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Post-harvest conservation practices, related insect pests of stored pearl millet (*Pennisetum glaucum* (L) R. Br.), and their management in northern Benin

Tayé Obédatou Alagbe¹, Yeyinou Laura Estelle Loko^{1*} , Innocent Djègbè², Julien Gandjala¹, Dieudonné Gavodo¹ and Manuele Tamò³

Abstract

Background Pearl millet (*Pennisetum glaucum* (L.) R. Br.) production has decreased over the years due to several constraints, including insect pest attacks, which contribute to its status as neglected and underutilized species in Benin. In order to develop an integrated pest management strategy, we documented farmers' post-harvest conservation practices, perceptions, and management of storage insect pests. Four hundred millet producers were surveyed using a semi-structured questionnaire in 76 villages in northern Benin. The entomofauna associated with stored pearl millet was identified by extracting samples from farmers' storage structures and incubating them for a month in the laboratory.

Results Our results showed that farmers perceived insect pests as the most important constraint to pearl millet storage. Vernacular taxonomy and local nomenclature of insect pests of stored pearl millet varied among sociolinguistic groups. Four species of insects were associated with stored millet with the weevils *Sitophilus oryzae* L. and *Sitophilus zeamais* L. as the most important ones. Three storage structures (attic, bedroom, and store) and a storage tool (polypropylene bags) were inventoried. Synthetic chemical insecticides were the most commonly used method for protecting stored millet. Also, farmers employed four plants that repel and kill insects to safeguard stored pearl millet. A differential sensitivity of pearl millet varieties to storage insect attacks was reported with four potential resistant varieties. Some factors that influence the use of a pest management method were determined.

Conclusions The development of an integrated pest management needs to test the sensitivity of resistant varieties and the bioactivity of recorded insecticidal plants. The farmers' perception suggests that the Souhoun n'nin gberenou landrace and the usage of bark of *A. senegalensis* and leaves of *A. indica* are the best ways to preserve millet for a long time. Raising awareness among pearl millet producers on good storage practices and the biological management of storage insect pests were recommended. Factors that influence the use of pest management methods must be integrated into the development of national strategies.

Keywords Storage constraints, Control methods, Varietal resistance, Determinants, Benin

*Correspondence:

Yeyinou Laura Estelle Loko
lokoestelle@yahoo.fr

Full list of author information is available at the end of the article

Background

Pearl millet is a cereal native to tropical West Africa of particular interest in the current context of climate change due to its tolerance to drought (Das & Rakshit, 2016; Srivastava et al., 2022). This cereal, although rich in essential nutrients and having a high-energy value and considerable antioxidant properties (Mawuma et al., 2022), remains a neglected and underutilized species in the Republic of Benin (Ben Romdhane et al., 2022; Dansi et al., 2012). Indeed, pearl millet cultivation remains mainly in northern Benin through traditions and customs (Dagba et al., 2014; Zannou et al., 2022). In this region, a diversity of pearl millet is cultivated and some varieties have important nutritional qualities for the health and food security of local populations (Dagba et al., 2014; Adéoti et al., 2017a).

Despite its importance, pearl millet production in Benin has declined over the years from an estimated 40.75 tons per year in 2002 to 27.29 tons in 2020 (FAO, 2020). This decline in production is due to many constraints, including post-harvest losses due to poor storage practices that favour insect pest infestations (Das & Rakshit, 2016; Adeoti et al., 2017b). Indeed, the damage caused by insect pests to stored pearl millet depends on the storage system used (Lale & Yusuf, 2000). However, in Benin, other than the study conducted by Dagba et al. (2014) that mentioned the storage of millet in attics, gourds and bags, there is very little information on post-harvest practices used by local communities. It is therefore necessary to document the practices related to post-harvest conservation of pearl millet in Benin in order to identify those that can be improved to enhance food security and farmer's incomes (Njoroge et al., 2019).

Insect pests are a major constraint to pearl millet storage due to their attacks, which cause significant losses and affect the nutritional quality of grains (Meenatchi & Loganathan, 2022). Stored millet is known to be attacked by a wide range of insects, including *Rhyzopertha dominica* Fab., and *Sitophilus zeamais* L. (Lale & Yusuf, 2000). These pests cause damage by feeding on grains, destroy germs and cause grain warming and consequently grain deterioration (Sharma et al., 2007). Unfortunately, in Benin, little attention has been paid to insect pests in the stored pearl millet. Consequently, there has been no assessment of how farmers perceive insect pest infestation and the extent of their damage. The main insect pests that require an integrated pest management method for stored pearl millet are presently unknown. Similarly, the traditional management practices for insect pests in stored millet are little known. Filling these gaps is crucial to develop an efficient integrated pest management strategy for sustainable conservation of pearl millet in Benin.

This study therefore aimed to: (1) document pearl millet storage constraints and post-harvest practices; (2) document farmers' perceptions of storage insect pests of pearl millet and their traditional management practices; (3) identify the diversity of insect pests associated with stored pearl millet and tolerant/resistant landraces; and (4) identify the sociodemographic factors influencing the use of a specific method to manage insect pests in stored pearl millet.

Methods

Study area and site selection

The Republic of Benin is a country in West Africa located between the meridians 0°40' and 3°45'-East (longitude) and the parallels 06°15 and 12°25 North (latitude). Our study was carried out in northern Benin (Fig. 1), which is the main pearl millet growing region (Dagba et al., 2014; Adéoti et al., 2017a, 2017b), which include 4 departments (Alibori, Borgou, Donga, and Atacora). The northern region is characterized by the Sudanese climate with a single rainy season. The annual rainfall ranges from 1000 to 1200 mm/year, with a mean temperature around 28 °C. Ferruginous tropical and ferralitic soils are commonly encountered. In the five agro-ecological zones that cover northern Benin (Fig. 1), vegetation types vary from wooded and shrubby savannah in the south, to herbaceous and shrubby savannah area in the north, and a sparse savannah in the far north (Ollabode et al., 2022). Pearl millet production statistics, accessibility, and a good coverage of the study area were the factors that led to the selection of seventy-six villages across 20 municipalities in the northern region (Fig. 1).

Sampling

To determine the sample size of pearl millet farmers to be interviewed for the study, the following formula (Dagnélie, 1998) was utilized:

$$S = \frac{U_{1-\alpha/2}^2 \times p(1-p)}{d^2}$$

where S is the number of surveyed pearl millet farmers and $U_{1-\alpha/2}^2 = 1.96$ is the value of the normal random variable for a risk α equal to 0.05. The proportion of pearl millet farmers ($p = 0.99$) was determined by considering the number of agricultural households in the north Benin (337,517), the number of households involved in cereal production (334,314), and a single person interviewed per household (Adebo et al., 2018; INSAE, 2016; Loko et al., 2022). d is the 3% margin of expected error margin provided for any parameter to be estimated from the survey. The minimum number of households needed to be surveyed was estimated to be 42.25.

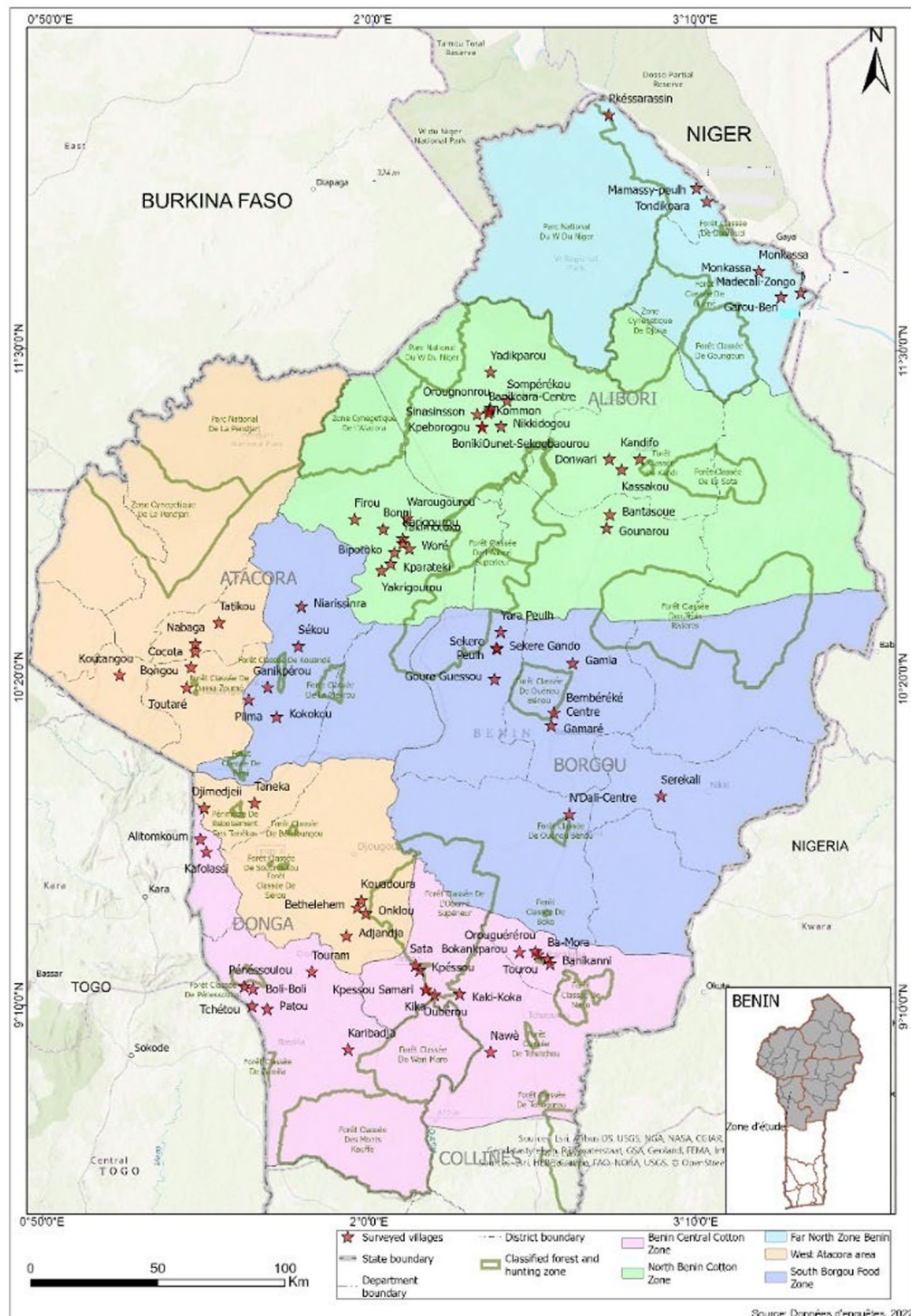


Fig. 1 Geographical localization of surveyed villages

Surveys

Data were collected between May and September 2022. In each village, the farmers who were surveyed were those who cultivate and store millet. These farmers

were chosen with the help of village chiefs or leaders of farmers' organizations, but also by the "snowball" sampling method. This method consisted of sampling households based on recommendations from previously

interviewed millet-producing households. Four hundred millet producers were surveyed throughout the study area. The ethnic diversity led to the recruitment of interpreters locally to facilitate discussions and exchanges with farmers. After presenting the research objectives to the pearl millet producers, data were collected using questionnaires and participatory research methods (individual surveys and field visits). The data collected included the socio-demographic characteristic of households, storage constraints, storage structures and places, millet storage practices, methods of conservation of millet seeds, farmers' knowledge and perceptions of storage insect pests associated with pearl millet, as well as traditional management methods. Farmers' perception of the susceptibility of each cultivated pearl millet variety to storage insect pests was also documented, as well as the possibilities of valorizing infested pearl millet.

Identification of insects associated with stored pearl millet

In each village surveyed, samples of pearl millet stored without insecticides were taken from the farmers' storage structures according to the method described by Loko et al. (2019). In each storage structure, 500 g of pearl millet were collected at three different depths of the stock using an electronic scale. The samples were conserved in labelled plastic boxes (19 cm in height, 7 cm in diameter), and incubated for 1 month in the Laboratory of Applied Zoology and Plant Health (ZASVE) of the National High School of Applied Biosciences and Biotechnologies under ambient conditions (25 ± 2 °C, $75 \pm 5\%$ of relative humidity, and a photoperiod of 12:12 (L:D) h). Taxonomic identification keys of stored commodities were used to identify different recorded insect species after this period (Halstead, 1986; Kumar, 2017). The relative abundance of each insect species was determined by the ratio of number of individuals of an insect species in the sample to the total number of insects in the sample.

Data analysis

The data collected were analysed using descriptive and multivariate statistics. A comparison of socio-demographic variables across different agro-ecological zones was made using ANOVA for quantitative variables and chi-square tests for qualitative variables. The data was arc-sin transformed before the ANOVA to homogenize variances. Multivariate logistic regression models were constructed to identify the determinants or socio-demographic factors associated with the use of a specific method to manage insect pests in stored pearl millet. IBM SPSS version 23 was utilized for all analyses.

Results

Socio-demographic characteristics

The majority (87.5%) of the surveyed pearl millet producers were men. These farmers belong to six socio-cultural groups including Fulani (22%), Bariba (21.7%), Yoa-lokpa (17.5%), Ottamari (16.3%), Betamaribe (13%), and Dendi (9.5%). The majority of them were Muslims (56.5%). The percentage of respondents who were Christian and animist millet producers was 29.7% and 13.8%, respectively. Farming was the main activity of the surveyed households (94%), with experience in pearl millet production varying across the prospective agro-ecological zones (Table 1). The surveyed farmers in the extreme north-west and west of Atacora of Benin had significantly more experience in pearl millet production than those in other prospected zones. The average age of the surveyed farmers was 41.2 ± 12.6 years. The yield of pearl millet mentioned by the surveyed farmers varied across the different prospected zones (Table 1).

Pearl millet storage constraints, and solutions proposed by farmers

The surveyed farmers revealed ten storage constraints for pearl millet (Fig. 2a). Insect attack was the main constraint (66.2% of responses), followed by mouse attack (18%), and millet grain rot (11.8%). Some farmers also mentioned the inadequacy of storage structures (1.6%), humidity (0.6%), and rodent attacks (0.6%) as constraints. Only 0.3% of the surveyed millet producers mentioned moulds, bushfires, grain germination loss, and the lack of pesticides suitable for storage as constraints. The surveyed farmers proposed 19 solutions to overcome these constraints. The most popular responses included efficient insecticides (38.3%), winnowing (22.4%), and drying grains (21.5%). The rapid sale of millet (4.6%), the harvest on the right date (3.2%), the hygiene of storage structures (2.6%), the use of varietal resistance (1.8%), and the construction of stores (1.4%) were also among the solution proposed by farmers (Fig. 2b).

Millet storage practices

Pre-storage practices

Only a few surveyed farmers (35%) adopted the practice of pre-storage for pearl millet. The main reason for pre-storage of pearl millet was to ensure good drying of the millet seeds (89.2% of responses). Some farmers practiced a pre-storage of pearl millet to facilitate ginning (4.3%), due to lack of time for conditioning the seeds (3.6%), and/or due to the distance between the field and the storage structures (1.5%), and/or due to the lack of

Table 1 Sociodemographic characteristics of the surveyed pearl millet farmers in the study area

Characteristics	Zone I (N=40)	Zone II (N=80)	Zone III (N=100)	Zone IV (N=120)	Zone V (N=60)	Study area (N=400)	X ² -test	F-test	P-value
<i>Gender (%)</i>									
Male	39	71	88	101	51	350 (87.5)	5.356 ns	–	P=0.253
Female	1	9	12	19	9	50 (12.5)			
<i>Age (Years)</i>									
Mean ± SD	38.5 ± 13.4	40.7 ± 13.5	39.0 ± 11.4	44.0 ± 12.5	41.4 ± 12.6	41.2 ± 12.6	–	2.790 ns	P=0.073
<i>Experience (Years)</i>									
Mean ± SD	20.1 ± 12 ^a	11.1 ± 8.4 ^b	12.05 ± 9.7 ^b	22.7 ± 12.5 ^a	11.25 ± 8.2 ^b	15.7 ± 11.6	–	24.788***	P<0.000
<i>Quantity (t/ha)</i>									
Mean ± SD	1.8 ± 1.2 ^a	1.3 ± 1.0 ^a	2.1 ± 2.1 ^b	0.4 ± 0.3 ^a	0.9 ± 1.8 ^a	1.2 ± 1.5	–	25.891***	P<0.000
<i>Religion (%)</i>									
Muslim	40	58	53	32	43	226 (56.5)	124.709***	–	p<0.000
Christian	–	19	35	48	21	115 (29.7)			
Animist	–	3	12	40	–	55 (13.8)			
<i>Marital status (%)</i>									
Married	39	74	92	112	59	376	9.668 ns		P=0.645
Single	1	6	8	8	1	24			
<i>Sociocultural group (%)</i>									
Fulani	5	29	33	6	15	88 (22)	512.759***	–	p<0.000
Bariba	–	44	24	1	18	87 (21.7)			
Yoa-lokpa	–	–	–	50	20	70 (17.5)			
Ottamari	–	4	20	40	1	65 (16.3)			
Betamaribe	–	2	22	23	5	52 (13)			
Dendi	35	1	1	–	1	38 (9.5)			
<i>Sources of income (%)</i>									
Farming	38	78	89	115	58	378 (94.5)	15.216 ns	–	P=0.509
Crafts	–	–	4	2	2	8 (2)			
Trade	2	2	7	3	–	14 (3.5)			

Zone I: Extreme North-Benin, Zone II: North-Benin, Zone III: South Borgou, Zone IV: West Atacora, Zone V: Central Benin cotton zone. Numbers followed by different letters showed a significant difference at 5%. ns: not significant

storage facilities (0.7%). Pre-storage was mostly done in the fields (82.9% of responses) or in homes (17.1%).

Storage forms and structures

The surveyed farmers adopted various forms and structures for storage of pearl millet. The majority of them stored millet in the form of shelled maize kernels (82.1%), either in polypropylene bags (62.2%), jute bags (0.3%), or jars (0.3%). Only a few surveyed farmers stored millet in the form of cobs with the husks (15.7%) or stripped cobs (2.2%) in the cribs (11.2%), and granaries (26%) (Fig. 3). The millet stored mainly in jute and polyethylene bags is generally stored in farmers' houses (85% of responses), and stores (15%).

Storage methods practices

Due to the lack of storage structure, pearl millet is usually stored with other foodstuffs by all the surveyed farmers. Maize was the most stocked commodity with pearl

millet (36.2% of responses), followed by sorghum (26.2%), soybeans (15.4%), rice (6.5%), beans (5%), peanuts (4.2%), cassava chips (2.8%), yam chips (1.9%), Bambara groundnut (0.8%), fonio millet (0.5%), cowpea (0.3%) and sesame (0.2%). The great majority of the surveyed farmers (92.9%) regularly clean their storage structures and remove old pearl millet seeds from them after each agricultural campaign.

Farmers' perception of the stored time of pearl millet and factors that favor insect infestation

The surveyed farmers in the study area preserved pearl millet for a short period (Fig. 4). For the great majority of the surveyed farmers (74.9%), the infestation of stored pearl millet by insect pests was observed during the first six months of storage (Fig. 4). Some farmers used heavily infested pearl millet grains, for animal (45.6% of responses) and human (25.8%) consumption. Some farmers throw them away (28.2%). Only a minority

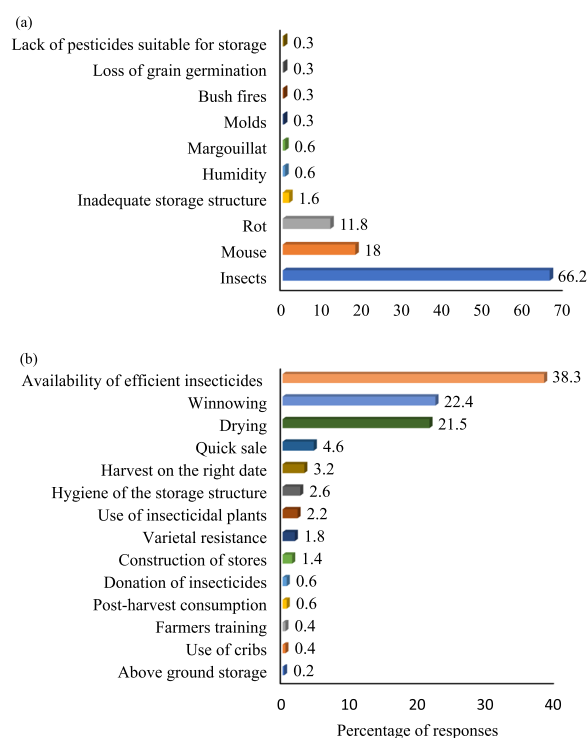


Fig. 2 a Farmer's perceptions of constraints related to stored millet, b proposal of solutions to the constraints listed

of the surveyed farmers mixed infested grains with non-infested grains and then sold them at a low price (0.4%). The surveyed farmers mentioned eight factors that favour the attack of stored millet by insect pests (Fig. 5). Among them, the humidity of the storage place (34.8% of responses), non-use of insecticides (31.2%), storage time (15.7%), pearl millet variety (7.3%), and seed immaturity (7%) were the most important.

Vernacular nomenclature and folk taxonomy of insect pests of stored pearl millet

Insect pests associated with stored millet had different names from one sociolinguistic group to another (Table 2). Fourteen different names of insect pests of stored pearl millet were identified across the study area. The names given to insects that are associated with stored pearl millet in the study area are meaningful. These meanings reflect, among other things, the damage caused (41.5% of responses), the pest species (18.8%), the mode of feeding (14.1%), and the insect colour (13.5%). Only a few names of insect pests were associated with the plant attacked (10.8%), and the stage of insect development (1.3%). The local taxonomy of insect pests associated with stored pearl millet has a hierarchical structure with a low level of classification among different sociolinguistic groups in the study area. Farmers used five

criteria to identify insect pests associated with stored pearl millet. Insect colour (53.9% of responses) and size (35.3%) are the main criteria for classifying these insects. Only 6.4% of the surveyed farmers associate this classification with the insect's shape, 4.1% with the noise emitted during insect feeding, and 0.3% with the damage caused by these insect pests.

Insects associated with stored millet and farmers' perception of their damage

At least one species of storage insect was found infesting all 76 samples of pearl millet incubated in the laboratory. Four insect pests were identified in the stored pearl millet in the study area (Table 3). The rice weevils, *Sitophilus oryzae* L., and *Sitophilus zeamais* L. (Coleoptera: Curculionidae) were found in samples from all the surveyed agroecological zones (Table 3). The prevalence of *Rhyzopertha dominica* F. (Coleoptera: Bostrichidae), and *Tribolium* spp. (Coleoptera: Tenebrionidae) was restricted respectively to two and four agroecological zones. The relative abundance of *S. oryzae* ($df=4$, $F=1.735$, $P=0.152$), *S. zeamais* ($df=4$, $F=1.827$, $P=0.133$), and *Tribolium* spp. ($df=4$, $F=0.759$, $P=0.555$) did not vary significantly between agroecological zones. The north-Benin agroecological zone showed the greatest ($df=4$, $F=35.035$, $P=0.000$) relative abundance of *R. dominica* comparatively to the extreme north-Benin zone. The surveyed farmers estimated that losses due to these insect pests can cause damage up to 25% (56.35% of farmers), 50% (9.9% of farmers), 75% (6.1% of farmers), and 100% (3.5% of farmers) of stored pearl millet.

Farmers' methods for preventing insect pests from infesting stored millet

The majority of the surveyed farmers (58.5%) did not use any methods to prevent insect pest infestation in the stored pearl millet. The remaining farmers (41.5%) took six measures to prevent the attack of stored pearl millet by insect pests. The majority of them (53.5% of responses) sprayed the storage structures with synthetic chemical insecticides. Some of the surveyed farmers isolated the bags of pearl millet from the ground (25.2% of responses) by placing them on wooden planks, bricks, plastic bags, etc. Some farmers sprinkled insect repellent and/or insecticide plant extracts (12.6%), as well as heated the granary (5.5%). Very few surveyed farmers ensured the maintenance of storage equipment (2.4%) and the reconstruction of the granary (0.8%) to prevent insect pest attacks.

Farmers' management of stored millet insect pests

The survey revealed that 48.3% of farmers have adopted at least one method to reduce the infestation of insect



Fig. 3 Pictures of some granaries used in northern Benin for the storage of pearl millet

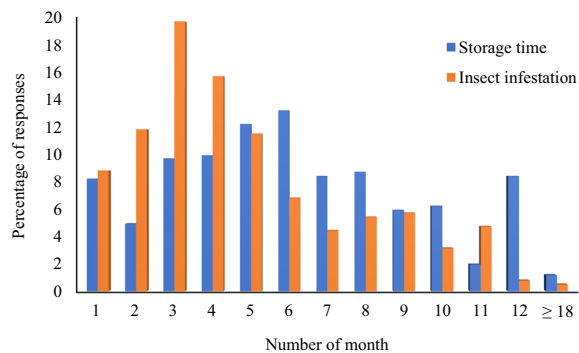


Fig. 4 Farmers' perception of pearl millet storage time and insect infestation period

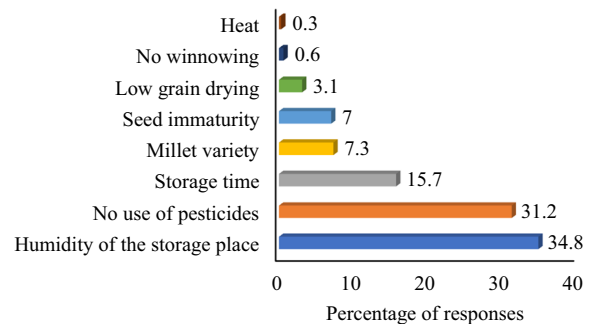


Fig. 5 Farmers' perception of factors favouring the attack of pearl millet by storage insect

pests in the stored pearl millet. Synthetic insecticides were the most significant method (61.9% of responses). Most of the surveyed farmers used storage insecticides such as Percal 100 EC (41.7% of responses), Sofagrain (23.2%), and Bextoxin (12.6%) to protect stored pearl millet (Table 4). However, some pesticides (Lambda Super 2.5 EC, Termicot, and Rambo insect powder) that are not specifically designed for the management of storage

insect pests have been used by 15% of the surveyed farmers. All synthetic insecticides were bought from local markets.

To safeguard their stored pearl millet, some farmers (21.3%) employed insecticidal and repellent plants. The surveyed farmers used the bark of *Annona senegalensis* Pers., the leaves of *Azadirachta indica* A. Juss., and the fruit of *Capsicum annuum* L. as insecticides (Table 5). The surveyed farmers also used the wood ash of some

Table 2 Vernacular nomenclature of insect pest associated with stored pearl millet ($N=304$)

Naming criteria	Percentage of responses	Local names	Sociolinguistic groups	Meaning
Damage	41.5	Nafa	Waama	Destructor
		Edoudoura	Ditamari	
		Boukasse	Lokpa	
		Soubossi, Ikoudounan	Bétamaribé	
		Yedoudoula		
		Minhoutchi	Natimba	
		Sansambé	Lama	
		Dress	Yom	
Species	18.8	Gouyouddji, Nonni	Peulh	Attic grinder
				Destroys everything into flour
		Coconou	Bariba	Ant
		Doussou, Hannoris	Dendi	
		Cocor	Bariba, Peulhs, Bô	Insect
		Boucassé	Lokpa	Sucking insect
		Coconou suanou	Bariba	Red insect
		Bo-Nams	Yom	Millet insect
Food mode	14.1	Gbérékokonou	Bariba	
		Diyannu kokonu	Bariba	Grain insect
		Djonayaou	Yom	Caterpillar
Colour	13.5			
Plant attacked	10.8			
Stage of development	1.3			

Table 3 Insect pests associated with stored pearl millet and their relative abundance in the study area

Family	Species	Parameters	Zone I (N=6)	Zone II (N=24)	Zone III (N=14)	Zone IV (N=12)	Zone V (N=20)	Study area (N=76)
Curculionidae	<i>Sitophilus oryzae</i> L	NIS	5	18	12	9	20	64
		RA	44.8±15.9	58.6±19.8	37.0±9.6	47.8±10.4	59.3±6.5	52.0±6.9
	<i>Sitophilus zeamais</i> L	NIS	3	13	9	6	8	39
		RA	19.0±9.2	25.9±5.8	47.1±11.3	14.7±4.8	22.9±7.1	26.7±3.6
Bostrichidae	<i>Rhyzopertha dominica</i> F	NIS	3	19	–	–	–	22
		RA	17.3±8.6	60.4±7.4	–	–	–	20.4±3.9
Tenebrionidae	<i>Tribolium</i> spp.	NIS	6	14	3	7	9	39
		RA	12±2.9	24.8±13.4	6.3±3.9	21.5±8.2	11.5±4.6	16.2±4.4

N: Number of samples, NIS: Number of infested samples, RA: Relative abundance (average count in 500 g of pearl millet). Zone I: Extreme North-Benin, Zone II: North-Benin, Zone III: South Borgou, Zone IV: West Atacora, Zone V: Central Benin cotton zone

plants (7% of the responses) as an insecticide to protect stored pearl millet. The bark of *Khaya senegalensis* (Desr.) A. Juss. and those of *Parkia biglobosa* (Jacq.) R.Br. ex G. Don were used by the surveyed farmers as insect repellents.

The use of varietal differential susceptibility (16.8%) is one of the management strategies developed by the surveyed farmers to reduce insect infestation in stored pearl millet. The long-cycle varieties (Souhoun n'nin gber-enou, 12 farmers), those with yellow (Zomonra, 18) and red seeds (Gbeï sonanrou, 8), and small-seeded varieties (Zoyouyous, 7) were perceived as resistant to storage

insect attacks by the surveyed farmers. This resistance was attributed to their bitter seeds, low starch content, and small size. The surveyed farmers (12.8%) identified five varieties of pearl millet as highly susceptible to insect attacks. The white seed variety called Zokpéra (18 farmers) was the most listed, followed by the early variety (Tcho n'ta gbeï, 7 farmers), the large grain variety (Gbeï kaka, 7 farmers), the black colour seed variety (Gbeï wonka, 6 farmers), and the late variety (Tcho n'nin gbeï, 5 farmers). According to the surveyed farmers, the sweeter taste of these seeds (18 farmers), high starch content (13 farmers), early maturity of the seeds (7 farmers), and the

Table 4 Chemical pesticides used by the surveyed farmers to protect stored pearl millet in the study area ($N = 166$)

Commercial name	Active ingredient	Chemical class ^a	Toxicological class ^b	Target pests	Percentage
Percal 100 EC	Permethrin 100 g/l	Pyrethroids	II	SIP	41.7
Sofagrain	Deltamethrin (0.05%) + Piri-miphos-methyl (1.5%)	Pyrethroids + Organophosphate	II	SIP	23.6
Bextoxin	Aluminium phosphide	Salt P and Al	U	SIP	12.6
Lambda Super 2.5 EC	Deltamethrin 25 g/l	Pyrethroids	II	IPVC	10.2
Antouka	Permethrine (3 g/kg) + Piri-miphos-methyl (16 g/kg)	Pyrethroids + Organophosphate	II	SIP	4.7
Rambo insect powder	Permethrin 0.60%	Pyrethroids	II	DU	3.2
Phostoxin	Aluminium phosphide	Salt P and Al	U	SIP	2.4
Termicot	Chloropyrifos 20% EC	Organophosphate	II	IPVC	1.6

SIP: Storage insect pests; IPVC: Insect pests of vegetable crops; DU: Domestic use; II = Moderately hazardous (WHO, 2005); U = Unlikely to present acute hazard in normal use

Table 5 Insecticidal and repellent plants used for insect pests management in the stored pearl millet ($N = 57$)

Plant used	Local name (sociolinguistic group)	Part used	Effect	Method of use	Percentage of responses
<i>Annona senegalensis</i>	Bâtôkô (Bariba)	Bark	Insecticide	Crush the bark and mix with the pearl millet	35.1
<i>Azadirachta indica</i>	Haaduyey, Nimou (Bariba), Kitcho (Peulh, Lokpa), Kassienan (Yom)	Leaves	Insecticide	Mix the powder of the dried leaves with the pearl millet	28.1
<i>Khaya senegalensis</i>	Kobou (Natimba) kouroubou (Waama),	Bark	Insect repellent	Sprinkle the store with bark powder	21.1
<i>Capsicum annum</i>	Djonki (yom)	Fruit	Insecticide	Mix the dried fruit powder with the pearl millet	7
<i>Parkia biglobosa</i>	Donn (Baribas)	Bark	Insect repellent	Crush the bark and mix with the pearl millet	1.7
Wood ash	All plants	Entire plant	Insecticide	Mix the ash with the pearl millet	7

big size of the seed (5 farmers) justified the susceptibility of these varieties to storage insect pests.

Determinants of the methods used to manage insect pests in stored pearl millet

From the multinomial logistic analysis, it appears that 46.22% (pseudo $R^2 = 0.4622$) of the variation concerning the control methods used to manage insects infesting stored pearl millet was explained by the variables of the model. A highly significant chi-square value ($p < 0.000$) revealed the strong explanatory power of the regression model. The results revealed that the religion (Christian or Muslim) negatively influenced the use of chemical and botanical pesticides by farmers to control stored millet insect pests (Table 6). Similarly, the storage of pearl millet with other cereals and the farmer's age had a negative and a positive influence on the use of botanical pesticides. The use of chemical and botanical pesticides was positively influenced by farming experience and pre-storage practices (Table 6). The use of integrated control methods was positively influenced by the farming experience and

the storage time. However, the use of integrated control methods was negatively influenced by the religion, farmers' age, and the storage of pearl millet with other cereals.

Discussion

In the study area, pear millet production was a male-dominated activity. Indeed, Adeoti et al. (2017b) showed that men were the most involved in on-farm activities for pearl millet production. The surveyed farmers in the extreme north-west and west of Atacora of Benin showed more experience in pearl millet production than those in other prospected zones. It is possible that the climate in these regions is more favourable for millet production. Furthermore, Clément (1997) notes that pearl millet is a crop that can compete against other plants. Pearl millet yields estimated by farmers in the study area are relatively low (0.4 to 2.1 t/ha) compared to those of countries such as Azerbaijan (14.8 t/ha) and Mexico (14.7 t/ha) (FAO, 2021). Consequently, actions such as the development of improved varieties adapted to local conditions

Table 6 Factors influencing the use of a specific method to manage insect pests in stored pearl millet in the study area

Variables	Methods used by farmers for managing insect pests					
	Synthetic pesticides		Botanical insecticides		Resistant varieties	
	Coefficient	p value	Coefficient	p value	Coefficient	p value
Age (years)	0.028	0.115	0.048	0.011**	−0.019	0.288
Women (1 = Yes, 0 = No)	−0.281	0.647	−1.216	0.127	0.433	0.432
Christian (1 = Yes, 0 = No)	−3.556	0.002***	−2.754	0.019**	15.582	0.992
Muslim (1 = Yes, 0 = No)	−3.958	0.000***	−3.656	0.002***	16.099	0.991
Farming experience (years)	0.079	0.000***	0.077	0.001***	0.020	0.373
Main activity farming (1 = Yes, 0 = No)	−6.043	0.998	17.784	0.998	13.860	0.996
Shelled maize (1 = Yes, 0 = No)	17.191	0.994	17.088	0.996	14.648	0.997
Polypropylene bags (1 = Yes, 0 = No)	13.057	0.999	19.577	0.996	14.894	0.996
Pre-storage practices (1 = Yes, 0 = No)	1.675	0.000***	1.702	0.001***	−0.436	0.366
Storage time (numbers)	0.682	0.306	0.042	0.570	0.050	0.375
Pearl millet stored with other cereals (1 = Yes, 0 = No)	−0.276	0.613	−1.500	0.009***	1.007	0.113
Storage location maintenance (1 = Yes, 0 = No)	30.999	0.982	16.268	0.994	0.128	0.885
					14.850	0.986

Table 6 (continued)

Variables	Methods used by farmers for managing insect pests					
	Synthetic pesticides		Botanical insecticides		Resistant varieties	
	Coefficient	p value	Coefficient	p value	Coefficient	p value
Constant	− 54.875		− 37.758		− 65.804	
Number of observations	399					− 38.915
Log likelihood	− 284.62204					
LR chi2 (50)	489.30					
Prob > Chi 2	0.0000					
Pseudo R2	0.4622					

***Significant at 1% and ** 5%. ^a "No control" used as the base category. Woman, animists, married, single, trade, craft, stripped cobs, jute bags, jars were omitted because of collinearity

should be taken to enhance the production of this cereal in the Republic of Benin.

The surveyed farmers mentioned insect attacks as the most important constraints during pearl millet storage. Ghanaian producers have also mentioned the damage caused by insect pests as an important constraint to the storage of pearl millet (Tanzubil & Yakubu, 1997). Losses caused by insect pests are both quantitative and qualitative and were estimated at 17.1% of pearl millet stored for 7 months (Baoua et al., 2015). The primary pests, *S. zeamais*, *S. oryzae*, and *R. dominica* across the study area were also mentioned as important pests of pearl millet in Nigeria (Lale & Yusuf, 2000), Senegal (Gueye & Delobel, 1999) and in West Africa in general (Gahukar, 1984). Similarly, the red flour beetle *T. castaneum* was found in Nigeria (Lale & Ajayi, 2000; Lale & Yusuf, 2000) and Niger (Baoua et al., 2015) as the main secondary pest found in the pearl millet stored. The distribution of these storage insect pests varied across the study area and this could be due to the climatic conditions prevailing in the different prospected agro-ecological zones, storage practices and management (Kalsa et al., 2019). The pre-storage practiced by some surveyed farmers could exacerbate infestations of pearl millet by these insect pests, as revealed by Mutungi et al. (2019) on maize. In order to minimize losses caused by insect pests, it is crucial to raise awareness and train pearl millet producers in good pre-storage practices.

In the study area, pearl millet was mainly stored in the form of grain in polypropylene bags, jute, granaries and cribs. Compared to grains stored in mud silos, clay pots, and underground pit storage systems, pearl millet stored in propylene bags is less likely to be attacked (Lale & Yusuf, 2000). According to Meenatchi and Loganathan (2022) and observed in the study area, pearl millet is primarily stored in the homes of farmers. This fact could be due to the lack of financial means of smallholder farmers to build storage structures. Consequently, pearl millet is stored with other commodities, which increases the damage caused by insects and the early infestation of stocks perceived by the surveyed farmers. In fact, it is known that pearl millet is susceptible to a wide spectrum of insects that infest other cereals such as maize and sorghum (Lale & Ajayi, 2000). It is therefore urgent to establish an agricultural policy to support pearl millet producers and train them on good storage practices.

Interviewed farmers displayed a strong inclination toward using synthetic pesticides. These products were sprayed in storage structures to prevent infestation, and their non-use was mentioned by many farmers as one of the important causes favouring the insect proliferation in stored millet. In addition, synthetic chemical

pesticides were the main control method used by farmers to protect stored pearl millet. The use of products such as Phostoxin and Betoxin, which have as active ingredient aluminium phosphide, are among the most dangerous pesticides used for the stored food protection (Eddleston, 2020). Indeed, aluminium phosphide has caused the death of many people around the world (Hasabo et al., 2015; Sulaj et al., 2015; Deraz et al., 2022). The use of synthetic pesticides that are not intended for the preservation of stored food was also revealed in the study area. Pearl millet producers should receive training from the Territorial Agricultural Development Agency (ATDA) on the risks associated with the misuse of pesticides on human health. A national policy must be implemented to prohibit the sale of these dangerous pesticides from local markets. In addition, the development of eco-friendly control methods for pest management on stored pearl millet is an urgent necessity.

Some of the surveyed farmers used local plants with potential insecticidal or repellent effects to protect stored millet. Among these plants, the leaves of *A. indica* (Barre & Jenber, 2022; Ojuu et al., 2023; Sintim & Ansah, 2023), fruits of *C. annuum* (Ashouri & Shayesteh, 2010; Cui et al., 2023), and essential oil of *A. senegalensis* (Ngamo et al., 2007) are already recognized as having an insecticidal effect on insect pests of stored pearl millet. Similarly, *K. senegalensis* (Sintim & Ansah, 2023) barks is known to have an insect repellent effect. Promoting and popularizing the use of these plants to protect stored pearl millet by farmers is necessary. The surveyed farmers also reported using the ashes of local plants to preserve pearl millet against storage insect pests. Besides some biochemical properties, ashes contains inert matter that fills the space between the grains and constitutes a barrier to the progress of female insects seeking to lay eggs (Stejskal et al., 2021).

With regard to the development of improved varieties, breeders should take into account the perceptions of pearl millet producers regarding the susceptibility of certain varieties. Farmers attributed the varietal sensitivity to insects to the sweet taste of pearl millet grains and their high starch content. In fact, the sensitivity of cereal grains such as maize (Demissie et al., 2015; Ngom et al., 2020), rice (Gowda et al., 2019), and sorghum (Chuck-Hernández et al., 2013) was significantly correlated with the amylose content, which is a basic compound that governs the resistance of pearl millet grains to insects (Meenatchi & Loganathan, 2022). The susceptibility of the four varieties of pearl millet (Souhoun n'nin gberenou, Zomonra, Gbei sonanrou, and Zoyouyous) mentioned as resistant to storage

insect pests must be explored and the most efficient must serve as basic material in breeding programmes.

It is not surprising that religion has a negative impact on the use of pesticides by surveyed farmers. Indeed, Muslim and Christian farmers' negative attitude to pesticide use could be explained by the harmfulness of chemical pesticides to human health and the environment (Clements et al., 2014; Hailu, 2017). Although holy books of both religions have mentioned various plant species that can be used as a means of controlling crop pests, their use is conditioned by doses that are not harmful to the environment (Clements et al., 2014; Hikmawati, 2021). The positive effect of the farmers' age on the use of botanical pesticides could be explained by the experience acquired over the years, which gives the oldest a better mastery of the plant species with insecticidal effects (Deng et al., 2016). However, since integrated pest management (IPM) is a modern practice (Dara, 2019), it is not surprising that farmers' age negatively affects its use. It is evident from our results that the experienced and farmers practicing pre-storage use more synthetic insecticides. This trend could be explained by the fact that experienced farmers are more able to invest in food protection because they have greater accumulated personal capital (Zhang et al., 2018). The storage time had a positive impact on the adoption of an integrated control method. Indeed, the abundance of insect pests increases with storage time (Jian, 2019), as well as the degradation of chemical pesticides (Lorini & Filho, 2007), thus increasing the probability of adoption of an integrated control method by farmers. The integration of methods to combat storage pests is an effective practice (Morisson et al., 2021) and must be popularized in the study area. According to the farmers, the Souhoun n'nin gberenou landrace and the use of *A. senegalensis* bark and *A. indica* leaves are the most effective methods for preserving millet for extended periods.

Conclusions

According to our study, the storage of pearl millet is largely hindered by the attack of insect pests. The rice weevil, *S. oryzae*, and *S. zeamais* were the most significant pests of stored pearl millet. Farmers use a variety of methods to overcome this constraint, with synthetic chemical pesticides being the primary method of control. The insecticidal and repellent effects of plants used by producers for stock protection must be tested and the best ones popularized. Millet producers must receive training on good food storage practices. The resistance of millet varieties perceived by farmers as tolerant to storage insects must be evaluated and the most resistant varieties promoted. The socio-economic characteristics that influence the use of a pest management method must

be taken into account when developing extension programmes for integrated pest management methods.

Abbreviation

IPM Integrated pest management

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TOA contributed to collection the data and writing—original draft. YLEL was involved in conceptualization, methodology, funding, supervision, and review and editing. ID contributed to review and editing. JG and DG were involved in collection the data. MT contributed to review and editing. All authors have read and approved the manuscript.

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Declarations

Ethics approval and consent to participate

Oral consent to participate in the survey was sought from each pearl millet producer prior to any comment.

Consent for publication

Not applicable.

Competing interests

The authors declare that they have no competing interests.

Author details

¹Laboratory of Applied Zoology and Plant Health (ZASVE), National High School of Applied Biosciences and Biotechnologies (ENSBB), Technologies, Engineering and Mathematics (UNSTIM), National University of Sciences, PO Box 14, Dassa-Zoumé, Benin. ²Département des Sciences de la Vie et de la Terre, Ecole Normale Supérieure de Natitingou, UNSTIM, Natitingou, Bénin. ³International Institute of Tropical Agriculture (IITA), Station du Benin, 08 BP 0932 Tri Postal, Cotonou, Benin.

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