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Assessment of effectiveness of maize seed treated with cyantraniliprole and thiamethoxam for management of fall armyworm, *Spodoptera frugiperda* (J. E. Smith)

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ABSTRACT

The effectiveness of maize seed treatments for management of fall armyworm (FAW) (*Spodoptera frugiperda*) was evaluated under natural infestation conditions in Zambia in 2019, 2020 and 2022. Two seed treatments were tested: cyantraniliprole (Fortenza® 600 FS) + thiamethoxam (Cruiser® 600 FS) (combination marketed as Fortenza® Duo) and Fortenza® 600 FS. Other treatments included each of the two seed treatments supplemented with threshold-based rotational sprays of Denim Fit® 50 WG (emamectin benzoate + lufenuron) and Ampligo® (chlorantraniliprole + lambda cyhalothrin), Denim Fit/Ampligo alone, untreated controls, Ecoterex® 0.5% GR (deltamethrin + pirimiphos methyl) and Mythic® FN SC (chlorantraniliprole). The incidence of FAW-infested plants and plant damage scores were recorded weekly for 4–5 weeks post-emergence. At harvest, grain yield, yield increase over untreated control and cost-benefit ratios were also determined. Although there were some seasonal variations in treatment effectiveness, plots established from Fortenza Duo-treated seed generally had significantly lower plant damage within the first 3–5 weeks of growth. The number of follow-on insecticide sprays were reduced from 2 to 1 in February 2022 plantings in plots established from Fortenza Duo-treated seed. Grain yields were highest in the Denim Fit/Ampligo plots (December 2021 plantings) and Fortenza Duo + Denim Fit/Ampligo plots (December 2021 and February 2022 plantings). In both plantings of the 2021-22 season, mean yield increase over untreated control was highest in Fortenza Duo + Denim Fit/Ampligo plots. Cost-benefit ratios were, however, highest where Fortenza Duo-treated seed was planted without any follow-on chemical sprays and lowest and negative in sole Fortenza plots. Due to method of application and systemic action, Fortenza Duo maize seed treatments may be a perfect fit in FAW integrated pest management (IPM) programs where there is need for judicious pesticide use.

1. Introduction

Fall armyworm (FAW) (*Spodoptera frugiperda* J.E. Smith) has unarguably become the most damaging pest of maize in sub-Saharan Africa following the first reports of its occurrence on the continent in 2016 (Goergen et al., 2016; Tindo et al., 2017). The pest is native to tropical and subtropical regions of North and South America and the Caribbean (Sparks, 1979; Mitchell et al., 1991) and is now endemic in every country in sub-Saharan Africa except Lesotho (FAO, 2018). Fall armyworm's lack of a resting stage (diapause), high dispersive capacity and adaptability to a wide range of environment conditions, enables it to closely track its principal host — maize — in space and time. The accompanying high levels of damage by FAW on maize have, for the first time, resulted in smallholder African farmers now needing to budget for chemical control in maize production. Prior to the pest's introduction onto the continent, the major field pests of maize which farmers had to contend with were stem borers (Kfir et al., 2002), and these were rarely controlled using insecticides at the smallholder level.

Due to their curative and fast-killing properties, farmers find synthetic chemical pesticides to be the most convenient and effective for

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controlling FAW. The uptake of biorationals such as entomopathogens and botanicals is much lower mainly because of perceived low efficacy relative to synthetic chemical pesticides, slow action, high cost, and lack of clear registration guidelines. The regulatory role of natural enemies, particularly insect parasitoids (e.g., Caniço et al., 2020; Abang et al., 2021; Agboyi et al., 2020, 2021; Hussain et al., 2021; Mohamed et al., 2021; Otim et al., 2021; Winsou et al., 2022), is also becoming apparent on the continent. Despite the widespread preference of synthetic chemical insecticides for FAW management by farmers, a high propensity by the pest to develop resistance to most insecticide molecules on the market, including to genetically modified maize hybrids (e.g., Van den Berg and du Plessis, 2022), poses challenges to its sustainable management in sub-Saharan Africa.

Systemic maize seed treatments are a new group of scalable integrated pest management (IPM) technologies which may have the greatest potential in managing FAW particularly in the early seedling stages of the crop. Oliveria et al. (2022) found treatment of maize seed with chlorantraniliprole, cyantraniliprole or a thiodicarb + imidacloprid combination to be effective in reducing FAW larval damage for 10 days after crop emergence for larvae feeding on the stalk base and 15 days after crop emergence for larvae feeding on whorl leaves. Additionally, surviving larvae that had fed on the seed-treated plants had reduced fitness. In a study to determine the bioefficacy, persistent toxicity, and residual effects of maize seed treated with thiamethoxam, fipronil, tetraniliprole, chlorantraniliprole, cyantraniliprole + thiamethoxam, tetraniliprole + fipronil, Suganthi et al. (2022) reported Chlorantraniliprole 625 FS applied at 6 ml kg^{-1} seed as providing the highest FAW protection in terms of reduced plant damage, with residues persisting for >26 days.

The current study had four specific objectives: 1) to determine the effectiveness of a binary commercial maize seed treatment comprising cyantraniliprole and thiamethoxam (Fortenza® Duo) against FAW relative to selected synthetic insecticide treatments applied post-emergence, (2) to determine duration of effectiveness, (3) to determine if planting treated seed could reduce the number of threshold-based follow-on post-emergence insecticide treatments, and (4) to determine yield, yield increase over untreated control and cost-benefits arising from planting treated seed.

2. Materials and methods

2.1. Study site

Trials were conducted at the International Institute of Tropical Agriculture's (IITA) Southern Africa Research and Administration Hub (SARAH) Campus, Lusaka, Zambia (15°18′09.6″S 28°18′17.3″E, altitude 1,190 m) in 2019 (2018-19 summer season), 2020 (2019-20 summer season) and 2022 (2021-22 summer season). Zambia's has three distinct seasons: a hot and dry season (mid-August to mid-November), a wet rainy (summer) season (mid-November to April) and a cool dry season (May to mid-August). SARAH Campus is in Agroecological Region II of Zambia. This agroecological region is characterized by annual rainfall averaging 800-1,000 mm, mean annual temperatures of 23–25 °C, 900-1,200 m altitude, and a growing season of length 100–140 days (Bunyolo et al., 1995).

2.2. Maize seed

Except for 2022, all seed treated with Fortenza® Duo was procured from the market already treated. In 2019, an early maturing (125–130 days) Syngenta hybrid, SY 5944, was planted while in 2020, a medium maturing (130–135 days) Seed Co hybrid, SC 647, and an early maturing (120–130 days) Afriseed open-pollinated variety, ZM 521, were planted. In 2022, a late maturing (135–150 days) and drought tolerant Seed Co hybrid, SC 719, was planted. The trial could not be conducted in 2021 due to a failure to obtain Fortenza Duo-treated seed on the market.

2.3. Insecticides

2.3.1. Seed treatments

Fortenza® Duo is the trade name for a twin-pack of two Syngenta commercial insecticide products in flowable solution (FS) formulation for application on seed. For treatment of maize seed, Fortenza® 600 FS (cyantraniliprole 600 g/L) and Cruiser® 600 FS (thiamethoxam 600 g/L) are mixed with seed at a rate of 292 ml of each insecticide per 100 kg of seed, or 2.92 L of each product per ton of seed. The mixing and treatment are done by seed companies, so farmers purchase a seed-packaged pest management technology. A sticker is affixed to bags of treated seed to enable their differentiation from untreated seed. According to the Fortenza Duo label, the seed treatment can potentially offer protection against FAW for the first 3–4 weeks of growth. Additional benefits of planting Fortenza Duo-treated seed are stated as including protection against a range of root feeders and Hemipterans thus enabling better establishment of the seedlings and optimized uptake of water and nutrients from the soil. For these trials, seed described as "untreated" was only so with respect to Fortenza Duo or Fortenza as it would still have been treated with Maxim® XL (fludioxonil) (1 L/ton) for control of soilborne and seedborne fungal diseases and Cruiser® 600 FS (200 ml/ton) for control of stored grain insect pests.

2.3.2. Post-emergence insecticide treatments

Due to the absence of a true standard on which to base the effectiveness of the seed treatments, four insecticide products (Ampligo®, Denim Fit® 50 WG, Ecoterex® 0.5 GR and Mythic® FN SC) (Table 1) for application post-emergence were included in the trials. A 16-litre backpack knapsack sprayer fitted with a hollow cone nozzle was used to apply liquid-based insecticide products. The knapsack sprayer mixing rates of the liquid-based products were determined from a pre-spray calibration exercise.

2.4. Land preparation, crop establishment, experimental design and treatment applications

To ensure that crops would be subjected to high pest pressure, planting was deliberately delayed beyond the normal mid-November to December planting period to January and February of the following year. Planting dates in the respective seasons were as follows: January 11, 2019 (2018-19 season), February 6, 2020 (2019-20) season, 21 December 2021 (2021-22 season, 1st planting) and 25 February 2022 (2021-22 season, 2nd planting). Residues from previous crops were first removed by harrowing and then land was ripped and disc-harrowed to a fine tilth and rows marked out. Planting holes were prepared using hoes and basal fertilizer (7:14:7 N:P:K) applied by hand at a rate of 300 kg/ha. One seed was placed in each planting hole. Two days after planting, the herbicide Lumax® 537.5 SE (37.5 g/L mesotrione + 375 g/L S-metolachlor + 125 g/L terbuthylazine) was applied at 4 L/ha (320 ml of product per 16 L water) for pre- and early post-emergence control of

Table 1
Product brand names, active ingredients, and application rates used in the trials.

Product brand name	Active ingredient(s)	Manufacturer	Application rate
Ampligo®	chlorantraniliprole 100 g/L + lambda cyhalothrin 50 g/L	Syngenta	5 ml/16 L water (200–240 ml/ha)[a]
Denim Fit® 50 WG	emamectin benzoate 100 g/L + lufenuron 400 g/L	Syngenta	5 g sachet/16 L water
Ecoterex® 0.5 GR	deltamethrin 0.1% + pirimiphos methyl 0.4%	EcoMed Manufacturing P/L	1 hand pinch/plant
Mythic® FN SC	chlorantraniliprole 200 g/L	Allchem S.R.L.	8 ml/16 L water (250 ml/ha)[a]

[a] Recommended volume application rate in brackets.

weeds. In all seasons, crops emerged 6–7 days after planting. After crop emergence, weeds were controlled by hand-hoeing. Supplementary irrigation was provided via a Linear Move system. Crops were split top-dressed with ammonium nitrate (34.5% N) (2019 and 2020) or urea (36% N) (2022) at the rate of 300 kg/ha at 3 and 7 weeks after crop emergence (WAE).

In all three seasons, plant spacings of 0.75 m between rows and 0.5 m within the row were used. The two outer rows in each plot were designated as guard rows. In the 2018-19 season, the trial field was divided into 24 plots each of which had six 28 m-long rows. Due to the need to obtain as much information as possible from the novel products Fortenza Duo and Ecoterex, a completely randomized design with unequal replications was adopted and treatments randomly allocated to different plots as follows: (i) Control (untreated seed) (3 replications), (ii) Fortenza Duo-treated seed (9 replications), (iii) Ampligo (3 replications), (iv) Denim Fit (3 replications) and (v) Ecoterex (6 replications).

In the 2019-20 season, the trial was laid out as a factorial experiment of two varieties (main effects) and three FAW treatments (factors) in three replications. A treatment net plot consisted of eight rows each of length 40 m. The treatments under each variety were as follows: (i) Control (untreated seed), (ii) Fortenza Duo-treated seed, and (iii) Fortenza Duo-treated seed + Mythic. In the 2021-22 season, a completely randomized design of six treatments in three replications was adopted with each net plot consisting of 10 rows each of length 25 m. The treatments were as follows: (i) Control (untreated seed), (ii) Fortenza Duo-treated seed with no post-emergence treatments, (iii) Fortenza-treated seed with no post-emergence treatments, (iv) untreated seed + rotational sprays of Denim Fit and Ampligo (Denim Fit applied first), (v) Fortenza Duo-treated seed + Denim Fit/Ampligo, and (vi) Fortenza-treated seed + Denim Fit/Ampligo. The action threshold adopted for post-emergence treatments was 20% infestation (Prasanna et al., 2018), i.e., if mean incidence of FAW-infested plants for a particular treatment was ≥20%, then spraying was conducted across all the plots for that treatment.

2.5. Parameters

Parameters assessed included incidence of FAW-infested plants (as a percentage), plant damage score, number of egg masses or larvae per plant, yield (2021-22 season) and cost-benefit ratios (2021-22 season). However, results on numbers of FAW egg masses and larvae per plant will be reported elsewhere and hence procedures for their assessment will not be described in this paper.

2.5.1. Incidence of FAW-infested plants and plant damage

The incidence of FAW-infested plants and plant damage were assessed starting at 1 WAE (baseline for post-emergence treatments) up to 4 or 5 WAE. Twenty plants were randomly selected in each plot and examined for characteristic FAW injury symptoms and presence of egg masses. To facilitate measurement of the curative effects of treatments, a plant was only considered to be infested if it had fresh damage symptoms in the whorl and/or egg masses. From 2 WAE onwards, only new damage symptoms present in the whorls were considered in the assessment of incidence of infested plants.

Plant (whole) damage was assessed using a 0–9 visual scale (0 = no visible damage at all, 9 = whorl and furl leaves almost totally destroyed or plant dead/dying due to “deadheart” development) modified after Davis et al. (1992) (Table 2). Thus, unlike incidence of FAW-infested plants, both fresh injury symptoms on the whorl leaves and older symptoms on other leaves were considered when scoring for damage.

Table 2
Fall armyworm whole plant visual damage scores modified after Davis et al. (1992).

Explanation/definition of damage	Score
No visible leaf damage	0
Only pinholes visible on whorl leaves	1
Pinholes and small windowpanes present on whorl leaves	2
Pinholes, small circular windowpanes, and a few small, elongated windowpanes of up to 1.3 cm in length present on whorl and furl leaves	3
Several small to mid-sized (1.3–2.5 cm long) elongated windowpanes present on a few whorl and furl leaves	4
Several large (>2.5 cm long) elongated windowpanes present on a few whorl and furl leaves and/or a few small- to mid-sized uniform to irregular shaped holes eaten from the whorl and/or furl leaves; small sections of a few whorl and furl leaves eaten from the margins inwards	5
Several large, elongated windowpanes present on several whorl and furl leaves and/or several large uniform to irregular shaped holes eaten from furl and whorl leaves as well as well the margins inwards	6
Many elongated windowpanes of all sizes present on several whorl and furl leaves plus several large uniform to irregular shaped holes eaten from the whorl and furl leaves as well as from the margins inwards	7
Many elongated windowpanes of all sizes present on most whorl and furl leaves plus many mid- to large-sized uniform to irregular shaped holes eaten from the whorl and furl leaves well as from the margins inwards, and copious amounts of frass filling up the funnel	8
Whorl and furl leaves almost totally destroyed with plants assuming a ragged and tattered appearance and copious amounts of frass filling up the whorl; plant drying up due to destruction of the growing point	9

2.5.2. Yield and yield increase over untreated

The crop was left in the field to dry out completely and then 20 plants were randomly selected from each plot. Cobs from each selected plant were dehusked and individually shelled and grain weighed before being placed in labelled khaki bags. If the selected plant did not have a cob, a ‘0’ weight value was recorded against it. If a plant had more than one cob, the individual cob grain weights were determined and added together to come up with the total grain weight for that plant. The weight of shelled grain per plant (wet weight) was corrected for grain moisture content. For grain moisture content determination, grain from each plot was first bulked and thoroughly mixed. Five composite samples (45–50 g each) were then withdrawn, and individual moisture content values of each sample measured using a digital moisture meter (Agratronix® MT-Pro+). The mean moisture content of grain from each plot was then obtained and used to determine the dry weight of grain per plant in each plot:

$$Dry\ grain\ weight\ (g) = wet\ weight\ (g) \times \frac{(100 - mean\ moisture\ content)}{100}$$

Using the plant spacings for the trial, the plant population per hectare was determined:

$$Plant\ population = \frac{10,000}{interrow\ spacing\ (m) \times intrarow\ spacing\ (m)}$$

The grain dry grain weight per plant in kilograms (kg) was then extrapolated to tons (t) per hectare by simply multiplying with the plant population and then dividing by 1,000.

For each FAW control method, yield increase over untreated (or avoidable yield loss) was estimated by determining the difference in mean grain yield (t/ha) between treated and untreated plots. This was then expressed as a percentage:

$$Yield\ increase\ over\ untreated\ (\%) = \frac{Mean\ yield\ in\ treated\ plots - Mean\ yield\ in\ unprotected\ plots}{Mean\ yield\ in\ protected\ plots} \times 100$$

2.5.3. Cost-benefit analyses of different FAW treatments

The cost effectiveness of planting treated versus untreated maize seed were estimated by calculating the cost-benefit ratios of the different treatments. Five factors were considered in the calculation of the cost-benefit ratios: (i) cost of seed treatment, (ii) cost of chemical insecticides (Denim Fit and Ampligo), (iii) cost of casual labor for spray operations (based on IITA rates), (iv) yield, and (v) prevailing market price of maize grain. Factors (i) – (iii) constituted the cost of protection. The costs of seed, land preparation, fertilizers and weeding were not included in the calculations as these were the same across all treatments. The cost-benefit ratio was calculated (Arbabtafti et al., 2014):

$$Cost\ benefit\ ratio = \frac{Treated\ benefit\ (US\$) - Untreated\ benefit\ (US\$)}{Cost\ of\ protection\ (US\$)}$$

3. Data analysis

Data on incidence of FAW-infested plants per plot (%), plant damage scores and yield were subjected to analysis of variance (ANOVA) (PROC GLM, SAS Institute, 2013). Percentage data were first checked for normality, and if not normally distributed, were transformed by arcsine square root before being subjected to ANOVA. Where the *F*-ratio was significant ($P < 0.05$), treatment means were separated using the Student-Newman-Keuls (SNK) test.

4. Results

4.1. Incidence of FAW-infested plants

In all three seasons and across all treatments, FAW leaf damage symptoms were first noted within 1–2 days of crop emergence. At 1 WAE in 2019, there were no significant ($P > 0.05$) differences in incidence of FAW-infested plants among all treatments (Table 3). However, subsequent assessments revealed significant differences ($P < 0.01$) among all treatments, with infestation in the Fortenza Duo-treated plots being lower relative to the untreated control at 2 and 3 WAE.

On application of Ecoterex, Denim Fit and Ampligo at 1 WAE, the incidence of infested plants declined thereafter. However, for Ecoterex, this was short-lived and despite a second application at 3 WAE, infestation had increased to 91.7% by the time assessments were terminated at 4 WAE. Of the two chemical sprays, Ampligo offered superior FAW control for the entire duration of assessments. In the case of Denim Fit, although the first spray resulted in a drastic reduction in the incidence of infested plants within one week, by the time a second application was needed at 4 WAE, infestation had rebounded to 86.7%.

In 2020, significant treatment ($F_{2,10} = 4.69$, $P < 0.05$) and treatment*variety interaction ($F_{2,10} = 7.34$, $P < 0.05$) effects were noted at 1 WAE. While incidence of FAW-infested plants at 1 WAE in untreated control of SC 647 hybrid was above 90%, this was below 50% in untreated control of ZM 521 open pollinated variety (Fig. 1). In SC 647 sole Fortenza Duo plots, infestation was significantly lower than in the untreated control only at 1 WAE. For both maize varieties, a single spray of Mythic at 1 WAE reduced infestation but by 4 WAE this had increased to 100% across all treatments.

In the first plantings of the 2021-22 season (21 December 2021), the incidence of infested plants in plots under sole Fortenza Duo remained significantly ($P < 0.05$) lower than that recorded in the untreated control up to 3 WAE (Table 4). In contrast, sole Fortenza performed poorly throughout the five weeks of assessment. For plots established from untreated seed and in which Denim Fit/Ampligo were applied, sprays were required at 1 and 4 WAE. On the other hand, in plots established from seed treated with Fortenza Duo and Fortenza and supplemented with Denim Fit/Ampligo, sprays were needed in the former at 1 WAE (Denim Fit) and 4 WAE (Ampligo) and at 1 and 3 WAE in the latter.

In the second planting of the 2021-22 season (25 February 2022), the incidence of FAW-infested plants in the sole Fortenza Duo and sole Fortenza treatments was significantly lower than in the untreated control only up to 1 and 2 WAE, respectively (Table 5). Where Fortenza Duo was supplemented with chemical sprays (Denim Fit at 2 WAE and Ampligo at 4 WAE), infestation was significantly lower than in the untreated control for the first three weeks after crop emergence and at 5 WAE. In contrast, where Fortenza was supplemented with chemical sprays at 2 and 4 WAE, the incidence of infested plants remained lower than in the untreated control throughout the five weeks of assessment. For plots established from untreated seed and under rotational sprays of Denim Fit and Ampligo (Denim Fit at 1 and 4 WAE and Ampligo at 2 WAE), infestation was significantly lower relative to the untreated control only at 2, 3 and 5 WAE.

4.2. Plant damage

In 2019, there were significant ($P < 0.05$) differences in plant damage scores among the different treatments in each of the four assessment periods (Table 6). Relative to the untreated control, damage in Fortenza Duo plots was significantly lower during the first three weeks but had increased to the same level by the time assessments were terminated at 4 WAE. Starting with baseline damage comparable to the untreated control, damage in plots under each of the three post-emergence treatments (i.e., Ecoterex, Denim Fit and Ampligo) declined significantly within a week after treatment. Damage in the plots sprayed with Ampligo was thereafter maintained below 1.0 up to termination of assessments. In contrast, plant damage in Denim Fit plots had increased to above that in Ampligo plots by the time assessments were terminated but was still lower relative to that in Ecoterex plots.

In 2020, treatment and treatment*variety interaction effects were highly significant ($P < 0.0001$) for each of the four assessment periods while varietal effects were significant ($P < 0.0001$) only at 1 and 2 WAE. For SC 647 hybrid, damage in sole Fortenza Duo plots was lower (below 0.5) than in the untreated plots at 1 and 2 WAE only (Fig. 2). Thereafter, damage in the sole Fortenza Duo plots steadily increased and was nearly 7.0 by the time assessments were terminated at 4 WAE. In the Fortenza Duo + Mythic plots, damage remained below 1.0 up to 3 WAE but had increased to nearly 4.0 at 4 WAE.

In the case of ZM 521 open-pollinated variety, damage in the untreated control was very low at baseline assessment (1 WAE) and was not significantly different from that recorded in the sole Fortenza Duo and Fortenza Duo + Mythic plots. Thereafter, damage in sole Fortenza Duo plots rose sharply and by 3 WAE, had even surpassed that recorded in the untreated control. By 4 WAE, damage in the sole Fortenza Duo and untreated control plots were just below 7.0 and statistically similar. In contrast, plant damage in the Fortenza Duo + Mythic plots remained below 1.5 up to 3 WAE but had increased to about 4.0 at 4 WAE.

In the first plantings of the 2021-22 season, plant damage in sole Fortenza plots was highest compared to all other treatments throughout

Table 3
Incidence of FAW-infested plants (%) (means ± SE) recorded weekly in different treatments during four weeks of assessments in January–February 2019.

Treatment	N	1 WAE	2 WAE	3 WAE	4 WAE
Control[a]	3	76.7 ± 6.0 a	71.7 ± 6.0 a	91.7 ± 8.3 a	91.7 ± 1.7 a
Fortenza Duo	9	55.0 ± 4.3 a	37.2 ± 3.2 b	76.7 ± 4.6 b	94.4 ± 2.3 a
Ecoterex	6	76.7 ± 3.1 a ●	15.0 ± 4.3 bc	46.7 ± 5.9 c ●	91.7 ± 3.3 a
Denim Fit	3	70.0 ± 14.4 a ●	8.3 ± 4.4 c	13.3 ± 1.7 d	86.7 ± 7.3 a ●
Ampligo	3	75.0 ± 7.6 a ●	3.3 ± 3.3 c	0.0 ± 0.0 e	21.7 ± 6.7 b ●

● Indicates when post-emergence treatments were applied.
Means within a column followed by the same letter are not significantly different (SNK, $P = 0.05$).
[a] Seed not treated with Fortenza Duo.

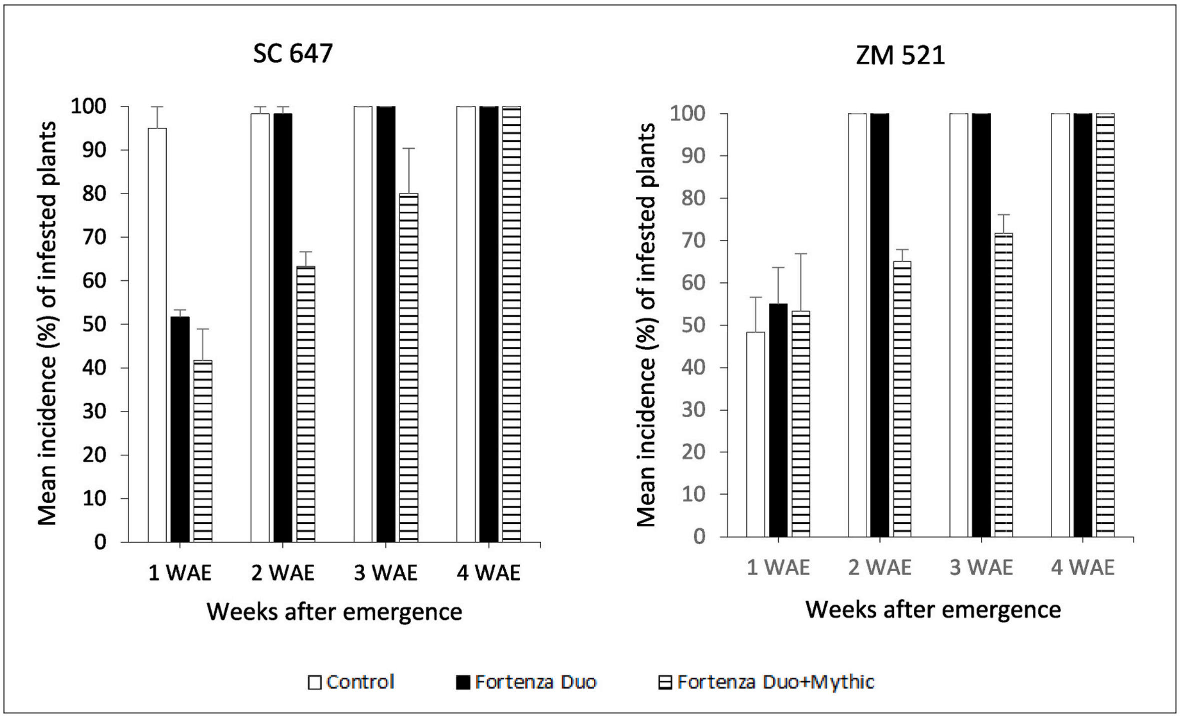

Fig. 1. Incidence of FAW-infested plants (%) recorded weekly in different treatments within two maize varieties during four weeks of assessments in February–March 2020 (Mythic sprayed only once after baseline assessment at 1 WAE).

Table 4
Incidence of FAW-infested plants (%) (means ± SE) recorded weekly in different treatments during five weeks of assessment in January–February 2022 (21 December 2021 plantings).

Treatment	N	1 WAE	2 WAE	3 WAE	4 WAE	5 WAE
Control	3	95.0 ± 2.9 a	83.3 ± 8.8 b	83.3 ± 8.3 a	43.3 ± 6.0 b	65.0 ± 15.3 a
Denim Fit/ Ampligo	3	35.0 ± 2.9 b ●	0.0 ± 0.0 c	11.7 ± 7.3 b	41.7 ± 6.7 b ●	1.7 ± 1.7 b
Fortenza Duo	3	23.3 ± 8.3 b	15.0 ± 5.0 c	46.7 ± 18.6 b	43.3 ± 11.7 b	58.3 ± 24.6 a
Fortenza	3	93.3 ± 4.4 a	100 a	93.3 ± 3.3 a	70.0 ± 7.6 a	78.3 ± 6.7 a
Fortenza Duo + Denim Fit/ Ampligo	3	46.7 ± 19.2 b ●	5.0 ± 2.9 c	13.3 ± 4.4 b	36.7 ± 8.3 b ●	3.3 ± 3.3 b
Fortenza + Denim Fit/Ampligo	3	40.0 ± 12.6 b ●	0.0 ± 0.0 c	23.3 ± 10.9 b ●	16.7 ± 1.7 c	11.7 ± 4.4 b

● Indicates when post-emergence treatments were applied.
Means within a column followed by the same letter are not significantly different (SNK, $P = 0.05$).

Table 5
Incidence of FAW-infested plants (%) (means ± SE) recorded weekly in different treatments during five weeks of assessment in March–April 2022 (25 February 2022 plantings).

Treatment	N	1 WAE	2 WAE	3 WAE	4 WAE	5 WAE
Control	3	76.7 ± 4.4 a	90.0 ± 5.8 a	95.0 ± 5.0 a	100 a	100 a
Denim Fit/ Ampligo	3	75.0 ± 17.6 a ●	41.7 ± 7.3 b ●	41.7 ± 3.3 c	91.7 ± 4.4 a ●	65.0 ± 12.6 b
Fortenza Duo	3	25.0 ± 7.6 b	65.0 ± 5.8 ab	83.3 ± 9.3 ab	100 a	100 a
Fortenza	3	20.0 ± 5.8 b	40.0 ± 18.9 b	95.0 ± 2.9 a	100 a	96.7 ± 3.3 a
Fortenza Duo + Denim Fit/ Ampligo	3	11.7 ± 3.3 b	55.0 ± 5.0 b ●	63.3 ± 4.4 bc	95.0 ± 2.9 a ●	63.3 ± 6.0 b
Fortenza + Denim Fit/Ampligo	3	13.3 ± 3.3 b	61.7 ± 3.3 ab ●	70.0 ± 2.9 bc	93.3 ± 3.3 a ●	80.0 ± 7.6 b

● Indicates when post-emergence treatments were applied.
Means within a column followed by the same letter are not significantly different (SNK, $P = 0.05$).

the five weeks of assessment (Table 7). In contrast, damage in sole Fortenza Duo plots remained lower relative to the untreated control up to termination of assessments. When compared to the treatments in which follow-on Denim Fit/Ampligo sprays were applied, sole Fortenza Duo plots had statistically the same level of damage at 1 and 2 WAE but higher thereafter. From 1 to 4 WAE, damage in Fortenza Duo plots supplemented with chemical sprays and in plots established from untreated seed and under rotational sprays of Denim Fit and Ampligo was low (below 1.5) and statistically similar. Compared between themselves, damage in plots under Fortenza Duo + Denim Fit/Ampligo and Fortenza + Denim Fit/Ampligo was below 1.0 and statistically similar during the first three weeks. Thereafter, damage in the former, though less than 1.75, was significantly higher than that in Fortenza + Denim Fit/Ampligo plots.

In the second plantings of the 2021-22 season, plant damage in all seed treatments (sole or needing supplementation with chemical sprays) remained significantly ($P < 0.01$) lower relative to the untreated control throughout the five weeks of assessment (Table 8). However, damage in sole Fortenza Duo or sole Fortenza plots, though still significantly lower than in the untreated control, was above 5.0 on termination of assessments. In comparison, where threshold-based sprays of Denim Fit/Ampligo were applied in plots established from untreated seed, the first spray at 1 WAE followed by two more at 2 and 4 WAE ensured that damage was maintained below 1.5 up to termination of assessments.

4.3. *Yield and yield increase over untreated*

In the December 2021 plantings, grain yields were similar and highest (6.55–6.94 tonnes/ha) in the Denim Fit/Ampligo and Fortenza Duo + Denim Fit/Ampligo plots while the lowest were recorded in the

Table 6
Plant damage scores (means ± SE) recorded weekly in different treatments during four weeks of assessment in January–February 2019.

Treatment	N	1 WAE	2 WAE	3 WAE	4 WAE
Control	3	1.62 ± 0.14 a	2.93 ± 0.38 a	3.65 ± 0.67 a	7.18 ± 0.02 a
Fortenza Duo	9	0.59 ± 0.09 b	1.47 ± 0.06 b	2.40 ± 0.15 b	6.01 ± 0.29 ab
Ecoterex	6	1.55 ± 0.27 a ●	0.93 ± 0.10 bc	1.60 ± 0.07 bc ●	5.27 ± 0.35 b
Denim Fit	3	1.83 ± 0.51 a ●	0.97 ± 0.07 bc	1.03 ± 0.08 cd	3.77 ± 0.42 c ●
Ampligo	3	1.18 ± 0.12 ab ●	0.62 ± 0.07 c	0.32 ± 0.04 d	0.93 ± 0.14 d ●

● Indicates when post-emergence treatments were applied.
Means within a column followed by the same letter are not significantly different (SNK, $P = 0.05$).

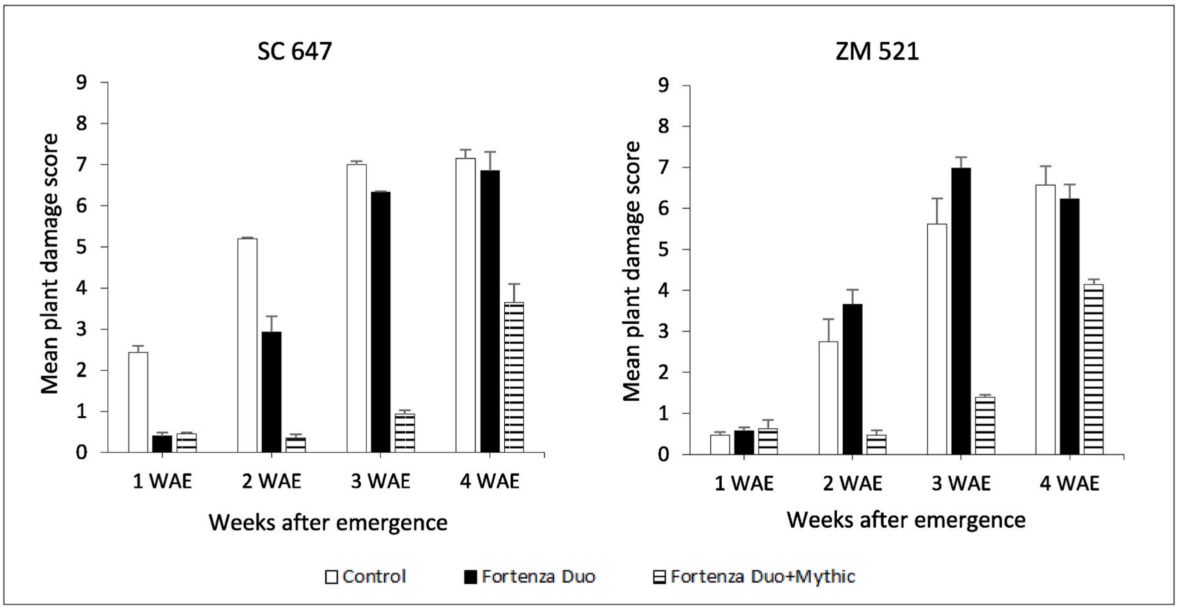

Fig. 2. Plant damage scores (means ± SE) recorded weekly in different treatments within two maize varieties during four weeks of assessment in January–February 2020 (Mythic sprayed only once after baseline assessment at 1 WAE).

Table 7
Plant damage scores (mean ± SE) recorded weekly in different treatments during five weeks of assessment in January–February 2022 (21 December 2021 plantings).

Treatment	N	1 WAE	2 WAE	3 WAE	4 WAE	5 WAE
Control	60	1.93 ± 0.13 b	3.33 ± 0.18 b	4.62 ± 0.23 b	3.80 ± 0.20 b	4.65 ± 0.19 b
Denim Fit/ Ampligo	60	0.37 ± 0.07 c ●	0.62 ± 0.10 c	0.73 ± 0.09 d	1.33 ± 0.08 d ●	1.08 ± 0.04 e
Fortenza Duo	60	0.23 ± 0.06 c	0.75 ± 0.11 c	2.02 ± 0.19 c	2.80 ± 0.21 c	3.27 ± 0.26 c
Fortenza	60	2.30 ± 0.13 a	4.23 ± 0.16 a	5.12 ± 0.21 a	4.45 ± 0.18 a	5.40 ± 0.14 a
Fortenza Duo + Denim Fit/ Ampligo	60	0.52 ± 0.08 c ●	0.85 ± 0.13 c	0.92 ± 0.11 d	1.48 ± 0.09 d ●	1.70 ± 0.11 d
Fortenza + Denim Fit/ Ampligo	60	0.45 ± 0.08 c ●	0.63 ± 0.09 c	0.78 ± 0.13 d ●	0.85 ± 0.07 e	1.13 ± 0.10 e

● Indicates when post-emergence treatments were applied.
Means within a column followed by the same letter are not significantly different (SNK, $P = 0.05$).

Table 8
Plant damage scores (mean ± SE) recorded weekly in different treatments during five weeks of assessment in March–April 2022 (25 February 2022 plantings).

Treatment	N	1 WAE	2 WAE	3 WAE	4 WAE	5 WAE
Control	60	1.45 ± 0.15 a	3.53 ± 0.12 a	5.23 ± 0.14 a	5.37 ± 0.13 a	5.97 ± 0.11 a
Denim Fit/ Ampligo	60	1.42 ± 0.15 a ●	1.48 ± 0.09 b ●	1.02 ± 0.02 c	1.18 ± 0.05 d ●	1.30 ± 0.06 c
Fortenza Duo	60	0.05 ± 0.03 b	0.92 ± 0.10 c	2.42 ± 0.18 c	2.82 ± 0.28 c	5.53 ± 0.09 b
Fortenza	60	0.08 ± 0.04 b	1.32 ± 0.07 b	2.58 ± 0.13 b	4.45 ± 0.12 b	5.43 ± 0.10 b
Fortenza Duo + Denim Fit/ Ampligo	60	0.03 ± 0.02 b	0.97 ± 0.02 c ●	1.07 ± 0.04 c	1.38 ± 0.06 d ●	1.40 ± 0.07 c
Fortenza + Denim Fit/ Ampligo	60	0.02 ± 0.02 b	1.53 ± 0.08 b ●	1.20 ± 0.06 c	1.37 ± 0.06 d ●	1.27 ± 0.06 c

● Indicates when post-emergence treatments were applied.
Means within a column followed by the same letter are not significantly different (SNK, $P = 0.05$).

untreated control and sole Fortenza plots (Table 9). In the February 2022 plantings, the highest yield (6.96 tonnes/ha) was recorded in the Fortenza Duo + Denim Fit/Ampligo plots and the lowest in the untreated control, Denim Fit/Ampligo and sole Fortenza plots. In decreasing order of magnitude, mean yield increase over untreated was Fortenza Duo + Denim Fit/Ampligo > Denim Fit/Ampligo > Fortenza Duo and Fortenza + Denim Fit/Ampligo > Fortenza in the December 2021 plantings. In the February 2022 plantings, the order was Fortenza Duo + Denim Fit/Ampligo > Fortenza Duo > Fortenza + Denim Fit/ Ampligo > Denim Fit/Ampligo > Fortenza.

Table 9
Estimated grain yields (means ± SE) and yield increase over untreated (%) recorded in different treatments from the 21 December 2021 and 25 February 2022 plantings.

Treatment	N	21st Dec 2021 planting		25th Feb 2022 planting	
		Yield (t/ha)	Yield increase over untreated (%)	Yield (t/ha)	Yield increase over untreated (%)
Control	60	5.12 ± 0.16 c	–	4.78 ± 0.21 bc	–
Denim Fit/ Ampligo	60	6.55 ± 0.16 ab	21.9	4.99 ± 0.22 bc	4.3
Fortenza Duo	60	6.04 ± 0.14 b	15.2	5.41 ± 0.19 b	11.7
Fortenza	60	4.99 ± 0.22 c	−2.6	4.32 ± 0.27 c	−10.7
Fortenza Duo + Denim Fit/ Ampligo	60	6.94 ± 0.17 a	26.2	6.96 ± 0.35 a	31.4
Fortenza + Denim Fit/ Ampligo	60	6.03 ± 0.16 b	15.0	5.35 ± 0.12 b	10.7

Means within a column followed by the same lowercase letter are not significantly different (SNK, $P = 0.05$).

4.4. Cost-benefit analyses of different FAW treatments

In the December 2021 plantings, FAW control through planting Fortenza Duo-treated seed supplemented with Denim Fit/Ampligo sprays resulted in a cost-benefit ratio of 2.17, and this was almost identical to that obtained when only chemical sprays were used on plots established from untreated seed (Table 10). Planting Fortenza Duo-treated seed and not controlling FAW at all gave an even higher cost-benefit ratio. Meanwhile, the lowest and negative (−2.82) cost-benefit ratio was obtained when Fortenza-treated seed was planted with no accompanying post-emergence chemical sprays.

For the February 2022-planted crop, planting Fortenza Duo-treated seed and not controlling FAW at all gave a cost-benefit ratio higher than that obtained with planting Fortenza Duo-treated seed and spraying Denim Fit/Ampligo as needed (Table 11). In contrast, a negative cost-benefit ratio was obtained when Denim Fit/Ampligo were sprayed in plots established from untreated seed. As was observed in the December 2021 plantings, using Fortenza-treated seed and not controlling FAW at all resulted in the lowest and negative cost-benefit ratio.

5. Discussion

The use of systemic seed treatments for controlling leaf-chewing lepidopteran larvae is relatively novel compared to their use for controlling sap-suckers. Their integration into IPM programs offers targeted and timely control of insect pests which are highly damaging at the seedling stage. The results of the trials provide evidence of the effectiveness of a cyantraniliprole (600 g/L) + thiamethoxam (600 g/L) seed treatment mixture for fall armyworm management in the early growth stages of maize. Unless they are assessing for crop germination, many smallholder African farmers are yet to appreciate the need to commence scouting for FAW in maize shortly after crop emergence. Thus, by providing significant protection against the pest right from the moment the crop emerges, Fortenza Duo gives the farmer an opportunity to attend to other critical field operations.

Although the 2020 results did not follow the same pattern as observed in 2019, there were a pointer on the likely effects of different maize genotypes on the incidence of FAW-infested plants and severity of plant damage. Thus, relative to the open pollinated variety ZM 521, the hybrid SC 647 could be more attractive to gravid FAW moths as well as being more palatable to larvae in the early growth stages hence the higher infestation and damage levels observed in plots of the latter. De La Rosa-Cancino et al. (2016) also pointed out the consequent but unintentional loss of natural defensive traits to insect herbivory in many modern varieties of maize due to selective breeding.

Changes in incidence of FAW-infested plants and damage over time in the Fortenza Duo plots could provide some indication of the duration of effectiveness of the translocated active ingredients in the seed treatment. Residual efficacy lasting for a period of between three and five weeks after crop emergence is very significant in terms of number of follow-on chemical sprays that may be needed. In the February 2022 plantings, follow-on sprays were needed at 1 and 4 WAE (Denim Fit) and 2 WAE (Ampligo) in untreated seed plots. In contrast, in Fortenza Duo plots, follow-on sprays were needed at 2 WAE (Denim Fit) and 4 WAE (Ampligo), and at 2 and 3 WAE, respectively, in plots established from

Table 10
Estimation of cost-benefit ratios of different treatments in the 21 December 2021 plantings.

Factors	Control (Untreated seed)	Untreated seed + Chemicals	Fortenza Duo	Fortenza	Fortenza Duo + Chemicals	Fortenza + Chemicals
Fortenza Duo* (584 ml/100 kg) @$157.05/L but 146 ml is enough for 1 ha (25 kg seed)] (US$/ha)	0.00	0.00	22.93	0.00	22.93	0.00
Fortenza (292 ml/100 kg) @$97/L but for 1 ha (25 kg seed), 146 ml is enough] (US$)	0.00	0.00	0.00	14.16	0.00	14.16
Cost of Denim Fit (150 g needed for a single spray) @ $1.70/ 5 g satchet (US$/ha)	0.00	51.00[a]	0.00	0.00	51.00[a]	51.00[a]
Cost of Ampligo @ $145.04/L (200 ml enough for a single spray) (US$/ha)	0.00	29.01[b]	0.00	0.00	29.01[b]	29.01[b]
Spraying cost @ $2/person/5 h day x 3 people for a single spray (US$/ha)	0.00	12.00[c]	0.00	0.00	12.00[c]	12.00
Total cost	*0.00*	*92.01*	*22.93*	*14.16*	*114.94*	*106.17*
Yield (ton/ha)	5.12	6.55	6.04	4.99	6.94	6.03
Return from harvest (US$) @ $200/ton)	1,024.00	1,310.82	1,207.38	998.28	1,387.44	1,205.00
Benefit/ha [Return *less* Cost of control] (US$)	1024.00	1,218.81	1,184.45	984.12	1,273.06	1,098.83
Cost-benefit ratio [Treated benefit *minus* Untreated benefit) ÷ Cost of control]		2.12	7.00	−2.82	2.16	0.70

*A discount of US$9.95 was given as Fortenza 600 FS (US$97/L) and Cruiser 600 FS (US70/L) were sold as a "combo" for seed treatment.
[a] Number of Denim Fit sprays = 1.
[b] Number of Ampligo sprays = 1.
[c] Number of spray operations = 2.

Table 11
Estimation of cost-benefit ratios of different treatments in the 25 February 2022 plantings.

Factors	Untreated seed	Untreated seed + Chemicals	Fortenza Duo	Fortenza	Fortenza Duo + Chemicals	Fortenza + Chemicals
Fortenza Duo (584 ml/100 kg) @$157.05/L but 146 ml is enough for 1 ha (25 kg seed) (US$/ha)	0.00	0.00	22.93	0.00	22.93	0.00
Fortenza (292 ml/100 kg) @$97/L but for 1 ha (25 kg seed), 146 ml is enough] (US$)	0.00	0.00	0.00	14.16	0.00	14.16
Cost of Denim Fit (150 g needed for a single spray) @ $1.70/5 g satchet (US$/ha)	0.00	102.00[a]	0.00	0.00	51.00[b]	51.00[b]
Cost of Ampligo @ $145.04/L (200 ml enough for a single spray) (US$/ha)	0.00	29.01[c]	0.00	0.00	29.01[c]	29.01[c]
Spraying cost @ $2/person/5 h day x 3 people for a single spray (US$/ha)	0.00	18.00[d]	0.00	0.00	12.00[e]	12.00[e]
Total cost	*0.00*	*149.01*	*22.93*	*14.16*	*114.94*	*106.17*
Yield (ton/ha)	4.78	4.99	5.41	4.32	6.96	5.35
Return from harvest (US$) @ $200/ton)	955.30	998.36	1,081.70	863.04	1,392.44	1,070.36
Benefit/ha [Return *less* Cost of control] (US$)	955.30	849.35	1,058.77	848.88	1,277.50	964.19
Cost-benefit ratio [Treated benefit *minus* Untreated benefit) ÷ Cost of control]		−0.71	4.51	−7.51	2.80	0.08

[a] Number of Denim Fit sprays = 2.
[b] Number of Denim Fit sprays = 1.
[c] Number of Ampligo sprays = 1.
[d] Number of spray operations = 3.
[e] Number of spray operations = 2.

Fortenza-treated seed. If extrapolated to hundreds of thousands of farmers in a country who rely on curative chemical sprays for managing FAW, that one extra spray needed in plots established from untreated seed is a significant cost to the national economy.

Due to cost constraints, smallholder farmers generally cannot afford to buy two insecticides to apply in rotation and rely on expert advice on the best chemical to buy and how to schedule its application. In a study in Ghana to evaluate the effectiveness of two rates of Ampligo (200 and 240 ml/ha) for FAW control in maize, Osaye et al. (2022) reported needing only two sprays of each rate but applied at 1 and 2 WAE to effectively bring down FAW damage from a baseline of 3.0 at 1 WAE and maintain it between 0 and 2.0 up to 63 days after crop emergence. Based on these findings, they went on to conclude that two sprays of Ampligo at 200 ml/ha applied between 14 and 21 days after crop emergence were enough to keep incidence of infested plants and damage low for the entire cropping season. However, caution needed to have been exercised before reaching this conclusion. For instance, no consideration was made of the fact that FAW larval numbers across all treatments, including the untreated control, had also fallen sharply from 35 DAE, with no significant differences among the treatments. In addition, the fact that the results were obtained from a single-season and single-location trial should have been considered as well.

An inconclusive result from the current study was on the effectiveness of cyantraniliprole (Fortenza 600 FS) when used alone for treating maize seed. While results from the December 2021 plantings showed Fortenza performing poorly throughout the five weeks of assessment, an opposite result was obtained from the February 2022 plantings. This calls for more multi-location trials before firm conclusions can be made on the effectiveness of cyantraniliprole 600 g/L as a sole seed treatment.

In India, Suganthi et al. (2022) reported chlorantraniliprole 625 FS applied at 6 ml/kg of seed as being the most effective treatment against FAW while cyantraniliprole + thiamethoxam 19.8 FS combinations applied at 4 and 8 ml/kg were ineffective. However, a perusal of the tabulated results by Suganthi et al. (2022) showed that these conclusions were reached based on misinterpretations of their own data. The correct inference should have been that in both the first and second seasons, chlorantraniliprole 625 FS applied at 6 ml/kg and cyantraniliprole + thiamethoxam 19.8 FS applied at 8 ml/kg had statistically similar FAW plant damage scores at 6–12 and 20 DAE. A further claim by Suganthi et al. (2022) of chlorantraniliprole 625 FS (6 ml/kg) being more effective and residual action persisting for >26 days based on bioassays using 1st instar larvae may also not be reflective of all field situations where infestations can be initiated by older instars crawling from outside the field. These older larvae would consume more leaf biomass (hence causing elevated damage) before succumbing to the chemical poison. Notwithstanding differences in formulation concentrations between Fortenza Duo (cyantraniliprole 600 g/L + thiamethoxam 600 g/L) used in the current study and cyantraniliprole + thiamethoxam 19.8 FS or chlorantraniliprole 625 FS used by Suganthi et al. (2022), it is clear that seed treatments based on diamides have a role in FAW IPM but more multi-location validations are needed.

Although thiamethoxam is known to have a high level of efficacy against hemipterans, its combination with cyantraniliprole in maize seed treatment helps to limit damage by root-feeding insects such as wireworms (e.g., Morales-Rodriguez and Wanne, 2015; Zhang et al., 2017) thus optimizing absorption of water and nutrients and ultimately resulting in vigorous and faster-growing plants. Another benefit of the Fortenza Duo (cyantraniliprole + thiamethoxam) maize seed treatment is that the neonicotinoid protects seed carried over to the next planting season from damage by beetle pests of stored grain of which the lesser grain borer, *Rhyzopertha dominica* (F.) and larger grain borer, *Prostephanus truncatus* (Horn) are the most susceptible (Tsaganou et al., 2021). The vigor-enhancing effects of thiamethoxam as reported by Afifi et al. (2015) were not investigated in the current study.

Data on yield, yield increase over untreated and cost-benefit ratios obtained from the 2021-22 season trials were indicative of the relative benefits that may accrue from planting treated or untreated maize seed and with or without accompanying chemical sprays. However, in the absence of multi-location and multi-seasonal validations, the cost-benefit ratios obtained with some treatments may be too simplistic and unrealistic for most field situations. Nevertheless, in the case of the Fortenza Duo + Denim Fit/Ampligo treatment, extrapolation of these data to national seasonal hectarages under maize may translate into significant savings in FAW control operations, a rise in national maize production figures as well as income security to many farmers. The need for fewer follow-on chemical sprays in fields established from Fortenza

Duo-treated maize seed also reduces potential exposure of millions of smallholder farmers to harmful synthetic chemical pesticide residues.

Results of the current study add to the increasing body of evidence on the effectiveness and usefulness of diamides in FAW IPM. Since formulations of these diamides are used both as seed treatments and foliar sprays, it is important to carefully manage their use to lessen selection pressure for resistance development. The use of Denim Fit [emamectin benzoate (an avermectin) + lufenuron (an insect growth regulator)] first followed by Ampligo [chlorantraniliprole (a diamide) + lambda cyhalothrin (pyrethroid)] in the rotational spray schedules adopted for the current study was deliberate. In case FAW larvae being exposed to translocated cyantraniliprole already had some resistance to the diamide, the use of Denim Fit in the same window is expected to eliminate many individuals carrying diamide-resistant/tolerant genes. Having eliminated these resistant individuals, a diamide + pyrethroid combination (Ampligo) would then be applied to quickly wipe out the survivors. By the time Denim Fit is needed again (5–6 WAE), this would likely be the last spray as the crop would shortly thereafter be at tasseling and silking stage. As well as not wanting to leave residues which would harm pollinators, a 6-7-week-old maize crop would be too tall to be sprayed safely without the spray mix drifting into the operator's face.

While the IPM strategy investigated in the current trials involved supplementation of Fortenza Duo with action threshold-based sprays of Denim Fit and Ampligo within the first 4–5 weeks of crop growth, this does not preclude the use of other effective plant protection products. Most of these are synthetic chemicals formulated for application as sprays. The inclusion of Ecoterex® 0.5 GR (deltamethrin 0.1% + pirimiphos methyl 0.4%) in the 2018-19 cropping season was aimed at determining if effective FAW control could also be achieved by selective targeting of larvae inside plant whorls using a granular insecticide formulation. Williams et al. (2004) reported excellent control of FAW larvae by ultralow rates of the naturally derived insecticide spinosad applied as flour-based granules to maize whorls. Other eco-friendly technologies such as smearing of grease to the maize whorl or tip of a drooping leaf that touched the soil (Kushwaha, 2022) were reported to be very effective in controlling FAW and require further validation.

Variable efficacy results among the different post-emergence insecticides used in the current study may be indicative of differences in susceptibility of local populations of FAW to one or more of the active ingredients in the formulations. In China, Zhao et al. (2020) reported higher susceptibility of FAW to emamectin benzoate, spinetoram, chlorantraniliprole, chlorfenapyr, and lufenuron but lower susceptibility to lambda cyhalothrin and azadirachtin. Bird et al. (2022) reported reduced toxicity of emamectin benzoate, chlorantraniliprole and methoxyfenozide on field populations of FAW in Australia during the first year of its establishment in the country. Denim Fit, Ampligo and Ecoterex are binary formulations for which one or both active ingredients in each product could be slowly losing their toxicity to FAW due to evolving resistance. It is thus imperative to have in place a proper FAW insecticide resistance monitoring and management strategy in a country or within a region. However, the biggest obstacle to such an initiative could be the tendency by many African Governments to include FAW pesticides among the agricultural inputs given to smallholder farmers. These pesticides are generally distributed with no consideration given to the need to rotate the insecticide classes.

The value of regular field scouting is also very important not only in effective and timely targeting of FAW eggs and larvae but also in lengthening the lifespans of the few plant protection products that we can still rely on to control the pest (Prasanna et al., 2018; Tepa-Yotto et al., 2021). The action threshold of 20% (range 10–30%) used in the current study for post-emergence treatments was adopted from the recommendation by Prasanna et al. (2018). However, as noted in this study, FAW infestations in all three seasons and across all treatment plots were detected as early as the first day after crop emergence. Thus, it could be that where FAW infestation commences soon after crop emergence, use of the lower limit in the 10–30% action threshold range (10%) rather than the middle rate (20%) would have lowered damage even further.

In conclusion, there are two main benefits in harnessing Fortenza Duo and other validated seed treatments for FAW management. Firstly, the technology comes ready-for-use in a seed pack and therefore is easily scalable. Secondly, seed treatments cannot be "washed away by rain" as is the case with post-emergence insecticide treatments where incessant rains may hamper application as well as field scouting. Due to method of application and systemic action, Fortenza Duo seed treatment appear to be a perfect fit in FAW IPM programs where there is need for judicious pesticide use. For a pest that is migratory, lacks a resting stage and is adaptable to a wide range of ecological conditions, three key recommendations arise from this study: more multi-location validations, studies to determine the influence of planting dates and edaphic factors, and studies to determine the influence of seed treatments on plant vigor and yield under different IPM treatment combinations and with maize variety as a factor.

CRediT authorship contribution statement

Peter Chinwada: Conceptualization, Methodology, Data curation, Writing – original draft, preparation, Writing – review & editing. **Komi Kouma Mokpokpo Fiaboe:** Writing – review & editing. **Chrysantus Akem:** Writing – review & editing. **Alfred Dixon:** Writing – review & editing. **David Chikoye:** Writing – review & editing, All authors have read and agreed to the published version of the manuscript.

Declaration of competing interest

The authors declare no conflict of interest.

Data availability

Data will be made available on request.

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