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INSECT PEST MANAGEMENT IN STORED MILLETS

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ABSTRACT

Recognizing the significance of millets as Nutri-Cereals, India celebrated the National Year of Millets in 2018, and subsequently, as proposed by India, the FAO of the United Nations declared 2023 as the International Year of Millets (IYoM). Consequently, there has been an intensive drive, globally, to increase the production and popularise the consumption of whole as well as processed millets by creating an awareness about their significant health benefits and richness in nutritional elements. Besides food, millets play a role as feed and in industrial uses. In commensurate with anticipated higher production, storage and international trade of whole millets and their products, it is important to protect millets throughout the supply chain from stored grain insects, the predominant biotic agent responsible for their qualitative and quantitative losses. In this context, this review focusses on the type of insect infestation encountered in millets from field to consumer levels affecting their market value and causing consumer concern. Insect management techniques adopted by the stakeholders such as farmers, traders, and government grain storage agencies are discussed. Due to financial constraints, small holder farmers use traditional storages and insect management measures using locally available plant products. Like other cereals, fumigation with aluminium phosphide (phosphine) preparations has a major role in insect pest management in millets at various storage levels. Hermetic storage bags of different capacities are used in India and in other millet producing countries especially at farmers level as a valuable insect management tool for whole millets and seed materials. Powdered and processed millets have shorter shelf-life and are more vulnerable to insect attack during storage. Hence, there are studies to increase their shelf life and to check infestation by suitable packaging material. Alternate insect management techniques investigated include ozone treatment, protective packaging materials, screening and breeding of millet varieties that are resistant to grain insects National regulations pertinent to insect management in stored millets have also been discussed.

Key words: Stored millets, processed millet products, infestation, insect management, phosphine, hermetic storage, regulations

Millets, considered as the powerhouse of nutrients serve as staple food for people with limited resources living in drought-prone African countries such as Ethiopia, Nigeria, Niger, Mali, Senegal, and Uganda and in certain dry regions in other producing countries in the world. For example, in India, sorghum, *Sorghum bicolor* (L.) Moench is used in some districts of Maharashtra state, finger millet, *Eleusine coracana* (L.) Gaertn in Karnataka and pearl millet *Pennisetum glaucum* (L.) R. Br. in Rajasthan state. Millets have potential as functional foods by fortification with fast foods such as noodles, pasta, vermicelli, and bakery products (Saini et al., 2021). When used alone or in fortified foods, millets have dual advantages of addressing the challenges of malnutrition i.e., mineral, protein, and vitamin deficiencies as well as over-nutrition such as cardiovascular diseases, colon cancer, hyperglycaemia, and obesity (PIB, 2023). Non-food or alternative uses of millets include cattle as well as poultry feed and as raw material in industries producing starch, biofuels and in breweries making alcoholic and non-alcoholic beverages. It has been observed that unlike wheat and rice, the production and consumption of millets except pearl millet showed a decreasing trend over the years 1970 to 2021 (Sendhil et al., 2023). Nevertheless, the global millet market, in recent times, has been reported to show an increasing trend i.e., more than 10 billion USD due to increased awareness about the nutritional benefits of millets. Global production of millets including pearl millet, buckwheat, fonio and sorghum in 2022 has been estimated as 91.33 million tonnes (FAO, 2023). As on 2022-23, India ranks as the number one in millet production in the world, annual production exceeds 17 million tonnes (Table 1) and India is the second largest exporter of millets (NAAS, 2022). India's export of millets jumped from 34 million USD before 2021 to 64 million USD worth. India has imported a small quantity of millets i.e., 293 metric

Table 1. Indian scenario of millets, 2022-23

Millet	Production (mts) (BASAI, 2023)	Export from India (APEDA, 2023a)	
		Quantity (mts)	Value (Million US$)
Pearl millet (Bajra) *Pennisetum glaucum*	11.43	0.082	30.51
Sorghum (Jowar) *Sorghum bicolor*	3.81	0.047	22.89
Finger millet (Ragi) *Eleusine coracana*	1.69	0.021	6.47
Minor/ other millets	0.38	0.018	15.58
Total	17.32	0.168	75.45

tonnes valued at 0.14 million USD in 2022-23. Recent reports indicate a promising trend of increase in millet consumption in India due to public awareness about the advantages of the commodity as Nutri-cereals (Sendhil et al., 2023). Moreover, Government of India and a few state governments have taken initiatives and schemes viz., National Millets Mission, National Food Security Mission, National Mission on Nutri-Cereals, Odisha Millet Mission, *Paramparagat Krishi Vikas Yojana*, Millet Village Scheme and Tribal Sub-Plan to promote the cultivation, output, consumption, management in storage and export of millets. Also, under the National Food Security Act, 2013, millets such as finger millet, pearl millet, and sorghum have been included in addition to wheat and rice for public distribution system of foodgrains.

Millets are vulnerable to different types of insect pests throughout the supply chain comprising farmers, Farmer Producer Organizations (FPOs), retailers, processors, and the consumers. Besides whole millets, infestation issue continues in processed millets and even in finished products. However, supply of wholesome food is desired and mandatory for the national and international markets. Hence, in consistent with the accentuation on the production and consumption of millets, protection of the produce from insect pests the major depredating agent for storage loss is important. Insect management in stored millets and their products will contribute in the enhancement of their shelf-life also. In contrast to other cereals, studies on insect management in stored millets in India are less. Earlier, Rajendran and Chayakumari (2003) reviewed briefly about the type of insect infestation in millets, effect of infestation on physico-chemical changes in stored sorghum and finger millet and insect management measures. Subsequently, Sharma et al. (2007) discussed about the sources and type of insect infestation in sorghum and pearl millet and control measures. Lately, drawbacks in traditional storages, infestation encountered and the need for an integrated approach for insect management in millets have been highlighted by Meenatchi and Loganathan (2022). Nimbkar et al. (2022) reviewed the merits of different storage systems including hermetic and modified atmosphere storage for millets. Furthermore, Guru et al. (2023) discussed about effective storage, types of infestation and different insect management options with specific reference to minor millets in India i.e., foxtail millet, *Setaria italica* (L.) Beauv., little millet, *Panicum sumatrense* Roth. Ex Roemer And Schultes, kodo millet, *Paspalum scrobiculatum* L., barnyard millet (*Echinochloa* spp.), proso millet, *Panicum miliaceum* L., and brown top millet *Urochloa ramose* (L.) T. Q.Nguyen. The current review deals with insect infestation in whole as well as processed/powdered millets, insect management techniques practiced by the stakeholders at present and potential alternative management methods. In addition, regulations in India related to insect management in stored millets are discussed.

Insect infestation in millet grains

In India, total quantity of millets produced when compared with other major cereals like wheat and rice, is small and is consumed in the same year. Harvested millets are held at farm level in traditional storage structures, underground or above ground, and as bag-stacks in warehouses by traders, distributors, and processors. Insect infestation during storage cause losses in quantity as well as quality of the millets. Stored grain insects comprising beetle (Coleoptera) and moth (Lepidoptera) pests are categorized into internal feeders i.e., the rice weevil, *Sitophilus oryzae* (L.), lesser grain borer, *Rhyzopertha dominica* (F.) and Angoumois grain moth, *Sitotroga cerealella* (Olivier) and external feeders such as rust-red flour beetle, *Tribolium castaneum* (Herbst), rusty grain beetle, *Cryptolestes ferrugineus* (Stephens) saw toothed grain beetle, *Oryzaephilus* *surinamansis* (L.) rice moth, *Corcyra cephalonica* (Stainton) and almond moth, *Ephestia cautella* (Walker). Larvae of primary grain insect pests are known to have stronger mandibles strengthened with zinc and magnesium metals enabling them to attack even intact grains (Morgan et al., 2003).

Millets are coarse grains, and inherently protected from insect attack due to their tougher pericarp or seed coat. Besides grain hardness, phenolic compounds like ferulic acid and higher levels of tannins present in millets including sorghum have been considered to resist insect attack during storage (Chandrashekar and Satyanarayana, 2006). Furthermore, little millet (*P. sumatrense*) and finger millet (*E. coracana)* are considered less susceptible to storage insects due to anti-metabolite compounds, α-amylase inhibitors which affect carbohydrate metabolism in insects (Sivakumar et al., 2006). Nevertheless, primary processing of millets i.e., separation of non-edible pericarp by decortication or dehulling results in mechanical damage and makes whole grains vulnerable to insects, particularly *S. oryzae* and *R. dominica*. In minor millets such as finger millet, foxtail millet, kodo millet, proso millet, barnyard millet, little millet, and pseudo- millets insect activity is less or negligible due to their smaller size. Presence of broken grains in both major and minor millets, however, favours multiplication of secondary insect pests such as *C. ferrugineus, O. surinamansis, T. castaneum,* and psocids (*Liposcelis* spp.). Incidence of insect infestation of millets is noticed at every stage of the supply chain of the commodity. Exceptionally, *S. cerealella* moths infest sorghum in the field itself (Dakshinamurthy and Regupathy, 1988). Among millets, pearl millet and sorghum constitute 90% of world production and these two millets, depending on the varieties are more susceptible to insect infestation. For instance, in laboratory tests, Jhala et al. (2019) demonstrated that among cereals, pearl millet and sorghum were noted to be highly favourable for the development of *C. cephalonica* as revealed by shortest developmental period (46 and 55 days respectively) and high fecundity (302 and 291 eggs/ female) at 31°C and 72% RH.

Field surveys in stored millets in a selected region in Andhra Pradesh state India, revealed notable infestation of *S. oryzae* and *R. dominica* in sorghum and pearl millet, whereas in foxtail, proso, kodo, barnyard millets, *T. castaneum*, *E. cautella* and, *C. cephalonica* infestation commonly observed (Swamy and Wesley, 2022). In a detailed survey on the incidence of insect pests and their parasitoids in stored sorghum and pearl millet in farmer's houses, state warehouses, Food Corporation of India warehouse and in a seed unit in Karnataka state, Katti et al. (2015) noticed *Sitophilus oryzae, T. castaneum, C. cephalonica* and *Sitotroga cerealella* infestation in grains as well as seed materials.

Khapra beetle, *Trogoderma granarium* Everts infestation in stored millets is not common except in sorghum and pearl millet. However, in studies in Poland on the potential of *T. granarium* to attack buckwheat millet, Ciepielewska et al. (2000) established that the insect can breed on the commodity particularly when it is dehulled.

Millets differ in their attraction and suitability for breeding of stored grain insects. Bhargude et al. (2021) studied the preference of *S. oryzae* to different whole cereals including millets. Pearl millet and sorghum showed more susceptibility to the insect than other cereals such as barley, maize, and rice. In an earlier study on the preference of *T. castaneum* to different dehusked millets, Swamy et al. (2020) noted proso millet as the most preferred one by the insect probably due to higher content of sugars and lesser amount of phenol. Subsequently, laboratory investigations on the choice of millets by stored grain insects for multiplication revealed, that among the tested millets viz., sorghum, white finger millet, pearl millet, foxtail millet, little millet, proso millet, kodo millet and barnyard millet both *T. castaneum* and *R. dominica* preferred sorghum or pearl millet. Increased levels of sugar and protein in pearl millet has been considered as a contributory factor for the preference by *T. castaneum* and *R. dominica*. Negligible or nil infestation was noted in little millet and finger millet (Swamy et al., 2023). In contrast, *S. cerealella,* showed higher population in proso millet among the millets tested.

There are several reports in India and other millet producing countries about the differential susceptibility of genotypes/cultivars/varieties of millets, especially sorghum to stored grain insects such as *S. oryzae, T. castaneum* and *R. dominica*. For instance, Bhanderi et al. (2015a) in tests on sorghum genotypes against *S. oryzae* noted significant differences in adult population emerged, grain weight loss and percent germination between genotypes following an incubation period of 180 days. Variation in susceptibility of 8 genotypes of sorghum to *S. oryzae* with respect to oviposition, rate of development, and extent of grain damage has also been reported (Katavkar et al., 2021). Notable differences in adult emergence, % germination and % grain damage between sorghum genotypes following infestation with *S. oryzae* over a monitoring period of 120 days was also observed (Pradeep, 2018). Differences in the susceptibility between sorghum cultivars to *S. oryzae* as indicated by F_1 progeny and extent of grain damage as well as quantitative loss has been noted in Indonesia (Hendrival et al., 2019). In susceptibility tests with different sorghum varieties against *R. dominica*, Arthur et al. (2020a) noted more progeny counts in red-tannin sorghum than in red non-tannin, red-waxy and white sorghum varieties. When *S. oryzae* and *R. dominica* separately and together were allowed to multiply in six sorghum varieties, it was found that frass production by the insects and their F_1 emergence varied between sorghum varieties (Agrafioti et al., 2023). Similarly, heterogeneity in susceptibility of sorghum genotypes to *Trogoderma granarium* and *Tribolium castaneum* has been reported (Gourgouta et al., 2021; Majeed et al., 2016).

An interesting study is about the influence of cross culture of insects to find out suitability of different hosts (millet vs pulses or other cereals) for the survival of *S. oryzae* and progeny production. Vijay and Bhuvaneshwari (2017) examined the influence of parent diet on population build-up (F_1 emergence) in alternate diets. Swapping of diets i.e., sorghum population breeding on rice and vice versa showed a clear reduction in F_1 population on alternate food when compared to corresponding diets. It has practical implications that in warehouse storage there will be different kinds of foodgrains and due to stack movements, there will be a rotation of different types of commodities in the same premises and under the conditions the productivity of insect species is likely to vary as revealed by the laboratory study.

Insect infestation in processed millets

There are many reports about vulnerability of millet flours particularly sorghum and pearl millet flours and millet fortified or millet flour-based products to stored grain insects. Kurre et al. (2021) demonstrated that infestation in processed millets such as pearl millet flour contribute in product contamination with insect fragments. It was noted that infestation due to *R. dominica* caused higher insect fragment levels than *S. oryzae*. In tests on flours of different cereals (maize, pearl millet, sorghum, wheat) and cassava, Ehisianya et al. (2022) observed that besides wheat flour, sorghum flour showed higher degree of susceptibility to *T. castaneum* as revealed by increased F_1 progeny. In an earlier study on insect infestation in pearl millet flour and flour-based products and fonio *Digitaria exilis* Kippist Stapf, Gueye and Delobel (1999) established that pearl millet flour and semolina were more attractive and vulnerable than whole millet grain to *T. castaneum, C. cephalonica* and *E. cautella*.

It is known that *T. castaneum* is the most successful among stored product insects with a broad-spectrum of host range. Accordingly, *Tribolium castaneum* has been noted to multiply readily on all kinds of sorghum fractions such as bran, coarse grits, fine grits, flour, and shorts (Arthur et al., 2020b). Milling fractions of sorghum have also been found to support multiplication of other storage insects such as *Trogoderma granarium* (Lampiri et al., 2021) and *O. surninamensis* (Lampiri et al., 2023). Psocids such as *Liposcelis* spp., are scavengers and common in powdered millets (Swamy and Wesley, 2022) and higher temperature and humidity results in population abundance (Campbell, 2023).

In tests about the suitability of flours of different millets such as sorghum, white finger millet, pearl millet, foxtail millet, little millet, proso millet, kodo millet and barnyard millet to *T. castaneum,* Swamy et al. (2023) observed that pearl millet flour was the most attractive for the insect. *T. castaneum,* nevertheless, multiplied significantly in finger millet flour also. In a study on the effect of polishing of millets including sorghum on the multiplication potential of *T. castaneum* more insect population was noted in flour or grits made from unpolished ones rather than that prepared from polished millets (Turaki et al., 2007). Lately, Sathyaseelan et al. (2023) reported that besides wheat flour, cracked sorghum and pearl millet flours were also attractive to *R. dominica, Tribolium* spp. and *S. cerealella*.

Ludwiczak et al. (2023) compared the development of infestation of *Tribolium confusum* Jacquelin du Val in whole pearl millet and its products (millet flour, flakes, and groats) and noted a positive correlation between degree of fragmentation of millet products and level of infestation. Higher quantity of crude fat content, linoleic acid—C (18:2) was also considered responsible for *T. confusum* abundance in milled products of pearl millet. Conversely, Kordan and Gabrys (2013) noticed increased rate of multiplication of *T. confusum* in whole buckwheat groats than in cut groats or steamed groats. In choice tests in the laboratory with psocids, *Liposcelis bostrychophilus* Badonnel revealed preference to buckwheat whole or grounded over other cereal products such as brown rice flour, pot barley, and wheat germ (Green and Turner, 2005).

Studies on the susceptibility of 18 types of commercially available flours including that of amaranth, buckwheat, quinoa, pearl millet, sorghum and teff to *T. castaneum* revealed higher rate of oviposition and development of the insect in buckwheat, sorghum and teff flours whereas, oviposition was lowest in amaranth and quinoa flours (Gerken and Campbell, 2020). In a subsequent test using different assay methods i.e., wind tunnel assay and in small- and large-scale choice tests for oviposition preference between millet flours and wheat flour, Gerken et al. (2023) reported that *T. castaneum* failed to show any clear preference for millet flours for oviposition over wheat flour.

Insect management practices

Millets are commonly stored in traditional storage structures by farmers and they use locally available plant products to protect grains and seed materials against insects. Enumerating the drawbacks in grain storage practices followed by small holder farmers in developing countries, Manandhar et al. (2018) stressed the need for efficient and economical storage system for millets at farm level. During storage at warehouse level, hygiene and housekeeping of the storage facilities are the foremost insect management tools. Apart from preventive measures, chemical control methods are immediate options to manage insect infestation in grain storage and processing centres. In this context, fumigation has a predominant role in controlling both internal and external infestation in whole millets. Aluminium phosphide preparations available as solid tablets and powder or granular formulations which release phosphine gas are used worldwide for the protection of various agricultural commodities including millets (Phillips et al., 2012). In India, for the exclusive use of farmers 56% aluminium phosphide powder in 10 g flexible pouch and 15% aluminium phosphide solid tablets in rigid container are available for treating one ton of millet in an airtight container or enclosure (Table 2). Recommended exposure period for aluminium phosphide fumigations is minimum of 7 days at ≥25°C; at lower temperatures, the exposure period must be extended to 10 days or more. For larger quantities of millets held by the traders, state, or central grain storage agencies as bag-stacks in warehouses, treatment under gas-tight fumigation cover or sheet, preferably 150 GSM multilayered cross-laminated film at the dosage of 3 g phosphine/ m^3 (=3 Aluminium phosphide tablets/m^3) for 7 days minimum is recommended. All seed materials can be safely treated with aluminium phosphide preparations at the above dosage and exposure period. For successful fumigation of food grains including whole and powdered millets with aluminium phosphide formulations, it is important to achieve a target terminal gas concentration of 500 ppm phosphine. In India, aluminium phosphide (phosphine) fumigation is also undertaken for pre-shipment treatment of different export commodities including millets. For instance, sorghum as feed material to New Zealand is treated with aluminium phosphide tablets at the rate of 2 g phosphine/m^3 for 5 days at ≥25°C (Rajendran, 2016).

Besides fumigation, prophylactic spray treatment of hard surfaces i.e., floor and wall surfaces inside warehouse and on jute or HDPE woven sack surfaces of grain bags with approved insecticides are carried out. Residual insecticide spray treatment with deltamethrin 2.5% WP at 3-month intervals and malathion 50% EC at fortnightly intervals are carried out (CWC, 2015). These residual insecticides kill both crawling (*T. castaneum* and *S. oryzae,*) and flying (adults of *C. cephalonica, E. cautella* and *R. dominica*) insects in the storage premises.

While reviewing the storage practices by small holder farmers in Africa, Fufa et al. (2021) and Okori et al. (2022) considered that for long term storage of cereal grains including millets, hermetic storage is appropriate and advantageous. In India, farmers are already using hermetic storage bags such as Ecotact bags®, Grain Pro®, GrainPro Super Grain Bags® and Save Grain Bags® for grain millets and seed materials (Guru et al., 2023). In hermetic storage, moisture content of the grain is critical (≤12%) as the higher moisture content can create hot spots due to lack of aeration during storage (Yewle et al., 2022).

There are regulations in India related to insect management in millets and other food grains. These regulations are primarily concerned about a) contamination of food grains with insects and insecticide residues, b) standards to be followed for fumigation and treatment with modified or controlled atmospheres and c) requirements for the import of various agricultural commodities including millets. Level of insect contamination in millets is indicated by uric acid content in the infested commodity, number of live insects and types present, and number of insect fragments present in representative millet grain samples (Table 3). The Food Safety and Standards Authority of India (FSSAI) under the Ministry of Health and Family Welfare, Government of India, the Directorate of Plant Protection, Quarantine, and Storage (DPPQ&S) under

Table 2. Insect management practices for stored millets

Management technique	Applicable for/ target insects	Details	Reference
Fumigation	Against internal and external feeders for grains and seed materials	Farmer level: 56% Aluminium phosphide (AlP), 10 g powder formulation in flexible pouches and 15% AlP 12 g tablet preparation, 4 or 5 tablets in a rigid container. Dosage-as per container LABEL	-
		Warehouse level: 56% AlP, 3 g tablets packed in 1 kg flask, & 56% AlP, 34 g powder formulation. Dosage- 3 tablets/ tonne, for minimum 5 days (7 days for *S. oryzae* and 14 days for *T. granarium*)	NSPM 22 (2017)
	Quarantine and Pre-shipment (QPS) Treatment	Methyl bromide at 32 g/ m^3 for 24 hr (commodity export/import treatments)	NSPM 11 (2005)
		Aluminium phosphide fumigation as per importer's requirement	Rajendran (2016)
Use of modified or controlled atmospheres	Both internal and external infestation	Applicable for larger quantities. 1. Storage in cocoons, flexible storage structure at NAP; Affordable for export and organic markets 2. Treatment under high pressures; carried out in air-tight rigid metal chambers with CO_2 at 20 to 30 bar high pressures	NSPM 25 (2023)
Prophylactic spray with residual insecticides	Crawling and flying insects in grain storages	Deltamethrin 2.5% W.P, 40 g/ L dilution applied at 3 L/100 mt^2 on hard surfaces at 3-month intervals	CWC (2015)
Hermetic storage in flexible and rigid structures	Resident infestation	Generation of insecticidal gas composition (high CO_2 and low O_2) in airtight storages of 50 kg and above	Waongo et al. (2019)
Admixture of insecticides for seed treatment	Internal and external infestation	Residual insecticides and local plant materials used by farmers for seed materials	Rajasri and Kavitha (2015)

the Ministry of Agriculture & Farmers' Welfare of the Government of India and the Agricultural and Processed Food Products Export Development Authority (APEDA) under the Ministry of Commerce and Industry are the concerned regulatory bodies in India. Recently, FSSAI has framed an elaborate group standard for 15 types of millets i.e., Amaranthus (*Amaranthus* spp), barnyard millet *Echinochloa esculenta* (A. Braun) H. Schulz, brown top millet, *Brachiaria ramose* (L.) Stapf, buckwheat *Fagopyrum esculentum* Moench, crab finger, *Digitaria sanguinalis* (L.) Scop, finger Millet (*E. coracana)*, fonio (*Digitaria exilis* and *Digitaria iburua*), foxtail Millet (*S. italica*), Job's tears, *Coix lacryma-jobi* L, kodo millet, *Paspalum scrobiculatum* L., little millet, *Panicum sumatrense* Roth, pearl millet, *Pennisetum glaucum*, proso millet, *Panicum miliaceum* Walter, sorghum (*S. bicolor)* and teff, *Eragrostis tef* (Zuccagni) Trotter for India and other producing countries. The above group standard effective from September 2023 specifies quality parameters including uric acid content (≤100 mg/ kg), and weevilled grains (≤ 4% by count) for millets for the availability of standardized millets in Indian and global markets (FSSAI 2023a).

Different management options explored

There are several studies in India and elsewhere evaluating different insect management techniques for suitability and efficacy against insects of stored millets and their products (Table 4). Ozone gas is used in food industries for preservation and as a disinfectant in water application and is environmentally safe as ozone has very short half-life of 20–50 min in the

Table 3. Indian regulations pertinent to insect management in stored millets

Authority	Details
Food Safety and Standards Authority of India (FSSAI), Ministry of Health and Family Welfare	Standards specific for millets (FSSAI, 2023a): International Group Standards for Millets Insect contaminants (FSSAI, 2023b): Uric acid level, % weevilled, insect fragments Pesticide contaminants (FSSAI, 2023c): Fumigant and insecticide residue limits
Directorate of Plant Protection, Quarantine, and Storage (DPPQS), Ministry of Agriculture and Farmers' Welfare	National Standards for Phytosanitary Measures (PPQS, 2023): Aluminium phosphide (phosphine) fumigation -NSPM 22 Methyl bromide fumigation -NSPM 11 and 12 Modified Atmosphere Treatment- NSPM 25 Plant Quarantine Order 2003: Import conditions and document requirements for agricultural commodities
Agricultural and Processed Food Products Export Development Authority (APEDA), Ministry of Commerce and Industry	Export specifications for millets (APEDA, 2023b)

atmosphere (Boopathy et al., 2022). Ozone is effective against microbes in food grains and external insect infestation when continuously purged at the rate of 50 ppm and above for more than 3 days with nil residues in treated grain (Pawar et al., 2015). In efficacy tests with ozone gas against the life stages of *T. castaneum* in the presence of proso millet, Muniswamy et al. (2023) observed that the tolerance of the life stages of the pest was in the following order: egg (highly tolerant)>pupa>adult>larvae (most susceptible).

Diatomaceous earth consisting of amorphous silicon dioxide, 2.5 to 30-micron particle size is known to act on external stages of insects as desiccant through absorption and abrasion of the insect integument (Shah and Khan, 2014). Different formulations of diatomaceous earth are available for application as a grain and seed protectant, as a surface treatment on bulk stored grain layer and spray treatment on hard surfaces such as walls and floor areas of silos and warehouses. Ceruti et al. (2006) studied the efficacy of diatomaceous earth at the dosages ranging from 500 - 1,500 g/ t, and stored at temperatures ranging from 15 to 30°C against *Sitophilus zeamais* Motschulsky in pearl millet. Application of the desiccant at the rate of ≥750 g/ ton and the treated grain held at ≥25°C proved effective. In a comparative study on diatomaceous earth and Actellic Super®Dust, a mixture of pirimiphos-methyl and permethrin against *S. zeamais,* and *T. castaneum* infestation in sorghum, it was noted that diatomaceous earth at an application rate of 0.5 to 6g/ kg proved superior to conventional chemical treatment, particularly to *S. zeamais* (Gondo et al., 2022).

Among the physical control methods, Subhashini et al. (2024) studied the efficacy of hot air and infrared heat treatment against *T. castaneum* in finger millet flour and its effect on the physicochemical parameters of treated flour. Complete insect mortality in the flour was achieved with hot air at 65°C for 10 min and infrared at 1760 W, 9 min exposure.

Phytocompounds have been evaluated in India and other millet-producing countries for insect management in stored millets as well as seed materials. Usage of indigenous botanicals such as *Ocimum basilicum* L. *Citrus sinensis* (L.) Osbeck, *Cymbopogon nardus* (L.) Rendle, *Euphorbia balsamifera* Aiton, and *Lawsonia inermis* L. as powders in the protection of stored grains including sorghum in traditional storage structures in Nigeria has been reviewed (Suleiman and Rugumamu, 2017). Lale and Ajayi (2000) investigated the efficacy of essential oils from clove, *Syzygium aromaticum* (L.) Merr. & L.M. Perry, West African black pepper, *Piper guineense* Schumach and Thonn., and ginger, *Zingiber officinale* Roscoe against *T. castaneum* in stored pearl millet and noted that essential oils of clove and West African black pepper were more efficient than ginger oil in suppressing *T. castaneum* population in the commodity. In India, while screening different plant compounds against *S. oryzae* in sorghum, Bhanderi et al. (2015b) observed that custard apple, *Annona squamosa* L. seed powder, neem *Azadirachta indica* A. Juss. seed kernel powder, and sweet flag, *Acorus calamus* L. powder as the most effective. In another case, botanicals such as holy basil, *Ocimum sanctum*, *Annona squamosa*, *Azadirachta indica* leaf, pongamia/Indian beech, *Millettia pinnata*

Table 4. Different insect management strategies explored

Technique	Applicable for/target insects	Details	Reference
Ozone treatment	*T. castaneum* infestation in proso millet	Egg stage was the most tolerant	Muniswamy et al. (2023)
Phytocompounds	*T. castaneum* in pearl millet	Clove (*Syzygium aromaticum*) and West African black pepper (*Piper guineense*) oil at 16 g/kg of seed material suppressed insect population	Lale and Ajayi (2000)
		Neem (*Azadirachta indica*) leaf powder was the most effective whereas, turmeric (*Curcuma longa*) powder was the least effective to the insect	Modi and Chhangani (2023)
	S. oryzae in sorghum	Sweet flag (*Acorus calamus*) powder and custard apple (*Annona squamosa*) seed powder showed higher adult mortality besides retaining grain quality	Gadewar et al. (2017)
		Among ten insecticidal plant powders tested, *Acorus calamus* 2% rhizome powder was the most effective	Govindan et al. (2020)
		Seeds treated with malathion singly or in combination with herbal textile dyes offered protection against the insect besides retaining germination parameters	Navi et al. (2006)
Desiccants	*S. zeamais* in pearl millet	*S. zeamais* controlled with diatomaceous earth above 750 g/ton dosages at ≥25 °C	Ceruti et al. (2006)
	S. zeamais, and *T. castaneum* in sorghum	*S. zeamais* was more susceptible to diatomaceous earth treatment at 500 g/ton level than *T. castaneum*	Gondo et al. (2022)
Physical control	Hot air and infrared heat treatment of finger millet flour	Hot air at 65^{o} C for 10 min. and infrared at 1760 W at 9 min effective against *T. castaneum*	Subhashini et al. (2024)
	Pearl millet stored at different temperatures in different containers	Storage at 5^{o}C in polythene bags effective against *R. dominica* and *T. castaneum* with least changes in quality and quantity	Mali and Sathyavir (2005)
Suitable packaging material for insect-free storage	*T. castaneum* and *C. cephalonica* in dehusked foxtail millet	Polyethylene terephthalate bag was noted as the best, based on grain quality characteristics, and reduced infestation levels	Pragnya et al. (2018b)
	Sorghum containing natural infestation (*R. dominica, T. castaneum, O. mercator,* and *C. cephalonica)*	The Purdue Improved Crop Storage bags (PICS) noted effective for long-term sorghum storage	Waongo et al. (2019)
	T. castaneum infestation in irradiated foxtail millet flour and white finger millet flour	Irradiated (1.5 kGy dose) foxtail millet flour and white finger millet flour packed in metalized polyester polyethylene and polyethylene terephthalate pouches and stored for 3 months showed nil infestation	Shobha et al. (2021; 2023)

Table contd..

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Insecticidal spray treatment of packaging materials	*R. dominica* in pearl millet seeds	Emamectin benzoate spray on HDPE bag was noted to be an effective combination for insect management	Ghelani et al. (2017)
Controlled / Modified atmospheres	*T. castaneum* in little millet	Controlled atmosphere packing of parboiled little millet noted effective against *T. castaneum* infestation	Vachanth et al. (2010)
	S. oryzae in sorghum	Storage under 15 and 20% CO_2 concentrations for 315 days resulted in 100% insect mortality	Jayashree et al. (2013)
Hermetic storage bin	Sorghum with resident infestation of *T. castaneum*, *R. dominica* and *S. cerealella*	For smallholder storage conditions, hermetic storage was efficient when compared to pesticide dust application	Mubayiwa et al. (2021)
Hermetic storage + reduced pressure	*T. castaneum* in de-hulled little millet	200 mm of Hg pressure at the lowest average temperature of 27.8± 1.08 °C helped in achieving 100% insect mortality in 3 days.	Sathiamoorthy et al. (2021)
Breeding for insect-resistant varieties	*S. oryzae*-resistant sorghum	Crossing resistant and susceptible varieties resulted in an improved cultivar that showed better insect resistance	Zhai et al. (2016)

(L.) Panigrahi powder, turmeric, *Curcuma longa* L. and *Acorus calamus* were assessed as seed protectants against *S. oryzae* in sorghum stored for 3 months and it was found that *Acorus calamus* powder and *Annona squamosa* seed powder at 2.5% level were promising besides maintaining germination characteristics of sorghum (Gadewar et al., 2017). In similar tests but against *T. granarium* infestation in forage pearl millet stored for the same period, *Acorus calamus* powder followed by *Annona squamosa* seed powder at a 2.5% level was found effective (Gadewar et al., 2018). Among several plant extracts tested *Acorus calamus* rhizome and *Annona squamosa* leaf extracts revealed fumigant toxicity to *S. oryzae* adults (Rani et al., 2019). Moreover, Govindan et al. (2020) reported that *Acorus calamus* 2% rhizome powder was the best against *S. oryzae* among ten different plant powders tested as indicated by nil F_1 emergence in sorghum stored for 60 days. In studies on the efficacy of leaf powders of *Azadirachta indica*, *Eucalyptus* sp., *Curcuma longa*, *Ocimum sanctum*, and *Psidium guajava* L. in controlling *T. castaneum* in pearl millet during 90 days storage period, it was noted that the insect was more susceptible to *Azadirachta indica* leaf powder, whereas *Curcuma longa* powder was least effective (Modi and Chhangani, 2023).

There are many studies focussing on package materials suitable for storing millets and millet products for extended shelf-life as well as insect-free commodity storage. Pragnya et al. (2018a) examined the performance of gunny bags with and without lining, cotton cloth bags, and nylon bags for storing dehusked foxtail millet as wholesale packaging materials (5 kg samples). Following 6 months of storage, it was noted that the gunny bag with liner was the best against *T. castaneum* and *C. cephalonica* infestation besides retaining the physico-chemical properties of the grain. Subsequently, polyethylene (PE), polypropylene (PP) and polyethylene terephthalate (PET) were tested as retail packaging materials (1 kg sample) for storing dehusked foxtail millet for 6 months. Polyethylene terephthalate was found suitable against *T. castaneum* and *C. cephalonica* besides maintaining grain quality (Pragnya et al., 2018b). Mali and Satyavir (2005) investigated the influence of storage temperature (5, 25 and room temperature, 15-37^{o}C) and storage containers (jute bag, 75-micron polythene bag, and tin container) on qualitative changes in pearl millet and infestation due to *R. dominica and T. castaneum* during one year storage period. It was found that storage at a low temperature of 5^{o}C in all cases revealed zero infestation and minimum qualitative changes in the commodity with all the three types of storage containers. However, at higher temperatures, infestation was heavy in jute bags as well as in tin containers. Shobha et al. (2021; 2023) assessed low-density polyethylene (LDPE), metalized polyester polyethylene (MPP), PP, and PET as packaging materials for storing irradiated (gamma radiation at 1.5 kGy dosage) dehusked foxtail millet flour and white finger millet for 3 months. Natural infestation of the commodity included *T. castaneum, S. oryzae* and *C. cephalonica.* Irradiated foxtail millet flour in MPP and PET pouches showed nil fungal colony as well as insect infestation.

Several studies have been carried out on the exploitation of controlled atmospheres with elevated CO_2 and depleted O_2 levels with different packaging materials/containers and use of hermetic bags for insect-free storage of millets and its products. For example, Vachanth et al. (2010) tested the efficacy of enriched CO_2 (35%) atmosphere in protecting raw and parboiled polished little millet packed in aluminium, high density polyethylene (HDPE), and LDPE pouches against *T. castaneum* infestation. Because of the satisfactory retention of CO_2, a notable reduction in infestation was observed in aluminium foil followed by HDPE pouch packing. Insect activity was relatively less in parboiled little millet than in raw millet. Waongo et al. (2019) compared the performance of 50 kg Purdue Improved Crop Storage bags (PICS) and PP bags for hermetic storage of sorghum with natural infestation comprising *C. cephalonica*, *R. dominica, T. castaneum* and *Oryzaephilus mercator,* (Fauvel) under ambient conditions for 12 months. Unlike the PP bag storage, the infestation level was nil in PICS-stored sorghum and grain quality as well as viability was found acceptable. In Zimbabwe, Mubayiwa et al. (2021) evaluated the efficacy of storage of sorghum in flexible PICS bags and GrainPro Super Grain Bags® and rigid (metal bin) hermetic structures and non-hermetic storage treatments such as direct admixture of insecticides viz., fenitrothion 1% + deltamethrin 0.13% mixture and pirimiphos-methyl 0.16% + thiamethoxam 0.036% mixture and storage in deltamethrin-incorporated polypropylene Zerofly® bags against natural infestation consisting *R. dominica*, *T. castaneum* and *S. cerealella*. Hermetic storage was found more effective than other types of storage against the insects tested and in maintaining grain quality. Chemical impregnation of storage bags as a management tool for stored millets need further studies. The advantages of hermetic storage of pearl millet and sorghum at 10, 12, and 14% moisture content levels in rigid polyvinyl chloride (PVC) bins, and hermetic grain storage bags i.e., woven PP or jute bags with inner GrainPro Super Grain Bags® for 90 days have been reported (Preethi et al., 2016). Mortality of *S. oryzae* reached 100% within a storage period of 30 days in PVC bins whilst, it took a longer duration of 90 days to achieve the desired insect mortality in hermetic grain bags. Grain quality was not impaired in the hermetic storage of the commodities. Sathiyamoorthy et al. (2021) investigated the influence of reduced pressure on the mortality rate of *T. castaneum* adults during hermetic storage of de-hulled little millet. In storage studies at normal atmospheric (760 mm of Hg) and reduced pressure levels ranging 200 to 620 mm of Hg in specially made 10 kg capacity stainless steel hermetic storage bins, insect mortality was found quicker as the pressure was reduced i.e., 3 days at 200 mm pressure and 18 days at normal atmospheric pressure levels. Divija et al. (2021) demonstrated that the use of oxygen scavengers (e.g., 'Swiss Pac' and 'Ecotact') in pouches could deplete oxygen levels inside multilayered gastight pouches containing dehulled foxtail millet resulting in 100% mortality of the test insect, *T. castaneum* in a week. The influence of hermetic storage has also been noted in studies on the storage of '*huriyittu*' a value-added product of finger millet containing natural infestation of *S. oryzae* and *T. castaneum*. The insect population was negligible when it was stored for 6 months in steel containers and highest in cloth bags (Latha et al., 2015a). In a subsequent study, vermicelli, another value-added product of finger millet containing *S. oryzae* and *T. castaneum* natural infestation was stored in five different structures such as cloth bags, containers made of glass, mud, polythene, and steel for 6 months and it was noted that infestation was negligible in vermicelli stored in steel containers and highest in the product stored in cloth bags (Latha et al., 2015b).

The efficacy of prophylactic spray treatment of packaging materials such as cloth bags, gunny bags, and HDPE bags for the storage of pearl millet seeds against *R. dominica* infestation was investigated. When emamectin benzoate, spinosad, and deltamethrin were tested, emamectin benzoate spray on HDPE bag was found effective for the management of *R. dominica* in the seed material during a storage period of 10 months (Ghelani et al., 2017).

Efforts are underway to develop millet cultivars that are resistant to stored grain insects by genetic manipulation. Listing the defense mechanisms such as grain hardness and α-amylase protease contents against insect and fungal attacks already present in sorghum and other millets, Chandrashekar and Sathyanarayana (2006) indicated the need to develop resistant genotypes based on the natural defense mechanisms as a management strategy. Mwenda et al. (2019) reviewed extensively the genetic approaches involving physical traits and biochemical parameters to develop suitable sorghum cultivars that are resistant to *Sitophilus* spp. While discussing different management options against

S. oryzae and *S. zeamais* in stored sorghum, Mofokeng (2016) highlighted the significance of breeding sorghum genotypes towards grain weevil resistance besides other parameters such as grain quality, higher yield, field pest and disease resistance. In this context, to develop weevil-resistant sorghum genotypes, Zhai et al. (2016) conducted breeding programs between insect-resistant and susceptible sorghum varieties and analysed the quantitative trait loci associated with *S. oryzae* and *S. zeamais*. The development of insect-resistant millet genotypes has been considered as an important control strategy for the protection of millets.

CONCLUSIONS

There has been a renaissance in the production and consumption of millets in India. However, unlike major cereals, the storage period of millets is still limited to less than a year. Insect infestation is an issue of concern for two major millets, sorghum, and pearl millet despite their inherent defense mechanisms against insect attack. Although, the shelf-life of milled and processed millets is shorter due to the problem of rancidity, their usage in fortification and mixture with other cereal powders is increasing. Unfortunately, all secondary insect pests proliferate rapidly in milled or processed millets and can cross-contaminate and survive in whole grains also. As powdered and processed millets are more vulnerable to stored grain insects, studies must focus on effective management methods specific to processed millets along the lines of improving their shelf-life. Currently, aluminium phosphide preparations serve the purpose of insect elimination in millets stored at farmer, trader, and government storage levels. The fumigant is safer for seed materials also. There are regulations in India with regard to pest and pesticide contaminant levels in stored millets and national standards to be followed for effective insect management. Further studies are needed for the use of ozone particularly against internal life stages in millets. Genetic studies to develop insect-resistant genotypes for sorghum and pearl millet, the most susceptible commodities for insect attack are already under progress in millet growing countries and expected to yield the desired results. Hermetic storage using hermetic bags by farmers and small-scale traders has gained prominence due to advantages in terms of nil pesticide residues and nil insect resistance to the treatment.

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