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ECONOMIC AND ENVIRONMENTAL PERFORMANCE OF UAV SPRAYING FOR FALL ARMYWORM CONTROL IN MAIZE

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ABSTRACT

Fall armyworm (*Spodoptera frugiperda*) has damaged Thai maize since 2018, yet growers predominantly use knapsack sprayers despite the availability of unmanned aerial vehicles (UAVs). This study compared UAV and knapsack spraying for pest control, drift, environmental impact, and economic performance in baby corn, sweet corn, and field corn. A split-plot design was implemented across six farmer fields in Kanchanaburi and Nakhon Sawan, Thailand, with two replicate plots per crop, each divided into UAV and knapsack subplots. Damage indices were statistically similar between methods at most assessments, suggesting comparable control. However, pre-spray differences in two plots and limited replication constrained this interpretation. UAV spraying generated greater drift distances and higher drift percentages near the spray line across all crops. Both methods remained within the very-low-risk Environmental Impact Quotient band; UAV scores were 24.5–26.5% lower because of lower cumulative active-ingredient application per hectare. UAV spraying also yielded higher net income and revenue–cost ratios across crops. Household ownership solely for on-farm use was financially unviable, with estimated payback periods of 81–151 years exceeding the five-year service life. Conversely, custom-hire services were financially viable under realistic and full-capacity utilization, with discounted payback periods of approximately 18.1 and 7.0 months, respectively, positive net present values, and internal rates of return exceeding the minimum attractive rate. UAV spraying therefore shows promise for fall armyworm management through custom-hire services, provided appropriate spray buffers and locally validated insecticide doses are used. Further trials across seasons and locations are needed to confirm efficacy, drift patterns, and economic performance under broader farming conditions.

***Keywords*:** Fall armyworm, Unmanned aerial vehicle, Spray drift, Environmental impact quotient, Cost–benefit analysis.

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1. INTRODUCTION

Maize ranks among Thailand's most economically important cereal crops. Field corn alone occupies roughly 1.09 million ha and generates production value exceeding THB 41.27 billion (USD 1.25 billion), and sweet corn and baby corn provide further income for smallholders in several regions. However, over the past decade, all three maize types have come under sustained pressure from fall armyworm (*Spodoptera frugiperda*), an invasive pest first recorded in Thailand in 2018. It's fast life cycle, high fecundity, and habit of hiding within the whorl or on the underside of leaves make it hard to reach with conventional spraying, and severe outbreaks can destroy up to 73% of yield (Zafar et al., 2020; Chaireunkaew et al., 2022).

Fall armyworm control in Thailand still relies primarily on knapsack sprayers, a method constrained by a shrinking agricultural labor force, rising labor costs, and health risks associated with prolonged chemical exposure during extended spraying sessions (Abro et al., 2021; Zafar et al., 2022; Khaehanchanpong et al., 2023; Zerbo et al., 2025; Haq et al., 2026; Shehzad et al., 2026). These constraints have driven broader adoption of agricultural UAVs since 2015, supported by government initiatives such as the One Tambon One Digital (Drone Community) program promoted as part of Thailand's digital-agriculture policy. Fleet-size projections for agricultural drones vary across

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sources and are not always dated or independently verifiable; we therefore describe the trend qualitatively rather than citing a single numerical projection, while noting that custom-hire UAV spraying services are increasingly available in maize-growing areas of Kanchanaburi and Nakhon Sawan.

A growing body of international research has examined UAV spraying performance since 2020. Studies in maize and related crops report that UAV-based low-volume application can match knapsack- or boom-sprayer efficacy against fall armyworm once flight height, nozzle type, and application rate are optimized (Shan et al., 2022; Shanmugam et al., 2024; Liu et al., 2025; Zhang, 2025), with rotor downwash proposed as one mechanism that helps droplets penetrate the whorl where young larvae reside. Parallel work on spray drift and droplet characteristics has consistently found that UAVs generate finer droplets and, correspondingly, greater off-target movement than ground equipment (Gibbs et al., 2021; Cunha and Silva 2023; Safaeinezhad et al., 2025). Recommended buffer distances differ considerably by region, crop, and measurement method: a few meters in Asian colorimetric trials (Xue et al., 2014; Punyawattoe et al., 2019, 2021; Dengeru et al., 2022) versus 15–25 m using more sensitive particle counters in the United States (Gibbs et al., 2021). Operator and bystander exposure has also begun to receive direct attention: Xiao et al., (2025) measured inhalation exposure to an airborne fungicide during UAV operation at concentrations warranting respiratory precautions, underscoring that UAV adoption changes, rather than eliminates, the health-and-safety profile of spraying. On the environmental side, several life-cycle assessments report that UAV spraying can reduce water use, chemical input, and greenhouse-gas emissions relative to conventional application (Jiang et al., 2022; Fathi et al., 2025; Ramteke et al., 2025), while economic studies from China, Indonesia, and Thailand generally find UAV services profitable at the enterprise level, even though ownership costs and per-hectare operating costs are sometimes higher than for ground equipment (Khofiyah et al., 2021; Cavalaris et al., 2023; Quan et al., 2023; Calderone et al., 2024).

Despite this expanding literature, few studies integrate biological efficacy, spray drift, pesticide-risk metrics, and investment feasibility within a single field trial, and none, to our knowledge, has done so for fall armyworm management in Southeast Asian maize systems. Farmers therefore lack an evidence base that jointly addresses three practical questions before adopting UAV spraying. The first is economic viability: custom-hire UAV spraying is competitively priced at approximately THB 375–500/ha (USD 11.40–15.20/ha), but purchasing a UAV outright costs more than 30 times as much as a knapsack sprayer; therefore, a systematic comparison of costs, revenues, and payback periods is needed to determine whether ownership or custom hire is the more rational choice at a given farm size. The second concerns technical efficacy: because fall armyworm larvae hide under leaves and within the whorl, it is reasonable to ask whether downward spraying from a UAV reaches these microhabitats as reliably as a knapsack operator who can angle the nozzle directly at them. The third concerns environmental and safety impact, since spray drift could expose neighboring plots and non-target organisms more than conventional ground spraying does.

This study addressed these three questions in a single integrated field trial. We assessed (1) financial cost-benefit performance through production costs, revenues, net income, revenue-cost ratios, and payback periods (Khofiyah et al., 2021); (2) biological efficacy using the Damage Index (DI) based on the scale developed by Davis et al. (1992); and (3) environmental impact through off-target drift and the Environmental Impact Quotient (EIQ) developed by Kovach et al. (1992). Specifically, the objectives were to (1) compare the effectiveness of UAV and knapsack spraying for fall armyworm control using the DI; (2) assess the environmental impact of both methods through off-target drift and field-use EIQ; (3) compare production costs, revenues, net income, and revenue-cost ratios for baby corn, sweet corn, and field corn under the two methods; and (4) estimate the payback period for UAV investment under both private-use and custom-hire business models. We hypothesized that UAV and knapsack spraying would achieve statistically comparable fall armyworm control; that UAV spraying would show greater off-target drift near the spray line but a lower field-use EIQ owing to its lower per-hectare active-ingredient dose; and that UAV ownership would be economically viable only when demand is pooled across many farms rather than confined to a single household. The findings are intended to give farmers, spraying-service providers, and policymakers a firmer basis for choosing spraying technology on economic, technical, and environmental grounds.

2. MATERIALS AND METHODS

2.1. Study Sites and Experimental Design

Trials were conducted in two of Thailand's principal maize-growing provinces: Kanchanaburi (sweet corn and baby corn) and Nakhon Sawan (field corn). Plots were selected on the basis of a history of fall armyworm outbreaks, suitable topography, and farmer willingness to participate. Two replicate plots per corn type were used, with an area of 0.32 ha each for sweet corn and baby corn and 0.48 ha each for field corn, totaling six plots and 2.24 ha. The plot, rather than the individual plant, was the true experimental unit in this trial (n=2 independent plots per corn type). Each plot was divided into two equal subplots, which were randomly assigned to UAV or knapsack spraying by coin toss, and separated by an untreated buffer strip of at least 30 m to limit cross-contamination between subplots. Within each plot, the two spraying methods were applied on the same morning. The UAV subplot was sprayed first, and the knapsack operator

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then worked outward from the buffer strip to avoid either treatment entering an already sprayed subplot.

Sweet corn plots were located in Tha Muang (13°58'36.2"N 99°41'02.7"E) and Mueang (13°57'00.4"N 99°27'03.9"E) districts. Baby corn plots were located in Tha Maka district (13°57'19.3"N 99°44'11.3"E and 13°55'24.7"N 99°49'39.6"E), all in Kanchanaburi. Field corn plots were located in Tak Fa district, Nakhon Sawan (15°20'35.0"N 100°27'00.6"E and 15°20'56.6"N 100°31'40.0"E) (Fig. 1). Field corn was grown on loamy sand soil between December 2025 and April 2026 (dry season), whereas sweet corn and baby corn were grown on sandy loam soil between April 2026 and July 2026 (hot season into early rains). Before spraying commenced, we recorded plot coordinates, size, planting density, crop age, and pest history, and we monitored fall armyworm infestation continuously. Spraying began once damage reached the economic threshold (Davis scale ≥ 4). Because each plot contained only one subplot per treatment, the plot (n=2 per corn type), rather than the individual plant, was the true unit for any claim of a general UAV-versus-knapsack effect. The plant-level sampling and t-tests used to evaluate efficacy therefore describe the damage pattern within a given plot rather than provide a fully replicated efficacy test across the trial.

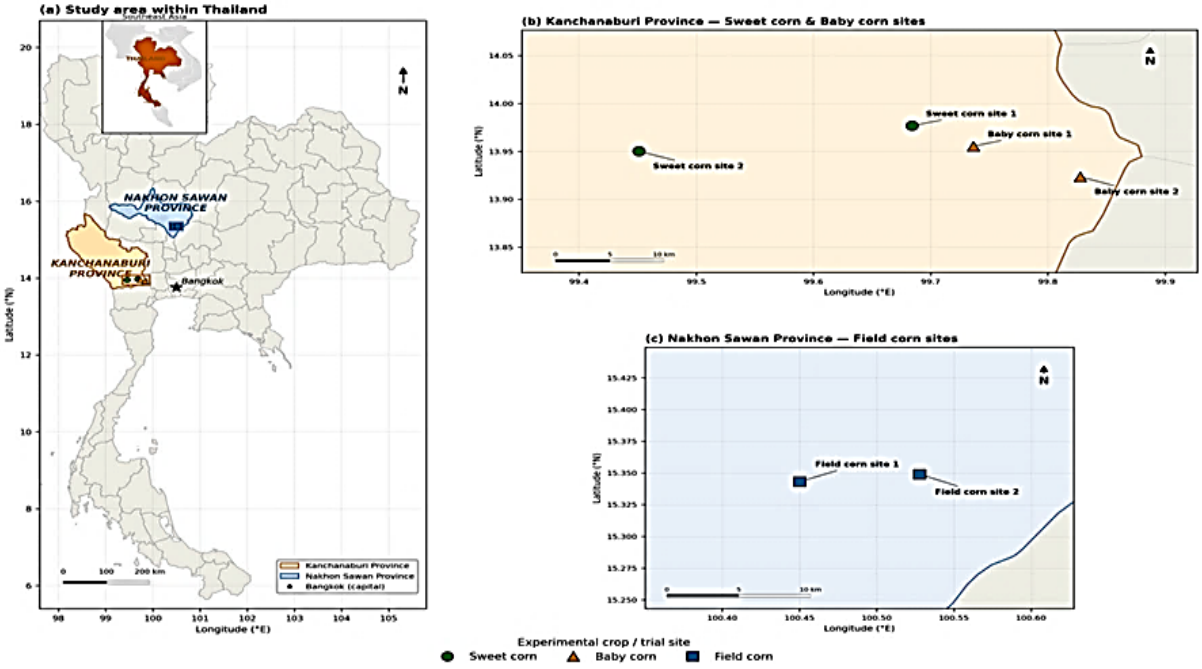


Fig. 1: Location of the six trial plots in Kanchanaburi Province (sweet corn and baby corn) and Nakhon Sawan Province (field corn): (a) Study area within Thailand; (b) Kanchanaburi Province – Sweet corn & Baby corn sites; (c) Nakhon Sawan Province – Field corn sites.

2.2. Climatic Conditions

Air temperature, rainfall, and relative humidity were compiled for each growing season from the nearest available meteorological records. These records were obtained from the Thai Meteorological Department for Kanchanaburi Province (sweet corn and baby corn trials) and from the Tak Fa agricultural meteorological station in Nakhon Sawan Province (field corn trial). Wind speed was not continuously recorded at either site; instead, spraying was restricted to periods when wind speed, measured with a handheld anemometer immediately before each application, was below 3 m/s and no rain was forecast, consistent with standard practice for reducing drift.

2.3. Spray Equipment and Application Parameters

Two treatments were compared: a DJI Agras T20P UAV (20 L tank) flown 3 m above the canopy at a flight speed of 2.0 m/s with a swath width of 6.0 m, a flow rate of 1.77 L/min, an application rate of 25 L/ha, and rotary nozzles; and a HONDA OZ-435 knapsack sprayer (25 L tank, 3 bar pressure) with a hollow-cone nozzle, operated approximately 0.5 m above the canopy at a walking speed of 0.5 m/s, a swath width of 3.0 m, a flow rate of ~1.0 L/min, and an application rate of 500 L/ha which is the method still used by most Thai farmers (Table 1).

2.4. Insecticide Programs

Both treatments used insecticides recommended by Thailand's Department of Agriculture: emamectin benzoate (1.92% EC in sweet corn and baby corn; 5% WG in field corn) and spinetoram (12% SC). Spinetoram was applied only once, during the third spray in sweet corn only, as part of a resistance-rotation program and at a time of heavy

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damage. Spraying occurred in the early morning (06:00-09:00) whenever wind speed remained below 3 m/s and no rain was anticipated. Spray frequency followed each crop's typical pest pressure: seven applications for sweet corn (14, 21, 28, 42, 49, 56, and 69 days after planting) and three applications each for baby corn (14, 22, and 36 days after planting) and field corn (10, 21, and 28 days after planting). Table 2 reports the exact insecticide product and rate applied at every spray, by corn type, spraying method, and active ingredient, expressed per hectare. These per-spray rates are reported separately from carrier-water volume and summed to give the cumulative seasonal totals used in the Field Use EIQ calculation.

Table 1: Operating parameters of the UAV and knapsack sprayer used in the field trials

Parameter	UAV (DJI Agras T20P)	Knapsack sprayer (HONDA OZ-435)
Spray height above canopy (m)	3.0	0.5
Forward speed (m/s)	2.0	~0.5 (walking)
Swath width (m)	6.0	3.0
Flow rate (L/min)	1.77	~1.0
Application rate (L/ha)	25	500
Nozzle type	Rotary	Hollow cone
Area coverage (ha/day)	8.0	2.6

Table 2: Insecticide details and spraying frequency

Corn type	Plot	Sprayer type	Insecticide	Application rate (mL or g)/hectare – Spray No.						
				1	2	3	4	5	6	7
Sweet corn	1	UAV	EB 1.92% EC	500	500	–	750	750	750	750
Sweet corn	1	UAV	SP 12% SC	–	–	250	–	–	–	–
Sweet corn	1	Knapsack sprayer	EB 1.92% EC	625	625	–	937.5	937.5	937.5	937.5
Sweet corn	1	Knapsack sprayer	SP 12% SC	–	–	312.5	–	–	–	–
Sweet corn	2	UAV	EB 1.92% EC	500	500	–	750	750	750	750
Sweet corn	2	UAV	SP 12% SC	–	–	250	–	–	–	–
Sweet corn	2	Knapsack sprayer	EB 1.92% EC	625	625	–	937.5	937.5	937.5	937.5
Sweet corn	2	Knapsack sprayer	SP 12% SC	–	–	312.5	–	–	–	–
Baby corn	1	UAV	EB 1.92% EC	500	500	750	–	–	–	–
Baby corn	1	Knapsack sprayer	EB 1.92% EC	625	625	937.5	–	–	–	–
Baby corn	2	UAV	EB 1.92% EC	500	500	750	–	–	–	–
Baby corn	2	Knapsack sprayer	EB 1.92% EC	625	625	937.5	–	–	–	–
Field corn	1	UAV	EB 5% WG	250	250	250	–	–	–	–
Field corn	1	Knapsack sprayer	EB 5% WG	312.5	312.5	312.5	–	–	–	–
Field corn	2	UAV	EB 5% WG	250	250	250	–	–	–	–
Field corn	2	Knapsack sprayer	EB 5% WG	312.5	312.5	312.5	–	–	–	–

Application rate expressed as mL or g per rai, by spray number (1–7). EB 1.92% EC = Emamectin benzoate 1.92% EC; SP 12% SC = Spinetoram 12% SC; EB 5% WG = Emamectin benzoate 5% WG. Sweet corn was sprayed 7 times (14, 21, 28, 42, 49, 56 and 69 days after planting); baby corn was sprayed 3 times (14, 22 and 36 days after planting); field corn was sprayed 3 times (10, 21 and 28 days after planting).

2.5. Efficacy Evaluation

Damage was assessed using the Davis scale (Davis et al., 1992), which rates leaf injury from 0 (no visible damage) to 9 (leaves almost completely destroyed). Fifty plants per subplot were sampled in a five-point W-shaped layout, with ten plants per point, and were tagged so that the same plants were re-surveyed on each occasion. The top three leaves per plant were scored before and after each spray. These fifty plant-level scores were treated as subsamples used to calculate a single, more precise subplot-time mean, rather than as independent replicates. The DI (%) was calculated as DI = [Σ (plant score) ÷ (total plants × 9)] ×100. Mean DI values for each treatment at each time point were compared using a two-tailed t-test (Microsoft Excel 2024, Microsoft Corporation, USA; significance set at $P<0.05$, $P<0.01$, and $P<0.001$), with analyses conducted separately for each corn type and each plot. Standard deviations are reported alongside each mean. Normality was checked by visual inspection of the score distributions, and Welch's correction was applied when subplot variances differed materially.

2.6. Spray Drift Assessment

Off-target drift was measured using a Kingkol tartrazine dye tracer (1.875 kg/ha) in place of insecticide, which is a standard substitute in spray drift research (Chen et al., 2020; Dengeru et al., 2022). Trials used 720 m² plots (18 × 40 m). The UAV flew 3 m above the canopy on three flight lines at its normal application rate, whereas the knapsack sprayer operated 0.5 m above the canopy on six walking lines at its normal rate. Petri dishes (90×15 mm) were placed at 1 m intervals for 10 m both upwind and downwind of the spray line (20 collection points per plot), with three spray repetitions per treatment. After 30 min of drying, samples were collected, rinsed in 10 mL of distilled water, and analyzed by spectrophotometer at 470 nm to determine dye concentration, which was then converted to percentage drift relative to the total volume applied.

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2.7. Environmental Impact Quotient

Environmental impact was assessed using the EIQ developed by Kovach et al. (1992) and maintained by Cornell University (2024). The EIQ integrates chronic toxicity, dermal toxicity, plant-surface half-life, ecological effects, leaching potential, fish toxicity, surface-loss potential, bird toxicity, soil half-life, bee toxicity, and toxicity to beneficial arthropods. The Field Use EIQ was calculated as the product of each active ingredient's constant EIQ value, its percentage active ingredient, and its cumulative application rate per hectare, following Kromann et al. (2011). The resulting Field Use EIQ values for multiple active ingredients in one program were summed to yield a total EIQ field rating per treatment. Constant EIQ values were 64 for emamectin benzoate and 31 for spinetoram. Ratings were then classified according to Kovach et al. (1992) into five bands: very low (<25), low (25 to <50), moderate (50-99), high (100-199), and very high (>200). It is important to distinguish the carrier water volume used for application (25 L/ha for UAV versus 500 L/ha for knapsack spraying) from the cumulative active-ingredient application rate used above, as shown in Tables 1 and 2. The Field Use EIQ formula depends on the cumulative amount of product, and therefore active ingredient, applied per hectare, not on the volume of water used to carry it. Because both methods here used the same active ingredients, concentrations, and number of sprays, the only difference is that UAV applications used a lower product dose per spray. This lower active-ingredient loading, not the lower carrier-water volume, is the sole reason for the UAV program's lower EIQ score.

2.8. Economic Analysis

The farm-level and household demand parameters used throughout this section were obtained from structured interviews with participating farmers and custom-hire UAV service providers operating in the two study provinces, and are summarized in Table 3. Annual per-household spraying demand (ha/yr) was calculated as planted area (ha) × cropping cycles per year × sprays per season, as shown in Table 3.

Table 3: General characteristics of the surveyed baby corn, sweet corn, and field corn production systems in Kanchanaburi and Nakhon Sawan, based on interviews with participating farmers and custom-hire UAV service providers

Item	Baby corn	Sweet corn	Field corn
Average planted area (rai/household)	4	4	15
Average planted area (ha/household)	0.64	0.64	2.4
Growing period, planting to harvest (days)	55	70	100
Cropping cycles per year	4	3	2
Sprays per season	3	7	3
Yield (kg/rai)	2,000	2,000	1,200
Yield (kg/ha)	12,500	12,500	7,500

Farm-level cost-benefit analysis followed standard production-cost accounting procedures (Khofiyah et al., 2021). Total cost (C) combined fixed costs, including straight-line equipment depreciation, licensing, and training, with variable costs, including land preparation, seed, planting labor, insecticide and spraying costs, herbicide, fertilizer, drip-irrigation tape, and harvest labor. Total revenue (R) included income from main and by-product sales. Net income (NI = R − C) and the revenue-cost ratio (R/C) were calculated for each method, and an R/C value greater than 1 indicated economic viability. The method with the higher R/C and NI was considered more economically efficient (Ghadge et al., 2023).

Investment analysis was based on the UAV cost structure and the custom-hire service data. The initial investment (THB 413,500; USD 12,568) included the drone, three spare battery packs, a field charging generator, an auxiliary charging station, pilot training, and first-year third-party liability insurance. The custom-hire rate was set at THB 500/ha (USD 15.20/ha), compared with a total operating cost of THB 262.5/ha (USD 7.98/ha), consisting of depreciation (THB 118.75/ha), pilot labor (THB 62.5/ha), vehicle fuel (THB 31.25/ha), and generator fuel (THB 50/ha); these costs were used in the R/C analysis. Cash-flow analysis for net present value (NPV) and internal rate of return (IRR) used cash variable costs (THB 143.75/ha; USD 4.37/ha, labor plus fuel), annual insurance (THB 4,300/yr; USD 130.70/yr), and maintenance costs, assumed to be 5% of the initial investment per year (THB 20,675/yr; USD 628.42/yr), while excluding depreciation to avoid double-counting.

Breakeven area was calculated using two metrics based on the IS: 9164-1979 approach to agricultural machinery costing (Ghadge et al., 2023) and the payback framework of Khofiyah et al., (2021): gross payback area = initial investment ÷ hiring rate; net economic breakeven area = initial investment ÷ (hiring rate − cash variable cost/ha).

NPV, IRR, and benefit-cost ratio (BCR) were computed over a 5-year project life, following Khofiyah et al., (2021). NPV was calculated as $\Sigma [(Bt - Ct)/(1 + i)^t]$; IRR was defined as the discount rate at which NPV=0; and BCR was calculated as PV(benefits)/PV(costs). Annual net cash flow was calculated as service revenue minus cash variable costs, annual insurance, and maintenance costs. These costs were assumed to remain constant across years, except when battery replacement was required, which occurred every 67.5 cumulative hectare-applications per three-battery set (THB 126,000 per replacement; USD 3,831). A salvage value of 10% (THB 41,350; USD 1,257) was recovered

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in the final year. The discount rate was based on the minimum attractive rate of return (MARR), computed as MARR = {(1 + (i + α))(1 + inflation)} − 1, where i is the lending rate of the Bank for Agriculture and Agricultural Cooperatives (6.625%/yr) (Bank for Agriculture and Agricultural Cooperatives, 2025), α is a business risk premium of 5%/yr, and inflation was assumed to be 2%/yr, resulting in MARR = 13.86%/yr. Sensitivity analysis examined how NPV responded to discount rates of 10%, 13.86%, 15%, and 20%, and to utilization changes of −10%, −5%, 0%, and +5% relative to the realistic-use baseline.

3. RESULTS

3.1. Weather Conditions during the Trial

Meteorological records showed a clear seasonal progression at both sites (Table 4). In Kanchanaburi, where the sweet corn and baby corn trials ran from April to July 2026, mean daily temperature ranged from 24 to 39°C in April and from 26 to 36°C in July. Rainfall increased steadily from 33 mm in April to 133 mm in July, and relative humidity rose from 40% to 60% in April to 70% to 75% in July, as the site transitioned from the hot-dry season to the early rainy season. In Nakhon Sawan, where the field corn trial was conducted from December 2025 to April 2026 during the dry season, maximum daily temperature increased from the low to mid-20s°C in December to a peak of 39°C in late March. Minimum temperature was lowest in mid-January (13°C) and increased thereafter, while relative humidity ranged from 43% to 77%, decreasing during the driest months (January to March) before rising again in April with the onset of pre-monsoon rain. Rainfall at the Nakhon Sawan site was negligible from December through mid-February, occurred intermittently in late February and March, and intensified in April, including three rain events of 18 mm on 9 April, 36 mm on 13 April, and 89 mm on 16 April 2026. Spraying was scheduled during calm early morning conditions (wind speed < 3 m/s, no rain) at both sites; however, continuous wind-speed and wind-direction records were not available for either site, which is noted as a limitation in the discussion section.

Table 4: Summary of temperature, rainfall, and relative humidity at the two trial sites, by month. Source: Thai Meteorological Department records for Kanchanaburi Province; Tak Fa agricultural meteorological station, Nakhon Sawan Province

Site/crop	Month	Temperature range (°C)	Rainfall (mm)	Relative humidity (%)
Kanchanaburi (sweet corn, baby corn)	Apr 2026	24-39	33	40-60
Kanchanaburi (sweet corn, baby corn)	May 2026	24-37	83	50-65
Kanchanaburi (sweet corn, baby corn)	Jun 2026	25-36	115	55-65
Kanchanaburi (sweet corn, baby corn)	Jul 2026	26-36	133	70-75
Nakhon Sawan – Tak Fa (field corn)	Dec 2025– Apr 2026 (range)	13-39	negligible (Dec–mid Feb) to 89.2 (max daily, 16 Apr)	43-77

3.2. Field Efficacy against Fall Armyworm

Before spraying, DI values across all six plots ranged from 51.3% to 76.4% (Table 5), corresponding to Davis scores above the economic threshold of 4 and indicating that fall armyworm pressure had already reached the economic threshold when treatments began. In all corn types, DI declined steadily with successive sprays under both UAV and knapsack treatments, with no significant difference between methods at most time points. In baby corn plot 1, DI fell from approximately 74% before spraying to 3.6% under UAV spraying and 8.0% under knapsack spraying after the third spray, with no statistically significant difference between treatments at any time point. In baby corn plot 2, the pre-spray DI already differed between subplots (UAV 61.3% versus knapsack 71.1%; $P<0.001$), and DI remained significantly lower under UAV spraying after the second spray (30.7% versus 48.7%; $P<0.01$) and third spray (17.3% versus 34.7%; $P<0.01$). Field corn showed a similar pattern to baby corn: DI declined to below 14% after the third spray in both methods, with no significant difference except for a pre-spray imbalance in plot 2 (69.6% versus 73.8%; $P<0.05$). Sweet corn, sprayed seven times, declined more slowly and unevenly during the first two to three sprays before stabilizing at 19.1% to 24.0% in both methods and both plots by the seventh spray, with no significant difference between treatments at any point (Table 5).

Table 5: Damage Index (DI, mean ± SD, %) before spraying and after the final spray of each season, by corn type, plot, and spraying method (KS = knapsack sprayer). Significance from two-tailed t-test comparing UAV and KS at the final assessment: ns = not significant, **=P<0.01

Corn type	Plot	n (plants/subplot)	Sprays	Pre-spray DI: UAV (%)	Pre-spray DI: KS (%)	Final DI: UAV (%)	Final DI: KS (%)	Sig. (final)
Baby corn	1	50	3	73.6 ± 9.8	74.4 ± 11.9	3.6 ± 11.5	8.0 ± 18.1	ns
Baby corn	2	50	3	61.3 ± 16.5	71.1 ± 12.1	17.3 ± 26.1	34.7 ± 34.0	**
Field corn	1	50	3	75.3 ± 6.8	76.4 ± 9.2	9.1 ± 14.0	13.6 ± 19.2	ns
Field corn	2	50	3	69.6 ± 8.0	73.8 ± 8.3	8.7 ± 12.4	11.8 ± 15.5	ns
Sweet corn	1	50	7	62.4 ± 7.1	65.3 ± 9.2	19.1 ± 14.0	24.0 ± 15.3	ns
Sweet corn	2	50	7	51.3 ± 7.1	54.2 ± 9.2	19.3 ± 14.9	24.0 ± 15.3	ns

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3.3. Off-target Spray Drift

In all three corn types, UAV spraying showed greater drift at 1 m from the spray line and extended farther than knapsack spraying (Table 6), a pattern consistent with its finer droplet size and greater release height above the canopy. For both methods, drift decreased in an approximately exponential pattern with increasing distance from the spray line across all three crops (Fig. 2). Field corn, with the tallest canopy, showed the greatest drift for both methods (7 m for UAV and 3 m for knapsack), whereas sweet corn and baby corn showed zero drift within 5 to 6 m for UAV and 2 to 3 m for knapsack (Table 6).

3.4. Environmental Impact Quotient

To make the active-ingredient dose fully transparent, Table 7 reports the Field Use EIQ calculation for each active ingredient separately, presenting its constant EIQ value, percentage of active ingredient, and cumulative product application rate per hectare, summed from the seasonal per-spray rates in Table 2, together with the resulting Field Use EIQ and the total per crop and method. For sweet corn, UAV spraying used a cumulative emamectin benzoate rate of 4.0 L/ha and a spinetoram rate of 0.25 L/ha (Field Use EIQ = 0.79 and 0.15; total = 0.94), compared with 5.0 L/ha and 0.31 L/ha for knapsack spraying (Field Use EIQ = 0.98 and 0.19; total = 1.17). For baby corn, cumulative emamectin benzoate use was 1.75 L/ha under UAV spraying versus 2.19 L/ha under knapsack spraying (Field Use EIQ = 0.34 vs. 0.43). For field corn, cumulative emamectin benzoate (5% WG) use was 0.75 kg/ha under UAV spraying versus 0.94 kg/ha under knapsack spraying (Field Use EIQ = 0.38 vs. 0.48). Because the constant EIQ value and percentage of active ingredient are identical between methods for each active ingredient, the ratio of UAV to knapsack Field Use EIQ values equals the ratio of their cumulative application rates. This confirms that application rate is the only driver of the EIQ difference. Values from replicate plots 1 and 2 of each corn type were identical in every case because both plots followed the same spray program; this reflects standardization of the spray program rather than an additional independent replicate.

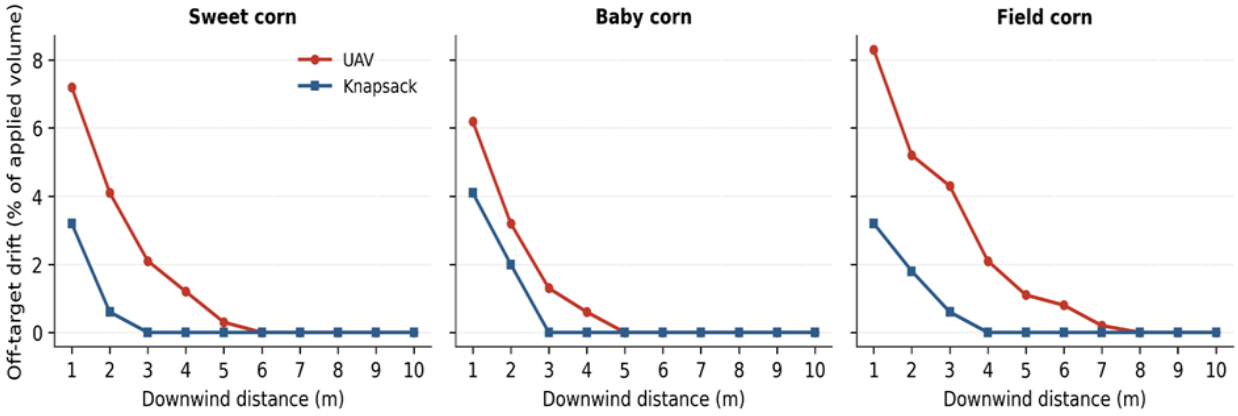


Fig. 2: Downwind spray drift (% of applied volume) as a function of distance from the spray line, by corn type and spraying method. Each point is the mean of three spray repetitions per treatment; per-point.

Table 6: Maximum downwind drift distance and peak drift percentage (at 1 m) for UAV and knapsack spraying across three corn types. Each value is the mean of three spray repetitions per treatment

Corn type	Method	Max. drift distance downwind (m)	Peak drift at 1 m (%)
Sweet corn	UAV	5	7.2
Sweet corn	Knapsack	2	3.2
Baby corn	UAV	4	6.2
Baby corn	Knapsack	2	4.1
Field corn	UAV	7	8.3
Field corn	Knapsack	3	3.2

Every treatment across all three corn types fell within the very-low-risk band of the EIQ scale (Fig. 3; Table 8), reflecting both the moderate-to-low constant EIQ values of the active ingredients used (emamectin benzoate = 64; spinetoram = 31) and the low cumulative application rates involved. Both methods used the same active ingredients, the same active-ingredient concentrations, and the same number of sprays; the 24.5 to 26.5% lower EIQ associated with UAV spraying is therefore attributable to a single variable, namely a lower cumulative active-ingredient application rate per hectare. In other words, the lower product dose, not a lower carrier-water volume, explains the difference. This pattern directly reflects the EIQ's linear dependence on application rate (Kovach et al., 1992).

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Table 7: Constant EIQ value, percentage active ingredient (%AI), cumulative product application rate, and Field Use EIQ for each active ingredient, by corn type and spraying method

Corn type	Method	Active ingredient	EIQ constant	%AI	Cumulative rate (L or kg/ha)	Field Use EIQ
Sweet corn	UAV	Emamectin benzoate 1.92% EC	64	0.0192	4.00	0.79
Sweet corn	UAV	Spinetoram 12% SC	31	0.12	0.25	0.15
Sweet corn	UAV	Total	–	–	–	0.94
Sweet corn	Knapsack	Emamectin benzoate 1.92% EC	64	0.0192	5.00	0.98
Sweet corn	Knapsack	Spinetoram 12% SC	31	0.12	0.31	0.19
Sweet corn	Knapsack	Total	–	–	–	1.17
Baby corn	UAV	Emamectin benzoate 1.92% EC	64	0.0192	1.75	0.34
Baby corn	Knapsack	Emamectin benzoate 1.92% EC	64	0.0192	2.19	0.43
Field corn	UAV	Emamectin benzoate 5% WG	64	0.05	0.75	0.38
Field corn	Knapsack	Emamectin benzoate 5% WG	64	0.05	0.94	0.48

Table 8: Total EIQ field rating and risk classification by corn type and spraying method; all values fall within the very-low-risk category (< 25), per Kovach et al., (1992)

Corn type	UAV EIQ field rating	Knapsack EIQ field rating	Difference	Risk level (both methods)
Sweet corn	0.94	1.17	24.5% lower (UAV)	Very low
Baby corn	0.34	0.43	26.5% lower (UAV)	Very low
Field corn	0.38	0.48	26.3% lower (UAV)	Very low

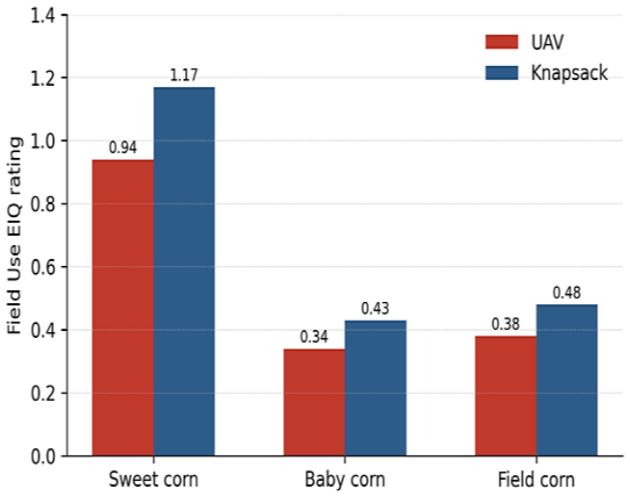


Fig. 3: Total EIQ field rating by corn type and spraying method (dashed line = upper bound of the very-low-risk band, EIQ < 25).

3.5. Farm-Level Cost–Benefit Outcomes

UAV spraying outperformed knapsack spraying in both net income and the revenue-cost ratio across all three corn types (Table 9), but the underlying mechanism varied by crop. In sweet corn, which was sprayed seven times per season, the UAV's advantage stemmed mainly from lower cumulative insecticide costs, a direct consequence of its lower per-spray application rate, whereas yields differed only modestly between methods. In field corn, by contrast, the advantage arose almost entirely from a substantially higher yield under UAV spraying (24.9 to 32.3% higher across the two plots) rather than from reduced chemical costs, as field corn requires only three sprays per season and chemical costs represent a smaller share of total production costs. When converted to annual household income based on typical planting area and cropping cycles (Table 3), field corn, despite having only two crops a year, showed the largest absolute gain from UAV adoption (THB 74,909/yr; USD 2,277/yr; 63.6% higher NI per hectare than knapsack spraying), mainly because households cultivate a larger area of it (2.4 ha) than baby corn or sweet corn (0.64 ha each).

Table 9: Mean net income (NI; THB/ha and USD/ha) and revenue-cost ratio (R/C) by corn type and spraying method (averaged across two replicate plots; USD 1 = THB 32.9)

Corn type	NI: UAV (THB/ha)	NI: UAV (USD/ha)	NI: Knapsack (THB/ha)	NI: Knapsack (USD/ha)	R/C: UAV	R/C: Knapsack
Baby corn	63,150	1,919	52,419	1,593	2.12	1.93
Sweet corn	82,613	2,511	71,556	2,175	2.47	2.26
Field corn	40,125	1,220	24,519	745	2.39	1.84

3.6. Breakeven Analysis and Household Versus Service-Business Viability

Two breakeven area metrics were calculated from the equations in Section 2.8: the gross payback area, defined as initial investment divided by the hiring rate, was 827.0 ha, and the net economic breakeven area, which also subtracts cash variable costs from the hiring rate, was 1,160.6 ha, or about 40% larger. These area-based metrics indicate the cumulative service area that must be sprayed to recover the initial investment. However, converting them into a payback time by simply dividing by annual utilization would omit fixed annual insurance and maintenance costs, as well as periodic battery replacement costs. Payback time is therefore reported only from the discounted cash-flow model, which incorporates all cash costs (Table 10; Section 3.7): 0.59 year (7.0 months) under full-capacity utilization and 1.5 years (1 year 6.1 months) under realistic utilization. The gross and net breakeven areas are retained only as area metrics, not as separate estimates of payback time.

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Table 10: Investment performance of a custom-hire UAV spraying business under two utilization scenarios (discount rate = MARR = 13.86%/yr, 5-year project life; USD 1 = THB 32.9)

Indicator	Full-capacity (2,400 ha/yr)	Realistic use (960 ha/yr)	Decision criterion
NPV (THB)	1,947,877	527,992	NPV > 0
NPV (USD)	59,207	16,048	NPV > 0
IRR (%)	166.43	60.00	IRR > MARR (13.86%)
BCR	1.88	1.46	BCR > 1
Payback period	0.59 yr (7.0 mo)	1.5 yr (1 yr 6.1 mo)	< project life (5 yr)

The comparison with household-level demand indicates a further constraint on individual ownership. Annual per-household spraying demand, derived from planted area, cropping cycles per year, and sprays per season, was only 7.68 ha/yr for baby corn, 13.44 ha/yr for sweet corn, and 14.4 ha/yr for field corn. Relative to the 1,160.6 ha net economic breakeven area, these values are 80 to 151 times smaller, meaning that a household purchasing a UAV solely for its own fields would need 81 to 151 years to recover the investment, well beyond the machine's 5-year usable life. By contrast, a custom-hire spraying business would need to aggregate demand from roughly 81 to 151 households per year, depending on corn type, to break even within a single year.

3.7. Investment Analysis and Sensitivity

Both utilization scenarios met all investment criteria (Table 10). The approximately 3.7-fold gap in NPV and nearly 3-fold gap in IRR between the two scenarios indicates that machine utilization, rather than financing cost, is the main determinant of profitability in this analysis. Sensitivity analysis supports this finding. Increasing the discount rate from 10% to 20%/yr reduced NPV by only about 14% at either utilization level (from THB 623,757 to THB 402,953, or USD 18,962 to USD 12,248, under realistic use), whereas increasing utilization from the realistic baseline (40% of capacity) to full capacity (100%) nearly quadrupled NPV. Even a 10% downward shock to utilization from the realistic baseline still left the business with a positive NPV (THB 410,184; USD 12,469) and an IRR (50.36%) above the MARR, indicating some margin against short-term demand fluctuations under the assumptions used here.

4. DISCUSSION

This study shows that UAV spraying controlled fall armyworm as effectively as knapsack spraying across baby corn, sweet corn, and field corn, with damage index scores that were statistically similar between methods at most assessment points. This finding is consistent with international studies showing that UAV-based low-volume application can match the efficacy of ground equipment against fall armyworm when flight height, nozzle type, and application rate are properly optimized (Liu et al., 2025; Zhang 2025). Liu et al. (2025) found that optimized UAV settings matched electric-knapsack efficacy in Hainan maize, while Zhang (2025) reported no significant difference in efficacy together with a greater than 90% reduction in water use. This result is broadly consistent with the roughly 20-fold lower application volume used here and with comparable trials in sugarcane, almond, alfalfa, and chestnut (Song et al., 2020; Li et al., 2021a; 2021b; Arakawa & Kamio, 2023), which similarly suggest that canopy-top deposition, rather than spray volume alone, determines control once flight and spray parameters are optimized.

The drift results obtained here are consistent with earlier Thai colorimetric studies. Punyawattoe et al., (2019, 2021) measured UAV drift extending 3 to 4 m farther than knapsack spraying in rice without a corresponding loss of efficacy, and a similar pattern was observed here. Finer UAV droplets remain the most likely explanation: Cunha & Silva (2023) reported a mean droplet diameter of 159 µm for a UAV compared with 199 µm for a knapsack sprayer in maize, consistent with larger differences in wheat and other row crops (Gibbs et al., 2021; Safaeinezhad et al., 2025). Recommended buffer distances vary substantially with crop, application method, and measurement sensitivity, ranging from 4 to 8 m in Asian colorimetric studies (Xue et al., 2014; Punyawattoe et al., 2021; Dengeru et al., 2022), from 5.7 to 7.6 m in maize (Cunha & Silva 2023), and up to 15 to 25 m in United States studies using particle counters (Gibbs et al., 2021). These differences indicate that buffer-zone recommendations should be developed locally rather than transferred across studies. The 30 m strip separating subplots here was therefore a conservative operational precaution, not a validated field-boundary recommendation. Flight parameters, rather than platform choice, appear to be the main factor for narrowing the UAV-ground drift gap (Wang et al., 2020; Li et al., 2022; Chen et al., 2025), supporting fixed buffers together with operator training. Xiao et al. (2025) also recorded UAV inhalation exposure to an airborne fungicide at concentrations that warrant respiratory precautions, showing that UAV adoption changes, rather than eliminates, spraying exposure risks.

A methodological point deserves emphasis, given how easily spray volume and pesticide load are conflated in the broader drone-spraying literature. The lower EIQ obtained under UAV spraying here resulted entirely from a

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lower cumulative active-ingredient mass applied per hectare, not from the UAV's much lower carrier-water volume. These two variables, although often reduced together in low-volume UAV programs, are conceptually and toxicologically distinct: carrier volume influences coverage, droplet behavior, and drift, whereas Field Use EIQ is a linear function of active-ingredient mass per hectare regardless of the water used for delivery. Because the present trial reduced both variables simultaneously, their individual contributions cannot be fully separated from these data, and a lower carrier volume should not be interpreted automatically as lower environmental risk. If a UAV operator applies the same product at the full label-recommended dose, the EIQ advantage documented here would not be expected to persist, and reduced-rate programs also require local efficacy validation to confirm that the lower dose still achieves the intended control. Extension guidance and future studies would therefore benefit from reporting active-ingredient dose explicitly (g a.i./ha) rather than describing UAV programs simply as "low volume." The EIQ ratings recorded here (0.34-1.17) are more than an order of magnitude below those reported for Thai Chinese kale and cabbage under comparable resistance-management programs (12.48-84.01; Sampaothong & Punyawattoe, 2024, 2025). This difference is attributable both to lower constant EIQ values for the active ingredients used here relative to fipronil and to the absence of tank mixing in these single-active-ingredient programs, reflecting differences in pest-management intensity between cropping systems rather than an inherent property of UAV application.

On the economic side, UAV spraying produced higher net income and revenue-cost ratios across all three corn types, although the mechanism differed by crop. In sweet corn, which was sprayed seven times per season, the advantage mainly reflected lower cumulative insecticide cost, a direct consequence of the UAV's lower per-spray rate, since yields differed only modestly between methods. In field corn, net income diverged more because of an observed yield difference of 24.9 to 32.3% between UAV and knapsack subplots. This result is directionally consistent with reports that UAV application can improve canopy penetration in other systems, such as mango orchards (Ghadge et al., 2023), but the limited replication here, with two plots per corn type in one season, together with a documented pre-spray damage imbalance in one of the two field corn plots, means that this difference is best interpreted as an association observed under the specific conditions of this trial rather than as a demonstrated causal effect. Confirming it as a stable UAV effect would require a larger, multi-plot, multi-season trial with pre-registered baseline-balance checks. The higher revenue-cost ratio obtained here, despite ownership costs exceeding 30 times those of a knapsack sprayer, suggests that profitability depended less on cost parity than on combined yield and labor-saving gains together with a service model that spreads fixed costs across many farms (Wang et al., 2019; Paul et al., 2023). This pattern is broadly consistent with Quan et al.'s (2023) finding that UAV adoption raised revenue by USD 434 to 488/ha among Chinese grain farmers, although evidence remains mixed elsewhere: Cavalaris et al., (2023) and Calderone et al., (2024) reported UAV operating costs 1.45 to 2 times higher than those of ground alternatives, which reduced benefit-cost ratios for smallholders. The contrast between household ownership and custom hire also matches models reported by Khofiyah et al. (2021) realistic-use internal rate of return here (60.00%) falls between their reported values (22.62% and 72.63%), suggesting that utilization intensity, rather than cost of capital, drives returns.

5. CONCLUSION

UAV spraying controlled fall armyworm as effectively as knapsack spraying across baby corn, sweet corn, and field corn in this trial, with DI scores statistically similar between methods at most assessment points. This finding is broadly consistent with international reports that UAV application can achieve efficacy comparable to ground-based spraying against fall armyworm once flight and spray parameters are appropriately set. Unmanned aerial vehicle spraying showed greater drift at close range in all three corn types, likely as a result of its finer droplets; however, both methods remained within the very-low-risk band on the EIQ, with UAV spraying scoring 24.5%–26.5% lower than knapsack spraying because of its lower cumulative active-ingredient application rate per hectare, not its lower carrier-water volume. Economically, UAV spraying yielded higher net income and revenue-to-cost ratios at the farm level across all three corn types, but its investment payback area (1,160.6 ha) was 80–151 times larger than a single household's annual spraying demand. Under the cost and utilization assumptions evaluated here, individual ownership was therefore not economically viable, with a payback period of 81–151 years. By contrast, a custom-hire service pooling demand across multiple households met standard investment criteria under both realistic- and full-capacity use, with machine utilization, rather than financing costs, being the main driver of profitability. Given the limited replication of this trial (two plots per corn type and one season per crop), these findings should be regarded as an initial, single-season assessment rather than a definitive characterization of UAV performance in Thai maize. Confirmation across additional seasons and locations is warranted, particularly for the field corn yield result. With that caveat, UAV spraying appears to be an efficacious and, under a custom-hire business model, economically favorable alternative to knapsack spraying for fall armyworm control in Thailand, provided that buffer zones are properly managed, spraying occurs under suitable weather conditions, and policy and

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business support shifts from subsidizing individual household ownership toward supporting community- or enterprise-level custom-hire spraying services.

Declarations

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Ethics Statement: This study did not involve human participants or animal subjects requiring formal ethics committee approval. Field trials were conducted with the informed consent and voluntary cooperation of the participating farmers on their own agricultural land, in accordance with institutional research requirements.
Author's Contributions: SS, PD, KS and PP: Conceptualization. SS and PP: Methodology. SS, PD, KS and PP: Investigation. SS and PP: Writing – original draft preparation. SS and PP: Writing – review and editing. All authors have read and agreed to the published version of the manuscript.

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