





# Updated assessment of potential biopesticide options for managing fall armyworm (*Spodoptera frugiperda*) in Africa

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## Abstract

The fall armyworm (FAW, *Spodoptera frugiperda*) has recently spread to many countries in Africa, the Near East, Asia and the Pacific. In sub-Saharan Africa (SSA), more than 300 million people depend on FAW's preferred host plant, maize, as a staple crop. Hence, the spread of FAW in SSA has the potential to negatively affect livelihoods and food security. Many farmers have responded to FAW by increasing their use of synthetic pesticides, but these are not always used safely or effectively. More information on sustainable alternatives to high-risk synthetic pesticides is needed to inform decisions by farmers and policy makers. In a previous paper, the authors responded to this information need by identifying fifty biopesticides which had been registered for FAW management in one or more of 30 countries in FAWs native region and Africa. For each biopesticide identified, detailed profiles with information on their efficacy against FAW; associated human health and environmental hazards; their agronomic sustainability; and whether or not they are practical for use by smallholder farmers were developed. Research for development (R4D) efforts is ongoing in Africa and Asia for development and use of biopesticides for FAW management. Hence, in this study the authors assessed the current state of knowledge and documented how information gaps have been filled (or not) since the previous paper was published. The authors found that for many biopesticides there is a growing body of information on their efficacy in the field in Africa and increased availability of commercialized products. They also note remaining information gaps, particularly the compatibility of the biopesticides with other recommended management practices, and cost-benefit analyses, important for developing and implementing sustainable IPM. An updated list of priority biopesticides for research, development and promotion is provided.

## KEYWORDS

biopesticide, botanical, macrobial, microbial, semiochemical, *Spodoptera frugiperda*

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## 1 | INTRODUCTION

Fall armyworm (FAW, *Spodoptera frugiperda* (J.E. Smith), Lepidoptera: Noctuidae) is a highly mobile, polyphagous species that has recently spread from the Nearctic and Neotropical regions to much of Africa, the Near East, Asia and the Pacific (FAO (Food and Agriculture Organization of the United Nations), 2020a; Goergen et al., 2016;; Sharanabasappa et al., 2018; Zhang et al., 2020). FAW is particularly a pest of cereals and one of the major pests of maize (De Groot et al., 2020; FAO, 2020b; Hruska, 2019; Kansime et al., 2019; Kassie et al., 2020; Rwomushana et al., 2018; Tambo et al., 2020). As maize is a staple food crop for more than 300 million people in sub-Saharan Africa (SSA), FAW is a threat to livelihoods and food security.

Many farmers have responded to FAW by increasing their use of high-risk synthetic pesticides (Kansime et al., 2019; Kassie et al., 2020; Kumela et al., 2019; Tambo et al., 2020), but these are not always used safely or effectively, (Rwomushana et al., 2018), and there is evidence that unsafe pesticide use is putting farmers' health at risk (Tambo et al., 2020). Given the concerns posed by high-risk synthetic pesticides, there is a pressing need for alternative management options that are appropriate for use by smallholder farmers. The identification of practices and products for FAW management that are effective, lower risk, sustainable, accessible and affordable such as biopesticides (refer to Table 1 for the definition used in this paper) is high on the list of near-term activities identified in action plans in Africa at national, regional and international levels.

In order to make information on biopesticides for FAW management readily available, in a previous review paper (Bateman et al., 2018), the authors assessed 54 commercially available biopesticide active ingredients (AIs) which had been registered for use against FAW, *Spodoptera* spp. or Lepidoptera in general<sup>1</sup> in one or more of 30 countries in FAW's native range or Africa. They collated information

on their efficacy, human and environmental safety profile, agronomic sustainability, practicality for use, availability and cost-effectiveness. Based on the profiles of the AIs, they assessed whether their use would pose a significant risk to the farmers who would apply them as well as to the wider community and environment, and whether the AI is practical for smallholder farmers. Using these data, a decision matrix (Table S1) was developed to provide a basis to design interventions that would make suitable biopesticides more widely available for FAW control in Africa. While there was evidence of efficacy from the field in FAW's native range for several of the AIs, data from the field in Africa were minimal. Likewise, at the time, few biopesticide AIs had been registered for most countries in Africa, and almost none of the AIs had been specifically registered for use against FAW. Also, there was virtually no information available for their cost-effectiveness. The authors concluded the previous assessment by recommending 23 biopesticide AIs for follow-up actions (such as field trials, participatory trials or laboratory studies) (Bateman et al., 2018).

This review paper follows up on that by Bateman et al. (2018) by providing updated information on the biopesticide AIs that have been registered and commercialized for the management of FAW in one or more of 30 countries in FAW's native range or in Africa. We compared our findings to those of the previous assessment to gain information on how the state of knowledge has changed.

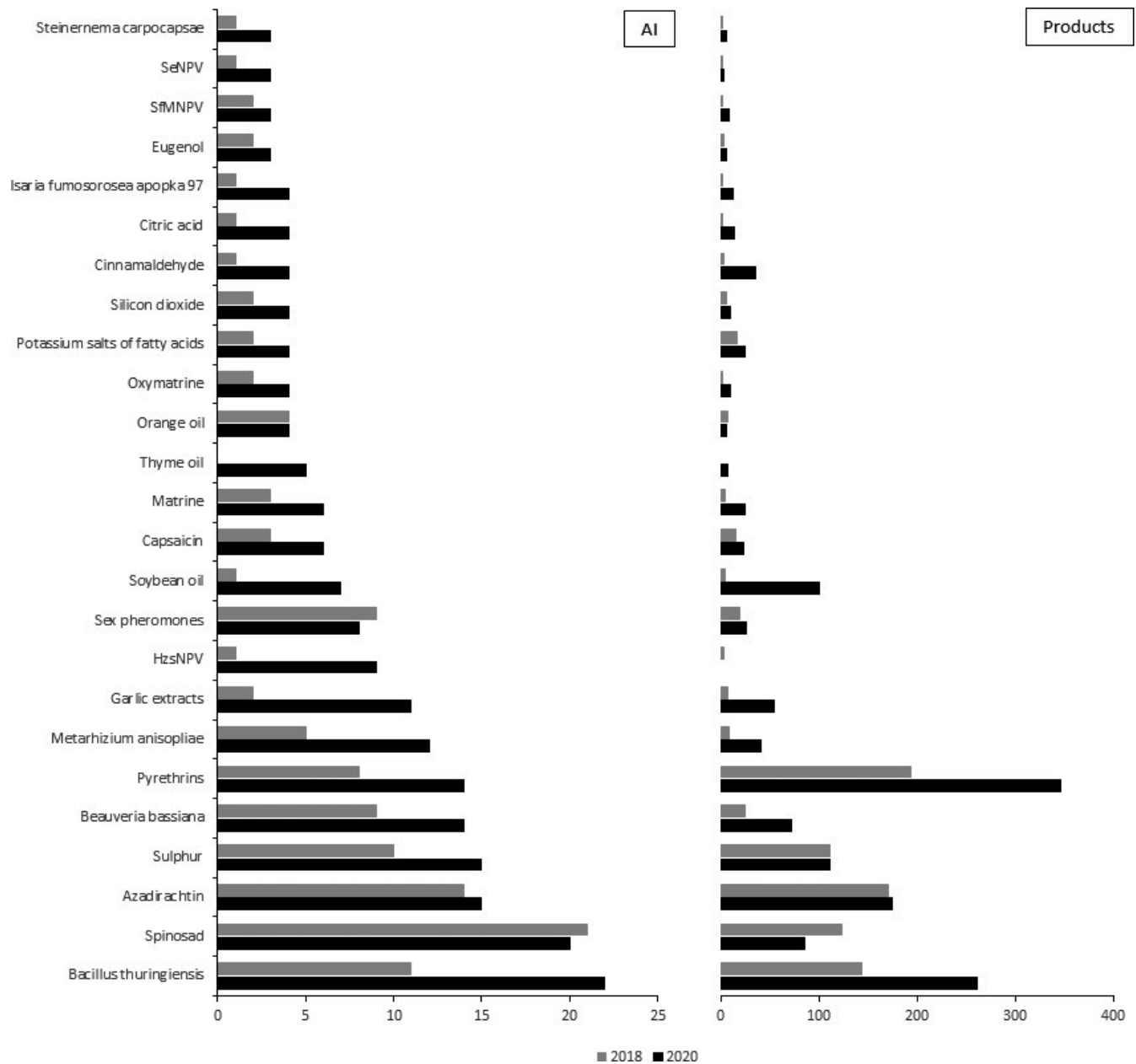
## 2 | MATERIALS AND METHODS

For each of the 30 selected countries, the most up-to-date versions of registered pesticides and biopesticides were used to identify the full list of biopesticide AIs and their corresponding products that can be used to manage FAW (Table S2). The lists of registered pesticides and biopesticides were accessed between April and August of 2020 and were filtered for any biopesticides which are already registered

**TABLE 1** For the purposes of this study, the national regulations were followed for those countries that identify which AI are biopesticides (or the equivalent) and, for countries where biopesticides are not identified, we used the same definition as the previous paper (Bateman et al., 2018)

Main substance groups	Sub-groups
Biochemical biopesticides	<ul style="list-style-type: none"> <li>• Plant extracts/botanicals</li> <li>• Synthetic pheromones/semiochemicals</li> <li>• Microbial extracts/fermentation products</li> <li>• Insect growth regulators</li> <li>• Compounds synthesized by other organisms</li> <li>• Inorganic compounds</li> </ul>
Microbial biopesticides	<ul style="list-style-type: none"> <li>• Bacteria</li> <li>• Fungi</li> <li>• Protozoa</li> <li>• Viruses</li> <li>• Oomycetes</li> <li>• Yeast</li> <li>• Algae</li> </ul>
Macrobials	<ul style="list-style-type: none"> <li>• Insect predators</li> <li>• Parasitoids</li> <li>• Entomopathogenic nematodes</li> </ul>

<sup>1</sup>Products which are registered for other specific Lepidoptera genera or species that are not *Spodoptera* were not considered.



**FIGURE 1** Numbers of active ingredients (AIs, left) and corresponding products (right) registered in three or more countries in 2018 (pale) and 2020 (dark)

and allowed for use against FAW, *Spodoptera* or Lepidoptera in general. As noted in Table 1, the registered pesticides list for 12 countries specifically identify biopesticide AIs, and the lists of registered pesticides for 19 countries include information about the specific pests for which the products are registered. Assessment of the lists of registered pesticides for countries in the Near East, Asia and the Pacific was beyond the scope of this study.

The profiles of previously identified AIs were updated based on any new information that has been published since the initial profiles were developed, and additional profiles were developed for newly identified AIs following the same approach as the previous assessment (Bateman et al., 2018).

### 3 | RESULTS

#### 3.1 | Overview of identified biopesticide AIs

Analysis of the national lists of registered pesticides and biopesticides for the 30 countries identified 41 biopesticide AIs in total that are registered and allowed for use for FAW management in at least one country (listed in Table S3). Among them, there are four biopesticide AIs which were not identified in the previous assessment: *Aspergillus oryzae*, *Autographa californica* multiple nucleopolyhedrovirus (AcMNPV), *Spodoptera littoralis* nucleopolyhedrovirus (SpliNPV) and thyme oil.

Three inorganic compounds (borax, cryolite and silicon dioxide), two microbial fermentation products (emamectin benzoate and spinetoram) and two insect growth regulators (lufenuron and methoxyfenozide) previously designated as biochemical biopesticides by at least one government are no longer categorized as such by any of the assessed countries, and, as a consequence, they were not assessed under the current study. Two other inorganic compounds (kaolin and sulphur), one other microbial fermentation product (spinosad) and one other insect growth regulator (s-methoprene) continue to be designated as biochemical biopesticides by one or more countries, though these AIs would not be considered as biopesticides by many definitions. No products were found to be registered for use against FAW or its relatives for three AIs that were identified through the previous study: 2-phenylethyl propionate, octanoate d-glucitol and sucrose octanoate. AIs that are no longer categorized as biopesticides, or are not registered for Lepidoptera, are excluded from all analyses which follow, and as a consequence the number of biopesticide AIs identified in this study is lower than the 54 biopesticide AIs identified in 2018.

Biopesticide AIs were represented by over 1,500 products in the 30 countries. The biopesticide products included 852 botanicals, 419 microbials and 85 microbial extracts or fermentation products, 125 inorganic compounds and seven insect growth regulators. Eight products containing parasitoids (*Trichogramma pretiosum* Riley) and six products containing entomopathogenic nematodes (*Steinernema carpocapsae* Weiser) were registered for FAW. Macrobiotics are expected to be under-represented since most countries do not include macrobiotics in their lists of registered pesticides, although in the present study, Brazil, Kenya and Uganda require these products to be registered. One product containing spider venom peptide was also identified.

Biopesticide AIs which were registered and allowed for use for FAW management in three or more countries are shown in Figure 1. In 2018, 18 of the biopesticide AIs were registered in three or more countries whereas in 2020, 30 of the AIs are registered in three or more countries. Azadirachtin, *Bt*, pyrethrins, soybean oil and sulphur were represented by the highest numbers of products.

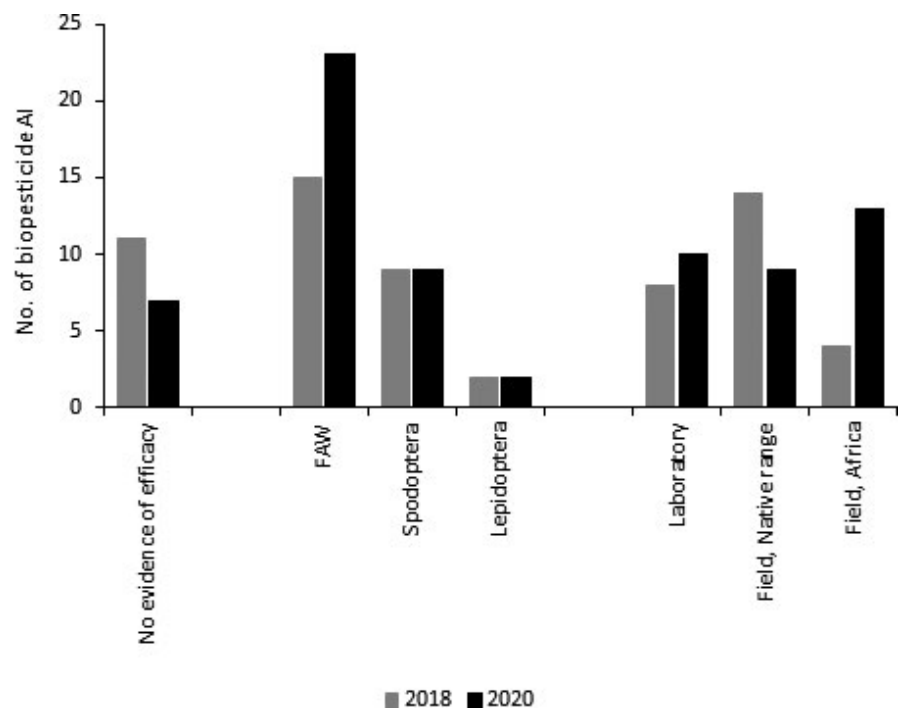
Detailed profiles of the biopesticides are provided in the supplementary data, and each category of information below is summarized in Table S5.

### 3.2 | Efficacy

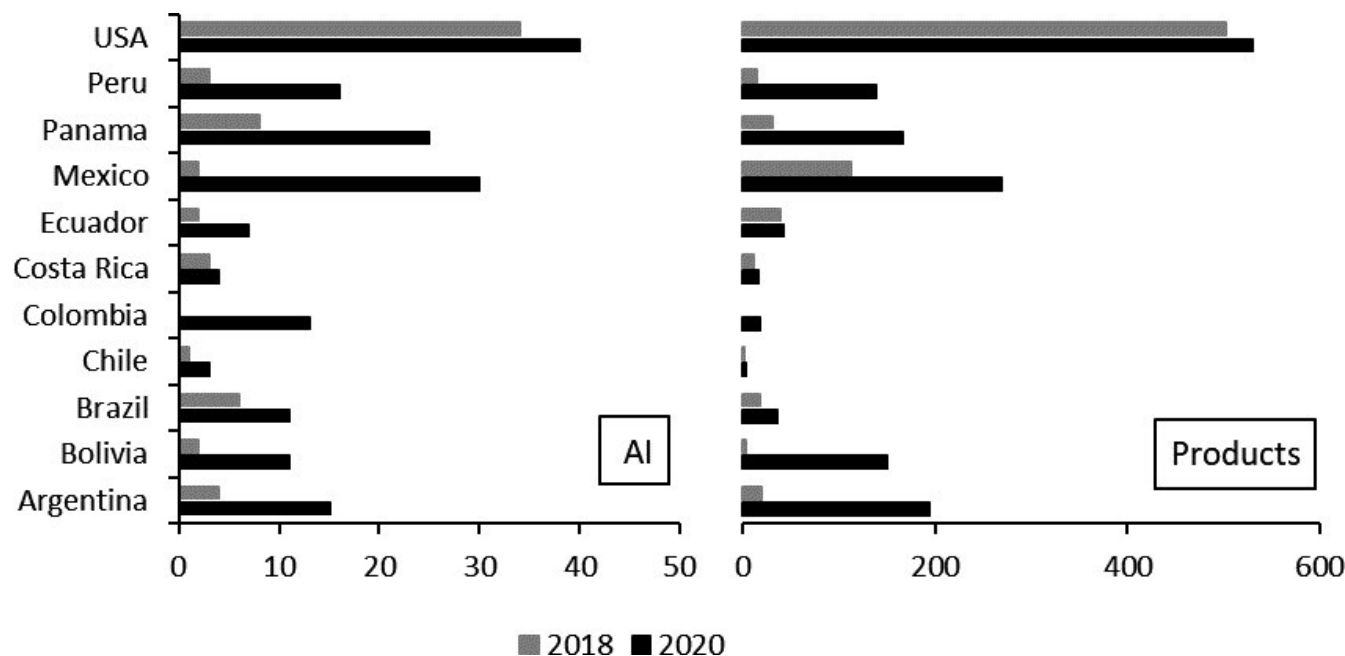
The number of biopesticide AIs that have been demonstrated to be effective against FAW, *Spodoptera* spp. or Lepidoptera is higher in 2020 than in 2018 (number of AIs in 2020 versus 2018 = 34 versus 26). As shown in Figure 2, this change represents an increase in evidence of efficacy specifically against FAW (number of AIs in 2020 versus 2018 = 23 versus 15) and more evidence from the field in Africa (number of AIs in 2020 versus 2018 = 13 versus 4). Only five of the studies reviewed at this time concluded that any of the AIs were ineffective against FAW.

### 3.3 | Hazard profiles of identified biopesticide AIs

Detailed information on the hazards associated with each AI is given in Table S3. Twenty-six of the hazard profiles were unchanged from the previous assessment; data gaps were filled for five AIs; three were assigned higher toxicity categories and three to lower categories. All 41 AIs have relatively low levels of hazard.



**FIGURE 2** Comparison of the findings of the assessment of the efficacy of the biopesticide active ingredients (AIs) in 2018 (left, pale) versus 2020 (right, dark)



**FIGURE 3** Numbers of biopesticide active ingredients (AIs) (left) and corresponding products (right) registered in 11 countries in FAW's native range in 2018 (pale) and 2020 (dark)

Only one of the biopesticide AIs met any of the HHP criteria: kaolin clay, based on notifications to ECHA that it is a carcinogen, but it is also noted that the US regulators have determined that kaolin has low acute toxicity and have categorized it as 'Generally Recognized as Safe' (US EPA, 2014) and the EC regulation on classification, labelling and packaging of substances (2018) do not list it as a carcinogen.

### 3.4 | Agronomic sustainability

Based on the review of the available literature on the agronomic sustainability of the biopesticide AIs, it was concluded that 28 of the biopesticide AIs would not compromise agronomic sustainability (i.e. low risks to non-target organisms, of the development of pest resistance, and of invasiveness). Eleven of the AIs would require appropriate mitigation measures as described in the Supporting information. Four AIs are highly toxic or very highly toxic to non-target organisms: allyl isothiocyanate, pyrethrins, S-methoprene and spinosad. There are examples in the literature of a build-up of FAW resistance to spinosad and to genetically modified maize incorporating genes of *Bacillus thuringiensis* Berliner, and there are also limited examples from the field of another Lepidoptera's resistance to products containing *Bacillus thuringiensis* (*Bt*) (Mota-Sanchez & Wise, 2020). Neem trees (*Azadirachta indica* A.Juss.) and *Dysphania ambrosioides* (L.) Mosyakin & Clemants, both of which have been proposed for local production, also have the potential to be invasive weeds in Africa (CABI (CAB International), 2017); thus, local production should only take place after risk assessments have been conducted.

Data on agronomic sustainability of matrine and oxymatrine were not available.

### 3.5 | Practicality in use for farmers

Literature and product labels indicated that 27 of the biopesticide AIs would be practical for smallholder farmers to use whereas six could be difficult for smallholder farmers to use, at least not immediately (allyl isothiocyanate, soybean oil, *Steinernema carpocapsae*, *Steinernema feltiae* and *Trichogramma* spp.). This assessment is virtually unchanged from the previous study's findings. These AIs were deemed impractical for smallholders for a variety of reasons, for example application equipment requirements, high frequency of application, storage requirements, shelf life and the need for application of an area-wide management approach.

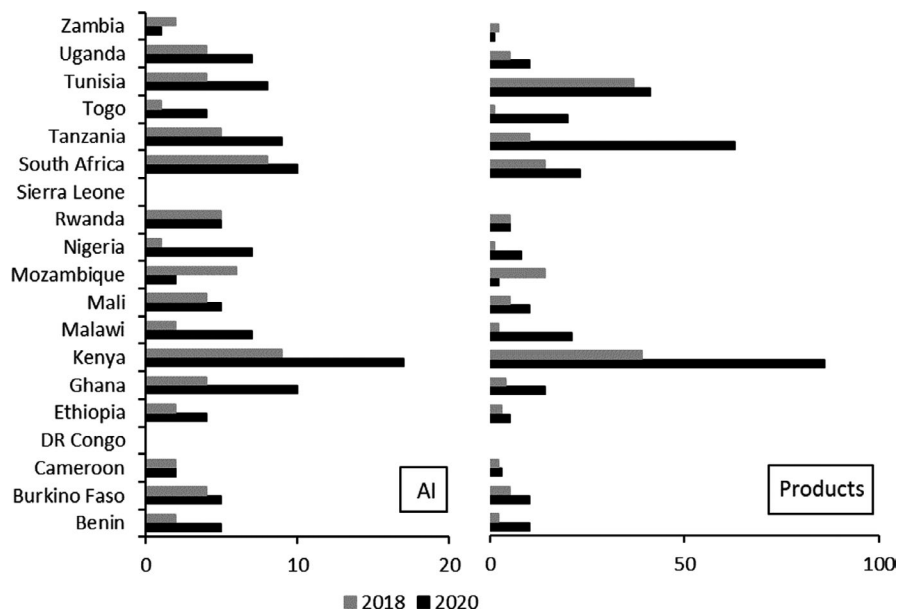
Biopesticide AIs and products registered for use against FAW in its native range in the Americas.

Information on the registration of AIs by country is given in Table SH. For each country in FAW's native range, the number of biopesticide AIs and products registered in 2020 has either increased or remained the same as compared to 2018 (Figure 3). In FAW's native range, the country with the highest number of biopesticide AIs registered for use against it was the United States (40 AIs).

### 3.6 | Registration status and availability of identified biopesticide active ingredients in Africa

The analysis of national lists of registered biopesticides for the 19 African countries identified products containing 32 of the 41 biopesticide AIs under assessment. Many countries saw an increase in the number of biopesticide AIs and products registered, but not all (Figure 4). In 2018, only South Africa had biopesticide products

**FIGURE 4** Numbers of biopesticide active ingredients (AIs) (left) and corresponding products (right) registered in 19 countries in Africa in 2018 (pale) and 2020 (dark)



specifically registered for use against FAW. As of the time of data collection in 2020, four of the assessed countries (Ghana, Kenya, South Africa and Tanzania) had registered products containing biopesticides specifically for use against FAW. In those countries and most of the other countries, there were examples of products which were broadly registered for Lepidoptera which would potentially be effective against FAW. Ghana has registered products containing *Bacillus thuringiensis*,<sup>2</sup> maltodextrin, and the combination of *Metarhizium anisopliae* and *Beauveria bassiana* for use against FAW in maize, and some other products like ones containing ethyl palmitate have registrations that broadly cover all caterpillars without identifying species. Many biopesticides are registered in Kenya, but only one product containing *Bacillus thuringiensis* is specifically registered for use against FAW. The countries with the highest number of biopesticide AIs and products registered that could potentially be used against FAW were Kenya (22 AIs and 125 products), South Africa (14 and 37), Ghana (14 and 26), and Tanzania (13 and 117, Figure 4).

Farmer surveys indicate that several of the biopesticides are also being used by farmers in the field, frequently through input support schemes: *Aspergillus oryzae*, azadirachtin, *Bacillus thuringiensis* (on its own and in formulation with *Pieris rapae* granulosis virus), ethyl palmitate, GS-omega/kappa-Htx-Hv1a and maltodextrin (Kansiime et al., 2019; Rwomushana et al., 2018; Tambo et al., 2020). There are also reports that homemade extracts of *Dysphania ambrosioides* are used by farmers in South Africa (Skenjana & Poswal, 2017).

### 3.7 | Affordability

For most of the biopesticide AI, there were no specific figures available on their cost and there was very little information on

cost-effectiveness. Based on data on costs in Africa from field trials and farmer surveys, there are indications that azadirachtin is cost-effective, and relatively affordable (Babendreier et al., 2020), whereas ethyl palmitate (Rwomushana et al., 2018) and maltodextrin (Babendreier et al., 2020) are less cost-effective, and not as affordable to smallholder farmers. In assessments of cost-effectiveness for other pests or in other continents, there was evidence that the following AI were cost-effective: capsaicin, *Chromobacterium subtsugae*, garlic extracts, *Isaria fumosorosea*, *Metarhizium anisopliae*, spinosad and *Trichogramma* spp. (Dougoud et al., 2019; Kivett et al., 2015; Manisha et al., 2020; Nayak et al., 2019).

## 4 | DISCUSSION

Given that many smallholder farmers are frequently using highly hazardous pesticides (Hopes) without personal protective equipment (Rwomushana et al., 2018) and the use of broad-spectrum pesticides can negatively impact natural enemies that are present (which could help to manage FAW), alternative management practices are needed. Increasing the use of biopesticides that are effective, of low risk to human health and the environment, agronomically sustainable, practical, available and affordable remains a high priority.

The findings of this update are encouraging. In the relatively short time since the last assessment, the number of biopesticide AIs registered per country that could potentially be used to manage FAW has more than doubled, and there have been similar increases in the numbers of products registered. For many of the AIs, the evidence of efficacy, particularly for FAW itself and from the field in Africa, has grown since the last iteration of this assessment. Even so, the findings are not always clear cut. For example, for several of the botanical extracts, it is uncertain what the basis is for efficacy and whether they are effective on their own or in combination with other AIs.

<sup>2</sup>Where strain names are not given, this is because they are not provided in the reference documents for the country or study in question.

**TABLE 2** Overview of conclusions regarding readiness of biopesticide active ingredients (AI) for deployment in Africa. Not all AI fit comfortably in this classification, and the detailed supplementary information should also be reviewed

Registered for field use against FAW or other Lepidoptera in our survey	Reported effective against FAW in field trials in Africa	Reported effective against FAW in field trials in native range; field trials and evaluation needed in Africa	Reported effective against FAW in lab bioassays; field trials needed in Africa	Reported effective against related pests; bioassays needed for FAW, followed by field trials if justified	Not recommended for follow up on available information (at this time)
No longer registered as a biopesticide					Borax Cryolite Emamectin benzoate Lufenuron Methoxyfenozide Silicon dioxide Spinetoram
Not registered					2-phenylethyl propionate Cinnamaldehyde d-glucitol, octanoate Sucrose octanoate
Registered outside sub-Saharan Africa			<i>Dysphania ambrosioides</i>	GS-omega/ kappa-Hctx-HV1a <sup>d</sup>	Allyl isothiocyanate Anagrapta falcifera NPV Autographa californica MNPV <i>Chromobacterium subtugae</i> Citric acid Helicoverpa zea SNPV <i>Isaria fumosorosea</i> Kaolin clay Spodoptera exigua NPV
Registered within sub-Saharan Africa	<i>Aspergillus oryzae</i> Azadirachtin <i>Bacillus thuringiensis</i> subsp. <i>Aizawai</i> Maltodextrin <sup>c</sup> Sex pheromones <sup>b</sup> Spinosad <sup>a</sup> Spodoptera frugiperda MNPV Spodoptera littoralis NPV <i>Trichogramma</i> spp. <sup>b</sup>	<i>Bacillus thuringiensis</i> subsp. <i>Kurstaki</i> Ethyl palmitate Garlic extract <i>Steinernema</i> spp.	<i>Beauveria bassiana</i> Eugenol <i>Metarhizium anisopliae</i>	Canola oil Capsaicin D-limonene	Matrine Oxymatrine Potassium salts of fatty acids Pyrethrins S-methoprene Soybean oil Sulphur Thyme oil

<sup>a</sup>There are concerns regarding toxicity.

<sup>b</sup>In many countries, sex pheromones and macrobials do not need to be registered, hence we include them here rather than list them as not registered or omit them from the table.

<sup>c</sup>Treatment costs are potentially too high to justify its use.

<sup>d</sup>Used by farmers in Zambia.

Field trials demonstrating efficacy have been carried out for eight AIs (*A. oryzae*, azadirachtin, *B. thuringiensis* subsp. *Aizawai*, maltodextrin, FAW sex pheromones, spinosad, *Spodoptera frugiperda* multiple nucleopolyhedrovirus and *Spodoptera littoralis* nucleopolyhedrovirus) (Table 2). This has resulted in products being registered across some countries in Africa. While some of these biopesticide AIs have already been incorporated into IPM schemes or are being provided to farmers, for most there are still IPM information gaps which need to be filled. For example, data on cost-effectiveness are lacking for most biopesticide AIs, including many of those that have been registered and are being recommended to farmers. Findings from the literature on cost-effectiveness in other cropping systems are not transferable as they will be out of date and not accurate for the other locations. Costs need to come from distributors in country at price sold to farmer and calculated as a per ha and per season cost. As noted by Hruska (2019), in Africa, most maize is grown by smallholder farmers for subsistence, making most pesticides (both synthetic pesticides and biopesticides) too expensive for use. Cost is likely to become a bigger issue as many governments and other initiatives that initially provided inputs to combat FAW are now scaling back the distribution of pesticides (Hruska, 2019). Without support from such programmes, the costs of some AIs may be prohibitively high, as demonstrated by the case of maltodextrin (Babendreier et al., 2020). For many of these AIs, further field work would be beneficial to establish the most cost-effective methods of use.

The conclusions developed using the decision matrix are listed in Table 2. Field trials are recommended for eight AIs (*B. thuringiensis* subsp. *Kurstaki*, *B. beauveria*, *D. ambrosioides*, ethyl palmitate, eugenol, garlic extract, *M. anisopliae* and *Steinernema spp.*), and for some of these AIs, field trials are already underway. Bioassays should be carried out to determine whether four AIs (GS-omega/kappa-Hx-tx-Hv1a, canola oil, capsaicin and D-limonene) are effective against FAW, and, if so, they could be followed up by field trials. Eighteen AIs are not recommended for follow-up at this time. This group of AIs is largely the same as the group which were not recommended for follow-up in the previous assessment (Bateman et al., 2018), though some AIs have been added since they are no longer registered for FAW in any of the 30 countries (e.g. sucrose octanoate), because the hazard data now indicate that the AI is an HHP (e.g. kaolin) or because studies do not indicate they are effective (matrine and pyrethrins).

As most countries do not include macro-organisms in their lists of registered pesticides, a separate review on natural enemies would be very helpful. Much research on egg parasitoids is in progress, including field trials on *Telenomus remus* and *Trichogramma* in Kenya. In terms of efficacy against FAW, *T. remus* seems more promising than *T. pretiosum* but so far it is more difficult to mass-produce and no commercial product is yet available.

While there has been an increase in the number of registrations of biopesticides in many countries, for a few countries, the number of biopesticide AIs registered remains the same. Overall, the increase in the number of biopesticide AIs which have been registered in Africa

is lower than that in FAW's native countries. Registrations for some biopesticide AIs in countries in Asia have moved more quickly. The lower number of new registrations could be due to registration costs, regulatory hurdles or inaction from manufacturers due to their perception of the size of the pesticide market (Constantine et al., 2020; Nyangau et al., 2020).

Finally, registration of an AI is not the same as availability or affordability to a farmer. Even where biopesticide AIs are registered and available, awareness and confidence in them by smallholder farmers are often a limiting factor for uptake. While surveys indicate that farmers in some countries are making use of biopesticides, the availability and affordability of biopesticides to farmers, together with their perception of efficacy, are aspects which warrant further examination.

With increased travel and movement of goods, new invasive species are likely to be more and more common and the FAW invasion provides an interesting case study in terms of the global response, in much the same way as COVID-19 has provided a case study in how to respond to future pandemics.

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## CONFLICT OF INTEREST

The authors declare that they have no conflict of interest and confirm that there are no disputes over the ownership of the data presented and all contributions have been attributed appropriately.

## AUTHOR CONTRIBUTION

M.L. Bateman, R.K. Day and I. Rwomushana conceived the research; M.L. Bateman analysed the data; M.L. Bateman, R.K. Day, I. Rwomushana, S. Subramanian, K. Wilson, B. Luke, D. Babendreier



and S. Edgington wrote and edited the manuscript and Supporting information; R.K. Day and I. Rwomushana secured funding; all authors read and approved the manuscript.

## DATA AVAILABILITY STATEMENT

The data that support the findings of this study are openly available in the CABI data repository's Fall Armyworm Community at [https://ckan.cabi.org/data/dataset/updated\\_biopesticides\\_faw](https://ckan.cabi.org/data/dataset/updated_biopesticides_faw).

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## SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section.

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