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# Mating disruption technology: An innovative tool for managing yellow stem borer (*Scirpophaga incertulas* Walker) of rice in Indonesia

## Teknologi gangguan kawin: Inovasi untuk pengendalian penggerek batang kuning (*Scirpophaga incertulas* Walker) pada padi di Indonesia

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### ABSTRACT

Yellow stem borer (YSB) of rice, *Scirpophaga incertulas* Walker, causes significant damage to rice production in Indonesia. YSB management largely depends on insecticide applications and alternative management practices are very few and impractical. Pheromone-mediated mating disruption (MD) is a new way to manage YSB while reducing dependence on conventional insecticides. Pheron™ RSB is an low-density polyethylene (LDPE) MD dispenser, containing 1.25 g of a four-way blended insect sex pheromone components - Z11-Hexadecenal, Z9-Hexadecenal, Z13-Octadecenal, Z9-Octadecenal in a ratio of 75, 8.6, 9.4, and 7 respectively. The objective is to evaluate MD by Pheron™ RSB as a tool for season-long management of YSB. Dispensers were applied at a rate of 20 dispensers/ha in a minimum area of 4 ha. We conducted these trials at 74 locations, non-replicated, across Java, in the wet and dry seasons of 2020–2021 where YSB are endemic and problematic. Efficacy of MD in pheromone foundational practice (PFP) was compared to conventional grower practice (CGP). Trap reduction, a measure of MD was significantly higher (>70%) in PFP as compared to CGP. A major benefit of MD is reduction in damage. Significantly lower damage to rice tillers (40–46%) was seen in PFP compared to CGP. Lower damage in PFP likely protected yield by 0.43 to 0.76 ton/ha compared to CGP. Compared to PFP, CGP required 40–56% higher insecticide applications to manage YSB. Pheron™ RSB provided season-long MD and proved to be a powerful tool for integrated management of YSB.

**Key words**: insect control, integrated pest management, pheromones

### ABSTRAK

Penggerek batang kuning (PBK) padi, *Scirpophaga incertulas* Walker, menyebabkan kerusakan yang signifikan pada produksi padi di Indonesia. Pengendalian PBK sangat bergantung pada aplikasi insektisida, dan praktek pengelolaan alternatif sangat sedikit dan dirasa kurang praktis. Gangguan kawin yang dimediasi feromon (*mating disruption* = MD) adalah cara baru untuk mengendalikan PBK untuk mengurangi ketergantungan pada insektisida konvensional. Pheron™ RSB adalah MD dispenser low-density polyethylene LDPE, berisi 1,25 g campuran 4 komponen feromon seks serangga - Z11-Hexadecenal, Z9-

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Hexadecenal, Z13-Octadecenal, Z9-Octadecenal dalam rasio masing-masing 75, 8,6, 9,4, dan 7. Tujuan dari penelitian ini adalah untuk mengevaluasi gangguan kawin/MD dengan Pheron™ sebagai alat untuk pengendalian PBK sepanjang musim. Dispenser dipasang dengan dosis 20 dispenser/ha dengan luas lahan minimal 4 ha. Uji coba ini dilakukan di 74 lokasi yang memiliki masalah endemi PBK, tanpa ulangan, di seluruh Jawa, pada musim hujan dan kemarau 2020–2021. Efikasi MD dalam *pheromone foundational practice* (PFP) dibandingkan dengan *conventional grower practice* (CGP). Pengurangan tangkapan perangkap sebagai tolak ukur MD secara signifikan lebih tinggi (>70%) pada PFP dibandingkan dengan CGP. Manfaat utama MD adalah pengurangan kerusakan. Kerusakan pada anakan padi secara signifikan lebih rendah (40–46%) terlihat pada PFP dibandingkan dengan CGP. Kerusakan yang lebih rendah pada PFP dapat melindungi hasil panen sebesar 0,43 hingga 0,76 ton/ha dibandingkan dengan CGP. CGP memerlukan aplikasi insektisida 40–56% lebih tinggi dari PFP untuk mengelola YSB. Pheron™ RSB menyediakan MD sepanjang musim dan terbukti menjadi alat yang efektif dalam pengendalian terpadu untuk PBK.

**Kata kunci:** feromon, pengendalian hama terpadu, pengendalian serangga

## INTRODUCTION

Rice is a staple food for most Indonesians and is consumed with all three meals a day, providing necessary nutrition. Several obstacles to achieving optimal production are common, such as water scarcity, climate change, and biotic factors, such as insect pests, diseases, and weeds (Siagian et al. 2020). One of the rice's most damaging insect pests is *Scirpophaga incertulas* Walker (Lepidoptera: Crambidae), the yellow stem borer of rice (YSB). In Indonesia, especially on the island of Java, YSB is a widespread, dominant, and destructive pest. The total damage caused by YSB is 35,543 ha in the 2022 planting season, which is the highest compared to other rice pests in Indonesia (BPPOPT 2022). It is also forecasted to increase to 48,838 ha in the 2023 planting season (BPPOPT 2022). This forecast indicates that YSB potentially can cause the most severe damage to rice in Indonesia.

YSB larvae attack rice plants by feeding internally and causing damage by tunneling. During the vegetative stage, the borer larvae will attack the tillers. With no translocation, tillers dry-up and die, symptoms commonly known as deadhearts. At the generative phase, the damage is indicated by empty panicles of striking whitish color called whiteheads (Gautam et al. 2020). In Indonesia, the damage levels can go up to 30% (Ramadhan et al. 2020; Bahar et al. 2020). This pest can cause significant yield loss in Asia (Heinrichs & Muniappan 2017).

Insecticide application is the only method frequently used. Several studies showed that the intensity of synthetic insecticide usage in Indonesia's rice production is very high. Wiyono et al. (2014) reported that synthetic pesticide usage in Karawang (West Java) and Klaten (Central Java) was about 11 and 12 times per planting season. However, control is less effective because the larvae are protected by the stems of rice plants and improper timing of insecticide applications (Bandong & Litsinger 2005). Furthermore, some reported that the level of knowledge about pesticides was not following the application of good agricultural practices for pesticide use (Istriningsih et al. 2022). Over-dependence on insecticides can adversely affect the bioecology of rice fields, insect resistance, and resurgence (Kartohardjono 2011).

One of the approaches in integrated pest management (IPM) is to manage insect pests sustainably and effectively by integrating all possible solutions. As a foundational practice, pheromone-mediated mating disruption (MD) is an effective way to practice IPM. MD is a strategy to disrupt chemical communication between males and females through competitive and non-competitive mechanisms to prevent mating and reproduction of the target insect pest (Rizvi 2021). The benefits of this technology are that it is species-specific and non-hazardous to beneficial insects and humans (Witzgall et al. 2010).

MD has been used to manage agricultural pests in more than 800,000 ha of crops for the past 30 years (Benelli et al. 2019). In Spain, to control striped stemborer (*Chilo suppressalis* (Walker) (Lepidoptera: Crambidae)), MD has been applied on around 10,000 ha annually (Casagrande et al. 1993). MD has also been used to manage YSB. According to growers practice in India, a study by Cork et al. (1996) showed that the treated plot with MD significantly reduced whitehead damage compared to plots treated with insecticide.

The successful cases above indicate that MD technology is a promising strategy in insect pest management and can be applied to manage YSB. The traditionally high cost of synthesizing insect sex pheromones has been a barrier to adopting this technology in low-cost, large-hectarage row crops (Holkenbrink et al. 2020). Provivi®, with our innovation and breakthrough technology, uses proprietary methodology (bio-catalysts) and low-cost raw materials to reduce the steps needed to synthesize pheromones (Wampler et al. 2021). Production of pheromones at a large scale and with reduced costs enables affordable pheromone products and the adoption of this technology in rice is economically viable for grower. With an affordable pheromone dispenser, the integration of MD technology into conventional grower's pest management will be easier and will help to reduce the number of insecticide applications to protect yield in a season. Reduced insecticide application for YSB will help the grower to reduce production cost and minimize the negative impact of insecticide to the rice ecology as well (Witzgall et al. 2010). Slow-release dispensers filled with YSB sex-pheromone (Pheron™ RSB) were evaluated in wide-area trials to understand the benefits of MD. Though there were few studies conducted to understand MD on YSB, none were from Indonesia and at such large scale. Our objective here was to compare trap reduction, crop damage, number of insecticide usage, and yield protection in pheromone foundational practice (PFP) to conventional grower practice (CGP) across rice-producing provinces of Java Island, Indonesia, in two consecutive seasons. Therefore, in this large-scale study we evaluate MD as an alternative, novel, practical and season-long foundational tool for implementing integrated pest management of YSB in rice agroecosystem.

## MATERIAL & METHODS

### Field trial locations and seasons

Field trials were conducted in two consecutive seasons, starting with December 2020 planting (wet season) and following by March 2021 planting (dry season). A total of 74 trials are spread across 27 districts and three provinces of Java Island where YSB populations are problematic and endemic. We have collaborated with 1,282 growers to procure 539 ha of land to conduct these trials. Details of locations are described in Table 1.

### Materials

Pheron™ RSB with four-way blend (Z11-Hexadecenal, Z9-Hexadecenal, Z13-Octadecenal, Z9-Octadecenal in a ratio of 75, 8.6, 9.4, and 7 respectively) in low-density polyethylene (LDPE) dispensers were used in all locations. Dispensers were installed on a thin bamboo stick with a cable tie 1.5 m above the ground. Pheromone water traps were used to trap the male moths and understand MD. Commercially available YSB lures with a three-way blend (Z9-Hexadecenal; Z11-Hexadecenal; Z9-Octadecenal) and water traps were purchased from PT. Rumah Bio Indonesia. YSB lures were installed at the same height as dispensers and replaced every 20 days. Both dispensers and traps were installed at transplanting. To maintain uniformity, we used the rice variety INPARI32 at all locations.

### Experimental design and plot layout

Each trial location consisted of two treatments, pheromone foundational practice (PFP), treatment with dispensers, and conventional growers practices (CGP), treatment based on common growers' practices to manage YSB.

Earlier field trials conducted by Provivi® suggested a minimum area of 4 ha is required to realize the benefits of MD and effectively manage YSB on rice (Unpublished 2020). To meet this requirement, the size of PFP treatment plots ranged from 4 ha to 9 ha. Dispensers were installed at the labeled recommended rate of 20 dispensers/ha with a 22 m distance between any two dispensers. Since the minimum area treated is unnecessary for CGP, a 2 ha plot in the same area was demarcated. We reduced the edge effects where possible by picking PFP and CGP plots of near-square shape. 200–500 m was maintained between PFP and CGP plots to minimize the drift of pheromones and contamination of CGP. All treatment plots have at least a 100 m distance to a light source to avoid interference towards pheromone traps.

**Table 1.** Details of trial locations in the wet season, 2020–2021 and dry season, 2021

| Province | Wet season 2020-2021 | | Dry season 2021 | |
|---|---|---|---|---|
| | Districts | Number of locations | Districts | Number of locations |
| West Java | Cirebon | 1 | Cirebon | 1 |
| | Indramayu | 2 | Indramayu | 1 |
| | Karawang | 6 | Karawang | 1 |
| | Bekasi | 2 | - | - |
| | Majalengka | 2 | - | - |
| | Subang | 4 | - | - |
| Central Java | Blora | 2 | Blora | 1 |
| | Sukoharjo | 1 | - | - |
| | Sragen | 1 | Sragen | 1 |
| | Karanganyar | 2 | - | - |
| | Pemalang | 2 | Pemalang | 1 |
| East Java | Tulungagung | 2 | - | - |
| | Blitar | 2 | Blitar | 1 |
| | Malang | 1 | - | - |
| | Jombang | 3 | Jombang | 1 |
| | Nganjuk | 1 | - | - |
| | Magetan | 1 | - | - |
| | Ngawi | 3 | Ngawi | 1 |
| | Madiun | 4 | Madiun | 1 |
| | Ponorogo | 4 | - | - |
| | Bojonegoro | 4 | Bojonegoro | 1 |
| | Lamongan | 2 | - | - |
| | Jember | 2 | Jember | 1 |
| | Lumajang | 2 | - | - |
| | Banyuwangi | 2 | Banyuwangi | 1 |
| | Pasuruan | 1 | Pasuruan | 1 |
| | Sidoarjo | 1 | - | - |
| Total | 27 districts | 60 locations | 14 districts | 14 locations |

One pheromone trap was installed in the middle of each hectare of each treatment.

Additionally, to monitor the YSB population in surrounding areas, four additional pheromone traps were installed in all directions of the trial location while maintaining at least 200 m from PFP plots. The PFP treatment plot was sprayed with premixture insecticide, Virtako®, registered in Indonesia by PT Syngenta® Indonesia (thiamethoxam 200 g/l + chlorantraniliprole 50 g/l) at 200 ml/ha as a prophylactic application at 15 days after transplanting. A threshold of 2% damage is fixed where additional insecticide applications would be warranted during the rest of the season. For CGP treatment, there was no restriction on insecticide applications, and they were made according to each growers' practice.

**Data collection**

To understand trap-reduction/MD, moth capture assessments were made every ten days until harvest (~90 days crop). The male YSB moths caught in the traps were counted and reset with water mixed with non-odor detergent. Damage assessments were conducted at regular intervals starting from ten days following the installation of dispensers in the field and ending close to harvest (~70–80 days crop). Damage assessments were made by scouting for deadhearts in the vegetative and whiteheads in the generative stages from 16 one-meter quadrat units per hectare. A total of 10 rice hills per quadrat were sampled. The number of total tillers and damaged tillers were counted and recorded. The number of insecticide applications with details such as brand name, the active ingredient, and the use rate of each collaborating grower was recorded in CGP plots starting from transplanting until harvest. Grain yield data was generated by sampling four quadrats/ha (*Ubinan*). Each quadrat is 6.25 square meters. The moisture content of each quadrat sample was measured using a grain moisture testing meter, LDS-1G. The grain yield result of the *Ubinan* was then converted into metric tons per hectare at a 14% moisture content by following the methodology from Makarim et al. (2017).

**Data analysis**

**Trap reduction as a measure of mating disruption.** Mating disruption is measured as a reduction in adult (male) moth trap counts. Trapping reduction is the percentage decrease in moth captures in PFP traps compared to no-dispenser areas, CGP. Moth counts were modeled as an overdispersed Poisson variable as a function of pheromone treatment, time, and spatio-temporal random effects to account for the inherent correlations within and between trials. A hierarchical Bayesian framework was used to allow for the expected nonlinear, nonincreasing trend in trapping reduction over time. The nonlinear function used to model the trapping reduction over time is highly flexible, and allows trapping reduction associated with the pheromone treatment to remain constant for many days before beginning its eventual expected decrease (at some point in time, all dispensers will eventually run out of A.I. and will stop working), and then plateauing at no pheromone effect, i.e., no trapping reduction related to the pheromone treatments. Alternatively, if no trapping reduction is observed, then the model also allows for that possibility. The model was fit in MATLAB (The Mathworks, inc. 2021) using customized sampling algorithms. For the wet season model, the results are based on 40 chains with 750 iterations each. There was an initial burn-in of 3250 iterations, and subsequent iterations were thinned by 5. For the dry season model, 40 chains were run for a total of 27750 iterations each. There was a burn-in of 7750 iterations, and the rest of the iterations were thinned by 5, leaving a total of 4000 iterations that the results are based on.

**Damage reduction as a result of mating disruption.** This analysis aimed to determine if there was a significant reduction in tiller damage for plots under the PFP treatment compared to plots under the CGP treatment. Damage reduction is the percentage decrease in number of damaged tilers in PFP fields compared to no-dispenser areas, CGP. The number of damaged tillers per sampling point were modeled as an overdispersed Poisson variable as a function of pheromone treatment and spatio-temporal random effects to account for the inherent correlations within and between trials. The model was similar to a GLMM, but with the spatio-temporal random effects defined as in the trap count model, and not based on qualitative groupings. Again, a hierarchical Bayesian model framework was used, and the the model was fit through a customized slice sampling algorithm in MATLAB (The Mathworks, inc. 2021) using customized sampling algorithms. For the wet season model, 64 chains were run for a total of 5250 iterations each. There was a burn-in of 2750 iterations, and the rest of the iterations were thinned by 5, leaving a total of 500 iterations that the results are based on. For the dry season model, 32 chains were run for a total of 56500 iterations each. There was a burn-in of 12750 iterations, and the rest of the iterations were thinned by 5, leaving a total of 43750 iterations that the results are based on.

**Yield protection due to mating disruption.** A paired t-test was used to determine significant differences between PFP and CGP plots. Before the tests were conducted, the differences between the treatments were plotted to ensure the data met the assumption of a normal approximation in MATLAB (The Mathworks, inc. 2021)

**Insecticide usage reduction with mating disruption.** The collected data of several insecticide spray applications in PFP and CGP plots were analyzed by comparing the median number with paired t-test in MATLAB (The Mathworks, inc. 2021).

## RESULTS

**Trap reduction as measure of mating disruption**

The analysis concluded that the PFP treatment significantly reduced trap captures compared to CGP. PFP resulted in trap reduction from transplanting until harvest in both seasons. Median trap reduction in both seasons was very similar, where trap reduction was higher than 70% until the vegetative phase (~45 days after installation), where the pest pressure is relatively higher, and the crop is attractive for adult yellow stem borer moths (Figure 1, Figure 2). Trap reduction during reproductive stages was higher than 40% until harvest.

**Damage reduction as result of mating disruption**

There was a significant reduction in damaged tillers and panicles in PFP plots compared to CGP in both seasons. Figure 3 and Figure 4 shows the cumulative distribution function (CDF) plot of the marginal posterior distribution for damage reduction. This means that at each x-value, the y-value gives the probability of the parameter being less than the x-value. The figures show that damage in PFP plots is significantly lower than in CGP in both seasons. The median damage in PFP-treated plots in the wet season is 40% lower than CGP, with a 95% credible interval of 31–48%. In comparison, the median damage in PFP plots in the dry season is 46% lower than CGP, with a 95% credible interval of 31–58%.

**Yield protection due to mating disruption**

Figure 5 shows that in the wet season 2020–2021, the yields from PFP and CGP plots were significantly different (p-value = 0.003). The mean difference in yield was 0.43 tons/ha at 14% moisture (95% confidence interval: 0.15–0.70 tons/ha). The yield analysis for dry season 2021 in Figure 6 shows that PFP is significantly different (p-value = 0.004) compared to CGP. The mean difference in yields was 0.76 tons/ha at 14% moisture (95% confidence interval: 0.29–1.22 tons/ha).

**Insecticide usage reduction with mating disruption**

Insecticide usage data in the PFP and CGP is plotted in Figure 7 and Figure 8 for the wet (2020–2021) and dry seasons (2021), respectively.

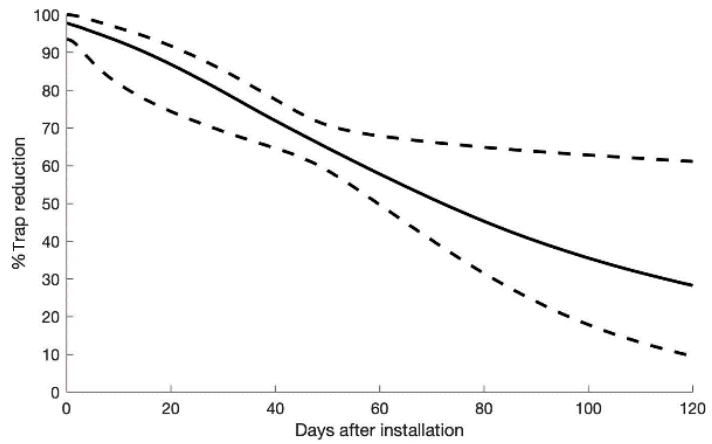


**Figure 1.** Percentage trap reduction in PFP compared to CGP over a wet season, 2020–2021. The solid line represents median trap reduction, and the dotted lines represent 95% credible intervals.

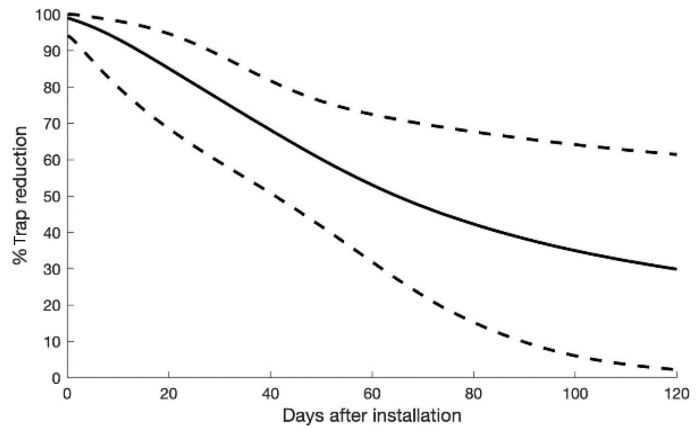


**Figure 2.** Percentage trap reduction in PFP compared to CGP over a dry season, 2021. The solid line represents median trap reduction, and the dotted lines represent 95% credible intervals.

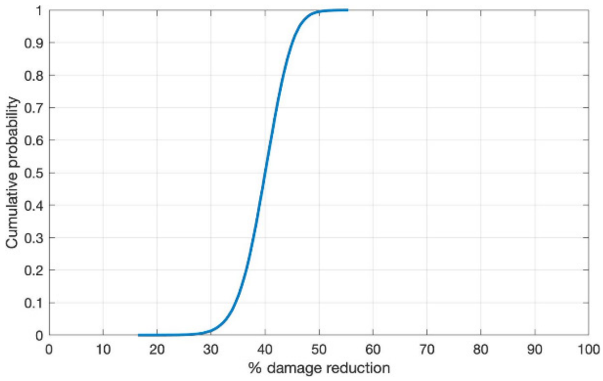


**Figure 3.** Cumulative distribution function (CDF) of % damage reduction due to yellow stemborer in PFP plot compared to CGP. The wet season, 2020–2021. The median damage reduction at the 0.5 mark on the y-axis gives value ~40% damage reduction.

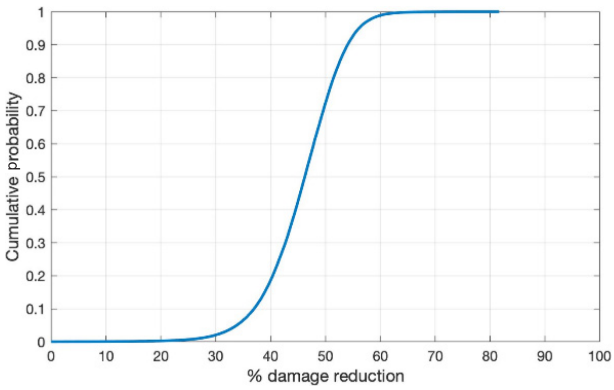


**Figure 4.** Cumulative distribution function (CDF) of % damage reduction due to yellow stemborer in PFP plot compared to CGP. The dry season, 2021. The median damage reduction at the 0.5 mark on the y-axis gives value ~46% damage reduction.

Insecticides applied for managing only YSB were considered. PFP had one mandatory insecticide application 15 days after transplanting in both seasons. Post that, the application of insecticide in PFP was based on the grower threshold. CGP growers applied more insecticides in both seasons, sometimes up to eight times to manage YSB. The CGP growers used 40% and 56% more insecticide sprays to manage YSB in the wet and dry seasons, respectively.

## DISCUSSION

*Scirpophaga incertulas*, the yellow stem borer (YSB), has been determined to be the most damaging rice pest in Indonesia (BPPOPT 2022). The larvae can cause tiller damage and empty panicles, which can potentially cause harvest losses and ultimately failure. Current insect pest management in Indonesian rice largely depends upon conventional insecticides (Prihandiani et al. 2021). The more challenging the insect pest control is the higher the number of insecticide applications. Often, insecticide applications are ineffective as the larvae are protected inside the rice stems (Nurhasanah et al. 2020). Field studies conducted by Fox & Winarto (2016) and Prihandiani (2021) on Java Island, Indonesia, reported that 60% of rice growers used three to five different active ingredients mixed in one spray solution. Almost 80% of growers sprayed 7 to 13 times per rice growing season.

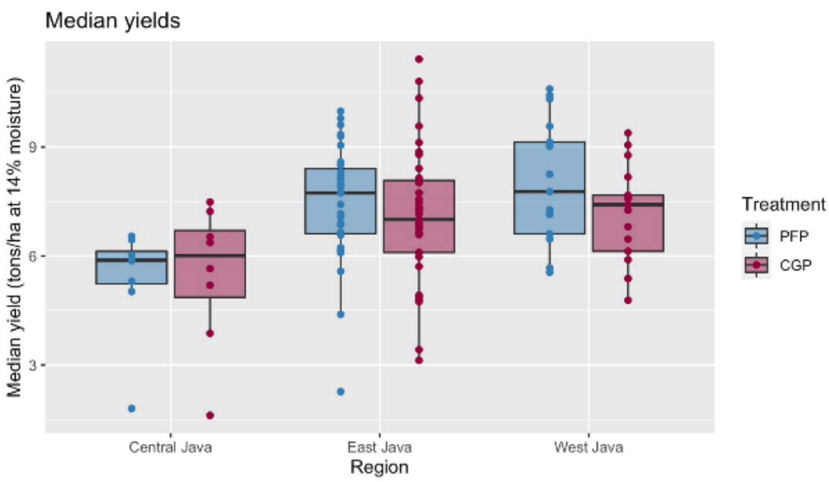


**Figure 5.** Yield differences between PFP and CGP differentiated for each province in Java Island, Indonesia. Yield represented as tons/ha, adjusted to 14% moisture content. The wet season, 2020–2021.

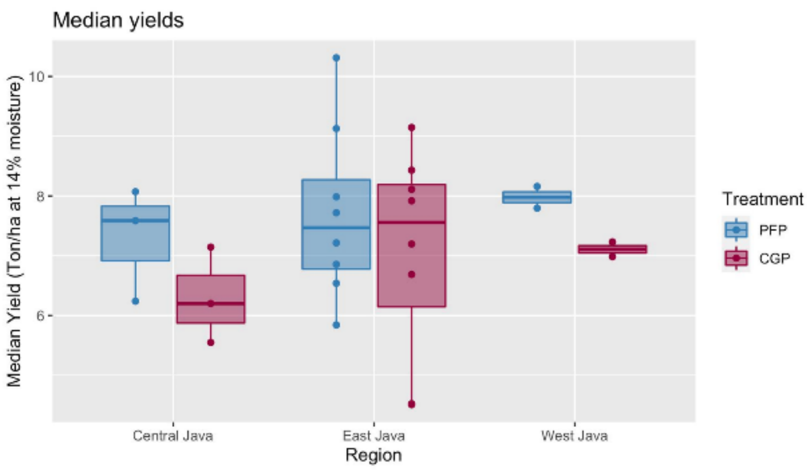


**Figure 6.** Yield differences between PFP and CGP differentiated for each province in Java Island, Indonesia. Yield represented as tons/ha, adjusted to 14% moisture content. The dry season, 2021.

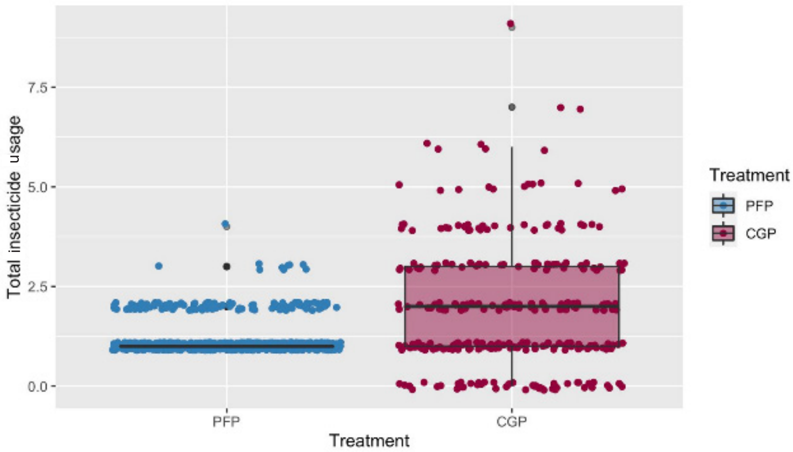


**Figure 7.** The number of insecticide applications made to manage yellow stem borers of rice in PFP and CGP plots. Each dot represents a spray application. The wet season 2020–2021.

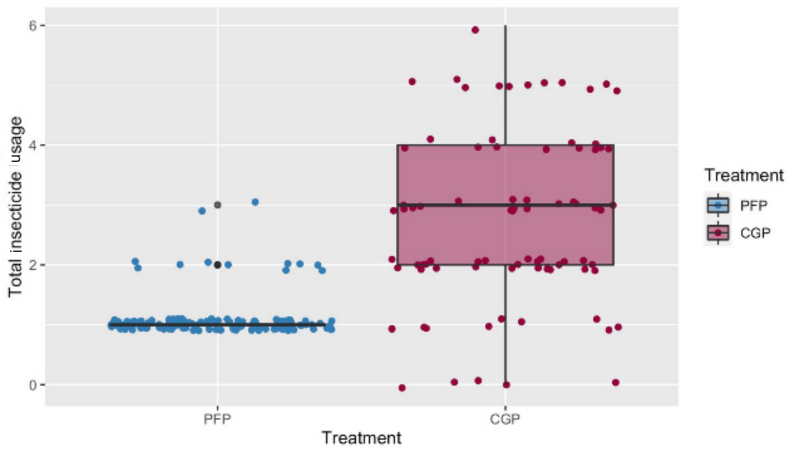


**Figure 8.** The number of insecticide applications made to manage yellow stemborers of rice in PFP and CGP plots. Each dot represents a spray application. The dry season, 2021.

Such intensive applications with synthetic conventional insecticides has negative impacts on the environment, such as the development of insecticide resistance, resurgence or secondary pest explosions, elimination of non-target organisms, and accumulation of insecticide residues in the field (Baehaki 2013). Croplife Indonesia confirmed insecticide resistance to diamide insecticide class in YSB populations collected from West Java, Indonesia (IRAC 2016). Though integrated pest management (IPM) approaches are well-known, most are not considered as practical solution by Indonesian rice growers. Pheromone-mediated MD can reduce YSB reproduction rate and resulting larval populations; thus, reducing the number of necessary insecticide applications (Rizvi et al. 2021).

In the past decades, lepidopteran sex pheromones have been used in many pest control techniques such as lure-and-kill, mass trapping, auto-confusion, and mating disruption (Cork et al. 2008). Lepidopteran behavioral control for pest management by MD uses field-wide application of synthetic species-specific sex pheromones to disrupt pheromone-mediated communication between the sexes of the target species, this technique is a practical tool for pest management (Miller & Gut 2015). However, compared to other techniques, MD requires more pheromone content to be released and potentially more costly (Cork et al. 2008). Furthermore, proving this technology in large area crops like rice is challenging due to the cost of sex-pheromone synthesis along with development of an efficient formulation that can last a season-long (Holkenbrink et al. 2020). Through proprietary (bio)catalysts and low-cost raw materials, Provivi® is able to produce pheromones on a large-scale at low cost (Wampler et al. 2021). As such, Provivi® is the first company to register pheromone-mediated MD in Indonesia to manage YSB in rice. Syngenta® Indonesia in partnership with Provivi® has commercialized Nelvium™ Powered by Pheron™ RSB in 2022 in Indonesia.

Typically, larger rice fields are required to understand the efficacy of MD. It is also important to utilize wider field plot areas to reduce the migration of mated YSB females flying into pheromone-treated areas for oviposition which can result in damage (Cork et al. 1996). Thus, the concept of minimum field size is an important consideration for MD trials. Previously, we tested the Pheron™ RSB in 1, 2, 4, and 9 ha rice fields at multiple dose rates. Our internal results (Provivi internal, unpublished data) determined that higher MD is achieved in areas where dispensers were installed in ≥4 ha. The maximum benefits of MD, reduction in damage caused by YSB larvae is also lower in larger areas, compared to <2ha. Lower insecticide applications were noticed when dispensers were installed in larger areas of rice. This phenomenon is very similar to other crop pests, where the efficacy of MD increases with increase in effective area (Chen et al. 2014; Cork et al. 2008). In this MD study, the effectiveness of Pheron™ RSB dispensers were examined at the registered rate of 20 dispensers/ha at the minimum 4 ha PFP plot size with 200 m distance of buffer zone from the CGP fields. Pheron™ RSB was tested at 74 sites in 3 provinces on Java Island with 1,282 participating growers during the dry and wet seasons to investigate further how Pheron™ RSB dispensers work in diverse conditions such as pest population density, weather, varied environmental conditions, and growers' practices. The efficacy of Pheron™ RSB was measured via reduction of YSB male moth captures in lure traps, damage reduction, insecticide application rates and frequency, and potential for yield protection compared to conventionally managed fields (Cork et al. 1998).

Reduction of YSB male moth captures is an indication that the MD is working because the pheromone emitting dispensers interfere with the YSB male's ability to focus on female sex pheromone or synthetic pheromone from lure inside the trap (as well as calling YSB females), which then hinders the male from locating these pheromone's sources (Bartell 1982). Median trap reduction in both seasons was very similar, where trap reduction was higher than 70% until the vegetative phase of the rice crop (~45 days after installation). This is when the pest pressure is relatively higher, and the crop is attractive for adult YSB moths (Figure 1 and 2). Trap reduction during reproductive stages was higher than 40% until harvest in both dry and wet seasons of 2020–2021. The results were similar to the studies by

Cork et al. (1998), where MD with a 2-component YSB blend consisting of (Z)-9-hexadecenal and (Z)-11-hexadecenal, at an application rate of 40 g AI per ha per season gave a trap reduction of 65% to 85% for initial 50 days of the crop period. A lower percentage of trap reduction may not indicate that the moths in PFP plots can mate (Cardé & Elkinton 1984). We still need to understand the optimal and effective trap reduction of YSB. Further studies need to be done to correlate trap reduction and direct measures of MD via tethered virgin females or mating tables (McVeigh et al. 1983).

Despite the lack of direct measures, we can still indirectly determine MD's effect by assessing the infestation of YSB (Cork & Basu 1996). The results from the two seasons study through rice crop damage assessment showed that tiller damage by YSB in PFP plots was significantly lower compared CGP plot, with a median of 40% and 46% damage reduction in the wet season and dry season, respectively (Figure 3 and 4). The large area of a 4 ha plot in PFP with 80 points sources of pheromone-emitting dispensers created an effective MD. This MD area decreases the YSB reproduction rate and larval number in the field, which may lead to fewer deadheart and whiteheads caused by feeding damage (Chen et al. 2014). The large area in our study has also reduced the likelihood of gravid female moth migration into PFP plots. The first generation of female moths of YSB would disperse into an attractive and suitable rice crop for oviposition. A mated female YSB tends not to fly considerable distances to reduce predation and mortality (Cork et al. 2008). This result is aligned with a study done in India which observed a significant decrease in YSB damage in a wide area of MD treatment compared to plots with conventional insecticide management (Cork et al. 2008).

Significantly lower damage in the PFP plots also positively affects other parameters, such as the number of insecticide applications and grain yield. Yield is a factor of many parameters, such as soil health, cultivation practices, timely irrigation, and crop protection from weeds and diseases. However, yield loss is possible when an insect pest such as YSB directly impacts the grains produced per tiller. Protecting the crop from YSB with MD with Pheron™ RSB has resulted in higher harvested grain yield than CGP. An increase of 0.43 tons/ha of grain yield in the wet season and 0.76 tons/ha in the dry season in PFP compared to CGP could be attributed to MD. This higher yield has been contributed by a healthy tiller and more filled grains in PFP plots compared to the CGP plot. The yield increase in MD treatment plots for managing YSB was also reported by Cork et al. (1998), where it provided a 10% higher yield compared to insecticide-treated plots and a 25% higher yield compared to plots without insecticide application.

Though a mandatory insecticide was applied in PFP plots as a prophylactic spray, insecticide usage to manage YSB in PFP saw a 40 to 56% reduction compared to CGP. Similarly, Welter et al. (2005) confirmed that MD in wide areas of plantation and row crops provided significant insecticide application reduction and maintained low damage. Studies done in India on YSB by Cork et al. (1998) reported that conventional growers' practice plots sprayed two additional rounds of insecticides to manage YSB compared to MD plots. The benefits of reducing insecticide application include conserving natural enemies, managing insecticide resistance, and reducing harmful chemical residue to the environment and humans. All these will significantly benefit rice's sustainable production and create economic benefits for the growers.

## CONCLUSION

Provivi® has made considerable progress in developing pheromone-based technology to manage yellow stem borer (YSB), where prophylactic, calendar-based applications are typical. Without alternative, practical, and adaptable technologies, pest resurgence, resistance, and residues from toxic insecticides is unavoidable. Pheromone-mediated mating disruption provides an alternative to insecticide applications. Research conducted at 74 locations across Java Island in multiple seasons in 2020-21 supports the proposition that fields treated with Pheron™ RSB incurred lower YSB damage, fewer insecticide applications, and yield protection compared to conventional practices. The results suggest that mating disruption offers smallholders a more efficacious means of control than current management practices. Pheromone-based insect management is a zero residue, nondetrimental to humans and the environment. This work and commercial adoption of Pheron™ RSB by growers in 2022–2023 across Java Island of Indonesia suggests it is sufficiently robust to extend it to other countries to manage YSB.

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