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Farmers' Perception of Viral Diseases and Their Management in Pepper (*Capsicum* spp.) Production in Benin

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Abstract. **Pepper (*Capsicum* spp.) is an important solanaceous cash crop in Benin; however, productivity is limited due to several key constraints, especially diseases caused by viruses. We sought to understand farmers' perceptions of viral diseases, management strategies deployed, and to identify the virus population affecting pepper production in Benin. To assess farmers' perceptions and management of viral diseases, a survey was carried out in four agroecological zones of Benin. A total of 144 pepper farmers were interviewed using the snowball method. A total of 52 pepper leaf samples with virus-like symptoms were collected and diagnosed by reverse-transcriptase polymerase chain reaction (RT-PCR) or PCR. Pepper production systems varied across agroecological zones ($P \leq 0.001$) with a predominance of farms practicing monoculture (82%). The majority of farmers (89%) indicated that pests and diseases were the main constraints to increased production. *Cucumber mosaic virus* (92% of the total samples), *Pepper vein yellow virus* (52%), and *Pepper veinal mottle virus* (50%) were the major viruses detected in pepper fields in Benin. There were both single (29%) and mixed (71%) infections of the viruses, suggesting that mixed infections are common for pepper in Benin, confounding efforts to reduce virus infections. Nearly 100% of the farmers surveyed were not aware of these viral diseases. They also could not directly relate symptoms of virus infection to the presence of aphids, whiteflies, or thrips. Farmers relied primarily on synthetic insecticides (93%) to control virus vectors. Interestingly, some farmers applied commercial (12%) and homemade (17%) biopesticides, with neem-based preparations being the most widely used. A total of 15% of farmers used companion cropping with maize, mint or basil and 43% of farmers used crop rotation as a cultural management practice to control viral disease and vector pressure in pepper fields. The implications of this work include the importance of training farmers and extension agents on diagnosis of viruses and their vectors causing viral diseases. This study provides baseline information for the development of host-resistant cultivars and deployment of integrated pest management strategies for pepper in Benin to reduce farmer losses.**

In Benin, pepper (*Capsicum* sp.) is one of the most important cultivated and consumed vegetable crops, generating substantial income for smallholder farmers (Orobiyi et al. 2017). The cultivated varieties of pepper in Benin belong to the species *C. annuum* (L.), *C. chinense* (Jacq.), and *C. frutescens* (L.) (Akoègninou et al. 2006). Orobiyi et al. (2013) found that farmers and consumers divide hot pepper into three colloquial classes: long chili called *takingaga* in the language Fon, round pepper (habanero) called *gbatakin* (in Fon), and the very hot small chili known as *danhomètakin* (Fon), which correspond to the three species, *C. annuum*, *C. chinense*, and *C. frutescens*, respectively. Over the past decade, pepper production in Benin has nearly tripled, increasing from 83,075 tons in 2010 to

274,094 tons in 2021 (FAOSTAT 2022). However, production is lower than nearby countries, such as Nigeria (821,884 tons), which has a far greater productivity and production area (FAOSTAT 2022). Pepper production in Benin faces numerous constraints, among which, the unavailability of improved varieties, losses to undiagnosed pests, diseases, and abiotic stresses are the most important (Orobiyi et al. 2013, 2017). Among biotic stresses, viruses are the predominant source of losses for pepper farmers in Benin (Afouda et al. 2017).

To control pests and diseases, farmers across Africa often indiscriminately apply a variety of pesticides, sourced from unlicensed dealers, without the technical know-how to use these pesticides safely and effectively (Jepson et al. 2014). The overuse and misuse of pesticides by vegetable farmers have long been reported in Africa (De Bon et al. 2014; Doumbia and Kwadjo 2009; Halilou et al. 2022; Kanda et al. 2013; Mushagalusa et al. 2019). Pesticides misuse can have negative effects on the environment and the health of farmers and consumers, while also limiting export potential and associated increased revenue opportunities. The negative impact of viruses on pepper production can be mitigated through the development of effective and long-term management strategies, including appropriate production practices, insecticide use, the use host resistant varieties, farmer's education, and ecological range. The strategies employed and recommended for virus control are essentially based on the management of the vector. Good cultural practices include the appropriate selection of production site (far from potential sources of the virus); production of pepper in association with crops such as plantain (*Musa ×paradisiaca* L.), cassava (*Manihot esculenta* Crantz), sorghum [*Sorghum bicolor* (L.) Moench], or maize (*Zea mays* L.) to control vectors such as aphids (Fajinmi and Odebode 2010; Waweru et al. 2021); and to apply adequate organic matter (Fajinmi and Odebode 2007). Biao et al. (2018) found that aqueous extracts of garlic (*Allium sativum* L.), hyptis (*Hyptis* sp. Jacq.) leaves, and neem (*Azadirachta indica* A. Juss.) seed could be an alternative to synthetic pesticides for integrated pest management (IPM) of pepper viral diseases and their vectors. Some research, especially in Europe and Asia, has been conducted to identify resistance genes associated with pepper viruses, and molecular markers have been developed to facilitate their use in breeding. In addition, pepper cultivars and breeding lines have been evaluated for resistance to viral diseases in Benin and across the region, some of which are moderately to highly resistant (Alegbejo 2002; Gniffke et al. 2013; Zohoungbogbo et al. 2022).

To date, studies on understanding how farmers manage pests and diseases of pepper in Benin are limited (Biao and Afouda 2019). As observed in other settings, it is important to understand farmer's knowledge and perception regarding pests and diseases, and current management practices, to develop appropriate management interventions and strategies (Abtew et al. 2016; Echodu et al. 2019; Schreinemachers et al. 2015; Uwamahoro et al. 2018). In this study we 1) surveyed farmers to assess their knowledge and perceptions of pepper viruses, vectors, and current management practices in the different agroecological zones (AEZ) and 2) diagnosed the virus diversity in the different agroecological zones in Benin.

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Data are available in a publicly accessible repository. All data collected during this experiment were deposited in the World Vegetable Center repository, HARVEST (https://worldveg.org/harvest) and are available to the public.
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Materials and Methods

The study was carried out in nine high-pepper-production municipalities across four agroecological zones in southern and central Benin. Following the description of agroecological zones by Aholoukpe et al. (2020), the four AEZs in our study were Zone V (Dassa and Glazoué), Zone VI (Abomey-Calavi), Zone VII (Adja-Ouèrè), and Zone VIII (Dangbo, Sèmè-Kpodji, Adjohoun, Grand Popo, and Ouidah) (Fig. 1).

In each municipality, pepper farmers were identified and interviewed using the chain-referral sampling technique (Parker et al. 2019). Also known as snowball sampling, the use of the chain-referral sampling method involved starting the survey with a small number of initial pepper farmers, who were then invited to recommend other farmers who might also be willing participants, who in turn recommended other potential participants, and so on. The data were collected in nine municipalities (42 villages/districts) and a total of 144 pepper farmers were interviewed individually (Table 1). A semistructured questionnaire was used to cover all the specific themes in conversational style (Raworth et al. 2012). Interviews were carried out using a smartphone equipped with KoBoCollect software (Nampa et al. 2020) in which the questionnaire was integrated. Farmers were asked both closed-ended (mainly yes or no questions) and open-ended questions (to obtain full answers). The response levels obtained are therefore directly derived from the conversation. All interviews were conducted in the local languages of the villages with the help of interpreters or in French if farmers were able to speak French. For more precision, the target respondent on a farm was either the head of the household or the farm manager or a family member of the farm responsible for making agricultural decisions.

The information collected included 1) basic information about the respondent, such as gender identity, age, level of education, and years of experience in pepper cultivation (but not identifiable personal information) (Table 2); 2) pepper production practices: areas under pepper production, mode of access to land, pepper varieties used, and seed origin; 3) farmers' knowledge of and management practices deployed regarding vectors and viral diseases; and 4) primary constraints in pepper production faced by the farmer.

What farmers knew about viral diseases associated with pepper production was referred to as their "knowledge"; however, we only assessed their knowledge on this specific point and no other topics. To assess what farmers understand by the term "pepper disease," we asked each farmer to select all pepper diseases they have observed in their fields, through the observed symptoms or if possible, the names of the diseases. Respondents were shown an A4 photograph of some pepper with typical symptoms of viral diseases common in Benin (vein yellowing, vein banding, leaf curling) and asked if they knew what type of problem it was. To facilitate discussion, and therefore access their understanding, other disease symptoms easily recognizable by farmers (wilting and rotting of fruits) were also added. Without correcting them, if respondents were unable to recognize and distinguish viral diseases, they were led to give the causes of the symptoms in relation to the viral diseases observed on the photograph and to describe the management methods used to control the disease. Respondents were also asked if they had ever heard of plant viruses. To get more information from the respondents who stated that they knew the viruses in pepper, we asked if they could give examples of virus names, specific symptoms, specific vectors, and the management methods used to control the diseases.

To assess farmers' knowledge of vectors of viral diseases, we also showed farmers a photograph of the vectors of the viral disease of pepper (e.g., aphids, whiteflies, and thrips). To facilitate the vector discussion, a photograph of *Helicoverpa armigera*, Hübner (Lepidoptera: Noctuidae) caterpillar on a bell pepper fruit was displayed to the surveyed farmers. We asked the farmers if they recognized the insects on the sheet, and if so, they were then asked to indicate the period of occurrence and the damage caused by each recognized insect vector. Farmers' understanding was scored (Table 3) following the methodology described by Abtew et al. (2016).

A total of 52 leaf samples (14 in AEZ V, 18 in AEZ VI, 4 in AEZ VII, and 16 in AEZ VIII) with virus-like symptoms were collected in all AEZs on 32 pepper production sites and stored in plastic sampling bags, which were labeled with an identifying tag number indicating the name of the place of collection and

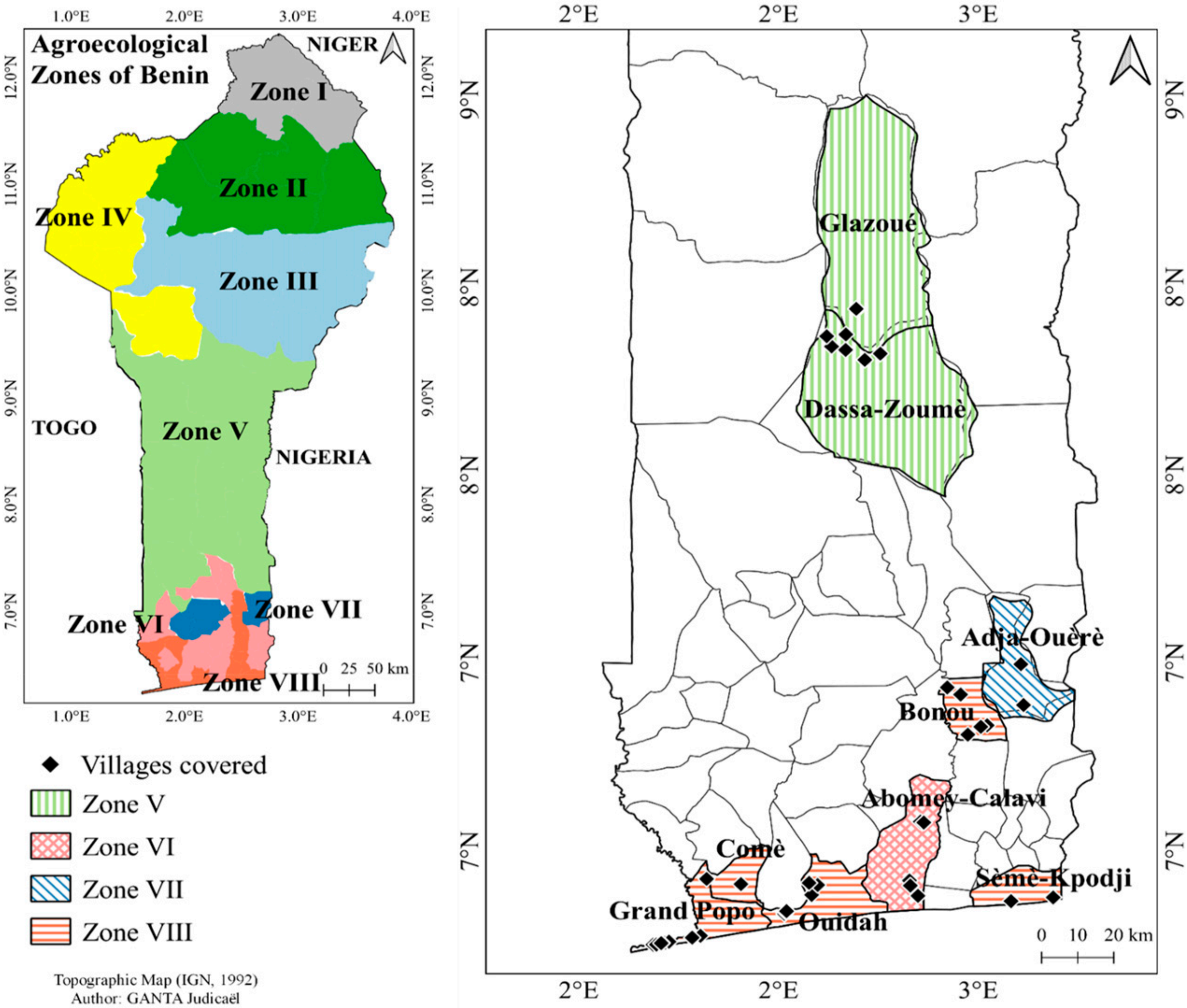

Fig. 1. Map illustrating the municipalities and the villages surveyed in the agroecological zones V, VI, VII, and VIII of Benin.

Table 1. Number of farmers and villages/districts per municipalities and agroecological zones.

Agroecological zone	Municipalities	No. of farmers	No. of villages/districts
V	Dassa	21	7
	Glazoue	12	1
VI	Abomey-Calavi	5	3
VII	Adja-Ouere	7	3
VIII	Bonou	11	5
	Comè	9	2
	Cotonou	2	1
	Gand Popo	26	11
	Ouidah	42	7
	Seme-Kpodji	9	2

GPS coordinates, cultivar name, and collection date. After collection, samples were dried using silica gel for about 72 h and sent to World Vegetable Center, Taiwan, following the phytosanitary requirements for sample import of the Bureau of Animal and Plant Health Inspection and Quarantine of Taiwan for diagnosis. Samples were tested for pepper viruses associated with whiteflies (*Begomovirus* and *Crinivirus*), aphids (*Potyvirus*, *Cucumovirus*, and *Polerovirus*), thrips (*Tospovirus*), and mechanically transmitted viruses (*Tobamovirus*). To determine the presence of *Begomovirus*, DNA was extracted from each collected sample and separately subjected to polymerase chain reaction (PCR) amplification using universal *Begomovirus*-specific primers (Table 4). For the detection of *Cucumber mosaic virus* (CMV), and members of *Polerovirus*, *Potyvirus*, *Tospovirus*, *Tobamovirus*, and *Crinivirus*, RNA was extracted from the samples and subjected to reverse transcriptase (RT)-PCR using primers specific for CMV or universal primers for the other genera (Table 4).

Data from the questionnaire were exported into Microsoft Excel spreadsheets and harmonized before analysis. Survey data were summarized, and frequencies, percentages, means, and standard deviation were calculated and used to evaluate or assess farmer characteristics and pepper production systems, constraints experienced by farmers, and farmers' perceptions of pepper viral diseases.

Fisher's exact test was used to determine differences between farmers of different agroecological zones for cropping systems, recognition, and level of knowledge of vectors. *P* values were used to evaluate the level of difference among the AEZs. All analyses were performed using R software (R Core Team 2021).

Results

The cultivated area of pepper by the surveyed farmers ranged from 0.002 ha (AEZ VIII) to 3.1 ha (AEZ V), with and an average of less than 0.5 ha. The mode of access to cultivated areas was through inheritance for more than half of respondents; however, land lease was dominant in AEZ VIII (Table 5). Monocropping was by far the predominant production system used by respondents at ~82% across AEZs (Table 5). The majority of farmers (85%) produced pepper once a year, with a period deployed by farmers ranging from 1 to 6 years with an average of with an average of less than 1.5 years between pepper crops (Table 5). The types of peppers

Table 2. Characteristics of pepper farmers surveyed in the agroecological zones (AEZs) V, VI, VII, and VIII of Benin.

	AEZ				
Variables	V (n = 33)	VI (n = 5)	VII (n = 7)	VIII (n = 99)	Overall mean
Gender identity					
Male	48.5	100.0	100.0	89.9	81.3
Female	51.5	0.0	0.0	10.1	18.7
Education level					
None	36.3	0.0	0.0	22.2	23.6
Primary school	33.3	20.0	14.2	28.2	28.5
Secondary school	27.3	20.0	71.4	34.4	34.1
University	3.1	60.0	14.2	15.2	13.8
Age					
≤30	18.2	40.0	42.9	28.3	27.1
31–40	36.3	40.0	42.9	34.3	35.4
41–50	21.2	20.0	0.0	25.2	22.9
≥51	24.3	0.0	14.2	12.2	14.6
No. years experience in agriculture					
1–10	33.3	80.0	57.2	55.5	51.4
11–20	45.4	20.0	42.8	29.3	33.3
≥21	21.3	0.0	0.0	15.2	15.3
No. years experience in pepper production					
1–5	15.2	20.0	14.2	39.4	31.9
6–10	18.2	60.0	57.2	33.3	31.9
≥11	66.6	20.0	28.6	27.3	36.2

Table 3. Criteria used for scoring farmers' understanding of viral diseases vectors affecting pepper production.

Scores	Knowledge level	Criteria
0	None	Farmer could not recognize any pepper viral disease vector
1	Low	Farmer recognize one insect vector, give its period of occurrence and one type of damage caused by the vector
2	Medium	Farmer recognize two insect vectors and give at least one feature (period of occurrence) and one type of damage caused by each vector
3	High	Farmer recognize three insect vectors and give at least one feature (period of occurrence) and one type of damage caused by each vector

Source: Adapted from Abtew et al. (2016).

Table 4. Molecular markers used for diagnosis of viral diseases in collected samples in the agroecological zones V, VI, VII, and VIII of Benin.

Viruses	Molecular markers	References
CMV	RW8/RV11	Golnaz et al. (2009)
Tobamovirus	Tobamo-s1/Tobamo-as1	Menzel et al. (2019)
Tospovirus	gl 2740/gl 3920c	Chen et al. (2012)
Potyvirus	CIFor/CIRev	Ha et al. (2008)
Crinivirus	crini-hspF1/crini-hspR2	Chan et al. (2022)
Polerovirus	Pol-G-F/Pol-G-R	Knierim et al. (2010)
Begomovirus	1978B/715H	Tsai et al. (2011)
CVMV	CPVMV up/CPVMV dw	Cheng et al. (2009)
PVMV	CPVMV up/CPVMV dw	Cheng et al. (2009)

CMV = *Cucumber mosaic virus*; CVMV = *Chili veinal mottle virus*; PVMV = *Pepper veinal mottle virus*.

produced were chili pepper (*C. annuum* and *C. frutescens)* (87%), habanero pepper (49%) (*C. chinense*), and bell pepper (11%) (*C. annuum)*. For habanero pepper, 100% of farmers produced local open-pollinated varieties (commonly called *Gbatakin* in Fon, one of the local languages in southern Benin), whereas 6% also grew improved varieties in addition to local varieties. For chili pepper, 67% of respondents produced local varieties (*Afoundja*, *Danhomètakin*, or *Takingaga*), and 58% of farmers grew improved varieties. All the bell pepper farmers used hybrid seeds from private seed companies because of the unavailability of local varieties. For pepper production, more than 60% of farmers purchased seeds, the majority of which were purchased from seed companies or suppliers.

Among those who practiced companion cropping across all AEZs, the majority (87%) did so to optimize production area, whereas 15% did so to reduce pest pressure. The companion crops included more than 10 species, with maize and okra (*Abelmoschus esculentus* L.) being the most frequent crops associated with pepper (Fig. 2). Among those who used maize in a companion cropping system with pepper, 12% did so to reduce pest pressure, and 2% of farmers combined mint (*Mentha* sp. L.), basil (*Ocimum basilicum* L.), and artemisia (*Artemisia vulgaris* L.) for pest management.

Among the surveyed farmers across the AEZs surveyed, 99% faced multiple and different constraints. The majority (89%) of the farmers across AEZs ranked diseases and insect pests as their most important problem in pepper production, followed by flower abortion (29%), difficulty of harvesting pepper fruits (18%), difficulty to access water (16%), lack of governmental support (13%), and difficulty accessing inputs (13%), among others. However, the importance of these constraints varied among AEZs (Table 6). Pest and diseases were cited as major constraint in all AEZs, followed by difficulty accessing inputs in AEZ V and VI, whereas the second most cited constraint was lack of quality seed in AEZ VII and vegetative organ drop in AEZ VIII (Table 6).

Across AEZs, 94% of the farmers surveyed faced disease problems in their pepper fields. The main symptoms cited by the farmers were yellowing leaves (43%), plant wilting (39%), leaf curling (29%), leaf spots (22%), and plant stunting (15%) (Table 7). Interestingly, we found that the respondents reported different symptoms among the different AEZs (Table 7). Plant wilt was overwhelmingly cited as major disease in AEZ V and VI followed by leaf curling, while in AEZ VII both diseases were equally important, followed by fruit drop. Contrastingly in AEZ VIII, leaf yellowing was the most important cited disease followed by leaf spot (Table 7). Approximately 2% of the pepper farmers surveyed had never heard of plant viruses, and 42% of respondents did not know the cause(s) of the symptoms of the viral diseases observed. Possible causes of viral diseases reported by farmers included mainly insects in general (35%), mites (8%), and rainfall (4%).

All farmers in the AEZs confirmed the presence of arthropod pests in their pepper fields. In total, 99% of respondents recognized at least one of the arthropod vectors presented to them. Vector recognition varied significantly across agroecological zones ($P = 0.011$). All respondents were able to recognize aphids in AEZ V, VI, and VII, whereas none of interviewees were able to recognize thrips in AEZ VIII (Fig. 3). Across all AEZ, ~90%, 70%, and 40% of farmers recognized aphids, whiteflies, and thrips, respectively. The level of vector knowledge significantly varied between AEZs ($P \leq 0.001$). In AEZ V, more than 60% of farmers had a low level of knowledge of vectors, whereas in AEZs VI, VII, and VIII, farmers mostly had a moderate level of knowledge (Table 8). A moderate level of knowledge regarding vectors was most common among respondents at 42%, followed by a low level at 31%. Approximately 26% of farmers were able to identify three vectors by name and give at least one feature (period of occurrence) and one type of damage caused by each vector, indicating a high level of knowledge. According to respondents, aphids occurred equally at nursery, vegetative, and pepper flowering stages whereas thrips were mainly present during pepper flowering stage (Fig. 4). However, whiteflies were reported to occur more during flowering stage, followed by vegetative and nursery stages (Fig. 4). According to interviewed farmers, aphids mainly

Table 5. Pepper farm characteristics and cropping practices in different in the agroecological zones V, VI, VII, and VIII of Benin.

Variables	Respondent per agroecological zone (%)				
	V (n = 33)	VI (n = 5)	VII (n = 7)	VIII (n = 99)	Overall mean
Land access[i]					
Gift	0.0	20.0	0.0	1.0	1.3
Lease	15.1	80.0	28.5	37.3	33.3
Inheritance	93.9	0.0	85.7	37.3	51.3
Loan	0.0	0.0	0.0	13.1	9.0
Purchase	6.0	0.0	14.2	15.1	12.5
Area under pepper production (ha), M ± SD	0.4 ± 0.5	0.4 ± 0.0	0.22 ± 0.17	0.4 ± 0.5	0.4 ± 0.5
Cropping systems[i]					
Mono-cropping	45.4	60.0	100.0	93.9	81.9
Companion cropping	87.8	40.0	28.5	14.1	32.6
Crop rotation					
No. pepper production seasons per year					
1	12.1	40.0	42.8	53.5	43.0
2	91.0	60.0	50.0	87.0	85.5
≥3	6.0	0.0	0.0	7.0	6.2
Type of pepper produced[i]					
Habanero pepper	81.8	100.0	100.0	32.3	49.3
Chili pepper	93.9	100.0	100.0	82.8	86.8
Bell pepper	0.00	20.0	0.0	15.1	11.1
Bird' eye pepper	6.0	0.0	0.0	2.0	2.7
Seed origin[i]					
Gift	18.1	20.0	0.0	2.02	6.2
Purchased	6.0	80.0	14.2	93.9	69.4
Self-production	100.0	60.0	100.0	9.09	36.1

[i] Multiple responses.

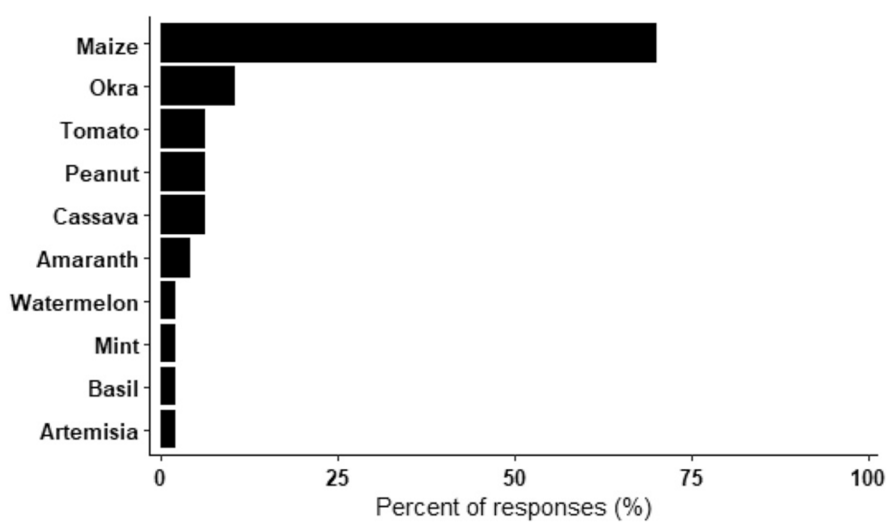

Fig. 2. Percentage of different crops used by farmers in companion cropping systems for pepper production in the agroecological zones V, VI, VII, and VIII of Benin.

induced leaf deformation, flower abortion, and defoliation, whereas thrips caused flower abortion. Whiteflies, on the other hand, caused flower abortion leaf deformation and defoliation, according to surveyed farmers (Fig. 5). When questioned about severity of damage, the majority of farmers reported very severe damage due to aphids. In contrast, farmers attributed minor damage due to thrips and minor to moderate damage associated with whiteflies (Fig. 5).

Samples were tested for viruses associated with aphids, thrips, whitefly vectors, and viruses not transmitted by invertebrate vectors. None of the leaf samples were positive for *Begomovirus*, *Crinivirus*, *Tobamovirus*, or *Tospovirus*. However, aphid-transmitted viruses (*Potyvirus*, *Cucumovirus*, and *Polerovirus*) were detected in all AEZs. The primary viruses detected in pepper fields across the AEZs were CMV (92%), PeVYV (52%), and PVMV (50%) (Fig. 6). The occurrence of mixed infection was common in all the AEZs. Mixed infection of two viruses was identified in all AEZs except for AEZ VII. Mixed infection of CMV+PVMV was the most predominant in AEZ V, whereas CMV+PeVYV was the most predominant in AEZ VI and VIII. Mixed infection of three viruses occurred in all the AEZs, and was most predominant in AEZ VII (Fig. 7).

Farmers in all AEZs applied different control methods for managing viral diseases and vectors. Among these, synthetic pesticide spray was the main control method reported by most farmers in all AEZs (Table 9). Interestingly 14% to 30% of farmers in AEZ V, VI, and VII applied commercial biopesticides sprays, whereas 60% to 86% farmers applied homemade biopesticides in AEZ VI and VII (Table 9). Approximately 20% of farmers in AEZ VI used crop association to control vectors (Table 9). Farmers in AEZ VII also cited destruction of infected plants as a control measure for vectors (Table 9). Regarding synthetic insecticide applications, farmers relied on a variety of insecticides, with Acarius 018 EC (Abamectin 18 g/L EC) being the most commonly used product (Table 10). The most common commercial biopesticides used, at 67% were Biomass (a.i. azadirachtine and allicin), followed by neem oil (20%) and 7% with Topbio (a.i. azadirachtin, nimbin, citronellal, citronellol, geraniol). Homemade pesticides are prepared with seven plants with neem leaves being the most frequent (Table 11). Supporting the use of farmer trainings as a tool to manage disease effectively, we found that 67% of farmers who used homemade pesticides learned to use these methods during training with agricultural extension workers, 48% acquired this knowledge from other farmers, and 11% through their professional experience. In addition, 54% of the respondents were aware of the ecological control methods but did not want to apply them for insect control in their pepper fields. The reasons given were the lack of concrete evidence of biopesticide efficacy (67%), financial inaccessibility of commercial biopesticides (32%), and the unavailability of raw material needed to make biopesticides (17%).

Discussion

We found that pepper farmers in Benin have limited knowledge of viral diseases. While more than 90% of farmers could recognize that they had observed a symptom of viral diseases in their field at least once, an extreme minority of pepper farmers surveyed had heard about viruses. This indicates an overall discrepancy among pepper farmers in Benin about viruses. Viral diseases are the primary constraint to pepper production in Benin, and almost all farmers recognized the symptoms of virus diseases; however, they were generally unable to credit the cause of the symptoms observe to viruses (Onditi et al. 2021). These findings aligned with the those of Schreinemachers et al. (2015) in tropical and subtropical Asia, where vegetable farmers could not identify viruses as the causal agent of specific disease symptoms. In this study, farmers listed many disease symptoms observed during pepper production, and leaf chlorosis was the most cited symptom by farmers. However, farmers usually associated the symptoms of viral diseases such as leaf curl or chlorosis with bad weather such as

Table 6. Different constraints to pepper production reported by farmers in the agroecological zones V, VI, VII, and VIII of Benin.

	Respondent per agroecological zone (%)				
Constraints[i]	V	VI	VII	VIII	Overall mean
Pest and diseases	72.7	75.0	100.0	94.9	89.4
Vegetative organ drop	0.0	0.0	42.8	38.7	28.8
Difficulty of harvest (high force required for fruit detachment)	6.0	0.0	0.0	24.4	18.3
Difficulty to access water	45.4	0.0	14.2	6.1	15.4
Lack of support from government of other institutions	33.3	0.0	0.0	8.1	13.3
Difficulty to access inputs	48.4	25.0	0.0	2.0	13.3
Low productivity	9.0	25.0	42.8	3.0	7.0
Difficult tillage	6.0	0.0	0.0	6.1	5.6
Lack of market access	0.0	0.0	0.0	3.0	4.9
Drought	3.03	0.0	0.0	6.1	4.9
Lack of labor	0.0	0.0	0.0	4.0	2.8
Low soil quality	0.0	0.0	14.2	2.0	2.1
Lack of quality seed	0.0	25.0	57.1	1.0	2.1
Transhumance herbivory	0.0	0.0	0.0	2.0	1.4
Low market value	0.0	0.0	0.0	1.0	0.7
Excessive rainfall	3.0	0.0	0.0	0.0	0.7

[i] Multiple responses.

Table 7. Diseases related symptoms observed by farmers during pepper production in the agroecological zones V, VI, VII, and VIII of Benin.

	Respondent per agroecological zone (%)				
Symptoms observed by farmers[i]	V	VI	VII	VIII	Overall mean
Defoliation	3.2	0.0	0.0	2.1	2.2
Flower drop	3.2	0.0	28.5	7.6	7.4
Fruit drop	0.0	0.0	42.8	15.2	12.5
Leaf curling	32.2	80.0	71.4	21.7	28.8
Leaf distortion	0.0	0.0	14.2	1.09	1.5
Leaf yellowing	9.6	0.0	14.2	58.7	42.9
Plant death	0.0	0.0	14.2	1.1	1.5
Plant stunting	12.9	0.0	14.2	16.3	14.8
Rot	0.0	0.0	0.0	17.3	11.8
Leaf spot	0.0	0.0	0.0	32.6	22.2
Plant wilt	74.1	100.0	71.4	21.7	39.2
Leaf puckering	0.0	0.0	0.0	1.0	0.74

[i] Multiple responses.

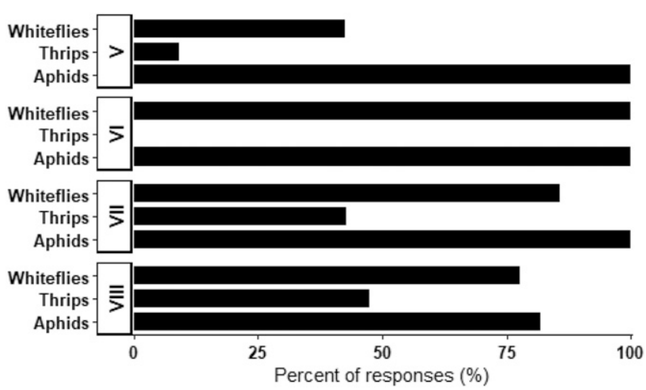

Fig. 3. Percentage of farmers who recognized the vectors of pepper viral diseases in the agroecological zones V, VI, VII, and VIII of Benin.

Table 8. Level of insect vector knowledge of pepper farmers in the agroecological zones V, VI, VII, and VIII of Benin.

	Respondent per agroecological zone (%)				
Vector understanding level	V	VI	VII	VIII	Overall mean
High	12.1	0	28.6	32.3	26.4
Low	60.6	0	0	25.3	31.3
Medium	27.3	80.0	71.4	42.4	41.7
None	0	20.0	0	0	0.7
P value		<0.001			

high temperatures or with arthropod pest damage (Nagaraju et al. 2002; Robinah et al. 2018; Waweru et al. 2020b). This lack of knowledge could be one of the reasons for the high virus prevalence reported in previous surveys in Benin (Biao and Afouda 2019). Farmers also observed symptoms of wilting, and some associated the wilt with the presence of root-knot nematodes, which may be the case (Carrillo-Fasio et al. 2021). However, wilting can also be caused by bacterial wilt (*Ralstonia solanacearum* species complex) (Mahbou Somo Toukam et al. 2009) or other soil-borne disease.

Farmers were able to classify diseases in general but were not able to distinguish between different types of diseases, which aligns with previous work in Tanzania (Adam et al. 2015). All surveyed farmers across the AEZs confirmed the presence of arthropod pests in their pepper fields and recognized at least one of the arthropod vectors presented to them. Farmers encountered whiteflies, thrips, and aphids in their fields, and the presence of these pests have been widely reported on pepper or other crops in Benin (Biao and Afouda 2019; Houngue et al. 2022; Sæthre et al. 2011; Tossounon and Onzo 2015). Among the arthropod vectors of pepper viruses, farmers across all AEZs recognized the presence of aphids in their fields more commonly. Whiteflies were ranked second in terms of frequency, and thrips were ranked third, which could be due to their very small size and that they often colonize the plant flowers. Aphids are normally more visible, especially as their colony gets larger. Also, aphids are generally among the most abundant insects in pepper fields in Benin (Tossounon and Onzo 2015). Unlike whiteflies and thrips, the majority of farmers reported very severe damage due to aphids during pepper production, characterized mainly by leaf deformation, as well as flower abortion, and defoliation. Recently, aphids were also considered as the most serious insect pest by hot pepper farmers in Rwanda (Waweru et al. 2020b). According to the surveyed farmers, aphids were noticeable beginning from the vegetative phase, which can occur if limited management measures are taken during the seedling stage. Thrips were most noticeable during the flowering period, according to the surveyed pepper farmers. For farmers, thrips and whiteflies caused less damage in their fields. The thrips species *Frankliniella schultzei*, which can colonize flowers (Kakkar et al. 2012), was previously identified by Tossounon and Onzo (2015) on pepper fields in Benin.

To confirm the presence of viral diseases in the surveyed AEZs, leaf samples were collected in farmers' fields and diagnosed for viruses, vectored by whiteflies, aphids, and thrips. We detected PVMV, CMV, and PeVYV in all the samples collected, whereas CMV was the most prevalent virus across AEZs. High coinfection of CMV with PVMV and PeVYV was also detected, which confirms our previous findings (Zohoungbogbo et al. 2022). Previously, *Polerovirus* (PeVYV) has been found in association with

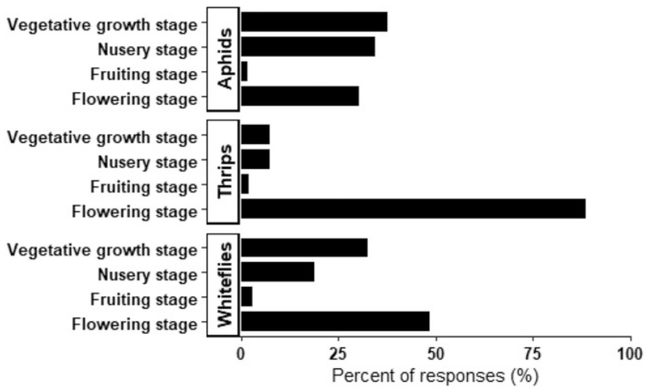

Fig. 4. Percentage of different pepper development stages at which farmers noticed the presence of viral disease vectors in the agroecological zones V, VI, VII, and VIII of Benin.

apparently less familiar with the concept of viruses that cause diseases in pepper. However, from a management perspective, the exact source, whether virus or vector, of the disease is likely less important, and the fact that farmers are already knowledgeable about the association of the presence of aphids and then the later appearance of a disease is a critical first step in developing sound management strategies. However, the first step in IPM is the use of host resistant varieties, and although host resistance to the major viral diseases detected in this study has been previously reported (Heo et al. 2021; Ruffel et al. 2005), resistance to arthropod pests, especially aphids, is rare (Frantz et al. 2004). The successful deployment of virus-resistant cultivars as a management strategy in Benin will require that farmers be better educated about viruses. Without additional virus education, there is a potential lack of trust from farmers if resistant cultivars were introduced and promoted as means to prevent disease and high aphid infestation was still observed, given that aphids are currently understood to be the causal agent of the diseases observed by farmers.

PVMV and CMV on pepper in Cote d'Ivoire (Bolou Bi et al. 2018). Similar levels of mixed infection with *Polerovirus* have been reported in other parts of Africa, including Rwanda and Tunisia (Buzkan et al. 2013; Waweru et al. 2020a, 2021). Only aphid-trasmitted viruses were detected in our study and were prevalent across all the AEZs. The detection of only aphid-vectored viruses strongly supports the finding that farmers mostly associated severe damage in the fields with aphids but not thrips or whiteflies. The identification of only aphid-transmitted viruses and the reports of farmers that aphids caused the most severe damage to their pepper crops indicates that the farmers are likely knowledgeable about the situation in their fields and are able to associate the presence of aphids with symptoms of disease that cause losses. Farmers in this study are

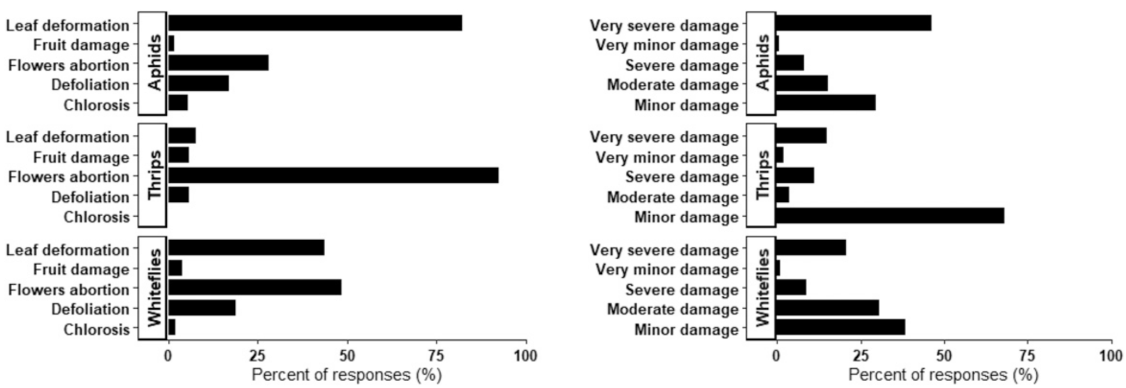

Fig. 5. Percentage of the type of damage caused by aphids, thrips, and whiteflies to pepper plants (**left**) and severity of damage (**right**) as perceived by farmers in the agroecological zones V, VI, VII, and VIII of Benin.

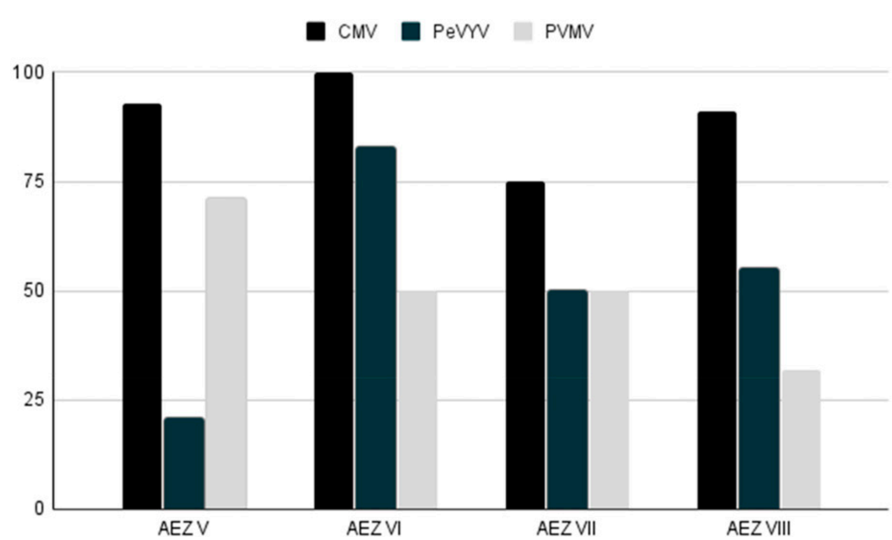

Fig. 6. Percentage of detected virus of CMV (*Cucumber mosaic virus; Cucumovirus*), PVMV (*Pepper veinal mottle virus; Potyvirus*) and PeVYV (*Pepper veins yellow virus; Polerovirus*) in the selected agroecological zones in the collected samples in Benin.

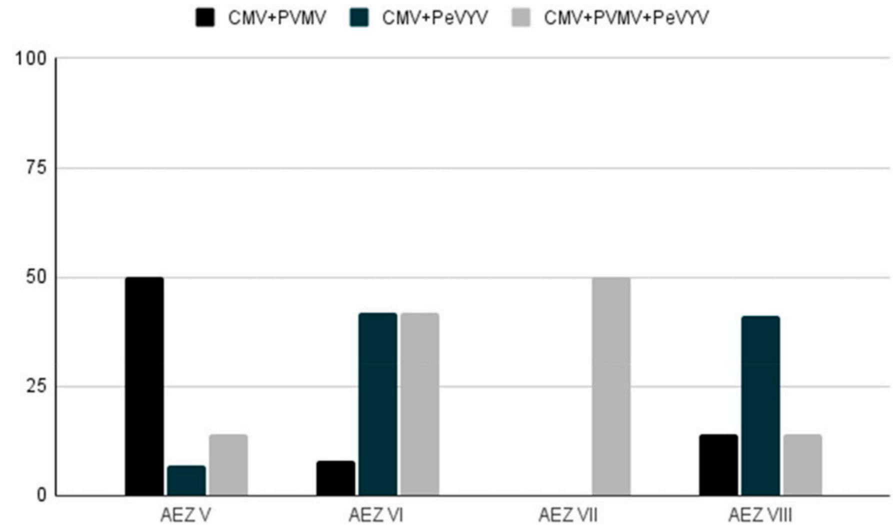

Fig. 7. Percentage of mixed infections of the virus of CMV (*Cucumber mosaic virus; Cucumovirus*), PVMV (*Pepper veinal mottle virus; Potyvirus*) and PeVYV (*Pepper veins yellow virus; Polerovirus*) in the collected samples from the selected agroecological zones in Benin.

Table 9. Method of vector control by pepper farmers in the agroecological zones V, VI, VII, and VIII of Benin.

	Respondent per agroecological zone (%)				
Management methods[i]	V	VI	VII	VIII	Overall mean
Crop association	3.0	20.0	0	0	1.4
Destruction of infected plants	0	0	14.3	1.0	1.4
Fertilization	6.1	0	0	0	1.4
Modification of the seeding date	0	0	0	5.1	3.5
Spraying chemical insecticides	87.9	80.0	100.0	95.9	93.8
Use commercial biopesticide	30.3	20.0	14.3	5.1	11.8
Use homemade biopesticide	9.1	60.0	85.7	13.1	17.4
P value			<0.001		

[i] Multiple responses.

Table 10. Pesticides used by pepper farmers in the agroecological zones V, VI, VII and VIII of Benin for the control of virus vectors.

Insecticides[i]	Active ingredient	Responses (%)
ABACE 50 EC	Abamectin 18 g/L +acetamipride 32 g/L	0.7
ACARIUS 018 EC	Abamectin 18 g/L EC	37.0
ALATAK 44 EC	Abamectin 20 g/L + emamectin benzoate 24 g/L	0.0
CONPYRIFOS 48% EC	Chlorpyrifos-ethyl 480 g/L	2.2
DURSBAN	Lambda-cyhalothrine 25 g/L	0.7
EMA Super 56 DC	Emamectin benzoate 54 g/L	0.7
EMACOT 019 EC	Acetamipride 24 g/L	8.8
K-OPTIMAL	Emamectin benzoate 19 g/L	10.3
LAMBDA SUPER 2.5EW	Lambda-cyhalothrin 15 g/L and acetamiprid 20 g/L	11.8
LaraForce	Lambda-cyhalothrin 25 g/L	0.7
ORIZON	Lambda-cyhalothrin 2.5 EC g/L	1.4
PACHA 25 EC	100 g/Lt acetamiprin +20 g/L abamectin	19.2
ROCKET 44 EC	Acetamiprid 10 g/L + lambda-cyhalothrin 15 g/L	1.4
SYCO-505	Chlorpyriphos 50% + cypermethrin 5% EC	0.7
Timan Super 25 EC	Imidacloprid 15 g/L + bifenthrin 10 g/L	2.9

[i] Multiple responses.
EC = emulsifiable concentrate.

To control arthropod pests (aphids, whiteflies, and thrips), the majority of pepper farmers used synthetic insecticides, which supports previous reports (Biao and Afouda 2019; Glodjinon et al. 2021; Waweru et al. 2020b). Without diagnosing the causes of the observed symptoms, farmers sometimes increase the frequency of application of the pesticides to reduce losses (Abtew et al. 2016). In Burkina-Faso, for example, Tarnagda et al. (2017) recently reported that pesticides used in some market gardening areas are intended for the treatment of cotton, and not for vegetable crops which can be dangerous for consumers. The use of cotton pesticides in market gardening has also been observed in Benin by Allogni et al. (2015). In addition, the use of chemical control alone does not guarantee effective control for all pests (Jensen 2000; Sonhafouo-Chiana et al. 2022). With growing concerns about the environmental and health impact of insecticides, it is important to promote more environmentally friendly approaches, and rely on chemical insecticides as the last step of an IPM program. The use of biological pesticides is one of these approaches. We found that a significant proportion of pepper farmers use biopesticides, mainly neem-based, to control vectors. Neem is effective against whiteflies and aphids (Biao and Afouda 2019; Nadeem et al. 2015). The insecticidal effect of papaya (*Carica papaya* L.) leaves extracts on aphids has also been demonstrated by some studies (Gupta et al. 2020; Ujjan et al. 2014). The efficacy of moringa (*Moringa oleifera* Lam.) extract for aphid control has also been demonstrated (Alghamdi 2018; Osman and Elsobki 2019; Shah et al. 2017; Taaban 2022). These findings support the use of various effective approaches by farmers in Benin.

Most of the farmers cultivated pepper in monoculture, which aligned with previous studies (Biao and Afouda 2019; Glodjinon et al. 2021). Some farmers also produced pepper in association (border or intercropping) with other crops, which was previously found (Food and Agriculture Organization of the United Nations; International Crops Research Institute for the Semi-Arid Tropics; International Center for Tropical Agriculture 2018). The crops that are mostly intercropped with pepper were maize and less commonly okra, cassava, peanut (*Arachis hypogaea* L.), tomato (*Solanum lycopersicum* L.), amaranth (*Amaranthus* sp. L.), artemisia, basil, mint, and watermelon [*Citrullus lanatus* (Thunb.) Matsum. & Nakai]. Cultural practices such as companion cropping can provide protection against several insect-vectors and associated diseases. The use of maize as a companion crop was employed by some farmers to help control vectors of pepper in Benin. Some farmers also highlighted the importance of companion cropping mint or basil with pepper for arthropod control. These two crops have been reported to act as repellent plants and can be used in intercropping for the control of insect vectors (Wang et al. 2022; Yarou et al. 2017). However, a limited number of farmers are aware of the use of companion cropping as part of pest and disease management. In contrast, companion cropping could have negative consequences for famers, as some of the crops used are also hosts for the arthropod vectors and contribute to the distribution and maintenance of viral diseases at pepper production sites (Ateka et al. 2017; Jacobson et al. 2018; Kenyon et al. 2014; Nadeem et al. 2015; Sæthre et al. 2011). It has been suggested to train farmers on the benefits of biopesticides and companion cropping to further promote their use (Nyangau et al. 2022; Waweru et al. 2021).

Conclusion

Viruses and their vectors are important constraints to pepper production in Benin. However, the farmers lack accurate information on the cause, sources, and management of the viral diseases. The surveyed farmers generally

Table 11. Homemade biopesticides used by farmers in the agroecological zones V, VI, VII, and VIII of Benin to control vectors.

Main components[i]	Responses (%)	Method of utilization
African basil leaves	14.8	The leaves are kneaded in water and then added to soap before applying.
African basil leaves + neem leaves	3.7	The leaves of both plants are kneaded in equal proportions in water and then soap is added before applying.
Gray cinchona leaves	18.5	The leaves are kneaded in water and then enclosed in a container for ∼3 days then added soap before applying.
Moringa leaves	3.7	The leaves are kneaded in water and then added soap before applying.
Neem leaves	40.7	The leaves are crushed and then soaked in water; soap is added before applying.
Neem leaves + papaya leaves	3.7	The leaves of both plants are kneaded in equal proportions in water, and then soap is added before applying.
Neem leaves + red pepper	3.7	Neem leaves are crushed and mixed with crushed red pepper plus water; soap is added before application.
Neem oil cake	7.4	Neem cake is soaked in water, and the mixture is left to rest for 2 days before application.
Papaya leaves	3.7	The leaves are crushed and then soaked in water; soap is added before application.
Wood ash	14.8	The ash is soaked. and the mixture is left to rest for ∼2 days before application.

[i] Multiple responses.

understood that the symptoms observed were associated with vectors but were unaware that the cause of the symptoms were actually viruses. Aphid-transmitted viruses were the most prevalent in the four AEZs in Benin. Farmers lack effective management strategy for the pests and diseases in all AEZs despite the wide use of different levels of management strategies, such as companion cropping and the use of biological and chemical pesticides by farmers. The best approach for farmers is IPM, which starts with deployment of host resistant cultivars. However, resistance to the viruses and not the vectors is likely to be promoted in the near future. Therefore, farmers should be trained to understand that viruses cause the diseases, not the vector. At the same time, because farmers already understand the presence of the vector is associated with diseases, farmers can also be better trained to control or manage the vectors, especially aphids, in combination with virus-resistant cultivars, to reduce losses. The development and promotion of resistant varieties against aphid-transmitted viruses combined with the good agronomic practices can greatly contribute to the management of the viral disease in Benin and reduced farmer losses. This study provides a basis for designing appropriate interventions for pepper production in Benin.

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