Journal of Integrated Pest Management, (2019) 10(1): 28; 1–10
doi: 10.1093/jipm/pmz026
Issues

OXFORD

Management of Economically Important Insect Pests of Millet

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Subject Editor: Tom Royer

Received 3 June 2019; Editorial decision 16 July 2019

Abstract

Grain of various species of millet is a staple food of rural communities in sub-Saharan Africa, the Indian subcontinent, and China. In addition, millet is used as poultry and cattle feed in the United States, and the foliage is fodder for cattle in India. The crop is damaged by at least 150 insect pests during its growth and development. Although the current status of all of these pests is not known, shoot flies, stem borers, leaf-sucking, and the panicle-attacking insects are considered economically important. Control measures include the application of synthetic pesticides (as both seed treatment and foliar applications) and cultural methods (timing of planting and field sanitation). Host plant resistance (screening of genotypes and breeding of pest-tolerant/resistant cultivars), and biological control (conservation of natural enemies and periodical releases of the larval parasitoid *Habrobracon hebetor*) have received much attention in recent years. Integrating available pest control options has been recommended, along with further adoption of new crop cultivation technologies by small and resource-poor farmers.

Key words: control measure, pest management, perspective, pest complex, yield loss

In the Indian subcontinent, Sub-Saharan Africa, and China, a major food ingredient is the millet grain which also forms a part of poultry and cattle feed in the United States. In India, millet foliage is fed to cattle. The global annual production of millet is estimated at 28.4 metric tons (mt), of which India produces 10.3 mt followed by Africa with 8.3 mt (FAO 2017). With a growing focus on nutritional security, the Indian government has declared 2019 the 'national year of millets'. In addition, the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT) added finger millet as its sixth mandate crop (Avadhani 2015).

Eight millet species are cultivated worldwide. Pearl millet, *Pennisetum glaucum* (L.) R. Br. is the major one, while the others are small millets cultivated for family consumption. However, the area under each millet is not documented. Finger millet/African millet/ragi (*Eleusine coracana* Gaertner) in India and Uganda and tef (*Eragrostis tef* [Zucc.] Trotter) in Ethiopia are regularly cultivated every year. Other small millets include the foxtail or Italian millet (*Setaria italica* [L.] P. Beauv.), ditch or kodo millet (*Paspalum scrobiculatum* L.), common or proso millet (*Panicum miliaceum* [L.]), little millet (*Panicum sumatrense* [Roxb.] Roth ex Roem. & Schultz) (=*P. miliare*), barnyard millet (*Echinochloa colona* [L.] Link), fonio millet (*Digitaria* spp.), and brown top millet (*Brachiaria ramosa* (L.) Stapf).

In recent years, millet production has increased. Millets are a sustainable food for economically poor people in rural areas and are also appreciated by urban populations for their rich mineral and vitamin content. Increasing market demand for millet has encouraged farmers to cultivate millet either by itself or intercropped with legumes. In fact, millets are underutilized in developing countries, where food security is becoming increasingly important with a rising human population (Gahukar 2014). In addition, millets are resilient crops, making them appropriate for mitigating the agricultural effects of drought and climate change and solving nutritional deficiencies in rural areas (Kumar et al. 2018).

Worldwide, at least 150 insect species are recorded as feeding on millets (Nwanze and Harris 1992); of these, 116 species have been recorded from India (Kishore 1996). Most of the pests are common to all species of millet (Gahukar 1989). In pearl millet, the short-cycle cultivars (cvs.) with 85–95 d to maturity are the most widely cultivated compared to long-cycle cvs. (120–130 d maturity), and have been more intensively studied in terms of pest management. Insect feeding on different plant parts at various plant growth stages results in economic losses due to decreases in crop productivity and grain quality, and decreased fodder yield (Arun Kumar and Channaveerswami 2015, Bekoye and Dadie 2015). For example, yield losses from millet insect pests ranged from 10 to 20% in India (Gahukar and Jotwani 1980) to 50% in Ghana (Tanzubil and Yakubu 1997). Despite the economic importance of millet pests, information on possible control measures is limited, in part because there is little crop protection research due to low crop value and the variation in species attack rates, especially on the less common millets.

Kalaisekar et al. (2017) give information on the systematics, biology, and control of pests attacking millets in India. Virtually no compilation on a global basis has been published since the review of Gahukar (1989), even though new research from developing countries have been published in regional or national journals on the management of major insect pests of millet. In view of the fragile ecosystem (drought-prone, soil erosion, erratic seasonal rainfall), the high incidence of some pests on short-cycle cultivars, difficulties in chemical treatments and increased cost, and the socioeconomic situation of farmers, concerted efforts to formulate integrated pest management (IPM) strategies are urgently needed for this crop.

The current status of many of these important millet pests is given as 'major pest' in these publications. Also, the economic importance of many other pests has not been defined. Here, we also classify pest status as either regular (regular occurrence, economic damage, high loss in grain yield) or occasional (occasional occurrence, sporadic attack with economic damage, high/moderate loss in grain yield; Table 1). Balikai (2009) suggested a rating scale to define pest status based on the infestation level as major >50% infested plants, moderate = 31–50%, minor = 11–30%, and negligible = <10% infested plants. Flaws in this system are that the severity of the plant damage is not considered and that it is hard to apply to both pests that have brief but intense outbreaks and occasional pests whose attack is sporadic. Here, changes in pest status during the last two decades and guidelines for IPM are discussed to facilitate the formulation and implementation of IPM in the forthcoming projects in research, development, and extension. The aim of this review is to consolidate the fragmentary or scattered literature, which is not readily available to research organizations and development agencies.

Pest Control Practices

Soil-Inhabiting Pests

Among soil-dwelling insects, termites, and cutworms feeding on or damaging millet roots are relatively minor pests (Gahukar 1989). In contrast, feeding damage to pearl millet roots from white grubs can be severe n arid and semi-arid regions (Choudhary et al. 2018). A common white grub species, *Holotrichia consanguinea* Blanch. (Coleoptera: Scarabaeidae), is a major, widespread pest of pearl millet in India. Larvae feed on roots, causing seedlings to wither and die, and patches of dead seedlings in the field are readily visible. The most effective treatment for white grubs available to farmers is seed treatment with imidacloprid 600FS at 10–12 ml/kg, which has been found to reduce seedling mortality from 28.6 to 2.1%, doubling grain yield from 12.30 to 27.52 q/ha and resulting in the highest cost: benefit ratio (1:24.8) (Choudhary et al. 2018). Next most effective treatment was treating seeds with clothianidin 50WDG at 10 g/kg, and equally effective was soil drenching with imidacloprid 17.8SL at 300 ml/ha or mixing chlorpyriphos 20EC or quinalphos 25EC at 4.0 liters/ha along with irrigation water 3 weeks after seedling emergence (WAE) (Kalaisekar et al. 2017). For furrow application, chlorpyriphos or quinalphos dust mixed with farmyard manure (FYM) in a 2:3 ratio and applied at planting is also effective. The pesticide applications can be recommended in areas with high endemic pressure from white grubs and during pest outbreaks.

Pests of Seedlings

Seedlings are infested by leaf beetles, gray weevils, and stem flies. Many species of shoot flies (Diptera: Muscidae) attack all millets in India (Kalaisekar et al. 2017) and Africa (Nigus and Damte 2018). The shoot fly larvae during early stages of development eat through the leaf sheath, cutting the growing point which results in shoot wilting, yellowing and the death of the seedling, commonly known as 'dead heart' (DH). Mature larvae feed on decaying material just above the cut. Pest damage from these flies has been found to result in 20–50% yield loss in pearl millet (Natarajan et al. 1973, Kishore 1996), 36% in common millet (Natarajan et al. 1974) and 39% in little millet (Selvaraj et al. 1974). Yield loss has not been evaluated in recent years.

The pearl millet shoot fly, *Atherigona approximata* Malloch, regularly infests pearl millet in India. TNAU (2016) and Biradar and Sajjan (2018) proposed a set of management practices for pearl millet shoot fly (Table 2). Cultural practices are relatively easy to employ and can be used with minimal extra cost, while synthetic insecticides should be used only when other measures fail.

The tef shoot fly, *Atherigona hyalinipennis* van Emden, causes damage at both the seedling and panicle stages and is considered a major pest of tef in Ethiopia, where yield loss from this fly was

Table 1. Economically important insect pests of millets cultivated worldwide

Common name	Insect species	Crop infested[a]	Pest status[b]	Country/ region	Reference
White grub	*Holotrichia consanguinea*	P. millet	Reg.	India	Choudhary et al. (2018)
Shoot fly	*Atherigona approximata*	P. millet	Reg.	India	Biradar and Sajjan (2018)
Shoot fly	*A. hyalinipennis*	Tef	Reg.	Ethiopia	Nigus and Damte (2018)
Shoot fly	*A. pulla*	C. millet	Occ.	India	Sathish et al. (2017a,b)
		L. millet	Reg.	India	Arun Kumar and Channaveerswami (2015)
Grasshopper	*Kraussaria angulifera*	P. millet	Occ.	Sahel	Maiga et al. (2008)
	Oedaleus senegalensis	P. millet	Occ.	Sahel	Maiga et al. (2008)
Green bug	*Schizaphis graminum*	P. millet	Occ.	Pakistan	Akhtar et al. (2012)
Chinch bug	*Blissus leucopterus leucopterus*	P. millet	Reg.	United States	Wright (2013)
Millet stem borer	*Acigona ignefusalis*	P. millet	Reg.	Sahel	Degri et al. (2014)
Pink stem borer	*Sesamia inferens*	F. millet	Reg.	India	Sasmal (2015)
Head miner	*Heiliocheilus albipunctella*	P. millet	Reg.	Sahel	Goudiaby et al. (2018)
Grain midge	*Geromyia penniseti*	P. millet	Occ.	Sahel	Gahukar (1990a)
Blister beetle	*Psalydolytta fusva*	P. millet	Reg.	Sahel	Zethner and Lawrence (1988)
Blister beetle	*Psalydolytta vestita*	P. millet	Reg.	Sahel	Zethner and Lawrence (1988)

[a]C. millet= common millet, F. millet= finger millet, L. millet= little millet, P. millet= pearl millet.
[b]Reg. = Regular occurrence, economic loss; Occ. = Occasional occurrence, sporadic attack, economic loss.

Table 2. Recommended management practices for pearl millet shoot fly

TNAU (2016)	Biradar and Sajjan (2018)
Treat seed with imidacloprid 70WS at 10 g/kg	Select pest-resistant pearl millet
	Cultivars: MP series- 16, 19, 53, 67
	MH series- 9, 49, 52, 82, 99, 105
Till 30 d after seedling emergence	Plant at onset of rainy season or with 15 d of onset
Remove and destroy dead heart infested plants	Increase seeding rate by 20–30%
Hang plastic meal traps impregnated with insecticide (30 traps/ha)	Avoid staggered plantings
Apply 5% neem seed kernel extract at 500 liters/ha or NeemAzal T/S 1% at 1.5 liters/ha	Remove and destroy dead heart infested plants
Plough field soon after harvest	

estimated at 9% (Mideksa et al. 2014) and 20% (Bayeh et al. 2008) in two different regions. Aleminew and Legas (2015) studied the effect of interaction of fertilizer doses (50–100 kg/ha), plant spacing (rows 15–30 cm long × 15 cm wide), and different methods of broadcast planting on shoot fly incidence (in 2012 and 2013) in eastern Ethiopia. However, because pest incidence was low (1.4–3.1%), no significant differences were found and their effectiveness is still unknown. Mideksa et al. (2014) assessed two botanical insecticides and two insect pathogens applied as foliar applications in field trials in western Ethiopia. A water extract of *Nicotiana* sp. leaf powder (3 kg in 500 liters water/ha) exhibited the highest pest mortality of 80–83%, irrespective of planting method. This treatment was followed by neem seed powder extract (3 kg in 500 liters water/ha) with 78% larval mortality. Two entomopathogenic fungi, *Beauveria bassiana* (Bals.) Vuill. and *Metarhizium anisopliae* (Mets.) Sorokin, were ineffective in reducing pest attack. A local wasp, *Neotrichoporoides nyemitawus* Rohwer (Eulophidae), parasitized 7–19% of larvae in eastern Ethiopia during peak pest incidence in August-September (Sileshi 1997), but the population dynamics of this parasitoid were not examined further. Despite the economic importance of the tef shoot fly, possible control measures were not experimentally assessed, and an IPM package is not available to farmers.

Another species, *Atherigona pulla* (Wiedemann), is a major pest of little millet (Arun Kumar and Channaveerswami 2015) and common millet (Sathish et al. 2017a) in southern India where it is also a minor pest of ditch millet and foxtail millet. Sathish et al. (2017b) studied, over two cropping seasons, the effect of intercropping little millet with cowpea, field bean, onion, garlic, coriander, or *Anethum sowa* Kurz at a 1:1 ratio. The lowest fecundity (0.27–0.47 eggs/plant vs 1.38–1.57 eggs/plant in the monoculture) was recorded with onion as the intercrop. The lowest DH infestation rate of 7.5–8.6% (28.4–31.6% in the monoculture) was recorded with garlic as the intercrop. However, the monoculture gave the maximum grain yield of 5.31–6.39 q/ha followed by onion intercropping (5.06–6.14 q/ha). As a result, the highest cost-benefit ratio of 1 to 4.38–4.71 was noted in the millet:onion system (compared to 1 to 1.22–1.72 in the monoculture) (Sathish et al. 2017b).

Regarding chemical and organic treatments in little millet, Sathish et al. (2017c) compared the efficacy of seed cakes of neem, castor, or pongamia, rice shell ash, azadirachtin (AZ), NSKE, carbofuran and imidacloprid during two crop seasons. Observations were recorded at 14, 21, and 28 days after seedling emergence (DAE). The most effective treatment was seed treatment of imidacloprid 600FS at 5 ml/kg which resulted in the lowest average shoot fly fecundity (0.27–0.49 egg/plant vs 1.60–2.01 eggs in control), and the lowest average rate of DH infestation (1.5–2.4% vs 24.3–31.7% in control). This same seed treatment also had the highest grain yield (12.01–12.07 q/ha vs 5.25–5.96 q/ha in control), fodder yield (78.99–81.54 q/ha vs 40.63–57.55 q/ha in control) and a cost:benefit ratio of 1 to 3.28–3.43 vs 1 to 1.08–1.66 in the untreated field. In another field trial, Sathish et al. (2017a) observed a maximum density of *A. pulla* eggs (2.09 eggs/plant) and a 20.9–23.0% rate of DH plant infestation on common millet planted on 15 August compared to that planted on 1 May (0.16 eggs/plant, 0.59% DH infestation). In addition, the maximum level of DH infestation (28.2%) was at 28 DAE versus 15.7% at 14 DAE. Predation by coccinellids (*Coccinella transversalis* F., *Cheilomenes sexmaculata* F.) and larval parasitism by wasps (*Halticoverpa* sp., *Trichopria* sp.) reduced the DH rate to the level of 0.44% and 0.61%, respectively (compared to 28.2% DH infestation in plots without natural enemies). Coccinellids were numerous on plantings sowed in November, whereas parasitoids were active on July–October plantings (Sathish et al. 2017c).

At present, a combination of timely planting, intercropping, seed treatment with imidacloprid, and application of botanical insecticides (cake or water extract) would be a proper IPM package for these pests. Whenever severe damage is observed, synthetic pesticides can be applied as an emergency measure.

Foliage Pests

Defoliators

Millet plants are regularly attacked by the lepidopterans including hairy caterpillars (Arctiidae), leaf folders (Pyralidae), leaf caterpillars (Noctuidae, Lymantriidae) and armyworms (Noctuidae) in India and Africa (Gahukar 1989, Nwanze and Harris 1992). Voracious feeding of these insects results in partial or complete defoliation which arrests plant development. Most of the defoliators are minor pests, but their sporadic attack may warrant proper and timely measures against them. Currently, grasshoppers are potential regular pests of millets in Africa, and pest outbreaks are common in arid and semi-arid areas.

Grasshoppers

Feeding of nymphs and adults of two common species, *Kraussaria angulifera* Krauss and *Oedaleus senegalensis* Krauss (Orthoptera: Acridiidae), caused 56% yield loss in pearl millet in one study (Coop and Craft 1993) and 90% in another (Maiga et al. 2008). During field trials in pearl millet in Mali, Passerini (1991) scored leaf damage of *K. angulifera* on a 1–5 scale, where 1 = no damage and 5 = heavy damage. A higher damage rating (3.01–3.18) was noted in pearl millet intercropped with cowpea or in fields that had fertilizer applied, while a lower damage rating (2.07–2.70) was recorded in delayed plantings or in fields with a high plant density as well as in a general survey of typical farmers' fields. Amatobi et al. (1988) reported that neem trees in millet fields adversely affected grasshopper development. In contrast, trampling by cattle in animal grazing areas did not significantly reduce the viability of grasshopper eggs in the soil (Amatobi et al. 1988). The most important natural mortality factors were found to be the onset of the rainy season and parasitism by two natural enemies of both the egg/first instar: the tenebrionid beetle *Pimelia senegalensis* Olivier and a *Eurombidium* sp. mite, whose attacks caused 40 and 51% mortality, respectively (Jago et al. 1993). Also, application of three entomopathogenic fungi—*B. bassiana*, *M. anisopliae*, and *Nosema locustae* Canning—caused considerable mortality (Maiga et al. 2008). These biological pesticides generally failed to control pest outbreaks due to the overwhelming number of grasshoppers and the typically slow action of biological products. In practice, farmers prefer the use of poison baits, ULV spraying, or ground applications to biological control agents (Maiga et al. 2008). However, considering the potential damage to ecosystems and the low crop return from millet, synthetic pesticides are not assigned high priority in control packages by the researchers (Jago et al. 1993). Farmers often do not follow field sanitation (weeding, intensive tillage, water flooding of fields) and do not cover millet heads with paper bags (Maiga et al. 2008) because these practices are considered impractical and farmers prefer chemicals due to their quick action.

Sap-Sucking Pests

Jassids, thrips, shoot bugs, plant bugs, and one spider mite species occur regularly in millet fields across the world (Gahukar 1989, Nwanze and Harris 1992). Generally, plant damage is not economically important, and these groups are considered minor pests, except green bug (*Schizaphis graminum* [Rondani]) (Hemiptera: Aphididae) and chinch bug, *Blissus leucopterus leucopterus* Say (Hemiptera: Blissidae). Both nymphs and adults suck the sap from young leaves and whorls, causing yellowing and distortion of leaves, and wilting or death of plants. Damaged plants produce shriveled, chaffy grain. Mature plants, however, can survive attack from these species.

Greenbug

Greenbug, *S. graminum*, is an occasional pest in Pakistan, causing high losses in pearl millet (Akhtar et al. 2012). In one field trial, 135 entries from a local varietal collection were screened on a 0–9 scale, where 0 was the most resistant and 9, the most susceptible. The most resistant entry (at 2.0) was cv. C-591, which was then selected for a breeding program. In this trial, 21 entries were found to be moderately resistant with a rating of 3.0 (Akhtar et al. 2012). No other control measures have been assessed. To develop an IPM strategy, field studies on all control measures remain to be undertaken.

Chinch Bug

Kennedy (2002) and Wright (2013) reported the chinch bug *B. leucopterus leucopterus,* to be a major pest of pearl millet in the southwest, midwest, midsouth, and eastern regions of the United States. Varietal resistance seemed to be a practical measure. As such, earlier work of Starks (1982) indicated that resistance was dominant in the F1 hybrids, but this dominance was not consistent in field tests on hybrids imported from Africa and tested in the United States (Wilson et al. 2008). This genetic resistance was, however, confirmed by Ni et al. (2007) who found that insect feeding was affected by both genetic and environmental effects. While screening pearl millet cvs. over the course of 2 yr in Nebraska and Georgia, Rajewski et al. (2009) recorded lower leaf damage of 33 and 0.7% on two inbred lines (59464B and 5968M-1) and one hybrid (03GH785xTift454), respectively, compared to 84% leaf damage in the most susceptible entry. However, the level of damage and rating of resistance varied considerably from place to place.

In other field trials, Buntin et al. (2007) compared the efficacy of three insecticides with untreated control. In observations after 13 d of treatment, the lowest number of 18 bugs/m^2 versus 92 bugs/m^2 in control was found in the field treated with zeta-cypermethrin (Mustang Maxx) at 0.03 kg a.i./ha followed by lambda-cyhalothrin (Warrior II) at 0.017–0.025 kg a.i./ha (20–47 bugs/m^2). The neem product Ecozim 3% sprayed at 0.021 kg a.i./ha was significantly less effective with 68 bugs/m^2.

Stem Borers

Lepidopteran stem borers attacking millets vary regionally in prevalence and importance. In the Indian subcontinent, important species are sorghum stem borer (*Chilo partellus* [Swinhoe]) (Pyralidae), finger millet stem borer or pink borer (*Sesamia inferens* Wlk.) (Noctuidae), and white stem borer (*Saluria inficita* Wlk.) (Pyralidae) (Kalaisekar et al. 2017). In Africa, millet stem borer (*Acigona* (= *Coniesta* or *Hambachia*) *ignefusalis* [Hampson]) (Pyralidae), pink stem borer (*Sesamia calamistis* [Hampson]) (Noctuidae), sugarcane borer (*Eldana sacchaina* Wlk.) (Pyralidae), and maize stalk borer (*Busseola fusca* Fuller) (Noctuidae) (Harris 1962, Nwanze and Harris 1992) cause damage to pearl millet. The spotted stem borer (*Chilo sacchariphagus* [Bojer]) had been reported in mainland China and Taiwan (Kalaisekar et al. 2017). In Senegal, *A. ignefusalis* is a major species on pearl millet, often forming 92% of the total larval stem borer population (Gahukar 1990a) whereas *S. calamistis* and *E. saccharina* are the dominant species in the Ivory Coast (Bekoye and Dadie 2015). Recently, Goudiaby et al. (2018) reported changes in the composition of borer populations in Senegal, with *S. calamistis* becoming a major species (31–72% of the borer larval population) followed by *A. ignefusalis* with 16–53% of the population. Similarly, *B. fusca*, which is a common pest in eastern Africa, has now spread to western parts of the continent (Goudiaby et al. 2018). In the Ivory Coast, Bekoye and Dadie (2015) reported an avoidable loss of 49–52% in cv. VPP-1 attacked by a stem borer complex. The loss was worked out by comparing grain yield in untreated fields with those treated with seed treatment of heptachlor + thiram (Thioral) alone or in combination with soil application of carbofuran granules and putting granules in leaf whorls. At 100 DAE, the incidence level was 43–564 stems attacked in a 25 m row, but this difference was not significant. The carbofuran 3G granules (3 kg a.i./ha)-treated fields gave the highest yield of 803 kg/ha (compared to 388 kg/ha in control).

These borers attack seedling plants from 4 wk of age through grain maturity. Early instar larvae enter the leaf whorl and feed on soft tissues; affected leaves show pinhole damage after they unfold. Later, larvae bore into stems, forming frass-filled tunnels. Drying or wilting of the central shoot or growing point during the vegetative stage results in the DH condition. Side tillers with chaffy spikelets are then produced in response to damage. Peduncles are damaged by late attacks, and many plants lodge, while those that remain standing produce white chaffy panicles (commonly known as 'white earhead').

Millet Stem Borer

Drame-Yaye et al. (2003) estimated yield loss by artificial infestation of pearl millet cv. ISM-19507 in Burkina Faso and losses of 100% and 24% were recorded on plants infested 2 wk after emergence with 10 larvae and 5 larvae, respectively. In contrast, losses were 16% (10 larvae) and 0% (5 larvae) on plants infested later (4 wk after emergence). Plants in naturally infested fields had an average yield loss of 20.9%. Under natural infestation in Niger, yield loss at lower level (8–41%) has been reported by Halilou et al. (2018). However, losses could reach 100% when the level of infestation was high (Goudiaby et al. 2018).

In Nigeria, Ajayi and Labe (1990) evaluated the effect of planting date and planting method on borer damage in local pearl millet cv. Dauro. The best planting date was from 10 July to 2 August. Direct sown crops suffered more damage than transplanted crops but there was no significant difference for planting methods. In Ghana, delayed planting increased the incidence of diapausing larvae in stems of the local cv. Zara (Tanzubil et al. 2002). Degri et al. (2014) evaluated intercropping patterns (millet: peanut in a ratio of 1:1, 1:2, 2:1) in Nigeria, and found lower stem infestation (31% in the intercrop vs 60% in the monoculture) with lower larval density (3.83 larvae/plant vs 9.17 larvae in the monoculture) and higher grain yield (12.09 q/ha vs 5.96 q/ha in the monoculture) in the 1:1 intercropping pattern. Gahukar (1990b) reported that the destruction of plant residue or partial burning of stems after harvest killed 61–84% of larvae and 98–100% of pupae. Similarly, sun-drying of stems in plastic bags resulted in 66–78% and 99% destruction of larvae and pupae, respectively. However, these measures are difficult for farmers to practice because millet stems are used for house fencing.

In Ghana, Tanzubil et al. (2004) noticed increased survival of larvae and greater crop damage when high doses of nitrogen were applied. However, FYM application had no effect on pest incidence. In Nigeria, application of NPK complex at 50–300 kg/ha or urea up to 150 kg/ha significantly increased stem infestation and larval population (Ajayi and Labe 1990). In Senegal, doses of NPK at 50–300 kg/ha (soil application before planting) or urea at 50–200 kg/ha (half dose at thinning and remaining dose at boot stage), significantly increased the level of stalk infestation and larval number/stem, whereas application of superphosphate at 50–200 kg/ha (broadcast along the rows at 20 DAE) reduced infestation rate from 54 to 47% in local cv. Souna and from 59 to 41% in an improved cv. IBV-8001 (Gahukar 1992).

Light traps used for monitoring moth populations did not detect a significant relationship between catch and larval density nor cause any mass reduction in moths in Senegal (Gahukar 1990b). Therefore, pheromone traps have been tested in Nigeria, Ghana, Benin, and Burkina Faso (Dakouo et al. 1997), as well as Niger (Youm and Beevor 1995). Later, Youm et al. (2012) assessed the male sex pheromone bait (Z7-12:OH as major component and Z5-10:OH and Z7-12:Ald as minor components) in a PVC resin capsule. In this trial, polyethylene vials loaded with 0.5 mg of pheromone at 400 dispensers/ha replaced every 21 d achieved up to 87% disruption in mating. However, mass trapping for reducing pest populations was not examined and cannot yet be recommended to farmers.

The egg parasitoid *Platytelemus* sp. (Hymenoptera: Scelionidae) in Niger (Youm and Gilstrap 1993) and the larval parasitoid *Syzeuctus* sp. (Hymenoptera: Ichneumonidae) in Nigeria (Harris 1962) were common in pearl millet, the latter causing up to 30% reduction in larval populations. Recently, Halilou et al. (2018) reported 11 larval parasitoids, but no pest mortality data. Further studies are needed to confirm the value of these parasitoids in reducing borer populations.

Various plant resistance mechanisms exist in pearl millet, such as antibiosis (cv. Zongo) or tolerance (cv. IBV-8004) (Gahukar et al. 1986). Gahukar (1990c) screened 33 cvs. and noted borer infestation of 30–58% with 15–89 larvae/10 stems in short-cycle cvs. and 26.8–41.5% infestation with 9–17 larvae/10 stems in long-cycle cvs. Since there were no significant differences found for both criteria, none of these entries were considered resistant or tolerant. In other trials, Gahukar (1990d) compared the performance of 9 cvs. during 2-yr trials in Senegal. Stem infestation varied from 2 to 19% and larval population from 5 to 19 larvae/10 stems.

In Mali, Passerini (1991) assessed the efficacy of three applications of NSKE (3%) at 500 liters/ha or cypermethrin 25EC at 250 ml/ha. Stem infestation rates were lower in the NSKE and cypermethrin treatments (11%), than in the untreated fields (19%). Cypermethrin ULV (Ripcord) applied at 50% male flowering (at 36 g a.i./ha) significantly reduced the rate of stem attack (Jago et al. 1993). In Senegal, Balde (1993) found a significant impact on borer attack from seed treatment with carbosulfan (Marshal) (125 g a.i./100 kg), isofenphos (Oftanol) (150 g a.i./100 kg) or a mixture of carbofuran + thiram + benomyl (Granox) (200 g a.i./100 kg). Soil application of carbofuran granules10G (Furadan) (at 650 g a.i./ha) applied three time by treatment of the leaf whorl at a monthly interval starting 1 mo after seedling emergence was equally effective.

In sandy soil, the planting time depends upon the arrival of heavy rains, after which farmers plant their seeds. Intercropping of legumes in millet is not practiced due to difficulty of weeding in intercropped fields. Farmers generally apply FYM, and chemical fertilizers are applied only if costs are subsidized by the government. Generally, the cost of pesticide application is not commensurate with grain yield and market rates.

Finger Millet Stem Borer/Pink Borer

Pink borer, *S. inferens,* is a major pest of finger millet in southern states of India where the crop is cultivated in winter (Sasmal 2018). The borer occasionally also attacks pearl millet, foxtail millet, barnyard millet, ditch millet, and common millet. Despite the economic importance of this borer, very little is known about its control. Since market demand and crop return are low, little research has been done. Sasmal (2015) evaluated 33 entries by counting the percentage of plants with DH infestations 45 d after planting. An infestation of rate up to 20.0% was reported on cv. GPV-93, whereas 18 other entries were free of pest attack. Sasmal (2018) examined six treatments in a 2-yr field trial: 1) release of the egg parasitoid, *Trichogramma chilonis* Ishii at 60,000 eggs/ha after first appearance of moths, repeated four times at weekly intervals; 2) foliar spraying of neem seed kernel oil (NO) containing 300 ppm AZ, at 1.5 liters/ha at 30 and 45 d after planting; 3) foliar spraying of *Bacillus thuringiensis* Berl. at 1 kg/ha at 30 and 45 d after planting; 4) soil application of fipronil granules 0.3 GR at 20 kg/ha at 30 d after planting; 5) soil application of cartap hydrochloride granules 4GR at 20 kg/ha at 30 d after planting; and 6) soil application of carbofuran granules 4GR at 30 kg/ha at 30 d after planting. Lower DH rates at 50 d after planting (3.2 vs 20.5% in the control), lower levels of white earheads at grain maturity (4.9% vs 17.0% in control), and higher maximum grain yield (22.1 q/ha vs 14.2 q in control) were recorded in the field treated with cartap hydrochloride. This treatment also gave the highest net profit of US$145.44/ha (INR 10250). A year later, TNAU (2016) recommended spraying phorate 10CG (Phoratops) at 1 liter/ha 1.0 liter/ha at 20 d intervals, starting from seedling emergence.

Currently, farmers follow certain cultural practices (removal and destruction of DHs, burning of stubble, plowing fields after harvest, and harvesting of the crop close to the ground level) that help reduce pest populations during the larval and pupal stages (Sasmal 2018). Whenever plant damage is excessive, granular pesticide formulations can be applied for early control since this measure does not disturb the activity of indigenous natural enemies, particularly egg parasitoids and entomopathogenic fungi (Sasmal 2018). Overall, the IPM package against stem borers should consist of seed treatment, timely planting, clean cultivation, planting of borer-resistant/tolerant cultivars, and conservation of indigenous parasitoids.

Earhead Pests

Several pests cause damage to the earhead during flowering and grain development, resulting in yield loss. This pest complex consists of head miner/spike worm, grain midge, head beetles, head caterpillars, bugs, thrips, and earwigs (Gahukar 1989, Nwanze and Harris

1992). During the last two decades, thrips and earwigs have not been reported on any of the millets. When attack by earhead pests occurred during head development, losses up to 58% occurred in pearl millet in the Ivory Coast (Bekoye and Dadie 2015). Of these pests, the head miner, grain midge, and blister beetles are regarded as major pests of pearl millet.

Millet Head Miner

Gahukar and Ba (2019) updated research findings on the millet head miner *Heliocheilus* (*Raghuva*) *albipunctalla* de Joannis (Lepidoptera: Noctuidae), which is a major pest of pearl millet in the Sahelian region of West Africa. Plowing fields up to 15–25 cm deep in the off-season (April–June) to expose the pupae to desiccation and natural enemy attack resulted in 20% pupal mortality (Gahukar 1990a). However, most farmers do not plow sandy soil because plowing can cause soil erosion after heavy rain, and evaporation can reduce soil moisture. In addition, if plowing is not carried out by all farmers in the area, moths could fly in from neighboring fields. Late planting of pearl millet has been recommended to prevent moth flight from coinciding with plant head development (Nwanze and Harris 1992). A 2-wk delay reduced larval densities in the short-cycle cultivars in Sudan (Hughes and Rhind 1988) and in Niger (Youm and Gilstrap 1993). However, delayed plantings are vulnerable to the loss of soil moisture and attack by stem borers and the millet midge (Gahukar et al. 1986).

In Sudan, application of triple superphosphate at 20 kg/ha enhanced plant growth and reduced pest infestation by 27–36% because the period from planting to heading was considerably reduced (Hughes and Rhind 1988). In Senegal, soil application of urea at 50–200 kg/ha or NPK (10:20:20) fertilizer at 50–300 kg/ha significantly reduced head infestation and the number of larvae in cvs. Souna and IBV-8001, but application of superphosphate at 50–200 kg/ha did not show any effects (Gahukar 1992). Application of synthetic fertilizers to pearl millet is not common in the Sahel due to the market price and purchasing capacity of farmers who therefore apply FYM in fields near the huts or around the village.

Pheromone traps for moths were not effective for pest control (Green et al. 2000). Therefore, light traps with mercury vapor lamps of 25–250 watts were installed in Niger (Guevremont 1983, Ba 2017) and Senegal (Bhatnagar 1983). Whether light traps can be used as a measure of pest control or be integrated into a pest management package is yet to be confirmed. Pest-resistant or tolerant cvs., however, have been identified, namely 3/4 HK, Souna and ICMS-7819 in Mali, Burkina Faso, Senegal, and Niger (Gahukar et al. 1986). Gahukar (1990a) screened 33 cvs. and noted pest infestation of 0.3–80.0% with the lowest infestation in cvs. PS90-2, P-8, IBV-8001 in Senegal. There was no significant difference in the number of larvae/10 spikes between millet cvs. While continuing screening tests, Gahukar (1990c) noted significantly fewer infested heads in improved cv. IBV-8004 (22–40%) than in the local cv. Souna (57–60%). In other trials, Gahukar (1990d) compared the performance of 9 cvs. The spike infestation rate varied from 26 to 94% and larval population density from 11 to 63 larvae/10 spikes. Based on these observations, cvs. IBV-8001 was considered resistant and was included for further field trials and a breeding program. Recently, Goudiaby et al. (2018) identified pest resistance in cv. ISM-19705 (infestation of 32% and larval population density of 3.2 larvae/head) and tolerance in cv. Thialack-2. Consistent resistance over three seasons has been observed in cvs. Moro, Souna-3 and PE-08043 (Ba 2017). Resistance to head miner has been attributed to various characteristics such as compact heads, small involucral bristles and small floral peduncles (Guevremont 1983, Gahukar et al. 1986), as well as antibiosis and antixenosis (Ba 2017).

Insecticides, including cypermethrin in Sudan (Hughes and Rhind 1988) and endosulfan, trichlorofon, acephate, chlordimeform, chlorpyriphos, and insect growth regulators (diflubenzuron, lufenuron) in Senegal and Niger (Gahukar et al. 1986), significantly reduced pest incidence with a single application at 75% flowering or two applications, the first at the beginning of flowering and the second 5–7 d later. In Mali, Passerini (1991) compared three applications of NSKE (3%) at 500 liters/ha or cypermethrin 25EC at 250 ml/ha with an untreated field as a control. The head infestation rate was lowest (14.1%) in the cypermethrin-treated field followed by NSKE (27.5% infestation), compared to the untreated field (34.7% infestation). The stage of head development for treatment differed with the maturity cycle of each cv. For example, the most susceptible stage in local cv. Souna in Senegal for insecticide application was found to be the head emergence stage (10–15 cm from flag leaf). Spraying at this stage resulted in head infestation rates of 21.2–24.4% and 7–24 larvae/10 heads compared to 34.2–73.2% infestation and 12–84 larvae/10 heads with application at the 50% female flowering stage, and 45.0–51.5% infested heads and 17–176 larvae/10 heads with application at the milky grain stage. Since the head emergence stage is preferred for oviposition, the crop should at least be treated in this stage (Gahukar 1990d). Farmers commonly use knapsack/backpack sprayers with which treating heads of tall plants is difficult. Moreover, the economic benefits to smallholder farmers of applying synthetic pesticides still need to be demonstrated because larvae feed in spikelets, where they avoid contact with insecticides (Gahukar et al. 1986).

The complex of natural enemies reported by Gahukar et al. (1986) included 11 predaceous insects, 12 parasitoids, one nematode, and three pathogens. Predators listed included ants, earwigs, mirid bugs, spiders, carabid beetles, an anthocorid bug, and various coccinellid beetles (Sow et al. 2018). The qualitative occurrence and distribution of these predators was noted from head emergence to grain maturity, but their role in causing mortality of eggs and larvae was not investigated (Sow et al. 2018). Parasitoids included 1) the egg parasitoids *Trichogrammatoidea* spp., *Trichogrammatoidea armigera* Nagaraja, *Telenomus* sp., 2) the egg-larval parasitoid, *Copidosoma* (= *Litomatix*) *primulum* Mercet, 3) the larval parasitoids *Schoelandella sahelensis* Huddleston & Walker (*Cardiochiles* sp.) and *Habrobracon* (*Bracon*) *hebetor* Say, and 4) the pathogens *Aspergillus* spp. High parasitism occurred at the stage of panicle emergence and early crop maturity of cvs. (Karimoune et al. 2018). Therefore, Soti et al. (2019) suggested the use of remote sensing and a geographic information system to map areas of pest infestation with vegetation in regularly damaged cvs. in 'hot-spot' areas. For example, Soti et al. (2019) observed that biological control was most successful (77% pest control) in fields that were close to huts and on fertile land. On the other hand, Thiaw et al. (2017) and Brevault and Clouvel (2019) discussed the role and potential effects of landscape features, including cultivated versus uncultivated habitats of pests, to enhance the conservation and augmentation of natural enemies. Furthermore, chemical pesticides are toxic to *H. hebetor* (Dastijerdi et al. 2009).

Periodic augmentative releases of *B. hebetor* were studied in millet fields in Burkina Faso, Mali, Niger, and Senegal (Ba et al. 2014, Baoua et al. 2018). To facilitate releases, Ba et al. (2014) developed a simple and effective technique comprised of a jute bag filled with millet grains, millet flour, larvae of the rice moth (*Corcyra cephalonica* [Staint.]) and mated females of *H. hebetor*. The bags are hung from trees in field sites with 3 km spacing. Parasitoids multiply within the bag, exit through the jute mesh, and disperse into the millet fields. By using this technique, up to 97% pest mortality was recorded in fields covering over 3 million ha in 500 villages in Mali, Burkina Faso, and Niger (Ba et al. 2013). Overall, the releases of *H. hebetor* led to a 34% increase in grain yield compared to control fields (Baoua et al. 2014). However, whether the resource-poor farmers would purchase the bags is rather questionable.

In Sahelian ecosystems, use of pheromone traps (if available), periodical releases of *H. hebetor*, selecting pest-resistant/tolerant cultivars and avoidance of synchronization between susceptible plant stages and peak millet head miner incidence by timely planting of short-cycle cvs. can form an efficient and practical IPM.

Grain Midge

The grain midge *Geromyia penniseti* (Felt.) (Diptera: Cecidomyiidae) has been considered a major pest of millet in savannah areas of Africa (Coutin and Harris 1968) and semi-arid regions in India (Santharam et al. 1976). Larvae feed on developing grain, resulting in empty glumes and white pupal cases attached to the tip of the spikelets. Plants have a blasted appearance. Yield losses of up to 90% in Senegal had been reported by Coutin and Harris (1968). In the 1990s, Gahukar (1990c) observed midge damage in long-maturity cvs. in Senegal where floret infestation varied from 80.4% in local cv. Sanio to 97.0% in improved cv. P-5. Since then, pest damage has not been reported, probably because midges are small in size and nocturnal in habit, and their damage is often not correctly diagnosed by farmworkers. The parasitoid wasp *Tetrastichus* sp. and the predatory bug *Orius* sp. are abundant during peak pest incidence (Coutin and Harris 1968). In the absence of IPM, farmers used available synthetic insecticides (Coutin and Harris 1968, Santharam et al. 1976). For example, whenever pest outbreaks or regular high pest incidence are noticed, farmers resort to dusting of carbaryl 10% dust at 20–25 kg/ha or endosulfan 4% dust at 10 kg/ha or spraying of cypermethrin 25EC at 250 ml/ha.

In the future, monitoring of pest occurrence and population dynamics of midge and its natural enemies, and more experimental data on available and new techniques is needed, particularly on pest-resistant cvs., to formulate an IPM suitable to different agro-ecosystems.

Blister Beetles

As many as 97 species of blister beetles (Coleoptera: Meloidae) have been reported from West Africa (Gahukar 1991). Their geographic distributions and economic importance on pearl millet vary by country. For example, *Psalydolytta fusca* Olivier and *P. vestita* Duf. are common species in the Sahelian countries from Senegal to Chad (Gahukar 1991), whereas species in the genera *Mylabris* and *Coryna* are widely distributed in Nigeria (Lale and Sastawa 2000). Adults feed on whole flowers or pollen and stigmas, inhibiting grain formation. Feeding on milky grains is also common (Zethner and Lawrence 1988). Loss in grain yield of 4–48% due to *P. fusca* in Gambia has been estimated (Zethner and Lawrence 1988). In Mali, sporadic outbreaks have destroyed millet fields, forcing farmers to completely abandon crop cultivation (Gahukar et al. 1989). In contrast, intercropping millet with sorghum or cowpea in Nigeria resulted in reduced pest infestation, although the highest yield was obtained from millet grown alone (Lale and Sastawa 2000), possibly because the yield gap might have been compensated for by late productive tillers.

In Gambia and Senegal, light traps effectively attracted beetles (Gahukar et al. 1989), but pest reduction due to the use of traps has not yet been demonstrated. In Gambia, farmers burn dry grass, crop residues, or other materials to repel beetles during evening hours, with peanut shells being the most effective in creating heavy smoke, causing significant reduction in *P. fusca* populations (Zethner and Lawrence 1988). The disadvantage of such burning is the potential to harm soil-inhabiting natural enemies. Overall, the practicality and efficacy of such measures has not been well studied.

Millets with a short maturity cycle, if planted late, can suffer from blister beetle attack, while long-cycle cultivars may escape attack due to late flowering. Heavy infestations of *Mylabris afzelli* (Bilb.), *M. fimbriatus* (Mars), *Coryna hermaniae* (F.), and *C. chevrolati* (Blair) have occurred on early plantings of pearl millet in Nigeria (Lale and Sastawa 2000). Generally, spikes possessing long and stiff involucral bristles were less attacked than those with short bristles (cv. GB-8735) (Zethner and Lawrence 1988, Lale and Sastawa 2000). In Gambia, a 72–91% reduction in *B. fusca* numbers in short-cycle millets was obtained by spraying flowering spikes with carbaryl, trichlorphon, or malathion at 1,275, 400–1,200, or 500–750 g a.i./ha, respectively (Zethner and Lawrence 1988). However, spraying with ground equipment on tall plants with bristle-bearing heads is difficult.

Looking Forward

Redefined Pest Management

With significant changes in climate, the introduction of high-yielding hybrids, deterioration in soil and water conservation measures, increasing cost of cultivation and fluctuating market rates for millet grains, current pest management strategies need certain changes. For example, Peterson et al. (2018) suggested managing host stress in ways that are ecologically and economically sustainable by including the ecology and evolutionary biology of pests in the control decision-making process. Furthermore, Kalaisekar and Padmaja (2016) confirmed that host plant selection by insects attacking millets is a behavioral process which is governed mainly by chemoreception, a finding that suggests that evolutionary changes in the chemosensory systems of insect pests should be studied. For this purpose, the genetic diversity and genomic resources currently available globally should be used in breeding programs to accelerate the production of more resistant small millets (Goron and Raizada 2015). According to Brevault and Clouvel (2019), agroecological factors such as landscape/biodiversity, cropping systems and uncultivated biota, and natural enemies can all influence pest management.

Leather and Atanasova (2017) emphasized that up-to-date economic threshold levels (ETL) for each major pest should be determined for each crop. The ETL is generally based on plant infestation levels and/or insect population per unit cropped area or number per plant part. Pest management is needed for the sustainable improvement of millet cultivation in the future. Some pests, including *A. hyalinipennis*, *A. pulla*, *G. penniseti*, and *Sesamia* spp., although recorded as major pests, have received little IPM planning. Likewise, for effective implementation of IPM in different agro-ecosystems there should be planned programs for farmer farm schools (FFS) and other extension techniques. Coordinated efforts of extension agencies and field workers may offer an opportunity to disseminate IPM among small and marginal farmers.

The new IPM strategy should have the following components: host plant resistance, ecology and evolutionary pest biology, knowledge of the local agroecosystem, threshold levels, and available efficient control measures, particularly natural enemies.

Plant Health and Human Nutrition

Kennedy (2002) reported pesticide phytotoxicity to pearl millet seedlings grown in the greenhouse where a 7% reduction in seedling emergence and 17% reduction in shoot weight was recorded when phorate granules were applied at 50.4–67.2 mg a.i./pot to control chinch bug in the United States. In India, endosulfan has been banned on food crops because of human deaths due to aerial spraying in southern states. During grain storage, fumigation with insecticides is a common practice. There is an urgent need to study the effect of fumigants on end-use products such as malt, dietary foods, fermented, and unfermented bread. When grains are distributed through a public distribution system, the consumption of contaminated grains may pose risks to human health. As such, post-harvest technologies need to be properly planned and executed.

Multi-Pest Management

In India, Parmar et al. (2015) recommended two applications of profenophos 50EC at 0.05% or fenobucarb 50EC at 0.1%, first spraying at 20 DAE and the second at 40 DAE, for controlling shoot fly and stem borer in pearl millet. Earlier, the IPM module for pearl millet suggested by Kishore and Barman (2003) consisted of seed treatment with imidacloprid 70WS at 5 g/kg, followed by spraying of NO (5%) at 30 DAE and dusting of endosulfan 4% dust at 10 kg/ha at 50% flowering. Sasmal (2015) screened 33 entries of finger millet in India against sap-sucking pests and stem borer. There were 12 entries with no infestation of shoot aphid, *Hysteroneura setariae* (Thomas) versus 4.6% on susceptible cv. GPU-45, and there was a 0% grasshopper feeding level on leaves and <2.3% on panicles due to the grasshopper *Colemania sphenarioides* Bol in 8 entries versus 11.2% on panicle in cv. GPU-91. The incidence of DH plants caused by the stem borer *S. inferens* in 18 of 33 entries was <1.0% versus 20.1% in cv. GPU-93. Overall, two cvs.VL-353 and GPU-88 were promising and were included in a breeding program. Predaceous spiders were abundant on the susceptible cvs. GPU-45, GPU-95. By planting susceptible cvs., the survival and spider number would increase and help in pest mortality, and natural pest control may be possible.

In Senegal, Goudiaby et al. (2018) ran field trials for 2 yr with five cvs. (Gawane, IBV-8004, Thialack-2. ISM-19507 and local Souna-3) for four stem borers (*A. ignefusalis, S. calamistis, E. saccharina, B. fusca*) and millet head miner. The lowest stem infestation (20%) and larval density (6.53 larvae/hill) were recorded on cv. IBV-8004 compared to 31% of stems infested and 4.40–12.07 larvae/hill on other cvs. In the case of millet head miner (*H. albipunctella*), the lowest head infestation (32%) and larval density (3.2 larvae/hill) were recorded on cv. ISM-19507 compared to 56% of heads infested and 7.4 larvae/hill on cv. Thialack-2. Interestingly, the average of 2-yr yield data indicated high grain yields of 1.92, 1.85, and 1.70 t/ha for cvs. Souna-3, Thialack-2, and IBV-8004, respectively, demonstrating that cv. Souna-3 showed tolerance to both pests even though it was considered a susceptible check in this trial.

No comparisons were made for pest mortality and grain yield between a single pest and a complex of pests to determine the economy of multi-pest management. If these data are obtained from field trials, farmers can be convinced of and advised to follow this practice to reduce their treatment cost.

Acknowledgments

This work is supported by the USDA National Institute of Food and Agriculture (Hatch) project (1009746).

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