Review

Advancements, Challenges, and Future Perspectives of Soybean Integrated Pest Management

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Advancements, Challenges, and Future Perspectives of Soybean Integrated Pest Management

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Abstract

Soybean is usually grown at large scales, with pest control based on insecticides. However, the overuse of chemicals has led to several adverse effects. Thus, integrated pest management (IPM) is the best way to protect yield through integrating different pest control tools, based on plant resistance (including *Bt* cultivars), adoption of economic thresholds (ETs), scouting procedures, use of selective insecticides, biological control, and other sustainable tools, which help maintain environmental quality in an ecological and economical manner. Soon, those tools will also include RNAi, CRISPR based control strategies, among other sustainable alternatives. In Brazil, results from the Soybean-IPM Program indicate that adopters of the technology have reduced insecticide use by approximately 50% relative to non-adopters, with yields comparable to or slightly higher than those of non-adopters. This reduction can be explained not only by the widespread adoption of *Bt* soybean varieties across the country but also by the adoption of ETs in Soybean-IPM, which has reduced insecticide use, thereby increasing natural biological control in the agroecosystem. However, low refuge compliance has led to the first cases of pest resistance to Cry1Ac, thereby growing reliance on chemical control and posing an additional challenge for integrated pest management practitioners. The obstacles to adopting IPM programs for commodity crops, such as soybean, may be mitigated by recent economic incentives within the new global agenda for decarbonized agriculture and the increase of bioinputs available in the Brazilian market. Such incentives can support the broader adoption of IPM, thereby reducing dependence on chemical inputs to achieve high yields.

Keywords: IPM; sustainability; *Bt* cultivars; economic thresholds; biological control

1. Introduction

Soybean, *Glycine max* (L.) Merrill, is one of the most important crops around the world [1], responsible for 60% of vegetable protein and roughly 30% of the world's supply of edible oil [2]. Production reached 396 million metric tons in the 2023/2024 season [3], and will continue to growth because of the increasing global demand for food and biodiesel [4]. Despite its increasing production, soybean yields can be severely impacted by outbreaks of a diversity of pest species, especially from caterpillars and hemipterans [5]. These pests cause global losses of 29% or higher when not properly managed [6,7]. In Brazil, the world leader in production, soybean losses from pests have reached 4.31 million tons each year [8].

Despite chemical insecticides remaining effective against pests [9] and playing an important role in managing soybean pests [3,10], the overdependency on chemicals has raised concerns about their lasting impact on the environment [11] and human health [12]. The overuse of chemicals can trigger several adverse side effects, including outbreaks of secondary pests [13], selection of resistant pests [14], detrimental effects to pollinators [15] and biocontrol agents [16], in addition to potentially harming environmental and human health [17]. Consequently, reducing the use of chemical insecticides in agriculture has been an increasing demand [18] and an important goal of public policies around the world [19].

Among the most efficient strategies to control pests in agriculture, the adoption of Integrated Pest Management (IPM) which includes limiting insecticide use to only when strictly necessary, [20] improves safety to non-target organisms [21] and final consumers [22] while also increasing farmer profits [10]. As a science-based pest management approach, Soybean-IPM aims to use a combination of strategies, including biological control agents, plant resistance, and less harmful chemicals, among others to manage pests while minimizing risks to people, non-target organisms, property, and the environment [23].

Despite the known benefits provided by its adoption, IPM has not been implemented with the intensity it should be by many growers [13]. For instance, in the state of Parana, Brazil, 78.8% of the soybean farmers declare knowing how to practice Soybean-IPM, but only 31.4% of those farmers have adopted the strategy. Despite increasing knowledge and adoption of Soybean-IPM over the last years, there are still a large number of farmers who do not know about IPM (21.2%, 2023/24) and even a greater number of farmers who, despite knowing the strategies, do not practice Soybean-IPM (68.6%, 2023/24) (Figure 1). Despite these challenges, soybean-IPM is considered the most successful IPM program developed in Brazil, resulting in the reduction in amount of insecticide used to control insect pests by about 50% [10,27].

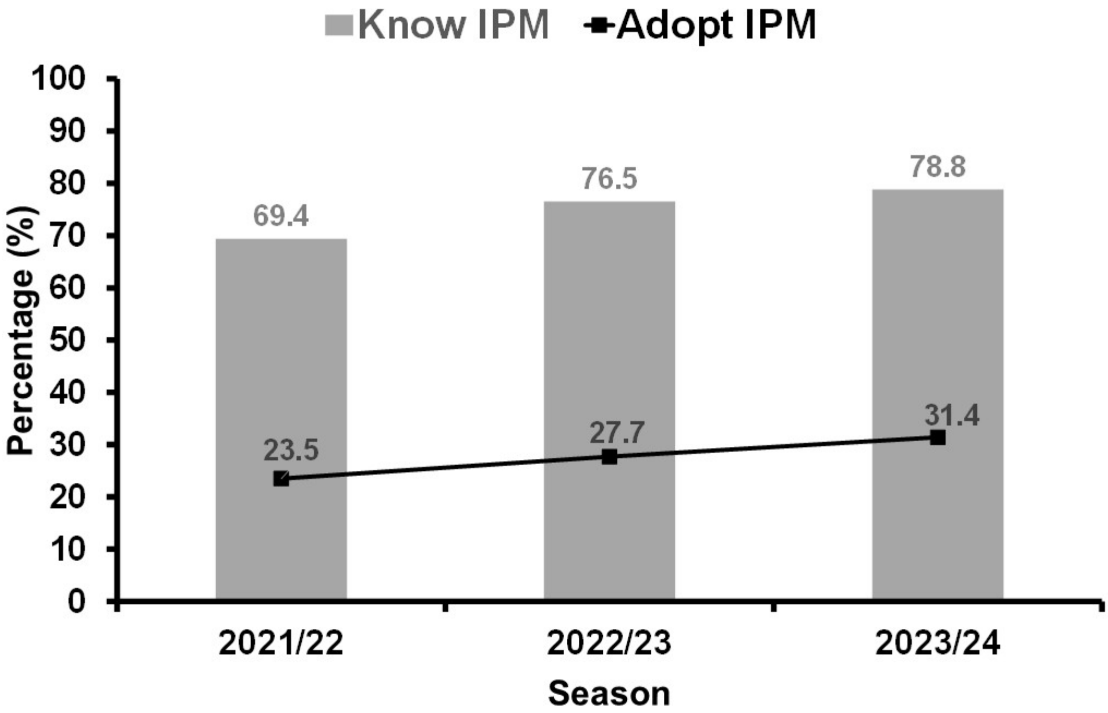


Figure 1. Percentage of soybean farmers in Paraná State, Brazil, who know the IPM principles (grey bars) and the percentage who adopt IPM (black line) in their fields over the seasons. Adapted from [24,26].

Since the 2013/14 growing season, the Soybean IPM program in the state of Paraná, Brazil, was reinforced by a joint force of federal (represented by the research institution, Embrapa Soja) and state (represented by the extension service and research institution, Paraná Rural Development Institute - IDR) governments as well as several farmers who made available their soybean fields each growing season to demonstrate the benefits of adopting sustainable Soybean-IPM. Those soybean fields have been called Unit of Technological Reference (UTR), which was identified and accompanied by the IDR-Paraná extension program throughout the whole soybean growing season. An extensionist was responsible for one or more weekly pest-sampling (scouting) in the field and for quantifying pests per meter and defoliation. Insecticides were applied only when Economic Thresholds (ETs) were reached or surpassed [10]. Simultaneously, a survey was carried out, with the aid of a questionnaire, with farmers not assisted by the Soybean-IPM program to quantify the number and time of chemical applications. With the answers, a comparison was made between non-assisted and assisted farmers to evaluate the results and challenges of the adoption of Soybean-IPM in the state, which is further discussed in the following sections.

2. Soybean-IPM: A Successful Case Study from the State of Paraná, Brazil

Comparing the results from Adopters of Soybean-IPM with Non-Adopters across eleven soybean seasons, adopters reduced the average number of insecticide applications by 52.8% (varying from 43.3% in 2019/20 to 69.2% in 2021/22 seasons) compared to farmers who did not adopt IPM. This reduction resulted in reduction of pest control costs of 51.6%, which is equivalent to 117 kg of soybean per hectare (ha). The adoption of IPM not only reduced pest control costs but also slightly increased average yield by 93.8 kg/ha (2.8%), resulting in an average increased profit of 210.7 kg/ha to the adopters of Soybean-IPM (Table 1). Thus, the adoption of Soybean-IPM triggered an increased profit to farmers associated with a more sustainable and efficient pest management [10]. These results are not surprising as the profitability of IPM adoption has been consistently reported in the scientific literature [36]. A profitable return from the adoption of IPM in soybean was reported ranging of $0.6 to $2.6 billion dollars in 2005 for USA farmers [37]. Similar positive economic results are also reported for soybean adopters in Brazil [38], Argentina [5], and India [39], as well as other world soybean producers, including Indonesia, for example [40].

Not only is Soybean-IPM adoption more profitable to farmers but also safer to the environment and biological control and pollinator preservation. The days from sowing the fields to the first insecticide application increased approximately 37% from 46.9 days (nonadopters) to 73.4 days for the Soybean-IPM adopters (Table 1). Delaying insecticide application by 26.5 days is an important strategy to conserve predators, parasitoids, and pollinators, which benefit critical ecosystem services provided by these organisms [10].

Despite not being universally adopted (Figure 1), Soybean-IPM is definitely a case of success in Brazil [27], leading to a significant reduction in insecticide sprays compared with non-adopters of the technology [10]. It is important to highlight that the reduction of traditional chemical insecticides used in soybean has been a result not only of the adoption of ETs as the core of IPM decisions [41], but also as a consequence of the increasing use of biological control agents as well as adoption of varieties of *Bt* soybean in Brazil. These are further discussed in the following sub sections of this review.

Table 1. Results from 11 years of adoption of Soybean-IPM[1] in the state of Paraná, Brazil, in comparison with farmers who did not adopt IPM. Adapted from [24,35].

Soybean season	**Number of fields**		**Number of sprays (insecticides)**		**Days until first insecticide spray**		**Pest control costs[2] (kg/ha)**		**Yield (kg/ha)**		**Increased profits[2,3] (kg/ha)**
	Adopter	Non-Adopter	Adopter	Non-Adopter	Adopter	Non-Adopter	Adopter	Non-Adopter	Adopter	Non-Adopter	
2013/14	46	333	2.3	5.0	57.5	33.0	144	302	2952	2922	186
2014/15	106	330	2.1	4.7	66.0	34.0	120	300	3612	3516	276
2015/16	123	314	2.1	3.8	66.8	36.0	120	240	3426	3282	264
2016/17	141	390	2.0	3.7	70.8	40.5	138	246	3870	3828	150
2017/18	196	615	1.5	3.4	78.7	43.6	138	324	3702	3630	258
2018/19	241	773	1.7	3.4	74.0	40.3	126	246	3006	2916	210
2019/20	255	553	1.7	3.0	75.0	56.0	108	186	3864	3804	138
2020/21	191	518	1.7	3.4	76.0	59.0	60	120	3654	3618	96
2021/22	175	522	0.8	2.6	85.0	57.0	36	96	1752	1740	72
2022/23	150	443	1.0	3.0	86.0	61.0	54	156	4128	4002	228
2023/24	138	543	1.7	3.3	72.0	56.0	162	276	3552	3228	438
Average	**160.8**	**484.9**	**1.7**	**3.6**	**73.4**	**46.9**	**109.6**	**226.6**	**3410.7**	**3316.9**	**210.7**

[1] IPM program where public consultants (from IDR - Paraná) sampled pests over the seasons and took all the decisions about IPM in the fields of selected farmers. At the end of the season, the results of IPM fields were compared with fields of non-adopters of IPM over the state. [2] Pest control costs and increased profits from adopting IPM compared with non-adoption were transformed into the equivalent of the value of kilograms of soybean, at each season, to avoid any depreciation of the currency due to possible effects of inflation. [3] Increase profits = (Yield of Adopters – Yield of Non-Adopters) + (Pest Control Costs of Non-Adopters – Pest Control of Adopters).

3. Use of Economic Thresholds (ETs) in Soybean-IPM

Pest monitoring (insect sampling and identification) and decision-making comparing pest populations with ETs, are the basis of Soybean-IPM (Figure 2) and crucial to its success [42]. ETs are based on the premise that cultivated plants can tolerate certain levels of injury without economically significant yield reductions [43] and, therefore, not all herbivorous insects will become pests and/or require control (Figure 3) [48,49]. In this context a decision to control any pest species in soybean should only be made when the pest population is equal to or greater than previously established ETs (Figure 3, Table 2) or is expected to surpass those levels within hours or a few days [41].

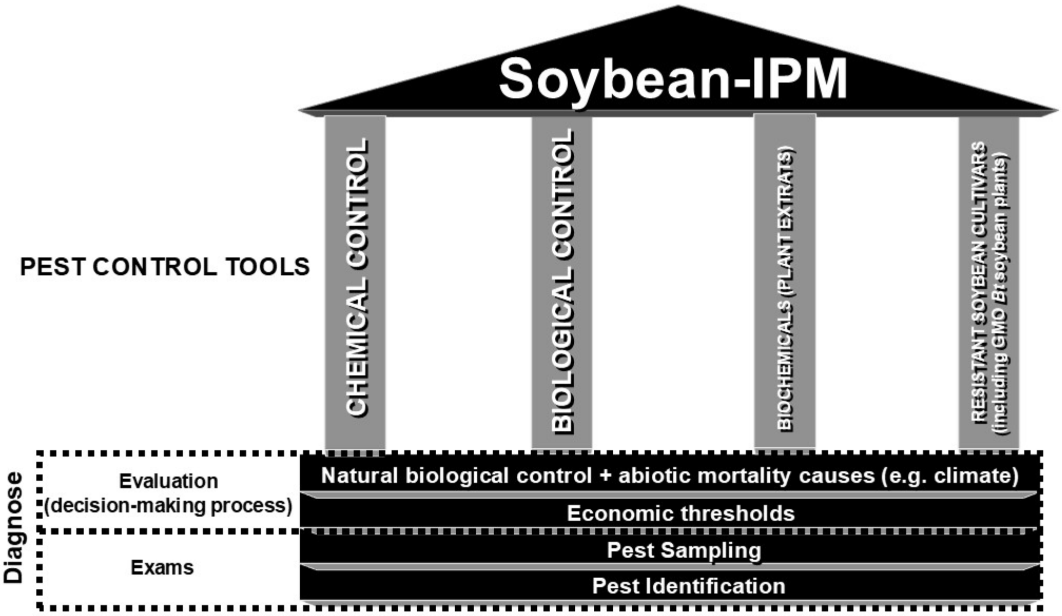
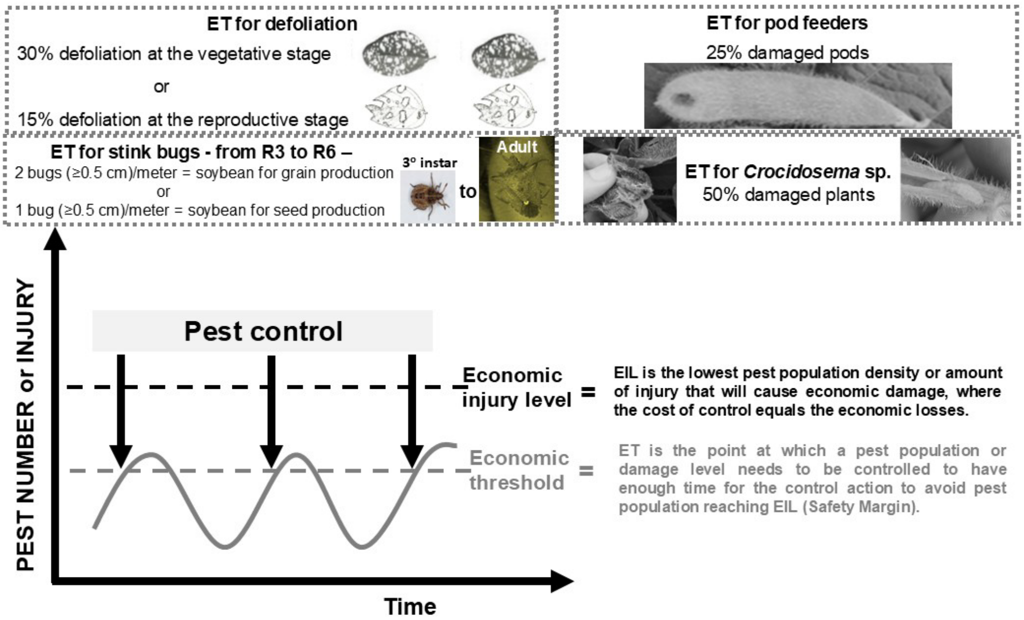


Figure 2. Soybean-IPM structure, sustained by the association of different pest management tools and based on diagnosis.



EIL is the lowest pest population density or amount of injury that will cause economic damage, where the cost of control equals the economic losses.

ET is the point at which a pest population or damage level needs to be controlled to have enough time for the control action to avoid pest population reaching EIL (Safety Margin).

Figure 3. Economic Injury Levels (EILs) in relation to the most important Economic Thresholds (ETs) for soybean pests recommended in Brazil. Adapted from [44–47].

Table 2. Economic Thresholds (ETs) recommended for soybean pests.

Pests	ET(s)	References
Aphis glycines	273 ± 38 aphids/plant	[50]
Bemisia tabaci	(**a**) 1.5 insect per leaflet (**b**) Beginning of sooty mood formation	[51]
Crocidosema sp.	50% of damaged plants	[47]
Defoliators	(**a**) 30% defoliation (soybean in the vegetative stage) - Brazil, Illinois, Iowa and North Dakota (USA) (**b**) 35% defoliation (soybean in the vegetative stage) – USA (**c**) 40% defoliation (soybean in the vegetative stage) – Michigan and Ohio (USA) (**d**) >40% defoliation (soybean in the vegetative stage) – Indiana (USA) **or** (**e**) 15% defoliation (soybean in the reproductive stage R1 to R6) – Brazil, Ohio and Michigan (USA) (**f**) >15% defoliation (soybean in the reproductive stage R1 to R6) – Indiana (USA) (**g**) 20% defoliation (soybean in the reproductive stage) – Illinois, Iowa and North Dakota (USA)	[44,53,54]
Helicoverpa zea	3.5 caterpillars /meter or sample cloth or 9 caterpillars/ 25 seweeps - USA	[55]
Heliothinae (*Helicoverpa* spp. and *Chloridea virescens*)	(**a**) four caterpillars/meter or sample cloth (soybean in the vegetative stage) – Brazil **or** (**b**) two caterpillars/meter or sample cloth (soybean in the reproductive stage) - Brazil	[24]
Pod feeders	25% damaged pods	[46]
Spodoptera spp.	10 caterpillars (≥1.5 cm)/meter or sample cloth	[56]
Stink bugs	(**a**) two stink bugs (≥0.5 cm)/meter or sample cloth (soybean for grain production) - Brazil (**b**) three stink bugs (≥0.6 cm)/meter or sample cloth – USA (**c**) nine stink bugs (≥0.6 cm)/25 sweeps - USA **or** (**d**) one stink bugs (≥0.5 cm)/meter or sample cloth (soybean for seed production) - Brazil	[45,53]
Tetranychus cucurbitacearum	21.23 mites/leaflet	[57]

The established ETs for soybean pests slightly differ around the world because of variations in crop value, different adopted cultivars, pest control costs, different pest species of occurrence, local environmental conditions and the availability and effectiveness of different control technologies available. All those factors play a significant role in determining ETs which differ as a result [58]. For instance, differences in the ETs for defoliators (Lepidoptera) and stink bugs (Hemiptera: Pentatomidae) have been reported between Brazil and the USA, which are the first and second global soybean producers, respectively. While ET for defoliators is 30% defoliation (in the vegetative stage) or 15% defoliation (in the reproductive state) in Brazil [41], in the USA, the ET is 35% defoliation at the vegetative stage and 20% at the reproductive stage [53]. Not only can ETs vary among countries but also among regions in the same country [54]. ET for defoliation in the USA varies from 40% to 30% defoliation during vegetative stages and from 25% to 15% defoliation during reproductive stages in different growing areas of the country (Table 2).

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Compared with defoliators, ET for stink bugs vary less. The recommended ETs for stink bugs in soybean is two insects larger than 0.5 cm (including nymphs from 3nd instar to adults) per row meter if the fields are intended for grain production or only one bug if the field is used for seed production in Brazil [41] while, in the USA, the ET is three bugs larger than 0.6 cm per row meter if a beat cloth is used as the sampling method or ten bugs per 25 sweeps [53].

In general, ETs are well-established for the most important pests of soybean (Table 2) despite remaining challenges. Some occasional or sporadic soybean pests such as mites, thrips and whiteflies require more research for a precise establishment of ETs [41]. For instance, [59], studying different ETs for whitefly control in soybean, recorded that yield was just reduced when whitefly outbreaks were extensive enough to trigger the growing of sooty mood, *Capnodium,* on the leaves. However, the growth of sooty mood on whitefly-infested soybean differs depends not only on pest infestation but also on soybean cultivars [51], making it difficult to establish a number of insects per foliar area as an ET.

Despite these challenges, [52] proposed an ET for whitefly on soybean of 1.5 insect per leaflet. This is a very conservative ET, which is for instance, 7 times lower than the ET of whitefly on cotton [60]. In fact, the yield results by [52] of 18.73 g.plant^{-1}, from treatment receiving seven insecticide sprays and resulting in 0.35 whiteflies per trifoliate (0.1 whitefly per leaflet), were statistically equal to results from the control (without any insecticide spray) with 27.35 whiteflies per trifoliate (9.1 whitefly per leaflet). These results contradict realistic ET and principles of IPM [43,61]. Moreover, the size of a soybean leaflet can vary considerably depending on plant's developmental stages, cultivar, and environmental conditions [62] reinforcing the need for further studies with whiteflies to determine ET.

Similarly, ETs for mites also remain understudied [13]. An ET of approximately 21 individuals per soybean leaflet of *Tetranychus cucurbitacearum* (Sayed) was proposed by [57]. However, as noted above, the size of a soybean leaflet varies [62]. Later, an economic injury level (EIL) for *Tetranychus urticae* in soybean based on population density was determined as one *T. urticae* per cm^2 of leaf area, considering the control cost of US$20.00 ha^{-1} and the soybean crop value of US$350.00 Mg^{-1} [63]. Nevertheless, the ET, which is the direct tool used by farmers to take decisions, is still unclear.

Thrips are common in soybean despite rarely causing direct economic damage, although dry and hot weather can lead to high populations. The Economic Injury Level (EIL) for thrips in soybean was estimated between 4.53 to 3.43 thrips per plastic beating tray (40 × 25 × 3 cm) placed beneath the plant’s apex while the branch bearing the apical foliage is struck sharply [64] but no ET has not been proposed.

Despite previously reported differences in recommendations and the remaining challenges posed by more sporadically occurring pest species, the principle behind ETs is to avoid preventive insecticide applications, which yield economic and ecological benefits [10]. Globally, threshold-based programs reduced overall insecticide applications by 44% and associated costs by 40%, without compromising pest control or yield compared to calendar-based programs [65], making them economically advantageous for farmers and ecologically beneficial to the environment. Nevertheless, farmers and pest managers often question these thresholds and apply insecticides when pest densities are well below recommended ETs [13,54].

Among the range of reasons for such slow adoption of ETs, two crucial challenges stand out: **1)** Farmers usually fear facing significant yield loss without spraying insecticides, consequently resulting in the refusal to fully adopt ETs, and especially **2)** the amount of work required for pest monitoring [13]. Assessing soybean pest numbers or their injuries is required for ET use but is frequently perceived as too time-consuming [13,54]. The shortage of farm labor is a reality for soybean farmers due to urbanization and the migration of people from rural to urban centers [66]. Furthermore, the lack of workers, inadequate training and capacity-building for IPM practitioners, and insufficient attention to IPM adoption are challenges for ET adoption [67]. After training, soybean farmers´ adoption of ET has increased, and, consequently, pesticide use decreased [68].

4. Use of Bt Cultivars in Soybean-IPM

In Brazil, the Soybean-IPM heavily utilizes prevention strategies [9]. Before sowing the soybean field, the choice for resistant cultivars plays and important role in the success of IPM [69] as an economical, ecological, and environment-safe decision [70]. Resistant plants suffer less damage from pests compared with susceptible counterparts, consequently, eliminating or at least reducing the need of insecticides to keep pests' populations below thresholds [71]. Genetically modified (GM) plants, resistant to insects, represent a more recent insect pest control method for IPM programs in various agroecosystems [72].

Since it is first commercial release in 1995, crops that have bee genetically transformed with the addition of Cry proteins from *Bacillus thuringiensis* (*Bt*) have increasingly been part of the agricultural landscape and an important tool in IPM. GM plants have been widely adopted by at least 26 different countries spread worldwide [73]. As in other crops, soybean-IPM has been transformed by the introduction of the *Bt* soybean technology expressing Cry1Ac (event MON 87701) protein (*Bt*) at high levels due to their high efficacy and simplicity of adoption [74]. Initially (2013) growers adopted the first generation of technology (expressing only Cry1Ac) and later (2021) with the addition of the second generation (expressing Cry1Ac + Cry1A.105 + Cry2Ab2 for Intacta 2 Xtend and Cry1Ac + Cry1F for Conkesta) (Figure 4). The adoption of *Bt* soybean has been especially high in South America, particularly in Brazil and Argentina, the first and third largest world soybean producers (Table 3). By the fifth year of *Bt* soybean adoption in South America, *Bt* soybean was cultivated over an area of 73.6 million hectares, generating an increase of US$ 7.64 billion in farmers' income [76] and reducing pesticide use by approximately 10.44 million kg. This reduction in pesticide use and field operations contributed indirectly to lower greenhouse gas (GHG) emissions, primarily by decreasing energy demand associated with pesticide manufacturing, transport, and application. Estimates indicate that this mitigation effect is equivalent to removing approximately 3.3 million cars from the roads in terms of CO_2-equivalent emissions [76,78].

Table 3. Adoption of *Bt* soybean cultivars in South American countries.

Country	Area (ha)	%	Year	Reference
Brazil	43.0 million	94%	2023/24	[74]
Argentina	4.3 million	16.2	2018	[75]
Paraguay	1.7 million	6.4	2018	[75]
Uruguay	0.4 million	1.5	2018	[75]

Interestingly, the reduction of insecticide applications in soybean fields has occurred both with and without adoption of IPM with the use of ETs (Figure 4A). Uniquely the adoption of *Bt* soybean (at farms not adopting IPM) reduced insecticide applications by 48.4% (2015/16 crop season) but only 14.7% (2022/23 crop season) more recently. When *Bt* soybean was adopted as a pest management strategy within the IPM framework, especially associated with pest sampling and insecticide application only when the pest population reaches or surpasses ET, insecticide use was reduced even further. Interestingly insecticide reductions follow a different trend for adopters with reductions of 57.8% (2015/16 crop season) increasing to 78.3% (2021/22 crop season) (Figure 4A). Taking areas cultivated with non-*Bt* cultivars and without IPM adoption as the reference, an average reduction of 33.3% in insecticide applications was observed in areas cultivated with *Bt* cultivars, even in the absence of IPM adoption. This reduction reflects the direct effect of *Bt* technology on lepidopteran pest control. In contrast, insecticide use was further reduced by 47.8% in areas where *Bt* cultivars and IPM strategies were adopted simultaneously, highlighting the additive effect of *Bt* technology combined with monitoring and economic threshold-based decision-making (Figure 4B). The reduction of insecticides associated with *Bt* crops has been previously reported in the literature in other crop systems. In the USA, insecticide applied in maize, *Zea mays*, fields decreased 75% with the

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adoption of *Bt* varieties, falling from 0.2 kg/ha in 1998 to about 0.05 kg/ha in 2011, when the adoption of *Bt* varieties exceeded 80% of the maize cultivated in the country [79]. This lower use of insecticide benefitted the conservation of natural biological control agents in different agroecosystems [73], including cotton, corn, potato, rice, and eggplant [80] as well as soybean [74]. Because *Bt* has negligible effects on non-target organisms [81], it is regarded as a safer choice than chemical insecticides [82] to manage target pests.

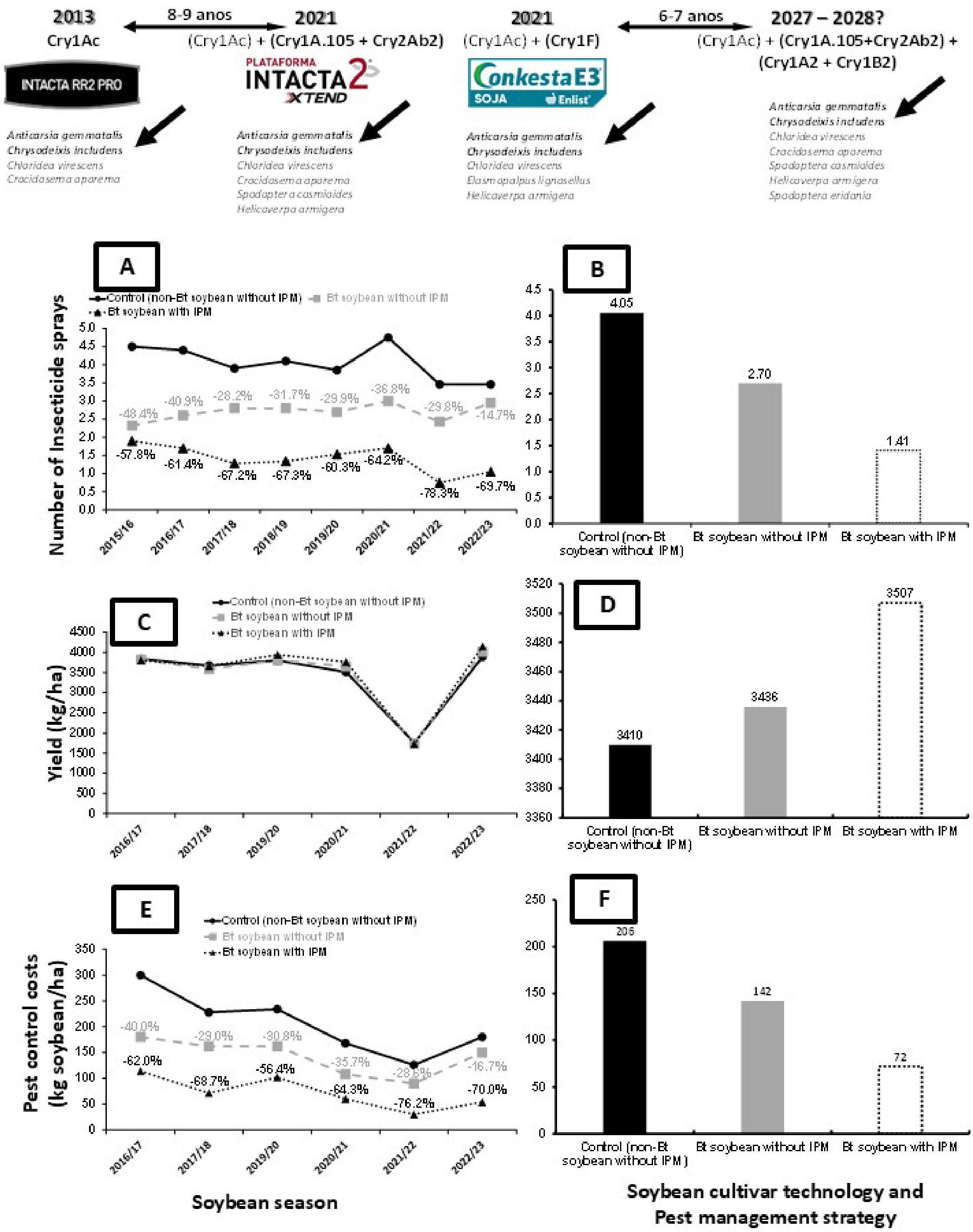

Figure 4. Results from the adoption of Bt soybean with and without the adoption of IPM in the State of Paraná, Brazil, over eight crop seasons from 2015/16 to 2022/23. (**A**) Insecticide spray per season and (**B**) Mean spray of insecticides among different pest management technologies. (**C**) Yield over the seasons and (**D**) Mean yield according to the adopted pest management technology. (**E**) Pest control costs over the seasons and (**F**) Mean pest control cost according to the adopted pest management technology. Adapted from [74].

Despite the recorded benefits of *Bt* soybean over insecticides, some negative effects from the non-compliance of refuge as Insect Resistance Management (IRM) have been recorded [74]. Resurgence of target pests associated with the resistant populations to the *Bt* toxins has been reported [83,84], including for *Rachiplusia nu* [85] and *Crocidosema* sp. [86] in Brazilian soybean fields.

Outbreaks of secondary pests in soybean have also been associated with the adoption of *Bt* cultivars [87]. With the reduction of the insecticide load used in the crop, *Spodoptera* spp., which has known resistance to *Bt* were previously controlled by other insecticides applied for other lepidopterans, have survived and have been reported attacking soybean leaves and plant reproductive structures, potentially reducing yield [88]. Despite these negative effects, also reported for conventional insecticides [13], the potential conservation of the biocontrol diversity in the soybean agroecosystem can still be valuable. Conservation biological control strategies have been reported in soybean, not only in Brazil [74], but also in Argentina [89], and Uruguay [90], which is certainly helpful to mitigate pest outbreaks in soybean fields [10].

Importantly, the reduction of conventional insecticide use triggered by the adoption of *Bt* soybean does not cause measurable yield reduction (Figure 4C). In fact, *Bt* soybean fields had a higher yield on average compared with non-*Bt* fields (Figure 4D) likely as a result of better lepidopteran control. In addition, fields planted with *Bt* cultivars had lower pest control costs (Figures 4E and 4F). Pest control costs (transformed to their equivalent in value of kg soybean/ha in each crop season) were between 16.7% (2022/23 crop season) to 40.0% (2015/16 crop season) lower for *Bt* fields without IPM than non-*Bt* fields without IPM. The adoption of *Bt* soybean in the IPM framework reduced pest control costs even more from 56.4% (2019/20 crop season) to 76.2% (2021/22 crop season) compared to control fields (non-*Bt* without IPM) (Figure 4E). This is an average reduction of costs equates to 64 kg/ha (31.1%) (*Bt* soybean with IPM adoption) compared to the control (non-*Bt* without IPM fields) (Figure 4F). The combined impacts of the adoption of *Bt* cultivars on reducing production costs associated with higher yields (consequences of better pest control) are clearly resulting in significant increases of profits. A national survey carried out from 1998 to 2017 in Brazil, including both soybean *Bt* and herbicide resistance traits, found that the profits of farmers adopting GMO soybean had 26% higher profits than those with conventional cultivars [91].

5. Role of Biological Control in Soybean-IPM

The intensification of agriculture has been constantly required to ensure food security to an increasing global population [92]. However, this intensification also provides a greater amount of food to pests, favoring their outbreaks [93]. This sequence of events demands more crop protection options because the pressure to decrease insecticides has also been increasing [18]. These apparently conflicting demands (intensification of food production versus reduction of insecticide use) increase the importance of new safer alternatives such as biological control [94] especially for soybean, as one of the most important commodities for food production [1]. Soybean is responsible for the main source of protein for many human populations [95], with high nutritional qualities [96]. Consequently, the global Augmentative Biological Control market has been increasing, and it is expected to surpass US$ 10 billion in 2027 [97].

Biopesticides are increasingly recognized for their effectiveness in controlling pests [98,99] These biocontrol agents play an essential role in IPM [10] and can be applied either alone or in combination with synthetic selective pesticides [100]. This approach not only enhances control efficacy but also reduces environmental risks and the exposure of farmers and consumers to synthetic pesticides [97]. Moreover, biopesticides help manage not only pests but also their resistance, as biopesticides allow the rotation and diversification of control tactics with distinct modes of action, reducing selection pressure associated with repeated use of the same chemical groups [101], which is a major problem for soybean production [14,102].

In addition to Augmentative Biological Control, Conservation Biological Control is important for the success of Soybean-IPM, because natural biological control has a frequently underestimated potential that helps to maintain soybean pests below ETs [100]. For instance, common hemipteran predators found in soybean, such as *Geocoris* and *Nabis*, have predation capacity of consuming nine and 21 Lepidoptera eggs per day [103]. The soybean agroecosystem is rich not only in hemipterans predators but also coleopterans [104] and a great number of other biocontrol agents including parasitoids [105] and entomopathogens [106].

Larvae of *Callida* spp. can consume around 65.6 velvetbean caterpillars, *Anticarsia gemmatalis* (Hübner) to reach the adult stage [107], while the egg parasitoid *Telenomus podisi* can parasitize around 100 eggs of the stink bugs *Euschistus heros* (Fabricius) [108] and *Diceraeus melacanthus* Dallas (Hemiptera: Pentatomidae) [109] during its lifespan. A recent study from China demonstrated that *Trichogramma leucaniae* reared on eggs of the Eri silkworm *Samia ricini* Willian Jones can parasitize 27-48 eggs of the soybean pod borer *Leguminivora glycinivorella* (Matsumura), a critical pest for local soybean fields, in a 24-hour period [110].

The potential of conserving those biocontrol agents in the soybean agroecosystem was illustrated by [111] who recorded the mortality of *Helicoverpa armigera* (*Hübner*) (*Lepidoptera: Noctuidae).* When the pest was first reported in Brazil in the 2013/14 crop season there was 70.2% of natural mortality [10]. Not only is natural control of pests important, but several other examples of the benefits of adopting biological control are reported in scientific literature, including the reduction of chemical pesticide residues, preservation of the environment, and farmers' and consumers’ health, in addition to other social and economic benefits [112]. In modern agriculture, biological control is crucial to the success of IPM, and IPM is essential for providing a more stable and favorable environment that enables biocontrol agents to express their full potential in pest control.

6. Opportunities for Increasing the Adoption of Soybean-IPM

As previously discussed in this review, despite successful examples of Soybean-IPM, and numerous benefits from its adoption, there are still barriers to increasing its acceptance and further adotpion. Key barriers include inadequate training and a lack of technical support for farmers; shortages of IPM specialists and extension agents; and, especially, the fact that IPM often struggles to manage multiple pest species, the most common situation faced by soybean farmers [13]. In order to increase Soybean-IPM adoption, strategies must address the whole soybean pest complex occurring in each region, and ideally offer simple, effective solutions that are common with insecticide sprays [113].

Pushed by the increasing public demand and campaigns for reduced chemical uses in agriculture, there are new pressures for increasing adoption of Soybean-IPM. While earlier IPM models were restricted to ecological and economic aspects based on chemical control, newer IPM models include management, business, and sustainability, emphasizing the importance of research and outreach as well as various social factors that influence the market of IPM products [20]. Moreover, the governmental banning of several harmful traditional chemical insecticides and the advent of more selective options further increases the potential for integrating chemical and biological control [114]. Finally, the new agenda of reducing carbon emissions from agriculture has more recently been intensified [115]. Agriculture’s significant greenhouse gas (GHG) emissions, including non-carbon gases, require immediate action to meet emission reduction goals and address global climate change [116]. Federal actions along with broader societal efforts focus on mitigating non-CO_2 emissions like methane and scaling up CO_2 removal initiatives [117]. This new global arena has encouraged the adoption and renewed interest in Soybean-IPM principles, giving the technology its momentum.

The reduction of insecticide use resulted from Soybean-IPM adoption is directly linked with a proportional reduction of diesel used to apply such chemicals, as well as a reduction of CO_2 emission related to the mitigation of this operation for pest control in the field. For instance, IPM adoption in Brazil in the 2021/22 crop season reduced the emission on 6,025.82 kg CO_2 eq. for each 100 hectares of adoption [10]. Similar benefits have been reported for the adoption of GMO soybeans in Brazil, saving 79.2 million liters of diesel from 1998 to 2017. This amount of fuel is enough to power around 53,000 cars for one year [110].

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Certification protocols of the Low Carbon Soybean Program (LCSP) initiative can also work as financial incentives to soybean farmers without depending on the federal government. This program aims to add value to soybean by certifying its sustainability, with the LCSP anticipating a reduction of approximately 30% in emissions per ton of soybean through methods like no-till farming and inoculants to reduce nitrogen fertilizer use [118]. Thus, soybean-IPM certainly fits in the scope of this initiative.

Increased federal actions provide an opportunity to favor the adoption of Soybean-IPM, including the offering of financial incentives to practitioners of the technology. For instance, in Brazil, federal government programs offer credit lines with subsidized interest rates and special conditions for other sustainable practices in agriculture, including the use of technologies that promote nutrient efficiency, such as inoculation. These subsidized credit lines have made inoculation practices more financially attractive, increasing adoption to 85% of the soybean cultivated area in the 2022/2023 season, using around 8.4 billion liters or kilograms of inoculants [119]. Similar support to Soybean-IPM would certainly increase its adoption.

7. Final Considerations and Future Perspectives of Soybean-IPM

There is increased interest in cultivating soybeans in a productive and ecologically sound manner that yields healthy food while protecting environmental integrity for future generations. Not all technologies that increase productivity are free of negative impacts on long-term sustainability. For these reasons, there is a need to develop approaches that are stable, resilient, and sustainable as well as productive and profitable for the farmers. Resistance to insecticides, herbicides, and other pesticides has led to higher application rates, greater crop losses, and increased production costs for soybean farmers. The increasing use of pesticides is closely linked to elevated health risks for farmers, farm workers, rural populations, and final consumers. Pesticides have adverse effects on soil health, water quality, and wildlife habitats and should be used only when strictly necessary. The non-market costs of their adverse impacts are only estimable, yet globally, they impose a significant burden.

Various pest control strategies, such as biotechnology, biological control, and insecticides, among others, have been recognized as important breakthroughs in food production. Nevertheless, they must be used within IPM to achieve long-term efficacy. In this context, biological control, the rational use of more selective insecticides, the adoption of ETs for control decisions, and the cultivation of *Bt* soybean have been key elements of the success of Soybean-IPM. The IPM concept integrates a wide array of alternative approaches, including microbial biopesticides (bacteria, fungi, viruses, nematodes), botanical pesticides (essential oils, plant extracts), and genetic pest management methods such as the sterile insect technique (SIT), genome–editing tools (e.g., CRISPR-Cas9, RNAi), and marker-assisted selection (MAS) as well as any other sustainable alternative focused on the multiple pest species scenario usually faced by farmers. Proposing simple, efficient, straightforward combined solutions will make the technology more acceptable to farmers.

Future trends of Soybean-IPM include **1)** maximizing the efficacy of biocontrol agents; **2)** development and use of genetic tools, such as DNA and CRISPR-Cas9 technologies; **3)** improvement of plant resistance, including the development of newer GMOs and genetically edited cultivars; **4)** nanoformulations and encapsulations for microbiological and botanical insecticides, including water–oil emulsion encapsulation for *Bacillus thuringiensis* to improve its stability, nano-formulations of *Bacillus* lipopeptides (Lps), and CRISPR-based technologies for managing pests. Mobile applications, in particular, have become vital to the dissemination of IPM. Apps that use artificial intelligence (AI) to identify pest problems and recommend suitable interventions will help increase IPM efficacy and the adoption of Soybean-IPM.

8. Conclusions

Pests should not be exterminated; instead, they should be kept below EILs. In a more balanced agricultural system, no pest control method should achieve 100% pest mortality, as most farmers generally desire. On the contrary, 100% control of a given pest is undesirable as it can lead to a decline of the biological control BC species due to the unavailability of prey or host. Thus, we are now experiencing a critical, broader shift in farmers' behavior, which may be among the most significant challenges to be overcome to achieve greater adoption of Soybean-IPM. GMO soybean, such as *Bt* cultivars, has been an essential technology for the success of Soybean-IPM, combining better conservation of natural biological control with increased farmers' profits. Nevertheless, resistance must be managed effectively to avoid issues that could permanently impair the technology's lifespan. In addition to biological control, Soybean-IPM is currently experiencing a positive phase. Still, greater efforts should be directed to outreach, practitioner incentives, and technology research to avoid losing the favorable momentum for IPM implementation and success.

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