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Integrated Pest Management in Pigeonpea: Progress and Prospects

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ABSTRACT

Pigeonpea is one of the world's most important grain legume crops. Mostly grown and consumed in India, where it is a staple food, pigeonpea production also occurs elsewhere in Asia, Africa, Latin America and Australia. Despite widespread cultivation and staple food status, pigeonpea yields have barely increased over the last half century. The prevalence and severity of insect pests present major constraints to increasing pigeonpea yields. Two of the most significant pests of pigeonpea are the lepidopteran 'pod-borers'–*Helicoverpa armigera* and *Maruca vitrata*. The pod fly (*Melanagromyza obtusa*) and several species of pod-feeding Hemiptera are also regular pests, and numerous other minor or sporadic pests have been recorded throughout the cultivated distribution of the crop. Current pigeonpea pest management practices rely heavily on the application of synthetic insecticides. Most research has focused on the management of *H. armigera*, *M. vitrata* and *M. obtusa* due to their damaging feeding behaviour, and the propensity of *H. armigera* to evolve resistance to synthetic insecticides. Not surprisingly, pest management in pigeonpea is largely based around these three major pests, particularly the lepidopteran pod-borers which appear to be more damaging to modern short-duration cultivars than to older cultivars. A large amount of research has attempted to develop pigeonpea cultivars with conventional host-plant resistance to pod-borers and pod fly, but with limited success. Future pigeonpea pest management research should take a more integrated approach, exploring underexamined areas such as: understanding how modern pigeonpea varieties and traditional landraces respond to pest herbivory, identifying what cultural control methods are available to smallholder farmers, and investigating how biological control can be incorporated into management practices. Future research has the potential to develop IPM strategies in pigeonpea and provide farmers with an alternative to an unsustainable dependence on synthetic insecticides.

1 | Introduction

1.1 | Background and the Importance of Pigeonpea

Pigeonpea (*Cajanus cajan* (L.) Millspaugh) is a multipurpose legume crop cultivated globally throughout the semi-arid tropics and sub-tropics. Mostly grown by smallholder farmers, it is a low-input crop that is relatively tolerant to both drought and heat (Mula and Saxena 2010). Domesticated in the Indian subcontinent, pigeonpea spread through Asia, into Africa and then to the Americas alongside the slave trade (Fuller et al. 2019; Kassa et al. 2012). The crop is now cultivated in more than 50 countries throughout Asia, Africa, the Americas and Australia (FAO 2024). In the semi-arid tropics, pigeonpea is one of the most important pulse crops and many people depend on it for their livelihood and nutrition. As an important source of protein (~20% grain protein), pigeonpea is used to feed both humans and livestock as either split seeds (dal), whole seeds, a green vegetable or as a forage (Mula and Saxena 2010; Saxena, Kumar, and Sultana 2010).

Over the last decade approximately 4.9 million tonnes of pigeonpea grain were harvested from approximately 5.7 million hectares of production annually (Figure 1) (FAO 2024). India is the largest producer of the crop, contributing approximately 77% of the area and 73% of the tonnage of global production over the last decade (FAO 2024). In India, pigeonpea is a staple crop and the mostly vegetarian population depend on it as a major source of dietary protein (Mula and Saxena 2010). Other significant pigeonpea producing countries include Myanmar (9% of global production) in Asia; and Malawi (8%), Tanzania (4%) and Kenya (3%) in Africa (FAO 2024).

Over the last half century, pigeonpea yields have stagnated and an increased supply has been generated by increasing the area of cultivation (Figure 1a) (FAO 2024; Saxena et al. 2021). Pigeonpea is regarded as an 'orphan crop', as it has experienced substantially less research interest/investment and consequent yield gains compared to major cereal crops that have benefited from the green revolution (Figure 1b) (Borlaug 1975; Cullis and Kunert 2017). Due to limited research investment, there are several major unresolved challenges for global pigeonpea production. Notably, the limited availability of high yielding cultivars and the limited management strategies to manage pests, diseases and weeds that affect pigeonpea production (Mula and Saxena 2010; Odeny 2007).

Arguably the largest biotic constraint to pigeonpea production is the crop's suite of insect pests (Saxena, Chauhan, et al. 2018; Shanower, Romeis, and Minja 1999) that limits yields in Asia (Mohapatra and Chattopadhyay 2012; Wankhade, Malthane, and Nemade 2009), Africa (Hillocks et al. 2000; Mergeai et al. 2001; Yohane et al. 2021), Latin America (Viteri et al. 2019), and which contributed to the collapse of pigeonpea production in Australia (Ryan 1998). Yield losses due to pests are likely exacerbated as most pigeonpea is produced by smallholder farmers, for whom appropriate education and pest management guidelines may not be available.

The goal of this review is not to extensively document every species of phytophagous insect that has been recorded in pigeonpea crops. Rather, we outline the key pests of pigeonpea, review the pest management strategies available for these pests and then identify the future research that is required to improve their management in the crop.

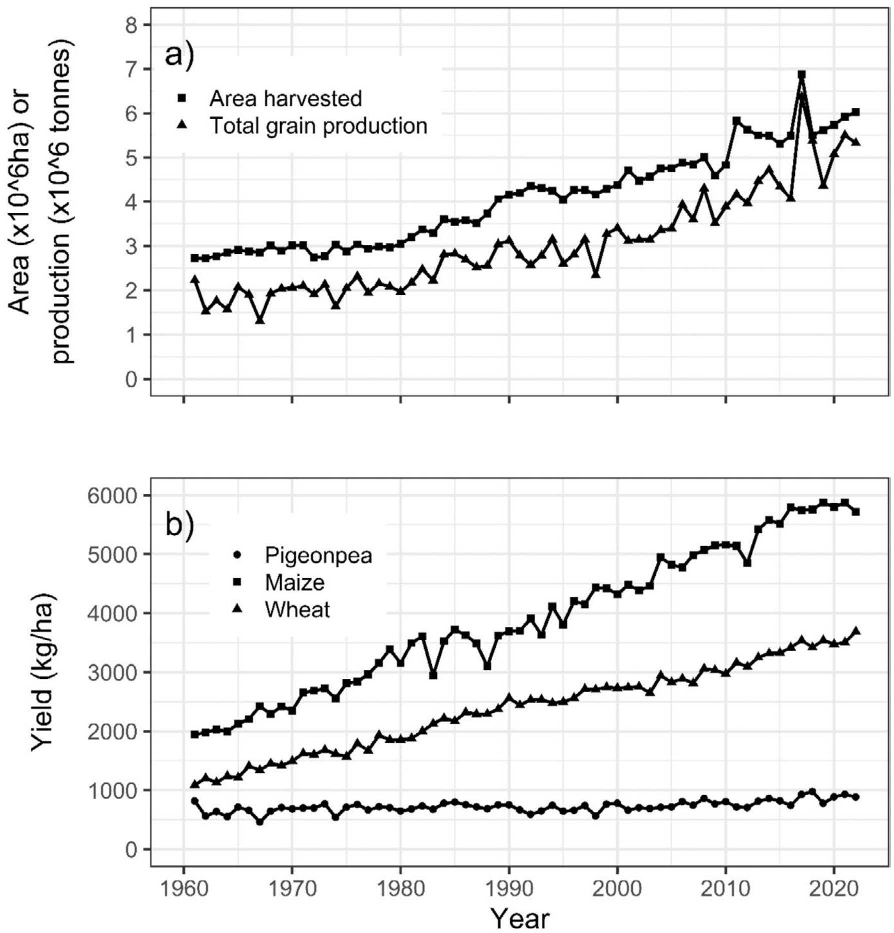

FIGURE 1 | Global pigeonpea production statistics (FAO 2024). (a) Pigeonpea area of production and total grain production have approximately doubled over the last half century. (b) Pigeonpea yield has remained stagnant, while yields of the major cereal crops (maize and wheat) have increased approximately 3-fold.

1.2 | Pigeonpea Agronomy and Physiology

To understand the context of pigeonpea pests and their management, we briefly outline the crop's agronomy and physiology. Renowned for its drought and heat tolerance (Subbarao, Chauhan et al. 2000 and Subbarao, Nam et al. 2000), pigeonpea can be grown in challenging conditions and respond to climate variability, making the crop productive in marginal areas that are not suitable to other legumes (Odeny 2007). Depending on the variety, pigeonpea may be cultivated either as an annual or as a perennial using ratoon management, whereby plant stems are cut near the base post-harvest and allowed to re-grow (Rogé et al. 2016; Snapp et al. 2019). In India, pigeonpea is grown as both a kharif (sown during monsoon, harvested in autumn) and rabi (sown in winter, harvested in spring) crop. The crop may be grown year-round in the tropics but it is restricted to the warmer seasons in the sub-tropics, limited by its lower temperature thresholds for germination and emergence (Mahendraraj et al. 2021).

Pigeonpea may be grown as a monocrop in rotation with cereals (e.g., wheat, barley, maize, sorghum, millet and rice) or other pulses (e.g., mungbeans, blackgram and chickpeas) (Mula and Saxena 2010), but it is mainly grown as an intercrop with cereals (especially maize, sorghum and millet) (Egbe and Kalu 2009; Saxena, Choudhary, et al. 2018; Yohane et al. 2021). Pigeonpea has a slow early vegetative phase compared to the rapid development of cereals, which are harvested before the pigeonpea intercrop flowers and sets pods (Saxena, Choudhary, et al. 2018). The pigeonpea intercrop crop fixes atmospheric nitrogen which benefits the cereal (Snapp et al. 2003), along with providing other agronomic and yield benefits (Daryanto et al. 2020; Myaka et al. 2006; Renwick et al. 2020).

Pigeonpea has other applications and uses in farming systems. Many smallholders use harvested pigeonpea stems as thatching or for fuel (Mula and Saxena 2010) and it can be used as a forage for grazing livestock due to its ratooning ability (Norman et al. 1980; Wallis, Whiteman, and Byth 1979). In Australian farming systems the current major use for pigeonpea is as a 'refuge crop' as a part of the Australian cotton industry's strategy to manage resistance to transgenic crops expressing *Bt*-toxins (Grundy, Chauhan, and Knight 2016; Whitehouse et al. 2017; Wilson, Whitehouse, and Herron 2018). Pigeonpea refuges are planted close to *Bt*-cotton crops and intended to act as 'genetic diluters' by allowing *Bt*-susceptible *Helicoverpa* spp. moths to develop and then randomly mate with conspecifics that have developed in the proximate *Bt*-cotton, thereby retarding the evolution of *Bt* resistance (Whitehouse et al. 2017; Wilson, Whitehouse, and Herron 2018).

Pigeonpea cultivars from different genetic backgrounds can have very different phenologies (i.e., time to flowering and subsequent maturity). Broadly, genotypes are separated into groups based on their time to harvest maturity, these include: super early (< 90 d), extra early (91–120 d), early (121–150 d), medium (151–180 d) and late (> 250 d) maturing varieties (Saxena, Chauhan, et al. 2018). Traditionally long-duration (i.e., late maturity) landraces have been cultivated as they are suitable as inter-crops and may be ratooned and re-harvested for several seasons. Modern pigeonpea breeding has shifted towards developing faster maturing (i.e., short-duration) genotypes, and breeders now focus on super-, extra- and early cultivars (Saxena, Chauhan, et al. 2018; Saxena et al. 2019).

Pigeonpea genotypes can also be separated into two major plant types or 'habits': determinate and indeterminate (Reddy 1990). Although there is some dispute among definitions (Van der Maesen 1985; Vanambathina et al. 2019), upon reaching flowering determinate genotypes largely cease vegetative growth and the apical meristems of the mainstem and branches form terminal racemes whereas, indeterminate cultivars continue vegetative growth from apical meristems. Determinate cultivars typically flower basipetally along branches, whereas indeterminate cultivars tend to flower acropetally. For both plant types however, flowering within racemes is acropetalous.

2 | Arthropod Pests of Pigeonpea

2.1 | Pests as a Function of Crop Phenology

Several hundred phytophagous arthropod species have been recorded feeding on pigeonpea (Lateef and Reed 1990; Shanower, Romeis, and Minja 1999). Plants may be attacked by pests throughout their development, but the suite of pests typically infesting crops changes drastically as a function of crop phenology. Pest infestations which occur during the flowering through to podding stages are most likely to result in yield loss. In this section we document the major pests of pigeonpea, along with several of the minor pests of significance. We selected species based on damage severity, frequency, research focus in the literature and our professional experience.

Although there are several insect species recorded feeding on germinating and emerging pigeonpea (i.e., emergence pests), few are of serious economic concern (Reed and Lateef 1990). During vegetative growth, pigeonpea may be attacked by a range of insects—mainly phloem-feeding hemipterans such as jassids, in the Empoascini. Jassids are regularly recorded from crops but typically don't require control (Sharma et al. 2010). Cowpea aphid *Aphis craccivora* Koch (Hemiptera: Aphididae) feeds on phloem and may cause yield reduction at high densities by decreasing plant vigour (Sharma et al. 2010). A potentially damaging vegetative stage pest is the stem fly *Ophiomyia centrosematis* De Meijere (Diptera: Agromyzidae), and heavy larval infestations can kill small plants (Reed and Lateef 1990). Spider mites *Tetranychus urticae* Koch (Trombidiformes: Tetranychidae), thrips *Megalurothrips usitatus* Bagnall (Thysanoptera: Thripidae) and whitefly *Bemisia tabaci* Gennadius (Hemiptera: Aleyrodidae) can all also feed on pigeonpea during its vegetative stage. However, these pests are all attacked by a suite of natural enemies and rarely reach levels that justify intervention (Reed and Lateef 1990).

There are several leaf-feeding lepidopterans that attack pigeonpea during vegetative growth. Including the leaf-webbers (Lepidoptera: Tortricidae) *Grapholita critica* Meyrick and *Leguminivora ptychora* Meyrick, and a suite of defoliating lepidopterans *Spilarctia obliqua* Walker (Lepidoptera: Arctiidae), *Chrysodeixis chalcites* Esper (Lepidoptera: Noctuidae) and *Thysanoplusia orichalcea* Fabricius (Lepidoptera: Noctuidae). Pigeonpea has also been listed as a host plant of fall armyworm (*Spodoptera frugiperda*) (Montezano et al. 2018), but the pest does not prefer to oviposit nor feed on pigeonpea plants and there are limited reports of field infestations (Volp, Zalucki, and Furlong 2022).

Upon reaching reproductive stages, pigeonpea becomes most attractive and susceptible to its major pests (Figure 2). As pigeonpea plants are flowering and podding they are at greatest risk of yield loss because pests can damage the plants yield-forming reproductive organs. Arguably the major pest of global pigeonpea production is *Helicoverpa armigera* Hübner (Lepidoptera: Noctuidae), known by several common names including pod-borer, gram pod-borer, cotton bollworm, *Heliothis*, etc. (Jaba, Bhandi, et al. 2021; Shanower, Romeis, and Minja 1999; Zalucki et al. 1986). However, other pests such as the spotted pod-borer *Maruca vitrata* Fabricius (Lepidoptera: Crambidae), the pod flies (Diptera: Agromyzidae) *Melanagromyza obtusa* Malloch and *Melanagromyza chalcosoma* Spencer, and the pod wasp *Tanaostigmodes cajaninae* La Salle (Hymenoptera: Tanaostigmatidae) are important during this period (Jaba, Jatin, et al. 2021). A complex of pod-sucking bug species belonging to the Hemipteran families Alydidae, Coreidae, and Pentatomidae also feed on pigeonpea crops during these reproductive stages. Blister beetles *Mylabris* spp. (Coleoptera: Meloinae) will also attack pigeonpea flowers during this period (Durairaj and Ganapathy 2000; Ghoneim 2013).

In addition to the pod-borers, there are several other species of lepidopterans that attack the reproductive structures of pigeonpea. The composition of lepidopteran pest species in pigeonpea varies geographically and seasonally but common pests include other species of Heliothines (Lepidoptera: Noctuidae) such as *Helicoverpa zea* Boddie and *Chloridea virescens* Fabricius in Latin America, and *Helicoverpa punctigera* Wallengren in Australia. Plume moths (Lepidoptera: Pterophoridae) including *Exelastis atomosa* Walsingham, *Exelastis pumilio* Zeller and *Sphenarches anisodactylus* Walker feed on pigeonpea reproductive structures along with the blue butterly *Lampides boeticus* L. (Lepidoptera: Lycaenidae), the lobster moth *Neostauropus alternus* Walker (Lepidoptera: Notodontidae) and the spiny pod-borer *Etiella zinckenella* Treitschke (Lepidoptera: Pyralidae).

Several arthropods vector pigeonpea diseases. The species of major significance is the pigeonpea mite, *Aceria cajani* Chan. (Acari: Eriophydae), which vectors sterility mosaic virus, perhaps the major disease of pigeonpea (Kulkarni et al. 2002). Pigeonpea grain is also attacked by a complex of bruchids (*Callosobruchus* spp.). Bruchids appear to infest grain in storage, rather than in the field (Dasbak, Echezona, and Asiegbu 2009; Nahdy et al. 1998), therefore we do not address bruchid management in this review.

The major pests of pigeonpea are largely consistent across the global growing regions (Hillocks et al. 2000; Minja, Shanower, Songa, et al. 1999; Rao et al. 2002) (Table 1). Due to its widespread distribution, the severity of damage that it inflicts, and insecticide

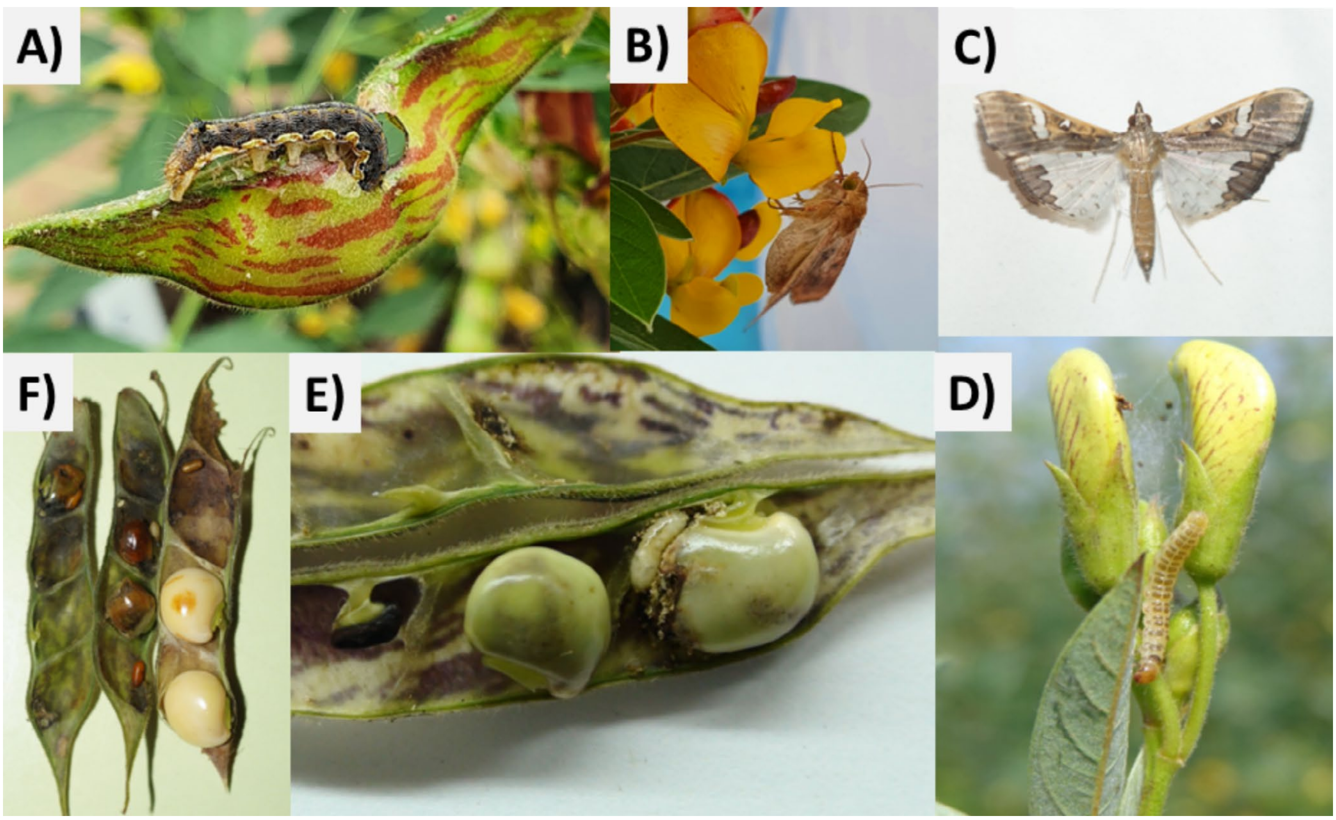

FIGURE 2 | Major insect pests of pigeonpea: (A) *H. armigera* larva, (B) *H. armigera* moth, (C) *M. vitrata* moth, (D) *M. vitrata* larvae, (E) *M. obtusa* larva and feeding damage and (F) *M. obtusa* pupae and seed damage. Photo credit: A and B—T.M.V; C, E, and F—B.L.J; D—J.J.

TABLE 1 | Major arthropod pests of pigeonpea and their distributions.

Pest complex	Species name(s)	Family	Order	Distribution			
				Asia	Africa	Latin America	Australia
Pod-borers	*Helicoverpa armigera*	Noctuidae	Lepidoptera	*	*	*	*
	Maruca vitrata	Crambidae	Lepidoptera	*	*	*	*
Pod flies	*Melanagromyza obtusa*	Agromyzidae	Diptera	*		*	*
	Melanagromyza chalcosoma	Agromyzidae	Diptera		*		
Blister beetles	*Mylabris pustulata*	Meloinae	Coleoptera	*			
Pod-sucking bugs	*Clavigralla gibbosa*	Coreidae	Hemiptera	*			
	Clavigralla tomentosicollis	Coreidae	Hemiptera		*		
	Clavigralla scutellaris	Coreidae	Hemiptera	*	*		
	Clavigralla elongata	Coreidae	Hemiptera		*		
	Clavigralla shadabi	Coreidae	Hemiptera		*		
	Anoplocnemis curvipes	Coreidae	Hemiptera		*		
	Nezara viridula	Pentatomidae	Hemiptera	*	*	*	*
	Riptortus dentipes	Alydidae	Hemiptera		*		
	Riportus serripes	Alydidae	Hemiptera				*
	Melanacanthus scutellaris	Alydidae	Hemiptera				*
Pigeonpea mite	*Aceria cajani*	Eriophyidae	Acarina	*			

*Confirmed presence.

resistance, *H. armigera* has been the focus of substantially more research than the other insect pests (Figure 3). As often is the case with serious pests that attack major crops, authors search for a cost estimate to attach to pests to indicate their economic implications. The estimated the annual loss from pigeonpea production due to *H. armigera* alone sits at US $300M (ICRISAT 1992). How such an estimate was derived is difficult to ascertain. Typically, such estimated costs are highly variable depending on the process used to calculate them and input or yield loss costs may vary considerably based on the geographic location of the crop, and pest management strategies used by farmers (Zalucki et al. 2012). Therefore, given the age of the estimate and the various factors that contribute to the calculation, we suspect there is a need to provide updated cost estimates for the major pests of pigeonpea.

2.2 | *Helicoverpa armigera*

Helicoverpa armigera is arguably the major pest of global pigeonpea production. Considered a 'key pest' of global agriculture, *H. armigera* attacks many agricultural crops (Cunningham and Zalucki 2014; Fitt 1989; Jaba, Bhandi, et al. 2021; Zalucki et al. 1986) and has evolved resistance to numerous insecticides (Ahmad 2007; Downes et al. 2017; Walsh et al. 2022). Pigeonpea is a highly preferred host of *H. armigera* (Rajapakse and Walter 2007). Moths typically infest pigeonpea crops at flowering (Volp, Zalucki, and Furlong 2024b), attracted to floral volatiles (Hartlieb and Rembold 1996; Rajapakse et al. 2006), and lay most of their eggs on floral structures (Volp, Zalucki, and Furlong 2023; Volp, Zalucki, and Furlong 2024b). Neonate larvae preferentially establish inside pigeonpea flowers, and as the larvae develop contemporaneously with the plant, they switch to feeding on pods, where they may cause substantial yield loss (Volp, Zalucki, and Furlong 2024a).

2.3 | *Maruca vitrata*

Maruca vitrata is also a major pest of pigeonpea and in conjunction with *H. armigera*, is often referred to as part of the 'pod-borer complex'. A serious pest of other key legume crops throughout its near global distribution, *M. vitrata* attacks mungbean and yard long bean in Asia, cowpea in Africa, lima bean in the Americas, and mungbean in Australia (Ba et al. 2019; Brier et al. 2008; Srinivasan, Tamò, and Malini 2021). Like *H. armigera*, *M. vitrata* populations preferentially infest pigeonpea and crops during flowering (Jackai and Singh 1983; Nebapure 2020; Sharma 1998). Moths mostly oviposit on leaves, buds, and flowers, and early instars typically establish feeding sites inside flowers. As larvae develop, they form a silk web around flowers, pods, and leaves, in which they shelter and eventually feed on pods (Srinivasan, Tamò, and Malini 2021). Due to their cryptic feeding behaviour, infestations of *M. vitrata* can be difficult to detect and subsequently control with insecticides.

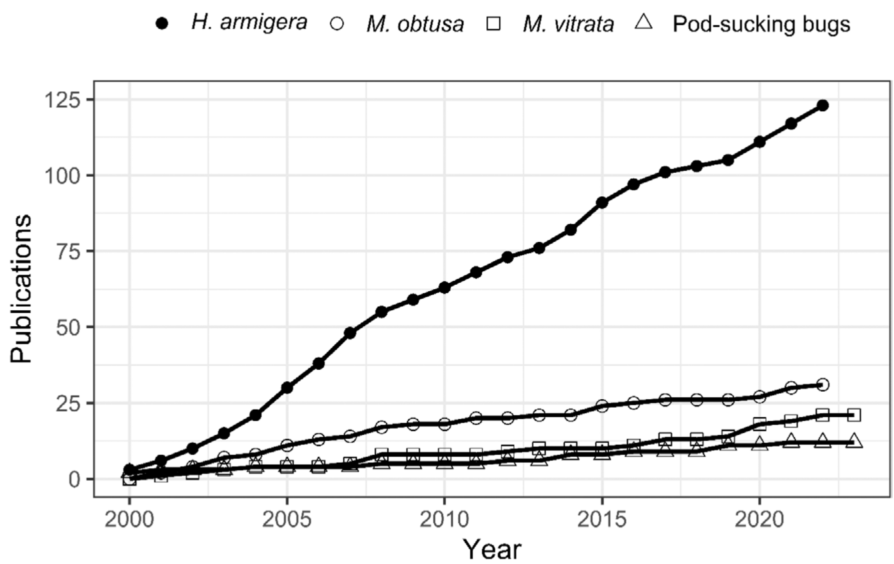

FIGURE 3 | Trends in pigeonpea pest research efforts—cumulative publication counts since 2000. Cumulative publication counts were obtained from Scopus by searching '*Cajanus+cajan*' then the pest species Latin binomial names. For pod-sucking bugs we searched for '*Clavigralla*', '*Riptortus*', '*Piezodorus*', '*Anoplocnemis*' and '*Nezara*' and pooled results, removing any duplicates.

2.4 | Pod Flies

The Asian pod fly (*Melanagromyza obtusa*) is an Agromyzid distributed through Asia, Australia, and Latin America that infests pigeonpea crops during podding (Makinson et al. 2005). Adult females lay their eggs through pod walls and larvae feed on and tunnel through developing seeds (Shanower, Lal, and Bhagwat 1998). Larvae chew a small exit hole through the pod wall as they approach pupation. Due to their small size, and cryptic feeding habit *M. obtusa* larvae are also difficult to detect and control. In Africa *Melanagromyza chalcosoma* inhabits a similar niche to the Asian pod fly, but less is known about its ecology (Hillocks et al. 2000; Shanower, Romeis, and Minja 1999).

2.5 | Blister Beetles

Blister beetles (*Mylabris pustulata* Thunberg) are regularly reported as pests of flowering pigeonpea (Ghoneim 2013; Yohane et al. 2021). The larval stage of these beetles are bee parasites, however the winged adults infest pigeonpea crops at flowering where they feed on flowers. At high densities, these beetles are capable of causing substantial yield loss in pigeonpea (Durairaj and Ganapathy 2000; Singh, Singh, and Singla 2022). However to what extent such high populations actually occur in farmers' fields is uncertain and this pest may present more of a problem in small-plot experiments (Reed and Lateef 1990).

2.6 | Pod-Sucking Bugs

During podding pigeonpea crops are attacked by a suite of pod-feeding Hemipteran pests, commonly referred to as pod-sucking bugs, which can cause substantial pod damage (Dialoke et al. 2010). The pest complex varies geographically and seasonally (Hillocks et al. 2000; Seni 2021; Shanower, Romeis, and Minja 1999), but mainly consists of species in the Alydidae, Coredidae and Pentatomidae. The most frequently reported species are *Clavigralla gibbosa* Spinola (Hemiptera: Coreidae), *C. tomentosicollis* Stål (Hemiptera: Coreidae), *C. scutellaris* Westwood (Hemiptera: Coreidae), *C. elongata* Signoret (Hemiptera: Coreidae), *Anoplocnemis curvipes* Fabricius (Hemiptera: Coreidae), *Riptortus dentipes* Fabricius (Hemiptera: Alydidae), *R. serripes* Fabricius (Hemiptera: Alydidae), *Melanacanthus scutellaris* Dallas (Hemiptera: Alydidae), and *Nezara viridula* L. (Hemiptera: Pentatomidae) (Dolling, 1978, Dolling, 1979, Materu, 1970). These bugs insert their stylets into developing seeds to feed which results in either shrivelled or stained seeds, defects which may render the grain unmarketable.

2.7 | Pigeonpea Mite

The pigeonpea mite (*Aceria cajani*) is a minute (~200 µm), host-specific eriyophid mite that feeds only on species of *Cajanus*. *Aceria cajani* significantly affects yield by vectoring pigeonpea sterility mosaic virus, a species of virus in the genus *Emaravirus* which is one of the major pigeonpea diseases (Kulkarni et al. 2002; Patil and Kumar 2015). Currently, the distribution of *A cajani* is limited to south Asia, however it poses an invasion risk to other pigeonpea growing regions. The mite is unable to survive long without access to its host plant (Kulkarni et al. 2002), so the invasion risk may be small.

3 | Pest Management Strategies

For the suite of pests that attack pigeonpea, a variety of pest management strategies have been researched and developed. Based upon the typical conceptual IPM 'framework' (for example see (Naranjo et al. 2008)) realised and potential strategies include monitoring and sampling, economic thresholds, cultural control, host plant resistance and tolerance, biological control and the use of conventional insecticides. Here we outline key research findings, strategies employed by pigeonpea farmers and gaps that require further research.

3.1 | Monitoring and Sampling

Although many species of pests infest pigeonpea, species composition and population levels within pigeonpea crops may vary substantially across crop phenology, seasons, growing regions and among fields. The starting point for in-field pest management is to detect and monitor pest populations. Although many species can be detected by light trapping, limited trapping techniques are available for key pigeonpea pests. Reliable pheromone traps are only available for *H. armigera* (Dent and Pawar 1988; Yadav, Keval, and Yadav 2021). A pheromone lure has been developed for *M. vitrata*, however, and it is efficacious in Africa (Downham et al. 2004) but not in Asia (Schläger et al. 2012). Even though both African and Asian male moths are attracted to female gland extracts from either region (Schläger et al. 2015). Therefore, the development of a pheromone lure for Asian *M. vitrata* requires further research (Srinivasan, Tamò, and Malini 2021). No pheromone lures are available for *M. obtusa*, although sticky traps may provide an appropriate sampling method (Mohan, Subba Rao, and Sundarababu 1994).

Limited work has been conducted on pheromone trapping for pod-sucking bugs in pigeonpea, although aggregation pheromone traps have been developed for species infesting other legume and horticultural crops. There are several cases of interspecific cross-attraction among pod-sucking Hemipterans, indicating the potential for multi-species traps (Adachi, Uchino, and Mochizuki 2007; Endo, Sasaki, and Muto 2010; Tillman et al. 2010). The usefulness of such traps in predicting in-field populations is questionable as studies must first demonstrate a correlation between trap catches and actual pest abundance in the crops. Traps even have the potential to increase in-field damage levels because of 'trap spillover' following the attraction of pests into crops (Rahman et al. 2018).

Although the inability to readily monitor several key pests through species-specific trapping methods may limit pigeonpea pest management, ultimately measuring in-crop pest populations is dependent on sampling methods that are more intensive than passive trapping. In-field sampling techniques are fundamental to obtain estimates of pest and natural enemy abundance to guide management decisions, along with ensuring farmers are educated about pest and natural enemy identification. Pigeonpea growers typically rely on visual assessments to measure pest populations; however these assessments are likely unreliable, particularly given the cryptic feeding habits of the key pigeonpea pests. The beatcloth (also referred to as 'beatsheet') sampling method is perhaps the most reliable technique for farmers and pest managers to measure the abundance of insect species in field crops (Duffield, Winder, and Chapple 2005; Wade et al. 2006). This method involves shaking plants onto a cloth or sheet of plastic spread on the ground to obtain an estimate of the of abundance pest and natural enemy species. This technique is used by some pigeonpea farmers, but the extent of adoption is uncertain (Sharma et al. 2010) and even researchers still rely on visual counts to sample pigeonpea pests (Seethalam et al. 2021). We suggest that developing the beatcloth as a standard sampling method for research in pigeonpea, and extending the technique to farmers, would be a major step forward in pigeonpea pest management.

3.2 | Economic Thresholds

Economic injury levels (EILs) and their consequent economic thresholds are fundamental components of integrated pest management (Pedigo, Hutchins, and Higley 1986). Yet, in modern farming systems the state of thresholds is regrettably poor (Leather and Atanasova 2017; Ramsden et al. 2017). For field crops in general, few empirical thresholds (i.e., those which are calculated from experimental data) are available, and most thresholds are nominal (i.e., threshold values are notional and not based on EIL calculations) (Ramsden et al. 2017). This is certainly true for pigeonpea, where the available thresholds are often nominal, variable, and often not supported by available data (Table 2). Although some studies have provided experimental evaluations and calculated thresholds based on input costs (e.g., Chiranjeevi and Patange 2017; Mahalle and Taggar 2017).

There are several reasons for the lack of proper threshold development in pigeonpea. These include poor sampling protocols (as previously discussed), the 'black box' approach often taken by entomologists when examining plant responses to damage (Peterson and Higley 2000), and a lack of research interest/investment in threshold development. Thresholds are complicated—they are influenced by the cost of control measures, the contribution of natural enemies to pest mortality, grain prices, crop variety, crop stage and environmental factors (Pedigo, Hutchins, and Higley 1986). Nominal thresholds do not incorporate these variable factors, and we suggest threshold development should be regarded as a high priority research area for pigeonpea pest management.

Shanower, Romeis, and Minja (1999) questioned whether the development of useful or practical thresholds could ever be achieved for pigeonpea pests given the crop's long reproductive period, compensatory ability, the large number of pests, and the socioeconomic constraints upon most pigeonpea farmers. We suggest that threshold development for pigeonpea pests is useful and practical. Without thresholds, pigeonpea farmers are forced to make uninformed decisions about their management tactics (Leather and Atanasova 2017), which renders judicious pesticide use and IPM in pigeonpea impossible. Additionally, threshold development is not a binary process, but rather management guidelines are developed incrementally. For instance, some basic information that contributes to threshold development has already been obtained and may be used to inform farmers' decision making. Pigeonpea plants can compensate for substantial floral damage but not later damage to filling pods (Sheldrake, Narayanan, and Venkataratnam 1979; Tayo 1980; Togun and Tayo 1990). Therefore, floral damage, caused by pod-borers and blister beetles may be tolerated, yet direct pod damage caused by pod-borers, pod fly and pod-sucking bugs is at greater risk of causing yield loss. Given this knowledge, farmers

TABLE 2 | Purported economic thresholds for pest management decision making in pigeonpea.

Pest	Economic threshold level	Reference
H. armigera	2 eggs or 1 larva/plant at flowering, or 1 larva/plant at podding, or 4–5 moths/trap/day, or > 5% pod damage	(Sharma et al. 2010)
	5 eggs or 3 small larvae/plant	(Jaba, Jatin, et al. 2021)
	0.6 larvae/plant	(Reddy, Singh, and Singh 2001)
M. vitrata	1 web/plant	(Sharma et al. 2010)
	5 webs/plant	(Jaba, Jatin, et al. 2021)
	3 larvae per m^2	(Mohapatra and Chattopadhyay 2015)
	4.2 webs/plant	(Mahalle and Taggar 2017)
	0.54 larvae/plant	(Vinayaka 2012)
M. obtusa	2.5% pod damage	(Sharma et al. 2010)
	7.7 larvae/plant or 4.6% pod damage	(Chiranjeevi and Patange 2017)
Pod-sucking bugs	2 bugs/plant	(Sharma et al. 2010)
	1 egg mass/plant	(Jaba, Jatin, et al. 2021)

may differentially prioritise the investment of their management tactics across different crop stages.

To improve the state of thresholds in pigeonpea, a proper understanding of how pigeonpea plants respond to damage must first be developed. Since the studies conducted in the 1970s and 1980s (Sheldrake, Narayanan, and Venkataratnam 1979; Tayo 1980; Togun and Tayo 1990), few studies on pigeonpea have taken a phytocentric approach to understand how plants respond to pest damage. As several key pests have similar modes of feeding, there may be potential to manage pest complexes using multispecies thresholds—a process that has been successful for other legume crop pests, such as defoliating lepidopterans in soybeans (de Freitas Bueno et al. 2011) and pod-sucking bugs in soybeans and mungbeans (Brier et al. 2008).

3.3 | Cultural Control

Modern pigeonpea research has experienced a strong shift towards developing short duration cultivars with higher harvest indices in attempt to increase yield. The modern focus for pigeonpea breeding is on short duration, determinate varieties to be cultivated as sole crops (Saxena, Chauhan, et al. 2018). Yet, traditionally pigeonpea has been either grown as an intercrop or a perennial, and most smallholder farmers still cultivate pigeonpea as an intercrop (Saxena, Choudhary, et al. 2018; Yohane et al. 2021). Although there is limited empirical evidence, many authors state that short-duration, determinate modern varieties are more susceptible to certain pests than traditional landraces (Reed and Lateef 1990; Saxena et al. 2002). Due to the substantial differences in phenology of the 'new' genotypes versus traditional landraces, it is understandably a difficult question to test experimentally. However, given the environmental sustainability of perennial production (Grabowski et al. 2019; Pimentel et al. 2012; Snapp et al. 2019), and if most farmers still rely on landraces grown as intercrops, it seems that modern pigeonpea research may be somewhat disconnected from actual production systems used by farmers!

3.3.1 | Intercropping

The pest management benefits of intercropping pigeonpea have been examined in several studies, with varied results. As pigeonpea typically reaches its most susceptible period after the cereal (or other legume) intercrops have been harvested, the purported benefit of intercropping is that natural enemy populations will establish on the faster intercrop and then move across to the pigeonpea as it begins flowering. There are two major limitations to overcome for this approach to be successful. First, if medium or long-duration pigeonpea cultivars are used, there may be a substantial gap between cereal and pigeonpea flowering (Shanower, Romeis, and Minja 1999) and second, natural enemies might not be effective unless the pests targeted in pigeonpea are common to both crops (e.g., *H. armigera*).

Short-duration pigeonpea cultivars present the opportunity to synchronise pigeonpea and cereal intercrop flowering. In a single season trial, intercropping short-duration pigeonpea with sorghum increased *Trichogramma* spp. parasitism of *H. armigera* eggs in pigeonpea (Duffield 1994). This result was purportedly due to parasitoids moving from sorghum to the pigeonpea intercrop, although parasitism levels peaked early and decreased as flowering/podding continued. These results were mostly not reproduced under similar conditions over 5 seasons when *H. armigera* eggs were predominately laid on reproductive structures (Romeis, Shanower, and Zebitz 1999). The location of *H. armigera* eggs on pigeonpea plants strongly affects *Trichogramma* spp. (mainly *Trichogramma chilonis* Ishii [Hymenoptera: Trichogrammatidae]) parasitism levels, and high parasitism levels were recorded from *H. armigera* eggs laid on leaves (41%) but not on to calyxes (4%) or pods (0.3%). The lower parasitism on reproductive structures occurs because *Trichogramma* spp. searching behaviour is negatively impacted by the trichomes and their glandular exudates on these plant parts (Romeis, Shanower, and Zebitz 1998). Parasitoids are also repelled by volatiles produced by reproductive pigeonpea (Romeis, Shanower, and Zebitz 1997).

Sowing a cowpea intercrop to act as a 'bridge' for natural enemies after a sorghum intercrop was harvested failed to benefit to predator populations in pigeonpea or *H. armigera* biocontrol (Sigsgaard and Ersboll 1999). Rather, there was little overlap in the predator species composition between reproductive sorghum and the reproductive pigeonpea. The cowpea intercrop instead increased *H. armigera* oviposition on pigeonpea (Sigsgaard and Ersboll 1999). Other experiments have documented a pest suppressive effect from sorghum intercropped with pigeonpea (Rao et al. 2007). Some early experimental work documented that a range of legume and cereal intercrops can delay and decrease pest infestations in pigeonpea (Singh and Singh 1978). For instance, intercropping with pearl millet decreased *H. armigera* eggs, larvae and resulting damage in pigeonpea; however there was a substantial yield loss from the intercropping compared with the sole crop (Hegde and Lingappa 1996).

Intercropping with cereals (maize, sorghum and pearl millet) may decrease *M. vitrata* infestation and damage in pigeonpea compared to sole crops (Kavitha and Vijayaraghavan 2023). Based on surveys of villages in Northern India, pigeonpea crops intercropped with mungbeans and turmeric experienced lower *H. armigera* populations compared with cereal intercrops and sole pigeonpea (Yogesh et al. 2015). However, the 'successful' intercrops still experienced substantial pod damage, averaging between 18% and 22% for pigeonpea intercropped with turmeric and mungbeans, respectively (Yogesh et al. 2015).

The push-pull approach, a form of well-researched intercropping, has now experienced substantial success for African smallholders growing maize (Midega et al. 2018). Although there are anecdotal records of pigeonpea being incorporated into push-pull systems, we were unable to find any published studies evaluating pigeonpea as push-pull intercrop, despite pigeonpea reducing *Striga* (i.e., the target weed of the push-pull technology) populations when used as a rotation crop (Oswald and Ransom 2001). Therefore, we suspect it would be worth investigating if pigeonpea also has the 'push' effect of *Desmodium* to repel stemborers. Intercropping may decrease pigeonpea yield compared to sole pigeonpea crop (Dasbak, Echezona, and Asiegbu 2012), but there are other documented agronomic benefits of the cereal-pigeonpea intercrop system (Renwick et al. 2020) along with the potential pest management benefits if the system is understood and implemented appropriately.

When conducting intercropping experiments, researchers should record pigeonpea (and intercrop) yields and economic returns, rather than simply natural enemy presence and pest mortality. Ultimately pest management is only one factor in the agricultural system. Most published research on intercropping on pigeonpea, has not sought to develop a mechanistic understanding of how intercropping may cause pest suppression. Future research should focus on determining how a given intercrop contributes to pest suppression in pigeonpea rather than simply documenting its effects.

3.3.2 | Other Cultural Control Methods

There is a suite of other cultural control tactics available to pigeonpea farmers, that have been less extensively researched than intercropping. One such tactic is manipulating sowing dates so that the pigeonpea crop flowers and sets pods either before or after the maximum insect threat period (Yadava et al. 1983). Early and late flowering pigeonpea varieties may escape insect damage, as they can complete the podding stage during periods of low pest pressure, while mid-season flowering crops may be conducive to heavier insect pressure (Jat et al. 2017). However, changing sowing date does not always influence in-crop pest pressure (Kabaria et al. 1990). Substantial data is available for the phenology of major pigeonpea pests, and this might be useful to design strategic planting times for pigeonpea, if analysed appropriately.

Several other agronomic factors may either exacerbate or decrease pest problems. There is some data to suggest increasing plant density within a crop may increase pest incidence (Dialoke et al. 2014). While surveys in Kenya have correlated fertiliser application with increased incidence of chewing and sucking pests in pigeonpea crops (Otieno et al. 2011).

Erecting bird perches is regularly mentioned as an IPM tactic to help manage insect pests of pigeonpea (Maurya et al. 2017; Rao et al. 2011; Sharma et al. 2010; Srivastava and Joshi 2011). Perches may be either inanimate (e.g., dead tree branches or bamboo sticks) or animate (e.g., planted tall sorghum or Kenaf plants (*Hibiscus cannabinus*)) and are supposed to attract birds which feed on insect pests in the pigeonpea field. Perhaps unsurprisingly, there is little published data on the effectiveness of bird perches to promote avian biocontrol in pigeonpea crops. Some non-replicated observations have been published, which document bird predation of *H. armigera* larvae and report yield benefits (Lingappa and Hegde 2001). We suggest that the ability of perches to provide biocontrol benefits to smallholder farmers should be properly investigated with replicated experiments at the field scale. There is evidence of the benefits of birds and bats for biocontrol in other crops (Garcia et al. 2020), along with relatively simple approaches to measure contributions to pest mortality (Maas et al. 2019).

Another cultural control tactic that may be useful for pest management is control of alternative host-plants or weeds that may harbour pest populations. Although we could not find any studies examining the effect of weed control on pigeonpea pest populations, several of the key pests are known to maintain their populations on weeds including *H. armigera* (Zalucki et al. 1986), *M. vitrata* (Srinivasan, Tamò, and Malini 2021), and *M. obtusa* (Khokhar et al. 1987). However, the suggestion of weed management tactics raises the important question—are the pest populations infesting crops generated locally or distantly? If populations are mostly generated within a local farming area, deep soil ploughing post-crop is another tactic to destroy overwintering lepidopteran pupae (e.g., *H. armigera*) in the soil (Fitt and Cotter 2005).

3.4 | Host-Plant Resistance and Tolerance

There has been an enormous research investment in developing pest-resistant cultivars of pigeonpea, most of which has focused on the three major pests: *H. armigera*, *M. vitrata*, and *M. obtusa* (Sharma 2016). The majority of the resistance research has been conducted by the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT), where by 1990 over 11,000 pigeonpea accessions had been screened for their susceptibility to pod-borers (Lateef and Pimbert 1990). Only low to moderate resistance/tolerance has been found in cultivated genotypes (Jaba, Bhandi, et al. 2021; Reed and Lateef 1990; Sharma 2016; Sharma, Ahmad, et al. 2005). Despite the considerable time and money invested in this area, there has been limited progress. Several resistant accessions have been identified, but so far no resistant, agronomically suitable genotype has been released (Sharma 2016).

3.4.1 | Plant Types and Susceptibility

As mentioned previously, the trend of plant breeding efforts to develop short duration cultivars (Saxena, Chauhan, et al. 2018; Saxena et al. 2019) appears to have increased pigeonpea susceptibility to pod-borers (*H. armigera* and *M. vitrata*) but decreased the incidence of *M. obtusa* as a major pest (Srivastava and Joshi 2011). Supposedly long-duration pigeonpea genotypes (traditionally grown by smallholder farmers) are better able to either avoid or compensate for pod-borer damage (Reed and Lateef 1990). Long-duration genotypes may flower and set pods during cooler periods with lower pest pressure, or alternatively they may be better able to compensate for pest damage.

Despite many comments within the pigeonpea literature suggesting short-duration, determinate types are more susceptible to pod-borer damage, few researchers have published empirical data testing this claim. This is an obvious area for future investigation with substantial practical outcomes. For instance, the variety 'Pusa Ageti' was not widely adopted by farmers due to its high susceptibility to pod-borers (Saxena et al. 2019). Some data have been published documenting that *M. vitrata* causes greater damage of short-duration determinate cultivars (Saxena et al. 2002; Sharma, Saxena, and Bhagwat 1999). However, these studies have relied on open-field screening, which does not enable controlled infestations, nor can this method disentangle resistance and tolerance. Research should focus on determining the mechanisms that increase plant susceptibility to the pests—i.e., does an earlier flowering time overlap with pest populations? Do pests oviposit more on these types? Do immatures establish better? Is larval mortality decreased on compact and determinate plant types? Or are short-duration cultivars simply less tolerant of pest damage?

On the other hand, *M. obtusa*, appears to be more of a problem in long duration pigeonpea varieties and early maturing genotypes have been reported to suffer less damage than mid and late maturing entries (Reed and Lateef 1990; Srivastava and Joshi 2011).

3.4.2 | Conventional Resistance

Host-plant resistance, in the form of antibiosis and antixenosis, has been putatively identified in a suite of pigeonpea accessions (Kumari, Reddy, and Sharma 2006; Kumari, Sharma, and Reddy 2010; Sharma 2016; Sharma, Ahmad, et al. 2005; Sison, Shanower, and Bhagwat 1993; Sison and Shanower 1994; Sunitha, Ranga Rao, et al. 2008). However, within cultivated genotypes typically only low to moderate levels of resistance has been documented. Within wild relatives of pigeonpea (particularly *Cajanus scarabaeoides*, *Cajanus acutifolius* and *Cajanus platycarpus*), high levels of resistance have been identified against *H. armigera* (Green et al. 2006; Green et al. 2002; Green et al. 2003; Sharma, Sujana, and Manohar Rao 2009; Stevenson et al. 2005), *M. vitrata* (Gangwar and Bajpai 2007) and *M. obtusa* (Sharma, Pampapathy, and Reddy 2003). The putative mechanisms for resistance in wild relatives against *H. armigera* are morphological (non-glandular trichomes) and biochemical (high levels of polyphenols and tannins) (Sharma, Sujana, and Manohar Rao 2009). Resistance has also been investigated for the pigeonpea mite *A. cajani* (Reddy and Nene 1980).

Conventional breeding techniques have thus far been unable to incorporate resistance traits from wild relatives into agronomically suitable pigeonpea cultivars. One moderately *H. armigera*-resistant/tolerant genotype 'ICPL332' was bred and released as 'Abhaya' to Indian farmers, however the variety was not successfully adopted because of its susceptibility to fusarium wilt (Saxena et al. 2016). An improved version of this cultivar was developed with potential fusarium wilt resistance (ICPL 332WR) was released as 'TDRG 4' in Telangana, India (ICRISAT 1992).

3.4.3 | Genetically Modified Plants

Over the last few decades, there has been a surge in the area of genetically modified crops grown globally (Xiao and Wu 2019). Predominately crops have been engineered to express a suite of insecticidal crystalline proteins from the soil bacterium *Bacillus thuringeinsis* (*Bt*) (ISAAA 2018; Sanahuja et al. 2011; Tabashnik, Fabrick, and Carrière 2023). *Bt* crops appear harmless to human consumers (Koch et al. 2015), enable IPM by supporting biological control (Romeis et al. 2019), and have revolutionised some modern farming systems (Qaim and Zilberman 2003; Wilson, Whitehouse, and Herron 2018). However, in response to the widespread adoption of Bt crops, there has been a surge in the level of *Bt*-resistant pests (Tabashnik and Carrière 2017; Tabashnik, Fabrick, and Carrière 2023).

Transgenic *Bt* pigeonpea expressing crystalline insecticidal proteins (Cry1Ac, Cry1AcF and Cry2Aa) to target *H. armigera* and *M. vitrata* have been developed (Ghosh et al. 2017; Kaur et al. 2016; Ramu et al. 2012; Sarkar, Roy, and Ghosh 2021; Singh et al. 2018). But evaluations of efficacy have focused on leaf (Ramkumar et al. 2020; Ramu et al. 2012) or pod tissue (Ramu et al. 2012) in bioassays, and flowers have been ignored. *Bt*-cowpea has recently been approved for *M. vitrata* management in some West African countries (Addae et al. 2020) but there should be caution if *Bt*-pigeonpea is similarly granted approval, as *H. armigera* has the capacity to evolve resistance to *Bt* toxins and currently non-*Bt* pigeonpea crops likely function as refuges delaying the evolution of *Bt* resistance when challenged by the selection pressures exerted by *Bt*-cotton in agricultural landscapes (Singh, Kukanur, and Supriya 2021). Therefore, if *Bt*-pigeonpea is released to growers, an appropriate resistance management strategy must be developed in conjunction with a resistance monitoring program (Dandan et al. 2019; Downes et al. 2017).

Recent progress has been made in the technologies of RNA interference (RNAi) and clustered regularly interspaced short palindromic repeats (CRISPR) that both present novel opportunities to develop insect resistant crop plants (Talakayala, Katta, and Garladinne 2020). One study has demonstrated that host-delivered dsRNA through RNAi can decrease *M. vitrata* larval feeding on pigeonpea leaves (Chatterjee et al. 2022). The potential of these new technologies is exciting, but substantial research is required in this area before commercial application in pigeonpea.

3.4.4 | Tolerance

Plant tolerance is an often-overlooked plant defence tactic in pigeonpea pest management research. Tolerance represents a plant's ability to compensate for pest injury, and has been relatively under-explored compared to traditional host-plant resistance (Peterson, Varella, and Higley 2017). Some research has examined pest tolerance in pigeonpea, with results indicating potential genetic differences in response to pod-borer complex herbivory (Durairaj et al. 2003). However, since the pioneering pigeonpea response to injury research (Sheldrake, Narayanan, and Venkataratnam 1979), little has been done in this area—despite the immense importance of the topic (e.g., threshold development). Tolerance may present a superior tactic compared with resistance, because insects cannot evolve to overcome tolerance mechanisms as they can for host-plant resistance traits (Stowe et al. 2000). However, given most of the major pigeonpea pests attack pigeonpea during its reproductive stages (i.e., stages critical to yield formation) the utilisation of pigeonpea tolerance may be limited—particularly in short-duration, determinate varieties.

3.4.5 | Plant Susceptibility Summary

There are several issues with resistance and tolerance research in pigeonpea. First, the term 'resistance' is often used to include both resistance and tolerance, with pigeonpea researchers rarely attempting to disentangle the effects of resistance and tolerance. Resistance refers to traits which decrease pest preference and performance, whereas tolerance refers to traits that increase a plant's ability to yield in response to injury (Stout 2013). Second, the methodology used to screen pigeonpea genotypes tend not to examine the pest-crop interactions at appropriate scales. There are two main methodologies that have been employed for screening pigeonpea for pest susceptibility: (i) laboratory assays (e.g., Sharma, Pampathy, et al. 2005), restricting insects to excised plant parts, and (ii) open field screening (e.g., Jat et al. 2018; Jat et al. 2021), where plots of different cultivars are planted in a field trial, natural infestations occur, and then pest abundance and damage levels are typically recorded.

Laboratory assays can fail to adequately consider pest behaviour and insect response to induced defences (Johnson et al. 2011; Volp, Zalucki, and Furlong 2023). In most of the assay-dependent studies (mostly conducted on *H. armigera*) larvae are restricted to feed on leaves, whereas early instar *H. armigera* larvae have a strong preference to feed on flowers (Rajapakse and Walter 2007; Volp, Zalucki, and Furlong 2023; Volp, Zalucki, and Furlong 2024a; Volp, Zalucki, and Furlong 2024b). Incorporating the feeding behaviour of lepidopteran larvae would present a major step forward in host-plant resistance screening in pigeonpea.

Open field screening, on the other hand, fails to separate resistance and tolerance. As pigeonpea varieties have different flowering times, earlier flowering varieties may experience more pest pressure in unsprayed field plots. Another issue with field screening is how results are usually presented—often the percent of pod damage will be recorded, which is not the most important metric. Percent pod damage is a result of several other variables—pest abundance in a plot, level of injury inflicted by the pest, and the amount of undamaged pods available for the pests to damage. Variables that are more relevant and should be reported from these studies include: pest abundance in undamaged plots (i.e., insecticide treated controls), pest abundance in damage plots (i.e., untreated plots), and the corresponding plot yields (including yield components: pod counts, seed counts and seed weight). Percent pod damage may be useful, but presentation of yield and pest population data are fundamental to understanding the relationship between pest populations and yield loss.

Future research on pigeonpea needs to disentangle the effects of resistance and tolerance to obtain a mechanistic understanding of pigeonpea plant defence traits. Conducting well-designed experiments using insects on either glasshouse or field-grown whole plants would present a step in the right direction (Jat, Dahiya, and Sharma 2024; Volp, Zalucki, and Furlong 2023). Examining the role of plant architecture as well as phenology on plant susceptibility to pests is an area that has been unexplored in pigeonpea. One hypothesis is that clustered racemes of determinate cultivars enable better early instar pest establishment (Volp, Zalucki, and Furlong 2023). Within pigeonpea germplasm a large variation exists in terms of architecture, even among short-duration determinate types. Therefore, could spreading determinate short-duration types be bred that are less susceptible to pests? Would such types also enable greater efficacy of insecticides and/or biological control?

Developing less susceptible pigeonpea varieties is not a panacea for pest management. Partial resistance may be a useful tactic—as resistance does not need to be 'complete' to provide benefits to farmers. Research in pigeonpea should shift from trying to identify an entirely resistant variety for the key pests without a clear understanding of the insect-plant interactions. Instead, an integrated approach using resistant/tolerant varieties, incorporating cultural and biological control may prove more appropriate.

3.5 | Biological Control

3.5.1 | Natural Enemies

Biological control presents a major tactic for managing insect pests of crops. For the suite of pigeonpea pests, a plethora of associated natural enemies (parasitoids, predators and pathogens) have been recorded. Lists have been published for natural enemies in pigeonpea crops in India (Romeis, Lawo, and Raybould 2009; Sharma et al. 2010), Africa (Minja, Shanower, Ong'aro, et al. 1999), and Australia (Lawrence, Tann, and Baker 2007). Similarly, lists of natural enemies have been published for key pigeonpea pests: including *H. armigera* (Riaz et al. 2021; Romeis and Shanower 1996; Berg, Waage, and Cock 1988; Zalucki et al. 1986), *M. vitrata* (Srinivasan, Tamò, and Malini 2021), *M. obtusa* (Shanower, Lal, and Bhagwat 1998), and pod-sucking bugs (Shanower, Romeis, and Minja 1999). Many of these natural enemies are parasitoids and pathogens, but a suite of generalist predators has also been recorded from pigeonpea crops (Romeis, Lawo, and Raybould 2009).

So far, there has been limited application of natural enemies in pigeonpea, due to a lack of understanding of tritrophic interactions. The most thorough understanding of tritrophic interactions in pigeonpea is the investigation of *Trichogramma* spp. parasitism of *H. armigera* eggs in Indian pigeonpea (Ballal and Singh 2003; Romeis, Shanower, and Zebitz 1998; Romeis, Shanower, and Zebitz 1999; Romeis, Shanower, and Zebitz 1997). Although species of *Trichogramma* have experienced significant success elsewhere (Romeis et al. 2005; Scholz 2000), their application in pigeonpea is limited. *Trichogramma chilonis* females are repelled by volatiles produced by reproductive pigeonpea (Romeis, Shanower, and Zebitz 1997) and their movement on plant surfaces is impacted by long trichomes and exudates, resulting in the low parasitism on reproductive structures compared to leaves (Ballal and Singh 2003; Romeis, Shanower, and Zebitz 1998; Romeis, Shanower, and Zebitz 1999).

Other parasitoid species may play an important role in biocontrol of key pigeonpea pests. High levels of *H. armigera* pupal parasitism, mostly by Tachinid flies and *Heteropelma scaposum* Morley (Hymenoptera: Ichneumonidae), has been recorded from Australian unsprayed pigeonpea refuges (Baker and Tann 2014; Baker, Tann, and Fitt 2008; Grundy and Spargo 2023) and other crops (Lloyd, Murray, and Hopkinson 2008). The ability of parasitoids to regulate *M. vitrata* populations appears limited (Shanower, Romeis, and Minja 1999; Srinivasan, Tamò, and Malini 2021) but other parasitoids that may to contribute substantially to pest population suppression in pigeonpea include larval and pupal parasitoids of *M. obtusa* (Patange, Sharma, and Chiranjeevi 2017; Shanower, Lal, and Bhagwat 1998) and egg parasitoids of pod-sucking bugs (Asante, Jackai, and Tamò 2000; Shanower, Romeis, and Minja 1999). The population suppression ability of these parasitoid species all warrant proper experimental studies.

Although generalist predators are frequently recorded in pigeonpea crops, their utility is not understood. For example, the generalist predator *Orius tantillus* Motschulsky (Hemiptera: Anthocoridae) is a not particularly effective predator of *H. armigera* eggs or larvae in pigeonpea crops in comparison with sorghum (Sigsgaard and Esbjerg 1997). The authors suggested larger *O. tantillus* populations in sorghum may be due to more alternative food resources available in sorghum crops (e.g., pre-anthesis aphid infestations and sorghum pollen) in addition to the negative effects of trichomes on pigeonpea plant structures.

Most natural enemy research in pigeonpea has focused on documenting predator/parasitoid species rather than actually investigating the efficacy of these natural enemies on pest population suppression. Future research should experimentally determine the impact of natural enemies on key pests in pigeonpea crops, and variety of approaches exist to do this (Furlong 2015; Macfadyen, Davies, and Zalucki 2015). Upon reaching such an understanding, the next step is to identify techniques to increase and conserve natural enemy populations, as without this understanding expecting farmers to adopt biocontrol practices is futile (Zalucki et al. 2015).

3.5.2 | Biopesticides

In modern agriculture, biopesticides have experienced substantial research interest and some successful application, but they are yet to take a large share of the pesticide market compared to synthetic chemical products (Glare et al. 2012; Lacey et al. 2015). There is a suite of biopesticide pathogens (viruses, bacteria and fungi) available that may be useful for controlling pests of pigeonpea.

Controlling *H. armigera* with baculoviruses (HearNPV) has experienced substantial commercial success (Lacey et al. 2015). HearNPV is highly effective in certain crops when used appropriately, even removing the need to use synthetic insecticides (Franzmann et al. 2008). We were only able to find two studies that have properly demonstrated HearNPV efficacy on *H. armigera* feeding on pigeonpea, both using laboratory bioassays (Aminu, Stevenson, and Grzywacz 2023; Rabindra, Muthuswami, and Jayaraj 1994). HearNPV was also evaluated as a control method for *H. virescens* in pigeonpea in Puerto Rico but it failed to show control in the field (Viteri et al. 2019).

For *M. vitrata* management, a virulent NPV strain (MaviMNPV) was discovered in Taiwan (Lee et al. 2007). MaviMNPV was then imported into Africa and field efficacy has now been demonstrated in several legume crops (Srinivasan et al. 2009; Tamò et al. 2012), but there are no published evaluations in pigeonpea.

Bacterial and fungal biopesticides have also been evaluated for pigeonpea pests. *Bt* formulations have demonstrated field-scale efficacy against both *H. armigera* (Vinayaka and Murali 2014) and *M. vitrata* (Sreekanth and Seshamahalakshmi 2018; Sreekanth and Seshamahalakshmi 2012). There is some evidence that pigeonpea pod surface chemistry may even improve the efficacy of *Bt* in controlling *H. armigera* (Paramasiva et al. 2016). *Metarhizium anisopliae* sprays have also demonstrated efficacy in the lab against *M. vitrata* on pigeonpea (Sunitha, Lakshmi, and Ranga Rao 2008) and *Beauvaria bassiana* may supress *M. vitrata* under field conditions (Sreekanth and Seshamahalakshmi 2012).

As is typically the case with biopesticides, experimental trials in pigeonpea have shown variable results. Future work should investigate efficacy and persistence of products more rigorously. A major complication for biopesticide use in the field is the tendency of the major pigeonpea pests to be cryptic feeders as larvae. Many biopesticide products have limited persistence and require ingestion, or in the case of fungal entomopathogens contact with the insect cuticle. Therefore, insects must feed on the external surfaces of plant organs to ingest or encounter the agent. When evaluating the efficacy and persistence of the pathogens, it is important to record the timing of applications (i.e., crop stage), the age structure of the larval populations (because as larvae grow they typically become more tolerant of biopesticides), and any potential microclimate effects (which strongly influence pathogen efficacy (Lacey et al. 2015)). Given most pigeonpea farmers are smallholders, the mass production, formulation, and application of biopesticides may present large limitations. Projects at ICRISAT have trained farmers in the production and application of HearNPV (Ranga Rao and Gopalakrishnan 2009) and future work should continue to develop viable biopesticide production and distribution systems.

3.6 | Chemical Control

3.6.1 | Botanical Insecticides

Largely ignored by the West, botanical insecticides have been embraced by Indian agriculture (Isman 2006). The major use of botanicals in pigeonpea is the two derivations from the neem tree (*Azadirachta indica*)–neem oil and neem seed kernel extract. Although numerous plant extracts from different plant species have been examined (Ranga Rao and Gopalakrishnan 2009), neem products are the main botanical insecticides recommended to pigeonpea farmers (Bhede et al. 2015; Sharma et al. 2015; Sharma et al. 2010). Neem products have documented efficacy against several pigeonpea pests, including *H. armigera* (Dialoke, Emosairue, and Akparobi 2017; Sambathkumar et al. 2015; Sreekanth and Seshamahalakshmi 2018), *M. vitrata* (Sambathkumar et al. 2015; Sreekanth and Seshamahalakshmi 2018), *M. obtusa* (Sambathkumar et al. 2015; Sharma et al. 2011), and pod-sucking bugs (Mitchell et al. 2004).

3.6.2 | Synthetic Insecticides

Synthetic chemical insecticides currently represent a mainstay in modern pest management programs for pigeonpea and several compounds provide adequate control of the major pigeonpea pests in the field. However, in terms of the amount of insecticides used by farmers, very little data is available. Large surveys of more than 1000 farmers from across major pigeonpea production areas in India during the late 1970s showed that most (79%) pigeonpea crops were intercrops and that < 5% of fields were sprayed with insecticides (Reed, Lateef, and Sithanantham 1980). Typically, substantial damage from pod-borers was recorded (Reed, Lateef, and Sithanantham 1980) resulting in yield losses of over 50% (Lateef and Reed 1983).

Shanower, Romeis, and Minja (1999) indicated an increase in insecticide use by Indian farmers, and suggested a similar trend was beginning with African pigeonpea farmers who were mostly not using insecticides at the time (Minja et al. 1996). Survey data from 2010 to 2011 from the Gulbarga district in India indicated 'non-IPM' farmers used approximately 6 sprays per pigeonpea crop, including organophosphates, carbamates, and organochlorines (Sharma et al. 2012). It is worth pointing out, that despite this widespread adoption of insecticides since the 1970s, pigeonpea yields have not increased (Figure 1)!

Given the toxicity and broad-spectrum nature of insecticides used by pigeonpea farmers, it is an imperative to obtain data on insecticide use patterns in pigeonpea from its global production areas. Clearly the easiest way to obtain such data is farmer surveys. Once current insecticide use patterns are determined, researchers may examine what broad-spectrum products (e.g., organophosphates, carbamates and synthetic pyrethroids) may be replaced with more modern, selective insecticides.

A plethora of recent studies has evaluated numerous insecticides and demonstrated field efficacy against the key pests of pigeonpea. A range of newer insecticides, including indoxacarb, spinosad, spinetoram, emamectin, chlorfenapyr, chlorantraniliprole, flubendiamide, and novaluron are effective against *H. armigera* (Dadas, Gosalwad, and Patil 2019; Karabhantanal and Dharavath 2022; Khinchi and Kumawat 2021; Mandal, Prasad, and Kumar 2023; Pal et al. 2022; Taggar et al. 2021), but some older products like synthetic pyrethroids, organophosphates and carbamates still demonstrate some field efficacy against *H. armigera* (Dadas, Gosalwad, and Patil 2019; Karabhantanal and Dharavath 2022; Khinchi and Kumawat 2021; Mandal, Prasad, and Kumar 2023; Pal et al. 2022). As for other key pests, *M. vitrata* (Nebapure and Sagar 2019; Nithish and Rana 2019b; Pal et al. 2022; Randhawa and Saini 2015; Taggar et al. 2021), *M. obtusa* (Dadas, Gosalwad, and Patil 2019; Khinchi and Kumawat 2021; Nithish and Rana 2019a; Pal et al. 2022; Wayal, Gaikwad, and Warad 2021), and pod-sucking bugs (Chethan et al. 2018; Lal and Jat 2015; Taggar et al. 2022; Thilagam, Gopikrishnan, and Dinakaran 2020) are all controlled by a suite of insecticides.

The challenge for entomologists lies not in demonstrating field-level efficacy of insecticides, but rather in identifying how to incorporate insecticides into sustainable pest management strategies. That is, practices that limit the evolution of insecticide resistance and enable conservation biological control by being 'soft' on natural enemies. Insecticide efficacy studies in pigeonpea rarely evaluate the toxicity of tested insecticides on natural enemy populations. Perhaps researchers could simultaneously evaluate the impact of key insecticides on natural enemies while examining the contribution of those natural enemies to pest suppression, as has cleverly been done in other crops (Knight et al. 2007; Vandervoet et al. 2018).

Undoubtedly, responsible use of 'newer' insecticides would make substantial progress in temporarily increasing pigeonpea yields. For instance, two sprays of indoxacarb or chlorantraniliprole increases pigeonpea yields by 79% and 67%, respectively, compared to unsprayed controls (Sambathkumar et al. 2015). However, if key chemical groups are overused, as is often the case, major pests will evolve resistance to insecticides in response to the unsustainable use patterns and such yield benefits will disappear.

Insecticide resistance is a key issue in pigeonpea pest management. The main pest *H. armigera*, has evolved resistance to numerous insecticide groups, but particularly the older products—synthetic pyrethroids, carbamates and organophosphates (Ahmad 2007; Riaz et al. 2021). Despite this, there appears to be no resistance management strategies or official guidelines for insecticide use in major pigeonpea production areas. Although *M. vitrata* has reported resistance to synthetic pyrethroids and organophosphates in the laboratory, there have been no field reports of control failures (Sreelakshmi et al. 2015). We were unable to find records of resistance for other key pigeonpea pests. We suggest that future pest management research and guidelines in pigeonpea should include the associated risk of these key pests evolving resistance to insecticides.

4 | Conclusion

Over the last several decades, slow progress has been made in managing the major pests of pigeonpea. Several studies report that IPM practices, referred to as 'IPM module', decrease pest populations and increases crop yields (Bhede et al. 2015; Maurya et al. 2017; Sharma et al. 2015). However, in these studies only the 'IPM' farmers are provided access to modern insecticides (e.g., indoxacarb, emamectin, and chlorantraniliprole) and we suspect IPM treatment effects are largely a reflection of the efficacy of newer insecticides.

Although IPM strategies available to pigeonpea farmers are still rudimentary, adoption of these tactics (including 'new' insecticides) has been shown to decrease pest pressure, reduce insecticide sprays, and increase yields (Sharma et al. 2015). Adopting such tactics in pigeonpea increases net returns, results in lower insecticide use, and has health benefits for farmers (by fewer pesticide poisoning events) (Rao et al. 2011).

Given the substantial yield cost insect pests impose on pigeonpea production, future research must catch up to developing pest management strategies that are farmer friendly. Modern pigeonpea research has shifted to short-duration varieties, which may be more susceptible to *H. armigera* and *M. vitrata*, potentially exacerbating pest problems. The traditional farming practices of pigeonpea should be properly investigated as they may provide ample opportunities to decrease crop susceptibility, meanwhile incorporating cultural and biological control methods. The key pests of pigeonpea are nearly identical across the global production areas, therefore an opportunity exists for a collaborative global research approach.

For the future of pest management in pigeonpea, some basic research is required to develop an understanding of how pigeonpea plants respond to pest damage (underlying economic threshold development), investigate which natural enemies are most important to provide biological control of key pests, examine the opportunities for cultural control, develop resistant and/or tolerant cultivars by conventional or gene-editing approaches, properly evaluate biopesticides, obtain data on insecticide use patterns and develop insecticide resistance management strategies. Outreach, education and collaboration with farmers will be integral to the adoption of these pest management strategies (Orr 2003). The current reality is that IPM has underdelivered over the last 50 years and pesticide usage has increased (Bakker et al. 2020; Deguine et al. 2021; Hokkanen 2015; Zalucki, Adamson, and Furlong 2009). For pigeonpea, there is the potential to enable farmers to step off the pesticide treadmill, if researchers can develop sustainable pest management approaches. But it is only through clearly defined research that such strategies can be developed.

Author Contributions

Trevor M. Volp: conceptualization, funding acquisition, writing – original draft, writing – review and editing, visualization. **Babu L. Jat:** conceptualization, writing – original draft, writing – review and editing. **Jagdish Jaba:** writing – review and editing. **Myron P. Zalucki:** writing – review and editing. **Michael J. Furlong:** writing – review and editing.

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Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

The authors have nothing to report.

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