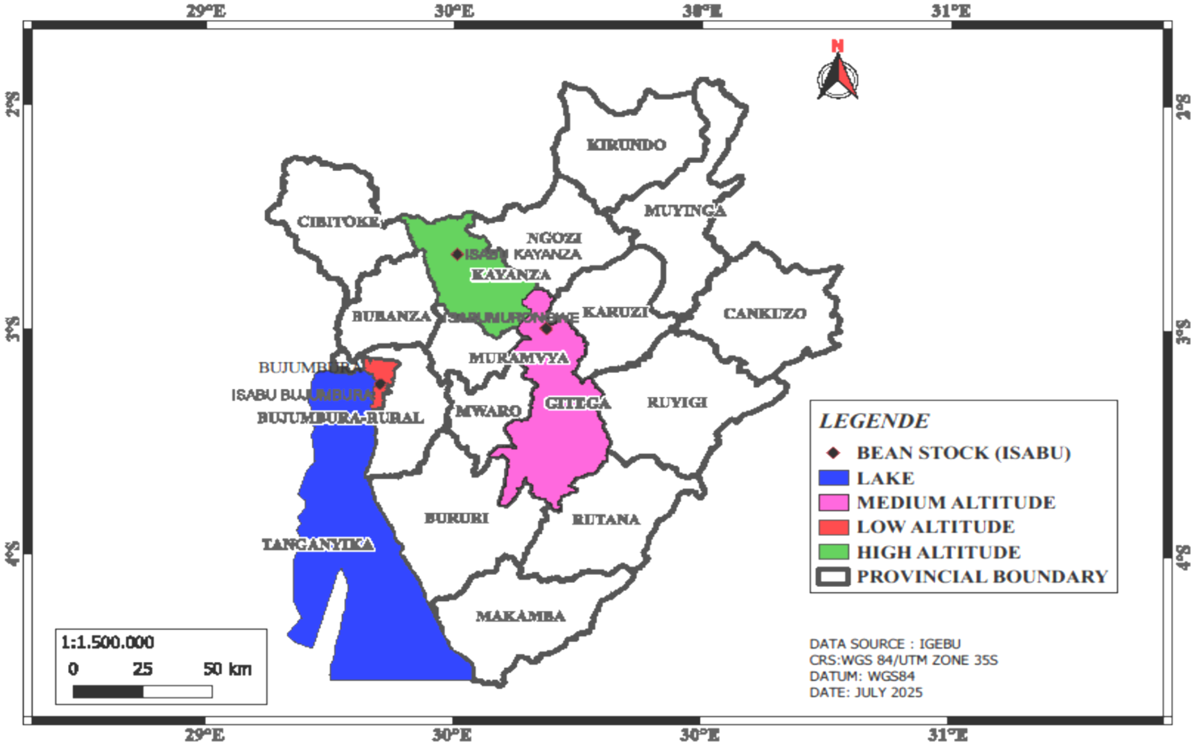

Figure 1. A map showing study sites across bean stock (ISABU)

Experimental design

Representative common bean varieties Kinure, Musore, Mukungugu, and Gasilida commonly grown in Burundi, were selected along with two bruchid species, *Acanthoscelides obtectus* and *Zabrotes subfasciatus*. After removing impurities, the beans were stored in clean plastic jars. The experiment was arranged as a Completely Randomized Design (CRD) with 72 treatments, including three replications and four control treatments for each variety. Two conditions were tested: no-choice and free-choice. In no-choice set-up (conditioned), 1 kilogram of seeds from each bean variety was placed in separate jars, each containing a moisture-absorbing desiccant packet. Five pairs of adult bruchids were directly introduced into each jar, which was then sealed with a lid as shown in Figure 2. In the free-choice setup 1 kilogram of seeds from each variety was placed in open jars, each also containing a desiccant packet (Figure 3). A sufficient number of adult bruchids were released in the vicinity of the jars, giving them the freedom to choose which variety to infest.

Figure 2. Set up of the no-choice condition storage in the laboratory

Figure 3. Set up of the free-choice condition storage in the laboratory

Data collection

Data collection was carried out over a 3.5-month storage period to monitor both seed condition and bruchid activity. Observations were conducted at three key intervals: 40 days after storage initiation (Dates 45742–45744; corresponding to 26–28 March 2025), 75 days (Dates 45777–45778; corresponding to 30 April–1 May 2025), and 105 days (Dates 45807–45809; corresponding to 31 May–2 June 2025). Before storage, baseline measurements were taken, including the moisture content standardized at 13% and the weight of each bean variety (1000 g), in line with recommended storage conditions. Environmental conditions within the storage areas were also monitored throughout the study. In Bujumbura, the average temperature was recorded at 26.7 °C with a mean relative humidity of 80%, while in Murongwe, the average temperature was 23.7 °C with 75% mean relative humidity, and in Kayanza, the average temperature was also 17 °C with a mean relative humidity of 75%.

Under each observation interval, records were taken on the number of *Acanthoscelides obtectus* and *Zabrotes subfasciatus* adults, including the counts of live and dead individuals for each species. To assess bean damage, a subsample of 100 seeds was randomly drawn from the 1000 g stored in each jar. Within this subsample, the number of perforated and unperforated seeds was recorded, and the weights of both healthy (unperforated) and perforated seeds were measured. These data allowed for the calculation of damage rates and preference indices for each bruchid species across the different bean varieties, as detailed in Equations 1–4.

$$Damage\ Rate(RT\ \%) = \frac{Number\ of\ Damaged\ Seeds}{Total\ Number\ of\ Seeds} \times 100 \qquad (1)$$

$$WL\ (\ \%) = \frac{WHSBS\ \ - WHSAS}{TWHSBS} \times 100 \qquad (2)$$

Where WL is weight loss; WHSBS is weight of healthy seeds before storage; WHSAS is weight of healthy seeds after storage.

$$Survival\ (Death)\ Rate\ (SR\ \%) = \frac{NL(D)AR}{TNAI} \times 100 \qquad (3)$$

Where NL(D)AR is the number of live or death adults recorded and TNAI is the total number of adults introduced in controlled storage.

$$Survival\ Rate\ (\%) = \frac{NL(D)R}{TNLD} \times 100 \qquad (4)$$

Where NL(D)R is the number of live or dead adults recorded and TNLDAR is the total number of live or dead adults recorded in non-controlled storage.

Statistical data analysis

The collected data were analysed using analysis of variance (ANOVA) to determine the effects of bean varieties, bruchid species, and storage conditions on the measured parameters. Treatment means were compared at a 5% significance level ($p < 0.05$). Where significant differences were detected, post hoc comparisons were performed to separate means and identify specific treatment effects. All statistical analyses were conducted using GenStat software, 20th Edition.

RESULTS

Acanthoscelides obtectus Under Controlled Storage Conditions

Effects of Bean Varieties and Site Conditions on Acanthoscelides obtectus Under Controlled Storage (Kayanza and Murongwe)

Variety had a significant ($p < 0.05$) effect on bruchid preference and seed damage for unperforated/perforated seeds, perforated seed weight, and also on seed weight attributes (Table 1). Kinure showed the highest resistance to bruchid infestation, with 92.5 % unperforated seeds and highest unperforated seed weight (37.9 g). Its perforated seeds were lowest (7.5 %) and perforated seed weight lower (2.9 g). Gasilida was the most susceptible: it had the lowest unperforated seeds (87.2 %), highest perforated seeds (12.8%), and highest perforated seed weight (3.8 g). Musore and Mukungugu were intermediate: Musore had 90.3 % unperforated seeds and the lowest perforated seed weight (2 g); Mukungugu had 88.7 % unperforated seeds and perforated seed weight of 2.7 g. Seed weight attributes were significantly ($p < 0.001$) different. Kinure had recorded the highest monthly lot weight (991 g). Gasilida followed with 32.4 g and 925.4 g respectively, while Mukungugu and Musore had lower values (25.6 g and 22.4 g; 914.9 g and 897 g respectively). The live bruchids were not significantly ($p = 0.062$) different between varieties. Still, Gasilida had the highest live bruchids (72.2%), suggesting it might favour bruchid survival more than other varieties; Musore had the lowest (67.6%). Site had no significant ($p > 0.05$) effect on any measured parameter. At Murongwe, unperforated seeds averaged 90.7%, perforated seeds 9.3%, perforated seed weight 2.6 g, lot weight 932.8 g. At Kayanza, unperforated seeds averaged 88.7%, perforated seeds 11.3%, perforated seed weight 3.1 g, lot weight 931.3 g. Live and dead bruchids were also statistically similar (67.1% vs. 66.7% and 32.9% vs 33.3% respectively). The interaction between variety and site was not significant ($p > 0.05$). For example, Kinure consistently showed high resistance at both sites (94% unperforated seeds at Murongwe, 91% at Kayanza). Gasilida consistently showed lower resistance (87–87.3% unperforated seeds) at both sites. Varietal differences significantly ($p < 0.05$) influenced bruchid damage and seed quality, while site differences and their interaction with variety were not significant ($p > 0.05$).

Table 1. Effects of bean varieties, sites, and their interactions on *Acanthoscelides obtectus* bruchid at Murongwe and Kayanza sites

Factor	Factor levels	Un-perforated seeds (%)	Weight of unperforated seeds (g)	Perforated seeds (%)	Weight of perforated seeds (g)	Weight of 1 lot/month (g)	Live bruchid (%)	Death bruchid (%)
Variety	V1	92.5^{a}	37.9^{a}	7.5^{b}	2.9^{ab}	991^{a}	65.3^{a}	34.7^{a}
	V2	88.7^{ab}	23^{c}	11.3^{ab}	2.7^{ab}	914.9^{c}	62.6^{a}	37.4^{a}
	V3	90.3^{ab}	20.4^{d}	9.7^{ab}	2^{b}	897^{d}	67.6^{a}	32.4^{a}
	V4	87.2^{b}	28.6^{b}	12.8^{a}	3.8^{a}	925.4^{b}	72.2^{a}	27.8^{a}
	L.S.D	3.246	1.2	3.2	1.1	2.4	6.8	6.8
	p value	0.031	<0.001	0.031	0.039	<0.001	0.062	0.062
Site	Murongwe	90.7^{a}	27.8^{a}	9.3^{a}	2.6^{a}	932.8^{a}	67.1^{a}	32.9^{a}
	Kayanza	88.7^{a}	27.2^{a}	11.3^{a}	3.1^{a}	931.3^{a}	66.7^{a}	33.3^{a}
	L.S.D	4.2	1.0	4.2	0.9	3.4	4.3	4.3
	p value	0.309	0.202	0.309	0.198	0.324	0.809	0.809
Variety × Site	V1 Kayanza	91^{a}	37.3^{a}	9^{a}	3.5^{a}	990.1^{a}	65.8^{a}	34.2^{a}
	V1 Murongwe	94^{a}	38.5^{a}	6^{a}	2.3^{a}	991.8^{a}	64.8^{a}	35.2^{a}
	V2 Kayanza	86^{a}	22.3^{cd}	14^{a}	3.3^{a}	912.5^{c}	61.2^{a}	38.8^{a}
	V2 Murongwe	91.3^{a}	23.7^{c}	8.7^{a}	2^{a}	917.3^{bc}	64^{a}	36^{a}
	V3 Kayanza	90.3^{a}	20.4^{d}	9.7^{a}	2^{a}	897^{d}	68.8^{a}	31.2^{a}
	V3 Murongwe	90.3^{a}	20.4^{d}	9.7^{a}	2^{a}	897^{d}	66.3^{a}	33.7^{a}
	V4 Kayanza	87.3^{a}	28.7^{b}	12.7^{a}	3.7^{a}	925.6^{b}	70.9^{a}	29.1^{a}
	V4 Murongwe	87^{a}	28.5^{b}	13^{a}	3.8^{a}	925.3^{b}	73.4^{a}	26.6^{a}
	S.E.D.	2.9	0.8	3.0	0.8	2.4	3.8	3.8
	p value	0.21	0.449	0.526	0.449	0.443	0.708	0.708

Key: V1 = Kinure; V2 = Mukungugu; V3 = Musore; and V4 = Gasilida; LSD = least significant difference; S.E.D. = standard errors of the differences of means. Means along the same column bearing different letter(s) differ significantly.

Main effects of variety and dates on *A. obtectus* at Murongwe site

The results showed highly significant ($p < 0.001$) differences among the four bean varieties in unperforated seed percentage, perforated seed percentage and weight, lot weight (Table 2). Variety Kinure recorded 92.3% unperforated seeds, perforated seed percentage of 7.67%, perforated seed weight of 2.967 g, lot weight of 990.9 g. Gasilida had 74.8% unperforated seeds, 25.22% perforated seeds, perforated seed weight of 7.466 g, lot weight of 914.1 g. Mukungugu had 85.6% unperforated seeds, 14.44% perforated seeds, perforated seed weight of 3.38 g, lot weight of 912.1 g. Musore showed 89.3% unperforated seeds, 10.67% perforated seeds, perforated seed weight of 2.219 g, lot weight of 896.3 g. No significant ($p = 0.121$) differences were found among varieties in live bruchid percentage, which ranged from 63.2% in Kinure to 71.3% in Mukungugu. Across storage dates, significant ($p < 0.001$) differences were observed. On day 45744, unperforated seed was 96.9%, perforated seed was 3.1%, perforated seed weight was 0.8 g, lot weight was 937.8 g. On day 45778, unperforated seed percentage was 90.7%, perforated seed percentage was 9.33%, perforated seed weight was 2.552 g, lot weight was 932.8 g. On day 45809, unperforated seed percentage was 68.9%, perforated seed percentage was 31.1%, perforated seed weight was 8.63 g, lot weight was 914.4 g. No significant ($p = 0.57$) differences were found in live bruchid percentage across storage dates, which ranged from 67.1% to 70.1%.

Table 2. Effects of bean varieties and storage time on seed damage, weight, and *Acanthoscelides obtectus* infestation in Murongwe

Factor	Factor levels	Unperforated seeds (%)	Weight of unperforated seeds (g)	Perforated seeds (%)	Weight of perforated seed (g)	Weight of 1 lot/month (g)	Live bruchid (%)	Death bruchid (%)
Variety	V1	92.3^{a}	37.86^{a}	7.67^{c}	2.967^{b}	990.9^{a}	63.2^{a}	36.9^{a}
	V2	85.6^{b}	22.16^{c}	14.44^{b}	3.38^{b}	912.1^{b}	71.3^{a}	28.7^{a}
	V3	89.3^{ab}	20.19^{c}	10.67b^{c}	2.219^{b}	896.3^{c}	68.5^{a}	31.5^{a}
	V4	74.8^{c}	24.53^{b}	25.22^{a}	7.466^{a}	914.1^{b}	71.2^{a}	28.8^{a}
	L.S. D.	3.7	1.4	3.7	1.3	2.9	7.7	7.7
	p value	<0.001	<0.001	<0.001	<0.001	<0.001	0.121	0.121
Day	45744	96.9^{a}	29.65^{a}	3.08^{c}	0.841^{c}	937.8^{a}	68.4^{a}	31.6^{a}
	45778	90.7^{b}	27.79^{b}	9.33^{b}	2.552^{b}	932.8^{b}	67.1^{a}	32.9^{a}
	45809	68.9^{c}	21.11^{c}	31.08^{a}	8.63^{a}	914.4^{c}	70.1^{a}	29.9^{a}
	L.S.D.	3.6	1.0	3.6	0.9	2.9	5.9	5.9
	p value	<0.001	<0.001	<0.001	<0.001	<0.001	0.57	0.57

Note: V1 = Kinure; V2 = Mukungugu; V3 = Musore; and V4 = Gasilida. LSD = least significant difference; Means along the same column bearing different letter(s) differ significantly.

Interaction effects of variety and dates on *A. obtectus at* Murongwe site

The results showed significant ($p < 0.001$) interaction effects between bean variety and storage date on unperforated seed percentage, perforated seed percentage and weight, weight of unperforated seeds, 100-seed weight, and lot weight (Table 3). No significant ($p = 0.33$) interaction effects were found for live or dead bruchid percentages.

For variety Kinure, unperforated seed percentage declined from 98.3% on day 45744 to 84.7% on day 45809, perforated seed percentage increased from 1.7% to 15.3%, and perforated seed weight rose from 0.6 g to 5.9 g, lot weight decreased slightly from 994.2 g to 986.6 g. Variety Mukungugu showed a decrease in unperforated seeds from 97.7% to 67.7%, an increase in perforated seeds from 2.3% to 32.3%, and perforated seed weight rising from 0.5 g to 7.6 g, lot weight dropped from 922.9 g to 896.1 g.

Variety Musore recorded unperforated seed percentage decreasing from 96.7% to 81%, perforated seed percentage increasing from 3.3% to 19%, and perforated seed weight rising from 0.7 g to 4 g, lot weight ranged from 901.6 g to 890.3 g. Variety Gasilida showed the largest changes, with unperforated seeds decreasing from 95% to 42.3%, perforated seeds increasing from 5% to 57.7%, and perforated seed weight rising sharply from 1.5 g to 17.1 g, lot weight dropped from 932.6 g to 884.4 g. Live bruchid percentages ranged from 61.6% to 78.4% across all combinations, without significant (p = 0.33) differences.

Table 3. Effects of *A. obtectus on* measured parameters following interaction of bean varieties and storage dates

Factors	Unperforated seeds (%)	Weight of un-perforated seeds (g)	Perforated seeds (%)	Weight of perforated seed (g)	Weight of 1 lot/month (g)	Live bruchid (%)	Death bruchid (%)
V1 45744	98.3^{a}	40.3^{a}	1.7^{e}	0.6^{ef}	994.2^{a}	61.6^{a}	38.5^{a}
V1 45778	94^{ab}	38.5^{a}	6^{de}	2.3^{def}	991.8^{a}	64.8^{a}	35.2^{a}
V1 45809	84.7^{bc}	34.7^{b}	15.3^{cd}	5.9^{bc}	986.6^{a}	63.1^{a}	36.9^{a}
V2 45744	97.7^{a}	25.3^{de}	2.3^{e}	0.5^{f}	922.9^{c}	71.5^{a}	28.5^{a}
V2 45778	91.3^{abc}	23.7^{eh}	8.7^{cde}	2^{def}	917.3^{c}	64^{a}	36^{a}
V2 45809	67.7^{d}	17.5^{h}	32.3^{b}	7.6^{b}	896.1^{de}	78.4^{a}	21.7^{a}
V3 45744	96.7^{a}	21.9^{efg}	3.3^{e}	0.7^{def}	901.6^{d}	68.9^{a}	31.1^{a}
V3 45778	90.3^{abc}	20.4^{fgh}	9.7^{cde}	2^{def}	897^{de}	66.3^{a}	33.7^{a}
V3 45809	81^{c}	18.3^{gh}	19^{c}	4^{cd}	890.3^{ef}	70.4^{a}	29.6^{a}
V4 45744	95^{ab}	31.2^{bc}	5^{de}	1.5^{def}	932.6^{b}	71.6^{a}	28.4^{a}
V4 45778	87^{abc}	28.5^{cd}	13^{cde}	3.8^{cde}	925.3^{bc}	73.4^{a}	26.6^{a}
V4 45809	42.3^{e}	13.9^{i}	57.7^{a}	17.1^{a}	884.4^{f}	68.6^{a}	31.4^{a}
S.E.D.	3.2	1.0	3.2	0.9	2.5	5.5	5.5
p value	<0.001	<0.001	<0.001	<0.001	<0.001	0.33	0.33

Key: *V1 = Kinure; V2 = Mukungugu; V3 = Musore; and V4 = Gasilida. S.E.D. = standard errors of differences of means. Means along the same column bearing different letter(s) differ significantly.*

Main effects of varieties and storage duration on *A. obtectus* infestation at Kayanza site

The results showed significant (p ≤ 0.002) differences among bean varieties in unperforated seed percentage, perforated seed percentage and weight, unperforated seed weight, lot weight (Table 4). Kinure had 90% unperforated seeds, perforated seeds at 10%, unperforated seed weight of 36.9 g, perforated seed weight of 3.9 g, lot weight of 989.6 g. Gasilida had 75.4% unperforated seeds, 24.6% perforated seeds, perforated seed weight of 7.3 g, unperforated seed weight of 24.8 g, lot weight of 914.7 g. Mukungugu and Musore showed intermediate values: Mukungugu with 85.2% unperforated seeds, 14.8% perforated seeds, unperforated seed weight of 22.1 g, perforated seed weight of 3.5 g, lot weight of 911.8 g; Musore with 88.9% unperforated seeds, 11.1% perforated seeds, unperforated seed weight of 20.1 g, perforated seed weight of 2.3 g, lot weight of 896 g. Seed quality also declined significantly (p < 0.001) over storage dates. At day 45743, unperforated seed percentage was 96.8%, perforated seeds 3.3%, perforated seed weight 0.9 g, unperforated seed weight 29.6 g, lot weight 937.8 g. By day 45808, unperforated seeds dropped to 69.3%, perforated seeds increased to 30.8%, perforated seed weight rose to 8.6 g, unperforated seed weight fell to 21.1 g, lot weight decreased to 914.9 g. No significant differences were found in live bruchid ($p = 0.182$) or dead bruchid percentages ($p = 0.581$) across varieties or storage dates. Live bruchid percentages ranged from 62.7% to 69.8%.

Table 4. Main effects of common bean varieties and storage duration on seed damage, weight, and bruchid infestation at Kayaza site

Factor	Factor levels	Unperforated seed (%) per 100 seeds	Weight of unperforated seeds (g)	Perforated seed (%) per 100 seeds	Weight of perforated seed (g)	Weight of 1 lot/month (g)	Live bruchid (%)	Death bruchid (%)
Varieties	V1	90^{a}	36.9^{a}	10^{b}	3.9^{b}	989.6^{a}	62.7^{a}	37.3^{a}
	V2	85.2^{a}	22.1^{c}	14.8^{b}	3.5^{b}	911.8^{b}	65.9^{a}	34.1^{a}
	V3	88.9^{a}	20.1^{c}	11.1^{b}	2.3^{b}	896^{c}	69.8^{a}	30.2^{a}
	V4	75.4^{b}	24.8^{b}	24.6^{a}	7.3^{a}	914.7^{b}	68.1^{a}	31.9^{a}
	L.S.D.	5.406	1.545	5.406	1.411	4.529	7.024	7.024
	p value	0.002	<0.001	0.002	<0.001	<0.001	0.182	0.182
Date	45743	96.8^{a}	29.6^{a}	3.3^{c}	0.9^{c}	937.8^{a}	65.3^{a}	34.7^{a}
	45778	88.7^{b}	27.2^{b}	11.3^{b}	3.1^{b}	931.3^{b}	66.7^{a}	33.3^{a}
	45808	69.3^{c}	21.1^{c}	30.8^{a}	8.6^{a}	914.9^{c}	67.9^{a}	32.1^{a}
	L.S.D.	3.785	1.153	3.785	1.047	3.292	5.135	5.135
	p value	<0.001	<0.001	<0.001	<0.001	<0.001	0.581	0.581

Key: V1 = Kinure; V2 = Mukungugu; V3 = Musore; and V4 = Gasilida. LSD = least significant difference; Means along the same column bearing different letter(s) differ significantly.

Interaction effects of variety and dates on *A. obtectus* at Kayanza site

The results showed significant interaction effects ($p < 0.001$) between bean varieties and storage dates on seed damage and weight parameters, while live and dead bruchid percentages did not differ significantly ($p = 0.275$) (Table 5). Kinure consistently showed the highest resistance, with unperforated seeds decreasing from 97% at day 45743 to 82% at day 45808, and perforated seeds rising from 3% to 18%. Perforated seed weight ranged from 16.9 g to 6.5 g. Despite this increase in damage over time, Kinure maintained a stable lot weight (985.1–993.5 g).

Mukungugu showed a marked decline in resistance, with unperforated seeds dropping from 97.3% to 72.3%, and perforated seeds increasing from 2.7% to 27.7%. Perforated seed weight ranged from 4.2 g to 3.5 g, lot weight decreased from 922.6 g to 900.3 g. Musore had intermediate resistance, with unperforated seeds decreasing from 96.7% to 79.7% and perforated seeds rising from 3.3% to 20.3%. Perforated seed weight varied between 3.3 g and 1.2 g. Lot weight decreased slightly over time.

Gasilida was the most susceptible, with unperforated seeds falling sharply from 96% to 43%, and perforated seeds rising from 4% to 57%. Perforated seed weight declined from 1.2 g to 0.6 g, lot weight decreased markedly from 933.5 g to 885 g. Seed damage and weight loss increased with storage duration, with Kinure showing the strongest resistance and Gasilida the greatest susceptibility. Bruchid live and dead percentages remained relatively stable ($p = 0.275$) across treatments.

Table 5. Interaction effects of common bean varieties and storage dates on seed damage, weight, and *A. obtectus* bruchid infestation at Kayanza site

Factors	Unperforated seed (%)	Weight of unperforated seeds (g)	Perforated seeds (%)	Weight of perforated seed (g)	Weight of 1 lot/month (g)	Live bruchid (%)	Death bruchid (%)
V1 45743	97^{a}	39.8^{a}	3^{d}	16.9^{a}	993.5^{a}	60^{a}	40.1^{a}
V1 45778	91^{ab}	37.3^{ab}	9^{cd}	7^{b}	990.1^{a}	65.8^{a}	34.2^{a}
V1 45808	82^{bc}	33.6^{bc}	18^{bc}	6.5^{bc}	985.1^{a}	62.5^{a}	37.5^{a}
V2 45743	97.3^{a}	25.2^{ef}	2.7^{d}	4.2^{bcd}	922.6^{bc}	63.5^{a}	36.6^{a}
V2 45778	86^{ab}	22.3^{fg}	14^{cd}	3.7^{b-e}	912.5^{cd}	61.2^{a}	38.8^{a}
V2 45808	72.3^{c}	18.7^{gh}	27.7^{b}	3.5^{b-e}	900.3^{ef}	73^{a}	27^{a}
V3 45743	96.7^{a}	21.9^{fgh}	3.3^{d}	3.3^{cde}	901.6^{de}	70.7^{a}	29.3^{a}
V3 45778	90.3^{ab}	20.4^{gh}	9.7^{cd}	2^{de}	897^{ef}	68.8^{a}	31.2^{a}
V3 45808	79.7^{bc}	18^{hi}	20.3^{bc}	1.2^{de}	889.4^{fg}	69.9^{a}	30.1^{a}
V4 45743	96^{a}	31.5^{cd}	4^{d}	1.2^{de}	933.5^{b}	67.1^{a}	32.9^{a}
V4 45778	87.3^{ab}	28.7^{de}	12.7^{cd}	0.7^{de}	925.6^{b}	70.9^{a}	29.1^{a}
V4 45808	43^{d}	14.1^{i}	57^{a}	0.6^{e}	885^{g}	66.2^{a}	33.8^{a}
S.E.D.	3.6	1.1	3.6	1.0	3.1	4.9	4.9
p value	<0.001	<0.001	<0.001	<0.001	<0.001	0.275	0.275

Key: V1 = Kinure; V2 = Mukungugu; V3 = Musore; and V4 = Gasilida. S.E.D. = standard errors of differences of means. Means along the same column bearing different letter(s) differ significantly.

Zabrotes subfasciatus maintained in a conditioned setting at the Bujumbura site

Main effect of varieties and storage duration on *Z. subfasciatus* infestation

The results showed significant ($p < 0.001$) differences among the four bean varieties in response to *Z. subfasciatus* infestation, particularly in seed damage and weight parameters (Table 6). Kinure had the highest resistance, with 92.3% unperforated seeds and an unperforated seed weight of 37.9 g. It also recorded the lowest perforated seed percentage (7.7%) and perforated seed weight (3 g), and lot weight (990.9 g). Gasilida was the most susceptible, with only 74.8% unperforated seeds, a high perforated seed percentage of 25.2%, and the highest perforated seed weight of 7.5 g. Despite a moderate, lot weight (914.1 g), the greater seed damage reflected poor resistance. Mukungugu and Musore showed intermediate levels of resistance, with 85.6% and 89.3% unperforated seeds, and perforated seed percentages of 14.4% and 10.7%, respectively.

Regarding storage dates, seed quality declined significantly over time ($p < 0.001$). On day 45744, seeds had 96.9% unperforated seeds, only 3.1% perforated seeds, and the lowest perforated seed weight (0.8 g). By day 45809, unperforated seeds dropped to 68.9%, perforated seeds rose sharply to 31.1%, and perforated seed weight increased to 8.6 g. The lot weight also decreased significantly over time ($p < 0.001$). No significant differences were found in live or dead bruchid percentages among varieties ($p = 0.121$) or dates ($p = 0.57$). Live bruchid rates ranged between 63.2% and 71.3%. Overall, Kinure maintained the strongest resistance to *Z. subfasciatus*, while Gasilida experienced the highest seed damage, and seed quality declined across all varieties as storage duration increased.

Table 6. Effects of bean varieties and storage time on seed damage and *Z. subfaciatus* infestation at Bujumbura site

Factors	Unperforated seeds (%)	Weight of unperforated seeds (g)	Perforated seeds (%)	Weight of perforated seeds (g)	Weight of 1 lot/month (g)	Live bruchid (%)	Death bruchid (%)
V1	92.3^{a}	37.9^{a}	7.7^{c}	3^{b}	990.9^{a}	63.2^{a}	36.9^{a}
V2	85.6^{b}	22.2^{c}	14.4^{b}	3.4^{b}	912.1^{b}	71.3^{a}	28.7^{a}
V3	89.3^{ab}	20.2^{c}	10.7b^{c}	2.2^{b}	896.3^{c}	68.5^{a}	31.5^{a}
V4	74.8^{c}	24.5^{b}	25.2^{a}	7.5^{a}	914.1^{b}	71.2^{a}	28.8^{a}
L.S.D.	3.7	1.4	3.7	1.3	2.9	7.7	7.7
p value	<0.001	<0.001	<0.001	<0.001	<0.001	0.121	0.121
45744	96.9^{a}	29.7^{a}	3.1^{c}	0.8^{c}	937.8^{a}	68.4^{a}	31.6^{a}
45778	90.7^{b}	27.8^{b}	9.3^{b}	2.6^{b}	932.8^{b}	67.1^{a}	32.9^{a}
45809	68.9^{c}	21.1^{c}	31.1^{a}	8.6^{a}	914.4^{c}	70.1^{a}	29.9^{a}
L.S.D.	3.6	1.0	3.6	0.9	2.9	5.9	5.9
p value	<.001	<0.001	<0.001	<0.001	<0.001	0.57	0.57

Key: V1 = Kinure; V2 = Mukungugu; V3 = Musore; and V4 = Gasilida. LSD = least significant difference; Means along the same column bearing different letter(s) differ significantly.

Interaction effect of varieties and dates on *Z. subfasciatus*

The results revealed significant interaction effects ($p < 0.001$) between bean varieties and storage dates on all seed damage and weight parameters related to *Z. subfasciatus* infestation (Table 7). Live and dead bruchid percentages showed no significant ($p = 0.33$) interaction. Kinure maintained the highest resistance across dates: unperforated seeds decreased from 98.3% on day 45744 to 84.7% on day 45809, while perforated seeds increased from 1.7% to 15.3%, and perforated seed weight rose from 0.6 g to 5.9 g. Despite this, Kinure consistently maintained high seed quality and a stable lot weight ranging from 994 to 986 g.. Mukungugu exhibited a sharper decline in resistance: unperforated seeds fell from 97.7% to 67.7%, perforated seeds rose from 2.3% to 32.3%, and perforated seed weight increased from 0.5 g to 7.6 g. Its lot weight dropped from 922.9 g to 896.1 g. Mukungugu also recorded the highest live bruchid percentage (78.4%) at the last storage date. Musore showed intermediate resistance: unperforated seeds declined from 96.7% to 81%, perforated seeds increased from 3.3% to 19%, and perforated seed weight rose from 0.7 g to 4 g. Lot weight dropped modestly from 901.6 g to 890.3 g. Gasilida was the most vulnerable: unperforated seeds dropped dramatically from 95% to 42.3%, perforated seeds surged from 5% to 57.7%, and perforated seed weight rose steeply from 1.5 g to 17.1 g. Its lot weight decreased from 932.6 g to 884.4 g, reflecting severe deterioration over time. The seed damage and weight loss increased significantly with storage duration for all varieties, with Kinure showing the strongest resistance and Gasilida the highest susceptibility. Live and dead bruchid percentages remained relatively stable, indicating infestation intensity did not differ significantly despite variations in seed damage.

Table 7. Interaction effects of bean varieties and storage dates on seed damage and *Z. subfaciens* infestation at Bujumbura site

Factors	Unperforated seeds (%)	Weight of unperforated seeds (g)	Perforated seeds (%)	Weight of perforated seeds (g)	Weight of 1 lot/month (g)	Live bruchid (%)	Death bruchid (%)
V1 45744	98.3^{a}	40.3^{a}	1.7^{e}	0.6^{ef}	994.2^{a}	61.6^{a}	38.5^{a}
V1 45778	94^{ab}	38.5^{a}	6d^{e}	2.3^{def}	991.8^{a}	64.8^{a}	35.2^{a}

V1 45809	84.7^{bc}	34.7^{b}	15.3^{cd}	5.9^{bc}	986.6^{a}	63.1^{a}	36.9^{a}
V2 45744	97.7^{a}	25.3^{de}	2.3^{e}	0.5^{f}	922.9^{c}	71.5^{a}	28.5^{a}
V2 45778	91.3^{abc}	23.7^{ef}	8.7^{cde}	2^{def}	917.3^{c}	64^{a}	36^{a}
V2 45809	67.7^{d}	17.5^{h}	32.3^{b}	7.6^{b}	896.1^{dc}	78.4^{a}	21.7^{a}
V3 45744	96.7^{a}	21.9^{efg}	3.3^{e}	0.7^{def}	901.6^{d}	68.9^{a}	31.1^{a}
V3 45778	90.3^{abc}	20.4^{fgh}	9.7^{cde}	2^{def}	897de	66.3^{a}	33.7^{a}
V3 45809	81^{c}	18.3^{gh}	19^{c}	4^{cd}	890.3^{cf}	70.4^{a}	29.6^{a}
V4 45744	95^{ab}	31.2^{bc}	5de	1.5^{def}	932.6^{b}	71.6^{a}	28.4^{a}
V4 45778	87^{abc}	28.5^{cd}	13^{cde}	3.8^{cde}	925.3^{bc}	73.4^{a}	26.6^{a}
V4 45809	42.3^{e}	13.9^{i}	57.7^{a}	17.1^{a}	884.4^{f}	68.6^{a}	31.4^{a}
Grand mean	85.5	26.18	14.5	4.01	928.34	68.5	31.5
S.E.D.	3.163	0.977	3.206	0.901	2.538	5.5	5.5
p value	<.001	<0.001	<0.001	<0.001	<0.001	0.33	0.33

Key: V1 = Kinure; V2 = Mukungugu; V3 = Musore; and V4 = Gasilida. S.E.D. = standard errors of differences of means. Means along the same column bearing different letter(s) differ significantly.

Acanthoscelides obtectus non-controlled storage conditions

Effects of *Acanthoscelides obtectus* infestation on bean varieties at Kayanza and Murongwe sites

The results (Table 8) showed that the effect of bean varieties on most seed damage parameters was not significant (p = 0.374), except for the weight of unperforated seeds (p < 0.001), and lot weight (p < 0.001). The effect of varieties on live and dead bruchids was also not significant (p = 0.822). Kinure had the highest proportion of unperforated seeds (95.5%) and the highest weight of unperforated seeds (37 g). Its lot weight reached 939.3 g. Mukungugu followed with 92.5% unperforated seeds and 24 g weight of unperforated seeds, and lot weight (918.3 g). Musore had 92% unperforated seeds, the lowest weight of unperforated seeds (21 g), and lowest lot weight (898.2 g). Gasilida showed the lowest unperforated seed proportion (89.2%) but had a relatively higher weight of unperforated seeds (29.3 g), and lot weight of 927.2 g. Perforated seeds and perforated seed weights were not significantly (p > 0.05) different among varieties. Across sites, the differences in unperforated seeds between Kayanza (90.9%) and Murongwe (93.7%) were not significant (p = 0.11). Similarly, perforated seeds (p = 0.11), weight of perforated seeds (p = 0.17), weight of unperforated seeds, and weight of lot weight did not differ significantly (p > 0.05) between sites. However, live bruchids were significantly (p < 0.05) higher at Murongwe (74.5%) compared to Kayanza (60.8%), while dead bruchids were lower at Murongwe (25.5%) and higher at Kayanza (39.2%). The interaction effect between site and variety on seed damage parameters and bruchid survival was not significant (p > 0.05). Nevertheless, Kinure consistently showed high resistance at both sites, with unperforated seeds of 94% at Kayanza and 97% at Murongwe, and stable lot weight (939.3 g). Mukungugu performed better at Murongwe (95.7% unperforated seeds) than at Kayanza (89.3%). Musore had minor differences between sites, with 91% unperforated seeds at Kayanza and 93% at Murongwe. Gasilida showed similar unperforated seeds at both sites (89–89.3%). Murongwe showed higher live bruchid survival than Kayanza, although seed damage levels did not differ significantly between sites.

Table 8. Effects of bean varieties, sites, and their interactions on measured varieties *Acanthoscelides obtectus* bruchid at Kayanza anad Murongwe sites.

Factor	Factor levels	Unperforated seeds (%)	Weight of unperforated seeds (g)	Perforated seeds (%)	Weight of perforated seeds (g)	Weight of 1 lot/month (g)	Live bruchid (%)	Death bruchid (%)

Variety	V1'	95.5^{a}	37^{a}	4.5^{a}	1.7^{a}	939.3^{a}	66.3^{a}	33.7^{a}
	V2'	92.5^{a}	24^{c}	7.5^{a}	1.8^{a}	918.3^{c}	70^{a}	30^{a}
	V3'	92^{a}	21^{d}	8^{a}	1.7^{a}	898.2^{d}	66.4^{a}	33.6^{a}
	V4'	89.2^{a}	29.3^{b}	10.3^{a}	3.2^{a}	927.2^{b}	67.8^{a}	32.2^{a}
	L.S.D.	8.0	1.1	8.0	1.6	5.1	10.9	10.9
	p value	0.374	<0.001	0.374	0.303	<0.001	0.822	0.822
Site	Kayanza	90.9^{a}	27.4^{a}	9.1^{a}	2.5^{a}	919.9^{a}	60.8^{b}	39.2^{a}
	Murongwe	93.7^{a}	28.1^{a}	6.3^{a}	1.7^{a}	921.6^{a}	74.5^{a}	25.5^{b}
	L.S.D.	1.5	1.0	3.5	2.3	3.6	6.9	6.9
	p value	0.11	0.098	0.11	0.17	0.201	0.002	0.002
Site × Variety	V1' Kayanza	94^{a}	36.4^{a}	6^{a}	2.3^{a}	939.3^{a}	61.7^{bc}	38.3^{ab}
	V1' Murongwe	97^{a}	37.5^{a}	3^{a}	1.2^{a}	939.3^{a}	71^{abc}	29^{abc}
	V2' Kayanza	89.3^{a}	23.1^{cd}	10.7^{a}	2.5^{a}	915.5^{c}	60.4^{c}	39.6^{a}
	V2' Murongwe	95.7^{a}	24.8^{c}	4.3^{a}	1^{a}	921.1^{bc}	79.7^{a}	20.3^{c}
	V3' Kayanza	91^{a}	20.6^{d}	9^{a}	1.9^{a}	897.5^{d}	60.7^{c}	39.3^{a}
	V3' Murongwe	93^{a}	21^{d}	7^{a}	1.5^{a}	899^{d}	72.1^{ab}c	27.9^{abc}
	V4' Kayanza	89.3^{a}	29.3^{b}	10.7^{a}	3.2^{a}	927.4^{b}	60.3^{c}	39.7^{a}
	V4' Murongwe	89^{a}	29.2^{b}	11^{a}	3.3^{a}	927.1^{b}	75.4^{ab}	24.6^{bc}
	S.E.D.	3.8	1.2	3.8	1.1	3.4	6.1	6.1
	p value	0.673	0.729	0.673	0.717	0.585	0.683	0.683

Key: V1 = Kinure; V2 = Mukungugu; V3 = Musore; and V4 = Gasilida; LSD = least significant difference; S.E.D. = standard errors of the differences of means. Means along the same column bearing different letter(s) differ significantly.

Effects of variety and dates on *A. obtectus* at Murongwe site

The results (Table 9) revealed that the effect of bean varieties on seed damage and weight parameters was significant ($p < 0.001$), except for live and dead bruchids, which were not significant ($p = 0.173$). Kinure maintained the highest resistance, with 93.2% unperforated seeds, highest weight of unperforated seeds (36.1 g). Its lot weight was also highest (939.3 g). Gasilida showed the highest susceptibility, with only 76.7% unperforated seeds and highest perforated seeds (23.3%) and perforated seed weight (6.9 g). Mukungugu and Musore had intermediate resistance: Mukungugu had 89.3% unperforated seeds and Musore 91%, though Musore showed the lowest weight of unperforated seeds (20.6 g) and lowest lot weight (897.5 g). Storage time had a significant ($p < 0.001$) effect on all seed damage and weight parameters, except live and dead bruchids, which were not significant ($p = 0.557$). At the first storage date (day 45743), unperforated seeds averaged 98.5%, perforated seeds were only 1.5%, perforated seed weight was 0.4 g, and lot weight was 925.3 g. By the last storage time (day 45808), unperforated seeds decreased to 76.6%, perforated seeds rose to 23.4%, perforated seed weight increased sharply to 6.6 g, and lot weight dropped to 908.8 g.

The interaction between variety and date was significant ($p < 0.001$) for all seed damage and weight parameters, but not significant ($p = 0.418$) for live and dead bruchids. Kinure preserved the highest resistance over time: unperforated seeds dropped from 99.3% at day 45743 to 87% at day 45808, perforated seeds increased from 0.7% to 13%, and perforated seed weight rose from 0.3 g to 5 g, while lot weight stayed at 939.3 g. Mukungugu exhibited a sharper decline in seed quality, with the proportion of unperforated seeds dropping from 99% to 79.7%, and lot weight decreasing from 924.1 g to 906.8 g. Meanwhile, perforated seeds increased from 1% to 20.3%, accompanied by a rise in perforated seed weight from 0.2 g to 4.8 g. In Musore, unperforated seeds declined from 98% to 84%, perforated seeds increased from 2% to 16%, and perforated seed weight rose from 0.4 g to 3.3 g, alongside a lot weight reduction from 902.6 g to 892.5 g. Gasilida showed the most severe deterioration, with unperforated seeds decreasing from 97.7% to 55.7%, perforated seeds increasing from 2.3% to 44.3%, and perforated seed weight rising significantly from 0.7 g to 13.1 g. Correspondingly, the lot weight dropped from 935 g to 896.6 g. Seed damage and weight loss increased significantly ($p < 0.001$) with storage duration for all varieties. Kinure showed the strongest resistance, while Gasilida was the most susceptible. Live and dead bruchid percentages remained relatively stable and were not significantly different over storage time.

Table 9. Effects of bean varieties, storage time, and interaction on seed damage, weight, and *Acanthoscelides obtectus* infestation at Murongwe site

Factor	Factor levels	Unperforated seeds (%)	Weight of unperforated seeds (g)	Perforated seeds (%)	Weight of perforated seeds (g)	Weight of 1 lot/month (g)	Live bruchid (%)	Death bruchid (%)
Variety	V1'	93.2^{a}	36.1^{a}	6.8^{b}	2.6^{b}	939.3^{a}	62.3^{b}	37.7^{a}
	V2'	89.3^{a}	23.1^{c}	10.7^{b}	2.5^{b}	915.5^{b}	71.7^{ab}	28.3^{ab}
	V3'	91^{a}	20.6^{d}	9^{b}	1.9^{b}	897.5^{c}	75.9^{a}	24.1^{b}
	V4'	76.7^{b}	25.2^{b}	23.3^{a}	6.9^{a}	915.8^{b}	70^{ab}	30^{ab}
	L.S.D.	4	1.2	4	1.1	3.4	12.9	12.9
	p value	<0.001	<0.001	<0.001	<0.001	<0.001	0.173	0.173
Date	45743	98.5^{a}	29.6^{a}	1.5^{b}	0.4^{b}	925.3^{a}	69.2^{a}	30.8^{a}
	45808	76.58^{a}	22.9^{b}	23.4^{a}	6.6^{b}	908.8^{b}	70.7^{a}	29.3^{a}
	L.S. D	3.9	1.1	3.9	1	3.4	5.6	5.6
	p value	<0.001	<0.001	<0.001	<0.001	<0.001	0.557	0.557
Variety × Date	V1' 45743	99.3^{a}	38.4^{a}	0.7^{d}	0.3^{c}	939.3^{a}	60^{b}	40^{a}
	V1' 45808	87^{b}	33.7^{b}	13^{c}	5^{b}	939.3^{a}	64.5^{ab}	35.5^{ab}
	V2' 45743	99^{a}	25.6^{c}	1^{d}	0.2^{c}	924.1^{b}	68.3^{ab}	31.7^{ab}
	V2' 45808	79.7^{c}	20.6^{de}	20.3^{b}	4.8^{b}	906.8^{c}	75.2^{a}	24.8^{b}
	V3' 45743	98^{a}	22.2^{d}	2^{d}	0.4^{c}	902.6^{c}	77.8^{a}	22.2^{b}
	V3' 45808	84^{bc}	19^{ef}	16^{bc}	3.3^{b}	892.5^{d}	74.1^{ab}	25.9^{ab}
	V4' 45743	97.7^{a}	32^{b}	2.3^{d}	0.7^{c}	935^{a}	70.9^{ab}	29.1^{ab}
	V4' 45808	55.7^{d}	18.3^{f}	44.3^{a}	13.1^{a}	896.6^{d}	69.1^{ab}	30.9^{ab}
	S.E.D.	2.9	0.8	2.9	0.8	2.5	6.3	6.3
	p value	<0.001	<0.001	<0.001	<0.001	<0.001	0.418	0.418

Key: V1 = Kinure; V2 = Mukungugu; V3 = Musore; and V4 = Gasilida. LSD = least significant difference; S.E.D. = standard errors of the differences of means. Means along the same column bearing different letter(s) differ significantly.

Effects of variety and dates on *A. obtectus* at Kayanza site

The effect of bean varieties on seed damage and weight parameters was significant ($p < 0.001$), but the effect on live and dead bruchids were not significant ($p = 0.876$), as shown in Table 10. Kinure recorded the highest resistance, with 90.3% unperforated seeds, highest weight of unperforated seeds (35 g), its lot weight was also highest (939.3 g). Musore had 91.3% unperforated seeds, lowest weight of unperforated seeds (20.6 g), and lowest lot weight (897.8 g). Mukungugu showed moderate resistance, with 85.7% unperforated seeds and 22.2 g unperforated seed weight. Gasilida was the most susceptible, with only 73% unperforated seeds and highest perforated seed percentage (27%) and perforated seed weight (8 g). Storage date had a significant ($p < 0.001$) effect on all seed damage and weight parameters, and a significant ($p = 0.021$) effect on live and dead bruchids. At the first storage date (day 45743), unperforated seeds were highest at 99.08%, perforated seeds were lowest at 0.92%, and perforated seed weight was only 0.24 g. Lot weight was 925.6 g. At the last storage date (day 45808), unperforated seeds declined sharply to 71.08%, perforated seeds rose to 28.92%, perforated seed weight increased to 8.21 g, and lot weight dropped to 905.3 g. The 100-seed weight decreased slightly from 29.98 g to 29.34 g.

The interaction between variety and storage date was significant ($p < 0.001$) for all seed damage and weight parameters, but not significant ($p = 0.376$) for live and dead bruchids. At the first storage date, all varieties had very high resistance: Kinure, Mukungugu, and Musore recorded more than 98% unperforated seeds, and Gasilida had 98.3% unperforated seeds. Perforated seed percentages and perforated seed weights were very low for all varieties. At the last storage date, Kinure's resistance decreased: unperforated seeds dropped to 80.7%, perforated seeds rose to 19.3%, and perforated seed weight increased to 7.5 g. Mukungugu's unperforated seeds fell from 98.7% to 72.7%, perforated seeds rose to 27.3%, and perforated seed weight increased to 6.4 g. Musore's unperforated seeds dropped to 83.3%, perforated seeds rose to 16.7%, and perforated seed weight grew to 3.5 g. Gasilida showed the largest decline: unperforated seeds fell sharply from 98.3% to 47.7%, perforated seeds increased dramatically to 52.3%, and perforated seed weight rose to 15.5 g. Lot weight also decreased: Kinure remained at 939.3 g; Mukungugu dropped from 923.8 g to 900.6 g; Musore from 903.5 g to 892 g; and Gasilida from 935.6 g to 889.3 g. Storage time significantly ($p < 0.001$) increased seed damage and weight loss for all varieties. Kinure showed the highest resistance over time; Gasilida was the most susceptible. Live and dead bruchid percentages varied but differences among varieties were not significant ($p = 0.376$).

Table 10. Main effects of common bean varieties, storage duration, and interaction on seed damage, weight, and bruchid infestation at Kayaza site

Factor	Factor levels	Unperforated seeds (%)	Weight of unperforated seeds (g)	Perforated seeds (%)	Weight of perforated seeds (g)	Weight of 1 lot/month (g)	Live bruchid (%)	Death bruchid (%)
Variety	V1'	90.3^{a}	35^{a}	9.7^{c}	3.7^{b}	939.3^{a}	61.8^{a}	38.2^{a}
	V2'	85.7^{b}	22.2^{c}	14.3^{b}	3.4^{b}	912.2^{b}	58.4^{a}	41.6^{a}
	V3'	91.3^{a}	20.6^{d}	8.7^{c}	1.8^{c}	897.8^{c}	62.3^{a}	37.7^{a}
	V4'	73^{c}	23.9^{b}	27^{a}	8^{a}	912.5^{b}	61.5^{a}	38.5^{a}
	L.S.D.	4.0	1.2	4.0	1.1	3.6	12.9	12.9
	p value	<0.001	<0.001	<0.001	<0.001	<0.001	0.876	0.876
Date	45743	99.1^{a}	29.7^{a}	0.9^{b}	0.2^{b}	925.6^{a}	54.8^{a}	45.2^{a}
	45808	71.1^{b}	21.1^{b}	28.9^{a}	8.2^{a}	905.3^{b}	67.2^{a}	32.8^{a}
	L.S.D.	3.3	1.0	3.3	0.9	2.6	9.9	9.9
	p value	<0.001	<0.001	<0.001	<0.001	<0.001	0.021	0.021
Variety × Date	V1' 45743	100^{a}	38.7^{a}	0.1^{d}	0.1^{d}	939.3^{a}	62.2^{ab}	37.8^{ab}
	V1' 45808	80.7^{b}	31.2^{b}	19.3^{c}	7.5^{b}	939.3^{a}	61.4^{ab}	38.6^{ab}
	V2' 45743	98.7^{a}	25.6^{c}	1.3^{d}	0.3^{d}	923.8^{b}	51.7^{b}	48.3^{a}
	V2' 45808	72.7^{c}	18.8^{e}	27.3^{b}	6.4^{b}	900.6^{c}	65^{ab}	35^{ab}
	V3' 45743	99.3^{a}	22.5^{d}	0.7^{d}	0.1^{d}	903.5^{c}	51.8^{b}	48.3^{a}
	V3' 45808	83.3^{b}	18.8^{e}	16.7^{c}	3.5^{c}	892^{d}	72.8^{a}	27.2^{b}
	V4' 45743	98.3^{a}	32.3^{b}	1.7^{d}	0.5^{d}	935.6^{a}	53.6^{ab}	46.4^{ab}
	V4' 45808	47.7^{d}	15.6^{f}	52.3a	15.5^{a}	889.3^{d}	69.4^{ab}	30.6^{ab}

	S.E.D.	2.6	0.8	2.6	0.7	2.2	8.1	8.1
	p value	<0.001	<0.001	<0.001	<0.001	<0.001	0.376	0.376

Key: *V1 = Kinure; V2 = Mukungugu; V3 = Musore; and V4 = Gasilida. LSD = least significant difference; S.E.D. = standard errors of the differences of means. Means along the same column bearing different letter(s) differ significantly.*

Effect of varieties and dates on *Z. subfasciatus* non-controlled storageed environment at Bujumbura site

The effect of variety on seed damage and weight parameters, Table 11, was significant ($p < 0.001$), but the effect on live and dead bruchids were not significant ($p = 0.182$). Kinure recorded the highest resistance, with 90.2% unperforated seeds, the highest weight of unperforated seeds (34.9 g). Its lot weight was also the highest (939.3 g). Mukungugu and Musore had similar moderate resistance: Mukungugu with 86.8% unperforated seeds and 22.5 g unperforated seed weight; Musore with 85.2% unperforated seeds and 19.3 g unperforated seed weight. Gasilida was the most susceptible, with only 73.7% unperforated seeds, highest perforated seed percentage (26.3%), and highest perforated seed weight (7.8 g). Its lot weight was the lowest (893.4 g). Storage date had a significant effect ($p < 0.001$) on seed damage and weight, and a slightly significant ($p = 0.046$) effect on live and dead bruchids. At the first storage date (day 45742), resistance was highest: unperforated seeds averaged 97.7%, perforated seeds were lowest at 2.3%, perforated seed weight only 0.6 g, and lot weight highest at 924.7 g. At the second storage date (day 45777), unperforated seeds declined to 86.6%, perforated seeds increased to 13.4%, and perforated seed weight rose to 3.6 g; lot weight dropped to 916.6 g. At the last storage time (day 45807), unperforated seeds dropped sharply to 67.7%, perforated seeds increased further to 32.3%, perforated seed weight rose to 9 g, and lot weight fell to 902.9 g.

The interaction between variety and storage date was significant ($p < 0.001$) for seed damage and weight parameters, but not significant ($p = 0.41$) for live and dead bruchid percentages. At the first storage date, all varieties had very high resistance: Kinure, Mukungugu, Musore, and Gasilida all recorded over 96% unperforated seeds, very low perforated seeds (1.7–3.3%), and low perforated seed weights (0.3–0.8 g). Lot weights were also high, above 902.8 g for all varieties. At the second storage date, resistance declined: Kinure still had 92.3% unperforated seeds, perforated seeds rose to 7.7%, and perforated seed weight increased to 3 g. Mukungugu's unperforated seeds dropped to 87.3%, perforated seeds rose to 12.7%, and perforated seed weight reached 3 g. Musore had 86% unperforated seeds and 14% perforated seeds. Gasilida showed a larger drop to 80.7% unperforated seeds, perforated seeds increased to 19.3%, and perforated seed weight rose to 5.7 g. At the last storage date, damage was highest. Kinure's unperforated seeds dropped to 80%, perforated seeds increased to 20%, and perforated seed weight reached 7.7 g.

Mukungugu's unperforated seeds fell to 76.3%, perforated seeds increased to 23.7%, and perforated seed weight rose to 5.5 g. Musore's unperforated seeds dropped to 71.3%, perforated seeds increased to 28.7%, and perforated seed weight rose to 6 g. Gasilida had the largest loss of resistance: unperforated seeds fell sharply to 43%, perforated seeds increased dramatically to 57%, and perforated seed weight reached 16.9 g. Lot weights also dropped, especially for Musore (down to 883.4 g) and Gasilida (885 g). Storage time significantly ($p < 0.001$) increased seed damage and weight loss for all varieties. Kinure consistently showed the highest resistance across dates; Gasilida was the most susceptible. Live and dead bruchids varied, but differences between varieties and their interaction with storage sites were not significant ($p = 0.182$ and $p = 0.41$).

Table 11. Effects of bean varieties, storage time, and interaction on *Z. subfaciatus* at Bujumbura site

Fac tor	Factor levels	Unperforated seeds (%)	Weight of unperforated seeds (g)	Perforated seeds (%)	Weight of perforated seeds (g)	Weight of 1 lot/month (g)	Live bruchid (%)	Death bruchid (%)
Variety	V1'	90.2^{a}	34.9^{a}	9.8^{c}	3.8^{b}	939.3^{a}	65.8^{a}	34.2^{a}
	V2'	86.8^{ab}	22.5^{c}	13.2^{bc}	3.1^{b}	913.2^{b}	70.4^{a}	29.6^{a}
	V3'	85.2^{b}	19.3^{d}	14.8^{b}	3.1^{b}	913.1^{b}	69.4^{a}	30.7^{a}
	V4'	73.7^{c}	24.2^{b}	26.3^{a}	7.8^{a}	893.4^{c}	70.1^{a}	29.9^{a}
	L.S. D	4.6	1.5	4.6	1.4	2.5	4.8	4.8
	p value	<0.001	<0.001	<0.001	<0.001	<0.001	0.182	0.182

Date	45742	97.7^{a}	29.3^{a}	2.3^{c}	0.6^{c}	924.7^{a}	66^{b}	34.1^{a}
	45777	86.6^{b}	26.1^{b}	13.4^{b}	3.6^{b}	916.6^{b}	66.8^{b}	33.2^{a}
	45807	67.7^{c}	20.2^{c}	32.3^{a}	9^{a}	902.9^{c}	74^{a}	26^{b}
	L.S. D	3.5	1.1	3.5	1.1	2.7	6.9	6.9
	p value	<0.001	<.001	<0.001	<0.001	<0.001	0.046	0.046
Variety × Site	V1' 45742	98.3^{a}	38.1^{a}	1.7^{f}	0.6^{cf}	939.3^{a}	60.6^{b}	39.4^{a}
	V1' 45777	92.3^{ab}	35.7^{b}	7.7^{ef}	3^{c}	939.3^{a}	64.8^{ab}	35.3^{ab}
	V1' 45807	80^{cd}	31^{c}	20^{cd}	7.7^{b}	939.3^{a}	72.1^{ab}	27.9^{ab}
	V2' 45742	96.7^{a}	25^{d}	3.3^{f}	$0.^{8c-f}$	922^{b}	67.7^{ab}	32.3^{ab}
	V2' 45777	87.3^{bc}	22.6^{e}	12.7^{de}	3^{cd}	913.7^{c}	68.2^{ab}	31.8^{ab}
	V2' 45807	76.3^{de}	19.8^{f}	23.7^{bc}	5.5^{b}	903.9^{d}	75.2^{a}	24.8^{b}
	V3' 45742	98.3^{a}	22.2^{e}	1.7^{f}	0.3^{f}	902.8^{d}	71.8^{ab}	28.2^{ab}
	V3' 45777	86^{bc}	19.4^{f}	14^{de}	2.9^{cde}	893.9^{e}	61.4^{ab}	38.6^{ab}
	V3' 45807	71.3^{e}	16.1^{g}	28.7^{b}	6^{b}	883.4^{f}	74.9^{a}	25.1^{b}
	V4' 45742	97.3^{a}	31.9^{c}	2.7^{f}	0.8^{cdf}	934.7^{a}	63.7^{ab}	36.3^{ab}
	V4' 45777	80.7^{cd}	26.5^{d}	19.3^{cd}	5.7^{b}	919.5^{b}	72.8^{ab}	27.2^{ab}
	V4' 45807	43^{f}	14.1^{g}	57^{a}	16.9^{a}	885^{f}	73.8^{ab}	26.2^{ab}
	S.E.D.	3.3	1.1	3.3	1	2.3	5.8	5.8
	p value	<0.001	<0.001	<0.001	<0.001	<0.001	0.41	0.41

Key: *V1 = Kinure; V2 = Mukungugu; V3 = Musore; and V4 = Gasilida. LSD = least significant difference; Means along the same column bearing different letter(s) differ significantly.*

Acanthoscelides obtectus **bruchid susceptibility and resistance by variety and environment**

Across the two study sites and storage environments, notable differences emerged among the common bean varieties in terms of their susceptibility or resistance to *Acanthoscelides obtectus* infestation (Table 12). Overall, seeds stored under conditioned environments at both Kayanza and Murongwe maintained higher proportions of unperforated seeds, and higher lot weights, indicating better protection against bruchid damage. For example, in conditioned storage, Kinure consistently showed the strongest resistance, retaining around 90% and 94% unperforated seeds, maintaining stable lot weights close to 990 g. In contrast, Gasilida, identified as the most susceptible, exhibited a lower count of unperforated seeds (approximately 74% to 87%) and higher perforated seed weight values reaching up to 7.4 g, alongside a lower 100-seed weight around 32 g. Under unconditioned storage at Murongwe, the resistant variety Kinure still performed well, retaining between 93% and 95% unperforated seeds and a relatively high 100-seed weight of around 38.7 g. Meanwhile, Gasilida again showed vulnerability, with fewer unperforated seeds (around 76% to 89%) and the highest perforated seed weight recorded at 6.9 g. At Kayanza, the same pattern was observed: Kinure remained the most resistant, whereas Gasilida showed relatively higher damage. Varieties Musore and Mukungugu generally fell into an intermediate category, with unperforated seed counts typically ranging between 88% and 92% and 100-seed weights around 22–26 g, consistently lower than Kinure but higher than Gasilida under unconditioned storage. The results indicated that conditioned storage effectively limits bruchid infestation across sites and varieties, while genetic resistance further strengthens protection. Kinure, in particular, showed stable resistance in both storage environments and sites, whereas Gasilida consistently suffered greater damage, highlighting the combined role of storage environment and varietal resistance in bruchid management.

Table 12. Summary of bruchid (*Acanthoscelides obtectus*) susceptibility and/or resistance in common bean varieties

Site	Environment	Variety	Bruchid susceptibility / resistance	Key findings

Kayanza & Murongwe	Conditioned	Kinure	Most resistant	High unperforated seeds (90–94%); low perforated seed weight (2.9–3.9 g); stable lot weight (990 g)
		Musore	Intermediate	Unperforated seeds 88–90%; perforated seed weight (2–2.3 g); lot weight (896–897 g)
		Mukungugu	Intermediate	Unperforated seeds 85–89%; perforated seed weight (2.7–3.5 g); lot weight (911–914 g)
		Gasilida	Most susceptible	Lower % unperforated seeds (74–87%); higher perforated seed weight (3.8–7.4 g); lot weight (914–927 g)
Murongwe	Unconditioned	Kinure	Highest resistance	Unperforated seeds (93–95%); lot weight (939 g)
		Musore	Intermediate	Unperforated seeds (91%); lot weight (898 g)
		Mukungugu	Intermediate	Unperforated seeds (89–92%); lot weight (918 g)
		Gasilida	Most susceptible	Lower unperforated seeds (76–89%); highest perforated seed weight (6.9 g); lot weight (927 g)
Kayanza	Unconditioned	Kinure	Highest resistance	Unperforated seeds (94%); lot weight (939.3 g)
		Mukungugu	Intermediate	Unperforated seeds (89.3%); lot weight (918 g)
		Musore	Intermediate	Unperforated seeds (91%); lowest lot weight (898 g)
		Gasilida	Most susceptible	Unperforated seeds (89%); perforated seed weight (6.9 g); lot weight (927 g)

Zabrotes subfasciatus bruchid susceptibility and resistance by variety and environment

Results in Table 13 summarize the susceptibility and resistance of four common bean varieties to *Z. subfasciatus* infestation under both conditioned and unconditioned storage environments at the Bujumbura site. The results highlight clear differences among varieties in terms of seed damage and weight parameters, reflecting varying levels of bruchid resistance. Under the conditioned environment, Kinure consistently exhibited the highest resistance to *Z. subfasciatus* infestation. Initially, Kinure maintained a very high proportion of unperforated seeds (approximately 98.3%), which decreased moderately to 84.7% by the end of the storage period. This decline was accompanied by a relatively small increase in perforated seed weight (from 0.6 g to 5.9 g), indicating limited seed damage over time. Additionally, Kinure preserved high seed quality, as reflected in its stable 100-seed weight (41 g) and lot weight (~986–994 g) throughout the storage duration. These parameters suggest Kinure's superior ability to resist seed deterioration even under prolonged storage.In contrast, Gasilida was the most susceptible variety under conditioned conditions. It experienced a dramatic reduction in unperforated seeds from 95% down to 42.3%, alongside a substantial increase in perforated seed weight from 1.5 g to 17.1 g, indicating severe seed damage. Gasilida's lot weight also declined notably (932.6 g to 884.4 g), signifying considerable deterioration of seed quality. Although Gasilida maintained a moderate 100-seed weight (32 g), the high level of physical seed damage reflects poor resistance to bruchid infestation.

Mukungugu and Musore showed intermediate levels of resistance under conditioned conditions. Mukungugu's unperforated seeds decreased sharply from 97.7% to 67.7%, with perforated seed weight increasing from 0.5 g to 7.6 g. Its 100-seed weight remained relatively low (~25 g), and lot weight declined from 922.9 g to 896.1 g. Musore's resistance was slightly higher, with unperforated seeds dropping from 96.7% to 81% and perforated seed weight rising from 0.7 g to 4 g, alongside a modest decline in lot weight (901.6 g to 890.3 g). Both varieties showed measurable deterioration over storage time but maintained better seed quality than Gasilida.Under the unconditioned environment, a similar trend in varietal resistance was observed, though overall seed damage tended to be higher. Kinure again demonstrated the highest resistance, with unperforated seeds around 90.2%, the greatest unperforated seed weight (34.9 g), highest 100-seed weight (38.7 g), and highest lot weight (939.3 g). This indicates Kinure's robustness across varying storage conditions.Mukungugu and Musore again exhibited moderate resistance with unperforated seeds at 86.8% and 85.2%, respectively, and lower unperforated seed weights (22.5 g and 19.3 g). Musore had the lowest lot weight (893.4 g), reflecting some vulnerability to seed damage over time. Gasilida remained the most susceptible under unconditioned storage, with the lowest unperforated seed proportion (73.7%) and the highest perforated seed damage (26.3%) and perforated seed weight (7.8 g). Its lot weight was also the lowest (893.4 g), consistent with poor resistance and greater seed deterioration. Storage time significantly increased seed damage and weight loss for all varieties, with Kinure consistently showing the strongest resistance to *Z. subfasciatus* infestation, regardless of environmental conditions. Gasilida was the most susceptible, experiencing the greatest seed damage and deterioration. Mukungugu and Musore presented intermediate resistance levels with moderate declines in seed quality.

Table 13. Summary of *Zabrotes subfasciatus* susceptibility and/or resistance in common bean varieties

Environment	Variety	Bruchid susceptibility / resistance	Key findings
Conditioned	Kinure	Most resistant	High unperforated seeds at start (98.3%); modest decline over time to 84.7%; lowest perforated seed weight increase (0.6 g → 5.9 g); lot weight stable (~986–994 g)
	Mukungugu	Intermediate	Unperforated seeds dropped from 97.7% to 67.7%; perforated seed weight rose from 0.5 g to 7.6 g; lot weight decreased from 922.9 g to 896.1 g
	Musore	Intermediate	Unperforated seeds declined from 96.7% to 81%; perforated seed weight increased from 0.7 g to 4 g; lot weight modestly decreased (901.6 g → 890.3 g)
	Gasilida	Most susceptible	Unperforated seeds dropped steeply from 95% to 42.3%; perforated seed weight increased sharply from 1.5 g to 17.1 g; lot weight decreased from 932.6 g to 884.4 g
Unconditioned	Kinure	Highest resistance	High unperforated seeds (90.2%); highest unperforated seed weight (34.9 g); lot weight highest (939.3 g)
	Mukungugu	Intermediate	Unperforated seeds 86.8%; unperforated seed weight 22.5 g; lot weight ~918 g
	Musore	Intermediate	Unperforated seeds 85.2%; unperforated seed weight 19.3 g; lowest lot weight (893.4 g)
	Gasilida	Most susceptible	Lower unperforated seeds (73.7%); highest perforated seed (26.3%) and perforated seed weight (7.8 g); lot weight (893.4 g)

DISCUSSION

Impact of variety and environment on bruchid infestations

The findings of this study show that varietal differences significantly influence bean seed susceptibility to infestation by bruchid species, specifically *Acanthoscelides obtectus* and *Zabrotes subfasciatus* (Szentesi, 2021;

de Oliveira Takaku et al., 2025). Varieties such as Kinure exhibited consistently higher percentages of unperforated seeds and reduced seed damage, suggesting inherent resistance mechanisms, while varieties like Gasilida were more preferred by bean bruchids, reflected in increased seed perforation and pest activity (Rubiales & Khazaei, 2022; Bornowski et al., 2023). This variation implies that intrinsic seed traits, including seed coat thickness, hardness, biochemical composition (such as phenolic compounds and protease inhibitors), and genetic factors, play a pivotal role in determining the extent of bruchid infestation (Letting et al., 2021; Sathish et al., 2023). These results are consistent with previous research demonstrating that varietal resistance is a critical factor in reducing damage from stored-product pests (Mengistu, 2022; Nboyine et al., 2024).

The study also revealed that seed damage and bruchid populations increased over time, indicating that prolonged storage creates favourable conditions for pest proliferation (Okori et al., 2022; Navarro et al., 2024). This pattern aligns with established knowledge on pest population dynamics in storage environments, where extended periods permit exponential growth of pest populations and consequent deterioration of seed quality (Sultana et al., 2021; Zhou et al., 2024). Moreover, the increase in perforated seed percentages and weight loss over storage time suggests the progressive impact of larval feeding, which compromises seed viability and nutritional content (Avezum et al., 2023; Packirisamy et al., 2025).

Environmental variability between the two sites, Murongwe and Kayaza, influenced the severity of infestation and seed damage. Differences in microclimatic conditions such as temperature, relative humidity, and airflow likely affected bruchid development and survival rates, corroborating findings from previous studies that abiotic factors are crucial determinants of storage pest biology and population dynamics (Achiri et al., 2021; Plestenjak *et al*., 2024). This spatial variation highlights the complex interplay between environmental conditions and pest pressure, emphasizing the importance of site-specific storage management strategies (Kessy et al., 2024; Cappa et al., 2025).

The interaction between bean variety and storage duration indicates that resistance levels may vary across the storage period, with some varieties potentially losing effectiveness over time (Kadyan et al., 2022; Segers et al., 2022). This suggests that the resistance traits observed may confer temporal protection, but their efficacy is influenced by storage length and pest adaptation (Ndakidemi et al., 2021; Plestenjak et al., 2024). Such findings support existing literature emphasizing that resistance is dynamic and context-dependent (Gutiérrez-Moreno et al., 2021; Lee Díaz et al., 2021). This temporal variation may also reflect changes in seed biochemical composition as seeds age, which could alter their susceptibility to pests (Lazarević et al., 2022; Michalczyk et al., 2023).

The observed differences in live and dead bruchid proportions across varieties suggest that seed characteristics might influence insect mortality, which is influenced by biochemical deterrents or toxicity (Ndakidemi et al., 2021; Gvozdenac et al., 2022). Key secondary metabolites such as phenolic compounds, protease inhibitors, and lectins, along with physical traits like seed coat thickness, hardness, and texture, have been shown to significantly deter bruchid infestation by affecting insect feeding, oviposition, and larval development (Shishehbor & Hemmati, 2022; Vuts et al., 2024). Such biochemical defences are known to reduce pest fitness and reproduction, contributing to lower infestation rates.

The findings corroborate prior evidence that varietal resistance is a fundamental component in managing bruchid infestations in stored common bean seeds (Maro et al., 2022; Cabral et al., 2024; Magubika et al., 2025). The variation in susceptibility across varieties and sites reflects a complex interaction of genetic, biochemical, and environmental factors shaping pest dynamics and seed preservation (Razzaq et al., 2023; Ouaarous et al., 2025). The integration of resistant varieties with consideration of storage conditions thus remains essential for sustainable pest management in common bean production systems (Singh et al., 2022; Diatta et al., 2024).

Practical relevance and challenges of the study

The findings of this study provide valuable insights for enhancing bean storage management and pest control strategies. The demonstrated variation in seed susceptibility to *Acanthoscelides obtectus* and *Zabrotes subfasciatus* among different bean varieties suggests that selecting less susceptible cultivars can effectively reduce bruchid infestation and seed damage during storage (Dell'Aglio & Tayeh, 2023; Osman et al., 2023). This varietal resistance offers a sustainable approach to minimize postharvest losses without relying solely on chemical controls, aligning with integrated pest management principles (Osei-Kwarteng et al., 2024; Montero-Vega et al., 2025). Furthermore, the observed differences between storage sites show the importance of considering environmental conditions in developing tailored storage practices to optimize seed preservation and maintain seed quality (Uebersax et al., 2022b; Sitoe et al., 2025).

The study also highlights the potential for combining varietal selection with improved storage conditions to enhance bean storability and reduce economic losses attributed to bruchid infestations (Misra et al., 2024). Such an approach supports food security efforts, particularly for smallholder farmers who may have limited access to chemical pesticides or advanced storage technologies (Fulano et al., 2021; Chidege et al., 2024). However, the implementation of these findings faces several challenges. Environmental variability across storage locations can influence bruchid population dynamics, potentially undermining uniform pest management strategies (Małek et al., 2023; Adewale & Abberton, 2024). Additionally, resource constraints among small-scale farmers, such as limited access to resistant varieties and appropriate storage infrastructure, may hinder adoption (Abraha et al., 2024; Vilakazi et al., 2025). The adaptability and reproductive capacity of bruchid species also pose a risk of resistance development, necessitating continuous monitoring and integration of multiple control measures (Ragul & Manivannan, 2024; Khan et al., 2025).

CONCLUSION

The findings of this study demonstrate significant variation among bean varieties in their preference and damage by *Acanthoscelides obtectus* and *Zabrotes subfasciatus*, with some varieties showing greater resistance and better seed preservation during storage Gasilida is a variety that is preferred by bruchid. These results highlight the crucial role of varietal traits in reducing seed damage, weight loss, and maintaining seed quality over time. The interaction between storage duration and pest activity further underlines the need for ongoing monitoring to manage postharvest losses effectively. Overall, the study provides valuable insights into how different bean varieties respond to bruchid infestation and how this affects seed storability. Based on these findings, it is recommended that farmers and seed producers adopt resistant bean varieties to enhance seed longevity and reduce pest damage during storage. Incorporating these resistant varieties into integrated pest management programs alongside proper storage hygiene and protective measures can improve the effectiveness of bruchid control. Further research aimed at identifying the specific physical and biochemical traits responsible for resistance is recommended, particularly for the Institute des Sciences Agronomiques du Burundi (ISABU), to support targeted breeding initiatives and inform future extension efforts. They should also organize training programs and extension services to build farmer capacity in integrated pest management and post-harvest handling. Moreover, assessing the combined impact of varietal resistance with complementary control strategies across varying agroecological zones will be critical in developing sustainable, site-specific storage pest management solutions.

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AUTHORS CONTRIBUTIONS

AN: Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Visualization, Writing – original draft, Writing – review & editing. LFS: Supervision, Validation, Visualization, Writing – review & editing. PJL: Supervision, Validation, Visualization, Writing – review & editing.

CONFLICT OF INTERESTS

The authors declare no conflict of interest.

ETHICAL APPROVAL

Not applicable.

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AVAILABILITY OF DATA AND MATERIALS

All datasets analyzed and described during the present study are available from the corresponding author upon reasonable request.

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