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Early-invasion efficacy of commercial Bacillus thuringiensis, Beauveria bassiana and azadirachtin biopesticides against fall armyworm (Spodoptera frugiperda) on maize in Zimbabwe

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Abstract

The fall armyworm (FAW), *Spodoptera frugiperda* (J.E. Smith), is a permanent pest of maize in sub-Saharan Africa, and smallholder control still relies largely on synthetic insecticides. We report laboratory and field data collected in Zimbabwe in 2017–2018, within two seasons of the pest's arrival, and reanalysed with current methods. Three commercial biopesticides, Delfin WG (*Bacillus thuringiensis* subsp. *kurstaki*), Dynamo (*Beauveria bassiana*) and ACHTA (azadirachtin), were compared with Super Dash (emamectin benzoate + acetamiprid) and an untreated control. In a laboratory bioassay on second-instar larvae (16 vials × 4 larvae per treatment), the biopesticides caused 73–84% mortality by 14 days after treatment (DAT) and could not be distinguished from one another, but Super Dash (98%) killed more larvae than each of them (Holm-adjusted $P = 0.011–0.021$). Median lethal times were 7.1–9.5 d for the biopesticides and 2.7 d for Super Dash. In a winter field trial at Muzarabani (three blocks), negative binomial mixed models showed that Delfin and Dynamo reduced live larvae per plant by 87–96% relative to the untreated control at all three application rates ($P \leq 0.003$), similar to Super Dash (86%, 95% CI 39–97%); the trial was too small to separate the products. ACHTA did not significantly reduce larval density (45–61%). The records were recovered after a computer failure, and product, exposure and weather details were not preserved, so the results are a historical baseline and not a basis for current recommendations.

1. Introduction

Maize (*Zea mays* L.) is the staple food crop of Zimbabwe and underpins the food security and income of most smallholder households (Matova et al. 2020; Tambo et al. 2021). The fall armyworm (FAW), *Spodoptera frugiperda* (J.E. Smith) (Lepidoptera: Noctuidae), was first reported in West and Central Africa in 2016 (Goergen et al. 2016) and reached Zimbabwe during the 2016/17 season. It has since become established across the continent (Kenis et al. 2023; Togola et al. 2025). Its polyphagy, high fecundity, lack of diapause and capacity for long-distance migration explain both its rapid spread and its persistence (Early et al. 2018; Kenis et al. 2023). In Zimbabwe, FAW damage and associated yield losses have been quantified on smallholder farms (Baudron et al. 2019), and the invasion has been linked to measurable losses in household income and food security (Tambo et al. 2021).

The initial response across sub-Saharan Africa relied heavily on synthetic insecticides, often applied without protective equipment or at non-label rates (Chimweta et al. 2020; Tambo et al. 2023). Nearly a decade later, this dependence remains the dominant FAW management practice, and the reasons to reduce it have become stronger. First, FAW has evolved field resistance to most major insecticide classes in the Americas and Asia, and resistance monitoring in Africa remains patchy (Gutiérrez-Moreno et al. 2019; Van den Berg and du Plessis 2022). Second, regulators are tightening residue limits for older chemistries. The European Food Safety Authority, for example, recommended lower toxicological reference values and maximum residue levels for acetamiprid in 2024, one of the two active ingredients in the synthetic standard used here (EFSA 2024). Third, Bt maize, the main non-chemical tool for lepidopteran control elsewhere, is approved for cultivation in only a few African countries. Zimbabwe

prohibits commercial cultivation of genetically modified maize (USDA FAS 2024), and FAW has already evolved resistance to Bt maize in the Americas (Horikoshi et al. 2016; Van den Berg et al. 2021). Finally, irrigation and a warming climate are extending the periods and areas in which FAW can breed year-round (Timilsena et al. 2022). This increases the number of generations exposed to whatever control tactic is used.

Biopesticides are therefore central to FAW integrated pest management (IPM) in Africa (Bateman et al. 2021; Kenis et al. 2023). *Bacillus thuringiensis* (Bt) Cry toxins kill lepidopteran larvae by binding midgut receptors and forming pores in the epithelium (Pacheco et al. 2023). The entomopathogenic fungus *B. bassiana* infects through the cuticle, colonises the haemocoel and produces insecticidal metabolites (Mascarin and Jaronski 2016). Azadirachtin, the principal limonoid of neem (*Azadirachta indica*), acts as an antifeedant and growth regulator. In FAW it blocks larval ecdysis by suppressing ecdysteroid signalling (Kilani-Morakchi et al. 2021; Fan et al. 2023), and it has controlled FAW larvae in soil-drench experiments (Acharya et al. 2023). Field studies in Ghana, Senegal and Burkina Faso show that Bt-, fungus- and neem-based products can reduce FAW density and damage (Agboyi et al. 2023; Sarr et al. 2023; Frimpong-Anin et al. 2025; Sanon et al. 2025). Efficacy is, however, product-specific. Commercial *B. bassiana* formulations registered in South Africa against other pests failed to kill second- and sixth-instar FAW larvae in recent laboratory tests (Louw et al. 2025). A global review of FAW biological control likewise highlights the shortage of well-replicated field data from Africa and of transparent, standardised analyses (Wyckhuys et al. 2024).

In this context, efficacy data on the specific commercial products available to Zimbabwean farmers remain scarce, and data from the early-invasion period are particularly scarce. The present study was conducted in 2017 and early 2018, within two seasons of FAW reaching Zimbabwe. We report it here with a reanalysis of the recovered raw data, using methods that respect the experimental unit, account for count overdispersion and estimate speed of kill. The objectives were to (i) quantify the laboratory efficacy and speed of kill of Delfin (Bt), Dynamo (*B. bassiana*) and ACHTA (azadirachtin) against second-instar FAW larvae relative to a synthetic standard; (ii) quantify their effect on live larval density under natural field infestation in a winter-season trial at Muzarabani; and (iii) test whether deviations of ± 10% from the label rate, typical of uncalibrated knapsack application, alter efficacy.

2. Materials and methods

2.1. Study sites and timing

Field and laboratory work were done in 2017 and early 2018. The field trial reported here was conducted at Muzarabani, Mashonaland Central province (16°19'48.4"S, 31°10'15.74"E; Natural Region IV), a hot, low-lying area with 450–650 mm annual rainfall, as a winter (dry-season) trial in 2017. A second field trial was conducted at Seed Co's Rattray Arnold Research Station (RARS) in the following summer season (2017/18). Its data are not reported because the numeric codes identifying its treatments could not be verified against original records (Section 2.5). Laboratory bioassays were conducted in early 2018

at the Plant Protection Research Institute, Department of Research and Specialist Services (DRSS), Harare (17°48'23.7"S, 31°03'06.7"E). Exact planting, spraying and assessment dates and the irrigation records were not preserved, and weather was not measured.

2.2. Products

Three commercial biopesticides were tested (Table 1): Delfin WG (*B. thuringiensis* subsp. *kurstaki*; label rate 1.0 kg ha^{-1}), Dynamo (*B. bassiana*; 2.5 kg ha^{-1}) and ACHTA (azadirachtin; 1.0 L ha^{-1}). The reference (positive control) was Super Dash (emamectin benzoate + acetamiprid; 500 mL ha^{-1}), and water served as the untreated control. Batch numbers, expiry dates and storage conditions were recorded at the time, but those records have been lost. The manufacturers, the Bt and fungal strains, the formulation types and the concentrations of active ingredient are not available, and no check of Bt potency or conidial viability is documented. The results therefore apply to the named products as sold at the time and cannot be attributed to a specific strain or concentration.

2.3. Field trial

The Muzarabani trial comprised 11 treatments (untreated control; each biopesticide at the label rate and at + 10% and − 10% of it; Super Dash at the label rate) arranged in a randomised complete block design with three blocks. The randomisation was generated in GenStat. Each plot was six rows of maize (variety SC 403), 4.5 m long, sown at 0.9 m between rows and 0.3 m within rows. Blocks were separated by guard strips of five maize rows. Plants were infested naturally. Larval numbers were assessed before spraying, but those pre-spray counts are not in the recovered dataset and were not used; injury scores and larval instars were not recorded. Fifteen plants per plot (five in each of three central rows, chosen in a systematic serpentine pattern) were tagged, and the same plants were assessed on every date. Treatments were applied once as foliar sprays with a 16 L manual knapsack sprayer five weeks after emergence, directed into the whorl. The untreated control was sprayed with water and sampled in the same way. Spray volume per hectare, nozzle type and calibration were not recorded. Live and dead larvae on each tagged plant were counted at 3, 7, 10 and 14 days after treatment (DAT), and dead larvae were removed at each assessment. Individual larvae were not tracked.

2.4. Laboratory bioassay

The bioassay followed Belay et al. (2012) with modifications. Five treatments (the three biopesticides and Super Dash, and a water control; Table 1) were arranged in a completely randomised design with 16 replicate vials per treatment. Vials were allocated to treatments at random, all were started on the same day, and their positions were fixed after allocation. Each 200 mL vial, closed with a perforated cap for gas exchange, held four second-instar larvae on freshly excised maize leaf tissue. Each vial contained different larvae, which had been reared under the same conditions, and all vials received the same food. Larvae came from eggs collected in a maize field at DRSS and were reared in the Plant Protection laboratory at DRSS; species identification was morphological. The generation of the larvae and the criteria used to select second instars were not recorded. Each vial was sprayed twice with a low-volume sprayer delivering 0.98 mL per application. The spray-solution concentration of each product was not

recorded and cannot be reconstructed; the authors recall that each product's concentration was kept constant among replicates. The bioassay therefore compares treatments within this study, but it cannot be converted into lethal concentrations or field-rate equivalents. Fresh maize leaves, treated with the same product, replaced the old leaves every 3 days. Temperature, relative humidity and photoperiod were not measured or logged. Dead and live larvae were recorded at 1, 3, 7, 10 and 14 DAT as new deaths since the previous assessment; larvae that did not respond to prodding were scored dead, and dead larvae were removed. Larvae were not separated within vials, and cannibalism occurred. Missing larvae and pupae were not recorded separately. A second independent run of the bioassay was also made, but its per-vial records are lost and it is not analysed here (summary means only, Table S2). Larval instars were recorded in the original study, but those records are also lost, so larval development is not reported.

2.5. Data provenance and statistical analysis

Data provenance. The raw records analysed here were recovered after a computer failure, and transcription errors cannot be excluded. Three surviving versions of the Muzarabani spreadsheet agreed closely on live larval counts but differed in dead-larva counts, so the field analysis uses live counts only. In the bioassay, five vials (ACHTA vials 3, 6 and 15; Delfin vial 44; Super Dash vial 49) have counts at 10 and/or 14 DAT in which cumulative deaths plus survivors do not equal the four larvae started (Table S3). The original records are lost and none could be corrected. Primary analyses use the recorded new deaths as entered, with the sensitivity analyses described below. The treatment key of the RARS trial, which linked numeric codes to treatments, could not be verified. Without it the RARS counts cannot be assigned to products, so that trial is excluded from all analyses.

Field trial. The primary endpoint was the number of live larvae per tagged plant at 7, 10 and 14 DAT. Counts at 3 DAT were taken after spraying, so they were not used as a pre-treatment baseline. Counts were modelled with a negative binomial (NB2) generalised linear mixed model (GLMM) with fixed effects for treatment, block and assessment date, and random intercepts for plot (the experimental unit to which treatments were randomised) and for plant within plot (the same plants were followed over dates). Block was fitted as a fixed effect because there were only three blocks; its estimated variance was negligible in earlier fits, and omitting it changed the estimates very little (Section 3.2). The model was fitted by maximum likelihood, integrating the random effects by Gauss–Hermite quadrature (25 nodes per level), and convergence was checked from the gradient and the Hessian. Treatments were compared with the untreated control by contrasts with simultaneous (Dunnett-type) adjustment from the joint normal distribution of the estimates. Field efficacy was expressed as percentage reduction in live larval density relative to the untreated control, 100 × (1 − rate ratio), with 95% confidence intervals; this is the model-based analogue of Abbott's correction for field counts (Abbott 1925). Products were compared directly with Super Dash by rate ratios averaged over the three rates. The effects of product and dose (− 10%, label, + 10%) were tested by Wald tests in a model restricted to the biopesticide plots, with Tukey-type adjustment for product pairs. Effects over time were examined in separate models for each assessment date. Model fit was checked by simulation from the fitted model (proportion of zero counts, maximum count and plot totals). As sensitivity analyses we (i) omitted block, (ii) omitted the one Super Dash plot

that held most of that treatment's larvae, and (iii) used block-restricted randomisation tests on plot totals (raw and log(1 + x)) for an overall treatment effect and for dose labels within product and block. Counts of dead larvae were recorded but not analysed as mortality: cadavers were removed, individual larvae were not tracked, larvae could fall, move or be scavenged, and no starting denominators exist.

Laboratory bioassay. The vial was the experimental unit. Cumulative mortality at 14 DAT (recorded deaths out of four larvae per vial) was tested overall by a quasi-binomial generalised linear model. Because mortality for Super Dash approached 100%, which makes logit-scale pairwise comparisons unstable, all ten pairs of treatments were compared with exact two-sided randomisation tests on vial mortality (difference in means), with Holm adjustment across the ten pairs. These tests assume random allocation of independent vials. Mortality was corrected for control mortality with Abbott's formula (Abbott 1925). Sensitivity analyses omitted the five inconsistent vials and, separately, counted the three larvae unaccounted for at 14 DAT (vials 15, 44 and 49) as dead. Speed of kill was analysed at the level of individual larvae as interval-censored time to death, since death was known only to lie between successive assessments. Larvae unaccounted for were treated as censored at 14 d. A Weibull accelerated failure-time model with cluster-robust variance by vial was used to estimate median (LT_{50}) and 90% (LT_{90}) lethal times with 95% confidence intervals (delta method, log scale). Differences among the three biopesticides were tested with a cluster-robust Wald test. LT estimates beyond the 14-day observation period are extrapolations.

Software and reanalysis note. Analyses were run in Python 3 (NumPy, SciPy, statsmodels and JAX; Virtanen et al. 2020). The laboratory quasi-binomial and Weibull models were also run in R 4.3.3 (R Core Team 2024; survival, Therneau 2024), with the same results. The script and data are provided as Supplementary Material. The data were originally analysed in GenStat with larval "mortality" computed per plant and plants treated as replicates (residual df = 482). That approach treats subsamples as independent replicates (pseudoreplication) and inflates precision. Moreover, the plot-level denominators used to express dead larvae as a percentage of a "starting population" could not be reconstructed from the raw counts. All field results reported here therefore come from the raw live counts, analysed at the plot level.

Use of generative AI tools. During preparation of this manuscript the corresponding author used Claude (Anthropic) and ChatGPT (OpenAI) to assist with language editing, reference checking, drafting of analysis code, reanalysis and a methodological review of the manuscript. The corresponding author reviewed the outputs, verified the analyses and edited the text, and takes full responsibility for the content.

Table 1
Treatments and application rates.

Code	Product	Active ingredient	Rate (ha⁻¹)	Level	Used in
UC	Water	—	—	Untreated control	Field, lab
SD	Super Dash	Emamectin benzoate + acetamiprid	500 mL	Reference	Field, lab
DE1 / DE2 / DE3	Delfin WG	*B. thuringiensis* subsp. *kurstaki*	1.10 / 1.00 / 0.90 kg	+ 10% / label / −10%	Field (DE2 also lab)
D1 / D2 / D3	Dynamo	*Beauveria bassiana*	2.75 / 2.50 / 2.25 kg	+ 10% / label / −10%	Field (D2 also lab)
A1 / A2 / A3	ACHTA	Azadirachtin	1.10 / 1.00 / 0.90 L	+ 10% / label / −10%	Field (A2 also lab)

Field = Muzarabani trial.

3. Results

3.1. Laboratory bioassay: mortality and speed of kill

Treatment strongly affected cumulative mortality at 14 DAT (quasi-binomial GLM, $F_{4,75} = 38.6$, $P < 0.001$; Table 2). Mortality was 6.3% in the control, 98.4% with Super Dash, 82.8% with Delfin, 84.4% with Dynamo and 73.4% with ACHTA (Abbott-corrected 98.3%, 81.7%, 83.3% and 71.7%). All four insecticide treatments differed from the control (Holm-adjusted $P < 0.001$). Super Dash killed 15.6, 14.1 and 25.0 percentage points more larvae than Delfin, Dynamo and ACHTA (adjusted $P = 0.011$, 0.021 and 0.013). No differences were detected among the three biopesticides (adjusted $P \geq 0.76$), but with 16 vials per treatment differences of about 10 percentage points could not be excluded. The conclusions were unchanged when the five inconsistent vials were omitted (mortality 100% for Super Dash, 83.3% Delfin, 84.4% Dynamo and 75.0% ACHTA; Super Dash versus each biopesticide, adjusted $P = 0.004$–0.006) and when the three larvae unaccounted for at 14 DAT were counted as dead (Super Dash 100%, Delfin 84.4%, Dynamo 84.4%, ACHTA 75.0%).

The products differed markedly in speed of kill (Fig. 2; Table 3). Super Dash killed 34% of larvae within 24 h and 89% by 7 DAT ($LT_{50} = 2.7$ d, 95% CI 1.9–3.7). Mortality from the biopesticides was delayed: Dynamo caused appreciable mortality from 3 DAT (31%), whereas Delfin and ACHTA acted mainly between 7 and 14 DAT. Estimated LT_{50} values were 7.1 d (Dynamo), 8.5 d (Delfin) and 9.5 d (ACHTA), all longer than for Super Dash (cluster-robust Wald, $P < 0.001$ for each), and the biopesticides could not be distinguished from one another (cluster-robust Wald $\chi^2_2 = 3.88$, $P = 0.144$). LT_{90} values for the biopesticides (16.8–22.6 d) lie beyond the 14-day observation period. They are model extrapolations and are not evidence of persistence or of a suitable spray interval.

Table 2
Cumulative mortality (%) of second-instar *S. frugiperda* larvae in the laboratory bioassay (n = 16 vials × 4 larvae = 64 larvae per treatment).

Treatment	1 DAT	3 DAT	7 DAT	10 DAT	14 DAT	Abbott-corrected 14 DAT
Untreated control	0.0	0.0	0.0	1.6	6.2 a	—
Super Dash	34.4	64.1	89.1	96.9	98.4 c	98.3
Delfin (Bt)	0.0	3.1	25.0	56.2	82.8 b	81.7
Dynamo (*B. bassiana*)	3.1	31.2	35.9	68.8	84.4 b	83.3
ACHTA (azadirachtin)	0.0	9.4	23.4	51.6	73.4 b	71.7

Recorded new deaths, cumulated. At 14 DAT, treatments sharing a letter did not differ (exact randomisation tests, Holm-adjusted $P > 0.05$). Five vials with inconsistent counts are listed in Table S3.

Table 3
Lethal times (days) of second-instar *S. frugiperda* larvae estimated from interval-censored time-to-death data (Weibull accelerated failure-time model, cluster-robust variance by vial; 95% confidence intervals on the log scale).

Treatment	LT_{50} (95% CI)	LT_{90} (95% CI)
Super Dash	2.7 (1.9–3.7)	6.3 (4.6–8.7)
Dynamo (*B. bassiana*)	7.1 (5.8–8.7)	16.8 (14.1–20.1)
Delfin (Bt)	8.5 (7.3–9.8)	20.1 (16.9–23.8)
ACHTA (azadirachtin)	9.5 (7.5–12.1)	22.6 (17.4–29.4)

LT_{90} values beyond 14 d (all three biopesticides) are extrapolations from the fitted Weibull model.

3.2. Field efficacy at Muzarabani

Treatment strongly affected live larval density (Wald $\chi^2_{10} = 77.1$, $P < 0.001$; date $\chi^2_2 = 18.5$, $P < 0.001$; block $\chi^2_2 = 1.7$, $P = 0.43$). Untreated plots carried 1.04 live larvae per plant visit (observed mean, 7–14 DAT; Table 4). All Delfin and Dynamo treatments reduced larval density significantly (Dunnett-adjusted $P \leq 0.003$): by 93–96% for Delfin and 87–94% for Dynamo, similar to the 86% reduction by Super Dash (95% CI 39–97%; Fig. 1). The confidence intervals overlap widely, and direct comparison with Super Dash did not separate them: averaged over the three rates, larval density under Delfin was 0.37 times (95% CI 0.14–1.00) and under Dynamo 0.54 times (0.20–1.43) that under Super Dash (Table S4). We therefore draw no conclusion that either biopesticide was better or worse than the standard. ACHTA reduced density by 45–61%, but no ACHTA treatment differed significantly from the control ($P \geq 0.36$); the confidence intervals (− 115% to 90%) do not exclude a moderate effect. Among the biopesticides, product had a strong effect ($\chi^2_2 = 60.7$, $P < 0.001$): larval density under ACHTA was 9.3 and 6.2 times

that under Delfin and Dynamo (95% CI 4.3–20.0 and 3.0–12.7; both $P < 0.001$), while Dynamo and Delfin did not differ detectably (rate ratio 1.50, 95% CI 0.65–3.48, $P = 0.50$). Neither dose ($\chi^2_2 = 1.16$, $P = 0.56$) nor the product × dose interaction ($\chi^2_4 = 4.23$, $P = 0.38$) was significant, and a randomisation test of dose labels within product and block agreed ($P = 0.75$). A lack of detectable dose effect is not evidence that rates are equivalent: there were three plots per rate and the range was only ± 10%.

Reductions were greatest at 7 and 10 DAT (Table S1). At 14 DAT the estimate for Super Dash was 76% ($P = 0.45$). Reductions for Delfin and Dynamo at 14 DAT were 73–98%, and remained significant for Delfin + 10% and − 10% and Dynamo at the label rate and − 10% ($P = 0.008$–0.019) but not for Delfin at the label rate (86%, $P = 0.081$) or Dynamo + 10% (73%, $P = 0.45$). These time-course contrasts rest on three plots per treatment and should not be read as evidence that the biopesticides outlasted Super Dash. Super Dash plot totals (7–14 DAT) were 4, 0 and 30 larvae: one plot in block 3 held 30 of the 34 live larvae recovered from Super Dash plots (Fig. 1b). No cause could be identified from the surviving records; spray drift between adjacent plots is one possibility that cannot be verified. The plot is included in all analyses. In a sensitivity analysis without it, the reduction by Super Dash was 97%, and density under Delfin and Dynamo was 1.7 and 2.4 times that under Super Dash (95% CI 0.5–5.7 and 0.7–8.0). The apparent decline of Super Dash by 14 DAT therefore depends largely on this plot.

Model checks gave no sign of misfit. Simulated data reproduced the proportion of zero counts (observed 79.0%; simulated 80.2%, 95% interval 76.7–83.4%) and the maximum count (observed 13; simulated median 11, 95% interval 6–28), and 94% of plot totals fell within their simulated 95% intervals. Dropping the block term changed efficacy estimates by at most 1.3 percentage points (likelihood-ratio $\chi^2_2 = 1.67$, $P = 0.44$). A block-restricted randomisation test on plot totals also detected an overall treatment effect (raw totals $P = 0.002$; log(1 + x) totals $P = 0.004$), though with three blocks it cannot resolve individual treatment contrasts.

Table 4
Live *S. frugiperda* larvae per plant at Muzarabani (7–14 DAT) and field efficacy relative to the untreated control from a negative binomial GLMM.

Treatment	Observed live larvae per plant visit	Observed reduction (%)	Model efficacy % (95% CI)	*P*
Untreated control	1.04	—	—	—
Super Dash	0.25	76	86 (39, 97)	0.002
Delfin + 10%	0.04	96	96 (79, 99)	< 0.001
Delfin label	0.09	91	93 (66, 99)	< 0.001
Delfin − 10%	0.07	94	95 (73, 99)	< 0.001
Dynamo + 10%	0.18	83	87 (43, 97)	0.001
Dynamo label	0.07	94	94 (72, 99)	< 0.001
Dynamo − 10%	0.07	94	94 (72, 99)	< 0.001
ACHTA + 10%	0.53	49	49 (-95, 87)	0.743
ACHTA label	0.65	37	45 (-114, 86)	0.865
ACHTA − 10%	0.45	56	61 (-53, 90)	0.365

Observed values are means of 45 plant visits (3 plots × 15 plants × 3 dates). Efficacy = 100 × (1 − rate ratio vs control) from the model, with Dunnett-adjusted 95% CIs and *P* values for 10 comparisons. Model: live count ~ treatment + block + date + (1 | plot) + (1 | plant), NB2.

4. Discussion

This study documents the efficacy of commercial Bt, *B. bassiana* and azadirachtin products available to Zimbabwean farmers within two seasons of FAW reaching the country. Three findings stand out. First, in the one field trial reported, Delfin and Dynamo reduced live larvae by 87–96% at all rates, a reduction similar to that of the emamectin benzoate + acetamiprid standard (86%). The trial was too small to show that either biopesticide was better or worse than the standard. Second, in the laboratory the standard killed more larvae, and killed them much faster, than any biopesticide, while the three biopesticides could not be distinguished from one another in final mortality or lethal time. Third, ACHTA reduced field larval density less (45–61%) and not significantly.

The performance of Delfin agrees with field reports of Btk products against FAW in Ghana and Senegal (Koffi et al. 2022; Agboyi et al. 2023; Sarr et al. 2023). It also agrees with a two-season Ghanaian trial in which Bt matched emamectin benzoate for larval mortality and was superior for cob damage and yield (Frimpong-Anin et al. 2025). Onset of Bt mortality at 3–7 DAT and an LT_{50} of 8.5 d are consistent with a Cry-toxin mode of action that depends on ingestion and progressive midgut damage (Pacheco et al. 2023). Zimbabwe prohibits commercial cultivation of genetically modified maize (USDA FAS 2024), so foliar Bt is currently the only practical way for farmers to use Bt toxins against FAW. It may therefore be a useful option in rotation with synthetic modes of action (Van den Berg et al. 2021).

The efficacy of Dynamo is notable given recent evidence that commercial *B. bassiana* products do not reliably kill FAW larvae. In South Africa, two registered *B. bassiana* formulations caused negligible mortality in second- and sixth-instar larvae (Louw et al. 2025). Among 12 isolates tested against FAW elsewhere, larval mortality ranged from 71% to 93% at 14 d (Idrees et al. 2022). Dynamo gave 84% mortality of second-instar larvae in the laboratory and 87–94% density reduction in the field, and it had the shortest LT_{50} of the three biopesticides, although the biopesticides could not be statistically separated. Efficacy against FAW therefore appears to depend on the product rather than on the fungal species alone. Because the strain and formulation of Dynamo could not be recovered, we cannot say which property was responsible. The results also show why commercial products need to be validated locally before they are recommended (Bateman et al. 2021; Louw et al. 2025). Fungal efficacy is sensitive to temperature, humidity and UV exposure (Mascarin and Jaronski 2016), but weather was not measured, so the role of conditions at Muzarabani cannot be assessed.

ACHTA killed 73% of larvae in the laboratory, with the slowest estimated kill (LT_{50} = 9.5 d). In the field it did not significantly reduce larval density, although its confidence intervals do not exclude a moderate effect. Azadirachtin is photolabile (Johnson et al. 2003), and the long lag before death leaves a long window in which larvae can feed and immigrate. We could not test either explanation. Field results for neem-based products against FAW have been variable (Agboyi et al. 2023; Ewansiha et al. 2023; Sarr et al. 2023). Our data are consistent with ACHTA being better regarded as a supporting component of IPM than as a stand-alone curative spray, but they do not establish this. The apparent ranking among ACHTA rates was within sampling error, and no dose-dependent response can be claimed.

The contrasting speeds of kill have practical implications. Super Dash gave rapid knockdown in the laboratory (89% mortality by 7 DAT), whereas the biopesticides needed 7–10 days to reach median kill. For smallholders this suggests that biopesticides should be applied early, against young larvae detected by regular scouting and before they move deep into the whorl or ear (Prasanna et al. 2018; Togola et al. 2025). The field data do not show that the biopesticides outlasted Super Dash. The lower Super Dash estimate at 14 DAT came mainly from a single plot, and without it Delfin and Dynamo were not lower than Super Dash. The LT_{90} estimates for the biopesticides (17–23 d) lie beyond the observation period and should not be used to infer persistence or spray intervals. No effect of ± 10% rate deviations was detected for any product, which is encouraging given that uncalibrated knapsack application is common among smallholders (Chimweta et al. 2020; Tambo et al. 2023). With three plots per rate and a range this

narrow, however, the trial cannot show that products tolerate calibration errors, and larger errors were not tested. Wider rate ranges would be needed for dose–response estimation.

Why do these 2017–2018 data matter in 2026? Resistance to synthetic insecticides in FAW continues to spread, and resistance management depends on rotating modes of action (Van den Berg and du Plessis 2022). Microbial products provide modes of action with no cross-resistance to emamectin benzoate or neonicotinoids. Regulatory pressure on residues, illustrated by the recent reassessment of acetamiprid (EFSA 2024), adds a market reason to reduce synthetic use in maize and in the horticultural crops that FAW also attacks. Dry-season maize, like the Muzarabani winter trial, can provide a "green bridge" that allows continuous FAW breeding (Timilsena et al. 2022), so tactics that are compatible with natural enemies are increasingly important (Harrison et al. 2019; Agboyi et al. 2023). Product-level results from the early-invasion period are rare for African FAW populations (Wyckhuys et al. 2024), and they give a reference point for later work, within the limits set out below.

The study has important limitations. Only one field trial is reported: a single winter season at one site with three blocks, so the confidence intervals in Table 4 are wide. A second field trial (RARS) is excluded because its treatment key could not be verified. The raw records were recovered after a computer failure, and data-entry errors cannot be excluded; five bioassay vials had inconsistent counts that could not be corrected, although conclusions did not depend on them. Cannibalism occurred in the bioassay, and missing larvae and pupae were not recorded separately. Product strain, concentration, batch and potency were not preserved, the laboratory spray concentration is unknown, and temperature, humidity, photoperiod and weather were not measured. Planting, spraying and assessment dates, spray volume and calibration are not available, and pre-spray larval counts were not recovered. The method used to identify larvae counted in the field is not documented in the surviving records. Natural infestation is realistic but variable, and continuous immigration of larvae may have masked treatment effects. Damage ratings and yield were not recorded, so the agronomic benefit of the density reductions could not be quantified. A second run of the bioassay and the larval-instar records are lost. The laboratory bioassay used a single discriminating rate, so lethal concentrations could not be estimated. Finally, the data are from 2017–2018, and FAW populations and product formulations may have changed since. For these reasons we present the results as a historical baseline, not as a current recommendation. Multi-season trials that include damage, yield and cost–benefit outcomes, with fully documented products, and that pair biopesticides with scouting-based thresholds, remain a priority (Sanon et al. 2025; Wyckhuys et al. 2024).

5. Conclusions

In the laboratory, commercial *B. thuringiensis* (Delfin) and *B. bassiana*-based (Dynamo) products killed 83% of second-instar FAW larvae, slightly less than Super Dash (98%), and acted slowly (LT_{50} 7–9 d). In the one field trial reported, they reduced live larval density by 87% at the label rate and at ± 10% of it, a reduction like that of the synthetic standard (86%), although the trial could not separate the products. Azadirachtin (ACHTA) did not significantly reduce field larval density and is not supported as a stand-

alone treatment by these data. The results are a historical baseline from the early-invasion period, limited by lost product and exposure records and by the exclusion of one field trial. They support local validation of microbial products for resistance-conscious FAW IPM, but not specific current recommendations.

Declarations

Competing interests.

Seed Co Limited provided in-kind support for the field work, and N. Chiuraise is employed by Seed Co Limited. The author declares no other known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Ethics approval and consent to participate.

Not applicable (the study involved insects and field crops only; no human participants or vertebrate animals).

Electronic Supplementary Material

Electronic supplementary material accompanying: Early-invasion efficacy of commercial *Bacillus thuringiensis*, *Beauveria bassiana* and azadirachtin biopesticides against fall armyworm (*Spodoptera frugiperda*) on maize in Zimbabwe. *International Journal of Tropical Insect Science*.

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Author Contribution

Dumisa Dlamini was responsible for Conceptualisation designing Methodology, primary Investigation, Data curation, Formal analysis, Writing – original draft, Writing – review & editing.

Acknowledgement

As in the manuscript

Data availability.

The per-plant field counts for the Muzarabani trial, the per-vial bioassay records and the Python script that reproduces all analyses, tables and figures are provided as Supplementary Material. An earlier version of the dataset is held at 4TU.ResearchData (https://doi.org/10.4121/4847b29a-e2c2-4e14-aa7f-7cb1ec81f82c). That version predates the corrections described here: it contains a laboratory file that is not the Experiment 1 bioassay, and some counts differ.

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Figures

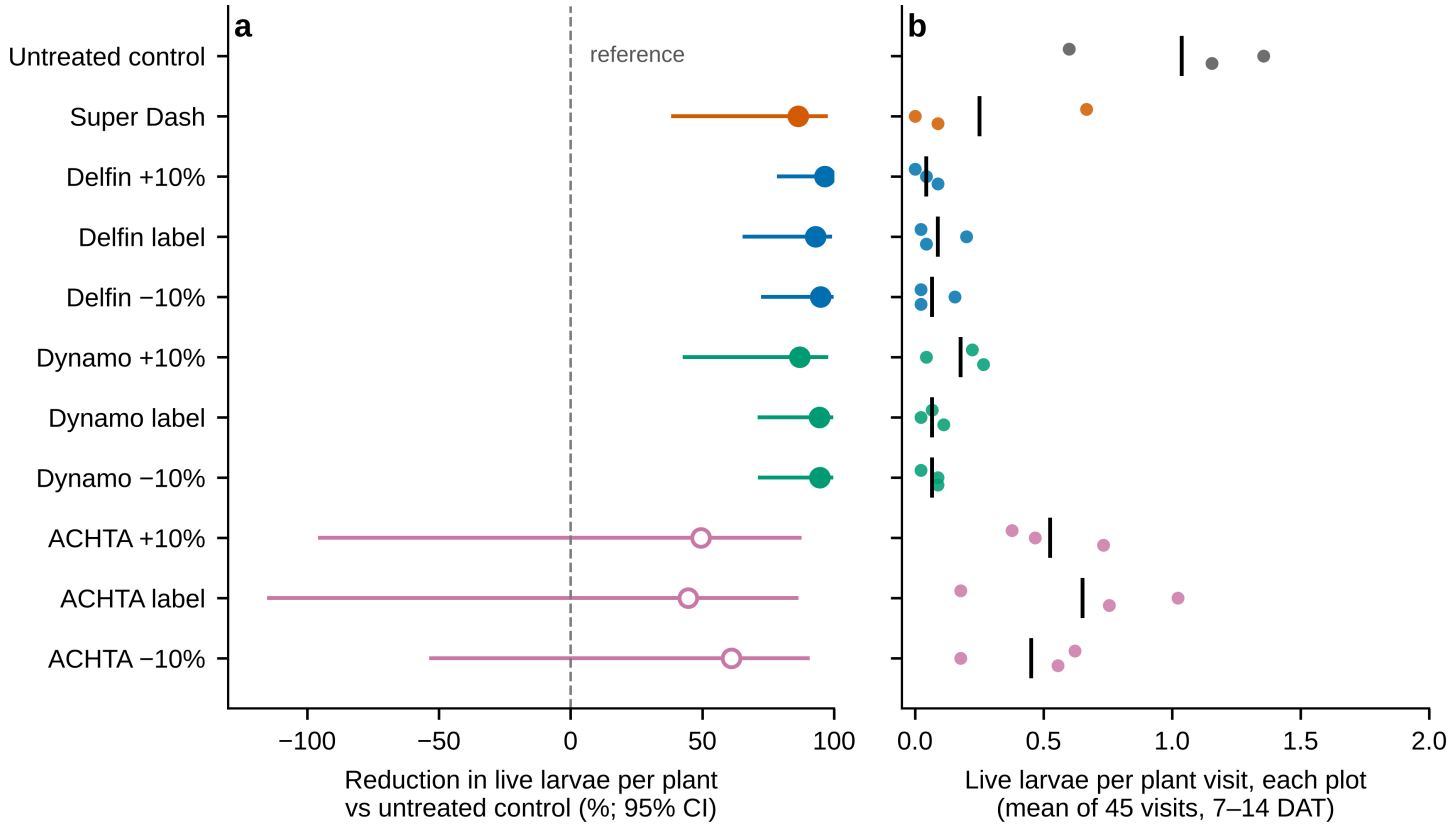


Figure 1

Field efficacy of biopesticides and the reference insecticide against *S. frugiperda* larvae at Muzarabani (Natural Region IV; 11 treatments, three blocks). (a) Percentage reduction in live larvae per plant relative to the untreated control (1 − rate ratio from a negative binomial GLMM; 7, 10 and 14 DAT pooled) with Dunnett-adjusted 95% confidence intervals; filled symbols, $P < 0.05$. (b) Live larvae per plant visit in each of the three plots per treatment (points) and the treatment mean (black bar). One Super Dash plot (block 3) held 30 of the 34 live larvae recovered from Super Dash plots.

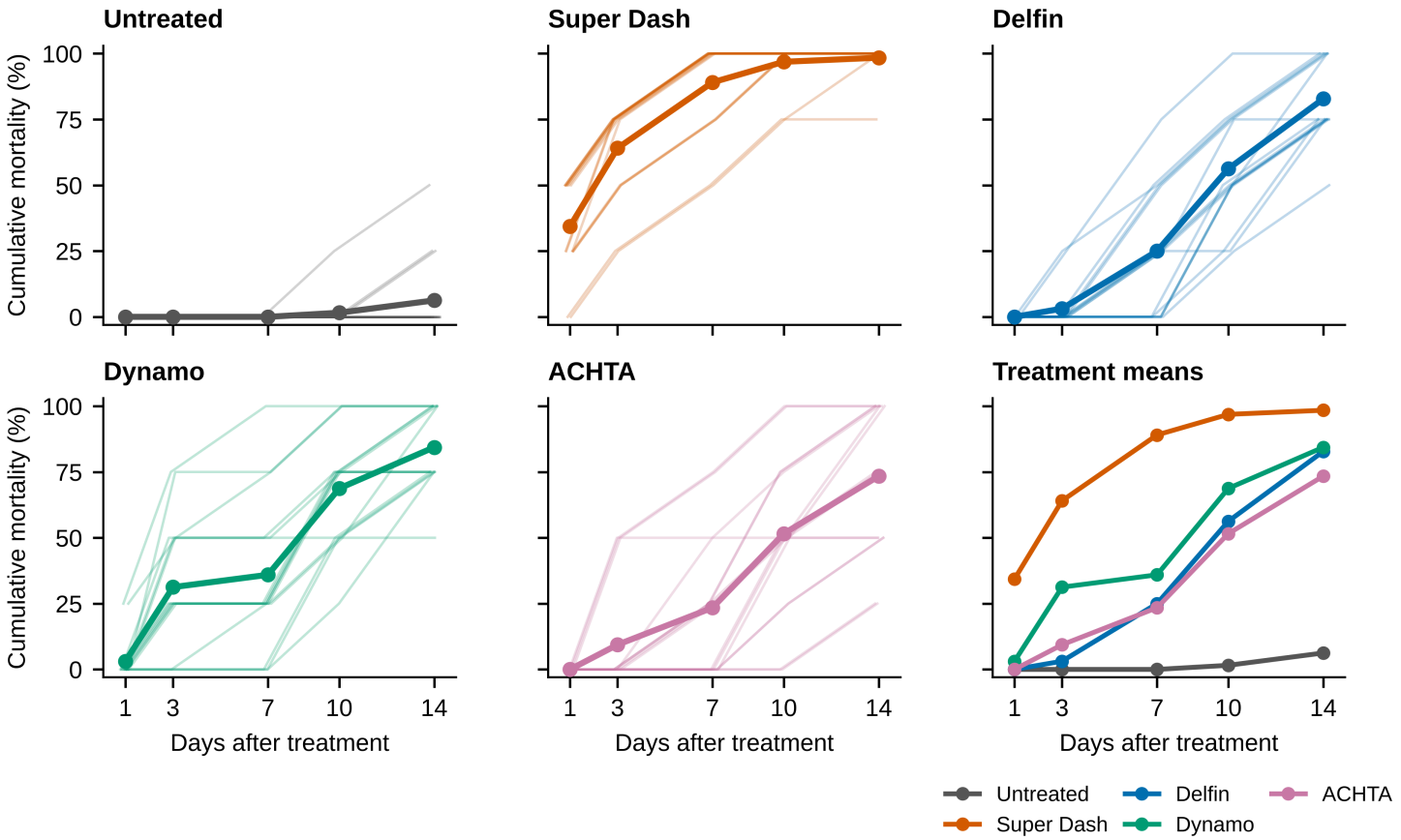


Figure 2

Cumulative mortality of second-instar *S. frugiperda* larvae over 14 days after treatment in the laboratory bioassay (Experiment 1). Thin lines are individual vials (four larvae each; small horizontal offsets added for clarity); bold lines and points are treatment means of 16 vials. The last panel overlays the five treatment means. Five vials had inconsistent counts (Table S3).

Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- IJTISESMd1.docx

- FAWbioassayexp1pervial.csv
- FAWfieldcountstidy.csv
- FAWreanalysis.py
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- READMEPythonreanalysis.txt