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Review

The Role of Economic Thresholds in Optimizing Insecticide Application in Soybean Production in the Major Producing Countries of the World

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Abstract

Global population growth has increased the demand for food production and, therefore, for higher crop yields, especially for soybean, which is one of the most cost-effective and affordable sources of high-quality protein for animal and human nutrition. This frequently leads to an overuse of traditional chemical insecticides to maximize yields, thereby triggering negative side effects. However, both consumers and governments around the world demand a reduction in chemical insecticides in agriculture. To address this challenge, pest control must be guided by proper adoption of economic thresholds (ETs), which indicate the most appropriate time to initiate control in the crop. Despite the well-documented science behind ETs, farmers have questioned the adoption and reliability in a search for higher production, highlighting the importance of reviewing this topic. Thus, based on the available literature, the role of ETs in optimizing insecticide application in soybean production around the world is herein discussed, highlighting the importance of their adoption to mitigate the overuse of chemicals by emphasizing examples from the major world soybean producers (Brazil, the United States of America, Argentina, and China). In conclusion, this review highlights the importance of changing farmers' perception that using more insecticide is necessary to guarantee higher yields. On the contrary, only by the adoption of ETs within Integrated Pest Management is it possible to obtain better pest management and, consequently, reduce yield loss. Despite some limitations related to their simplicity and risks of adoption, the use of ETs improves soybean sustainability and farmers' profits while benefiting the agroecosystem. For future directions, their complexity should increase to more realistically represent agroecosystems; in addition, tools should be developed (computer programs and smartphone apps using, for instance, artificial intelligence) to translate this complexity into easy-to-adopt ETs.

Keywords: IPM (integrated pest management); sustainability; chemical control; conservation biological control

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1. Introduction

Soybean (*Glycine max* L.) is one of the most important crops for human and animal nutrition because it offers a cost-effective and affordable source of high-quality protein and edible oil [1] and is critical for feeding an increasing world population, which is predicted to reach 9 to 10 billion by 2050 [2]. However, soybean production still deeply relies on the application of traditional synthetic chemical insecticides to manage economically important pests and achieve high yields [3]. Despite the important role played by chemical insecticides in agricultural production and food security, which revolutionized insect control [4], their overuse (which is the unnecessary and abusive use of insecticide sprays) has raised increasing concerns about their negative non-target effects [5]. The overuse of chemical insecticides can reduce natural biocontrol agents [6] and pollinators [7], select populations of resistant pests [8], trigger pest resurgence and outbreaks of secondary pests, and potentially affect human health [3]. Consequently, reducing chemical insecticide use, not only in soybean but also in the whole agricultural system, to allow for more sustainable food production, has been emphasized [9,10].

Similarly to other crop systems [11], the adoption of Integrated Pest Management in soybean (Soybean-IPM) has been recognized as the most effective approach for sustainably managing pest outbreaks in this crop [12,13] with positive economic results being reported in the major producing countries including Brazil [14], the USA [15], Argentina [16], and China [17], which are the top four producers, respectively. Soybean-IPM is based on the premise that not all plant-feeding insects require control, and even for those considered key pests, some infestation levels are tolerable without economic yield loss [13,18].

A pest population that causes economic damage to a crop is defined as reaching the Economic Injury Level (EIL), which is based on the costs of control, value of the crop, and amount of achievable control [19]. However, several factors are crucial to manage potential pests prior to populations reaching the EIL and consequent economic yield reduction. The necessary time required for the control strategy to be effective against the pest and unfavorable weather conditions that can delay the insecticide application, among other factors, can allow the pest population to keep increasing even after the decision to control it has been made [18]. Therefore, to prevent economic losses, pest populations are managed before the EIL is reached, at a percentage defined as the economic threshold (ET) (Figure 1). It is assumed that once the ET is reached or surpassed, there is a high probability that the pest population will reach the EIL if no management action is taken [20].

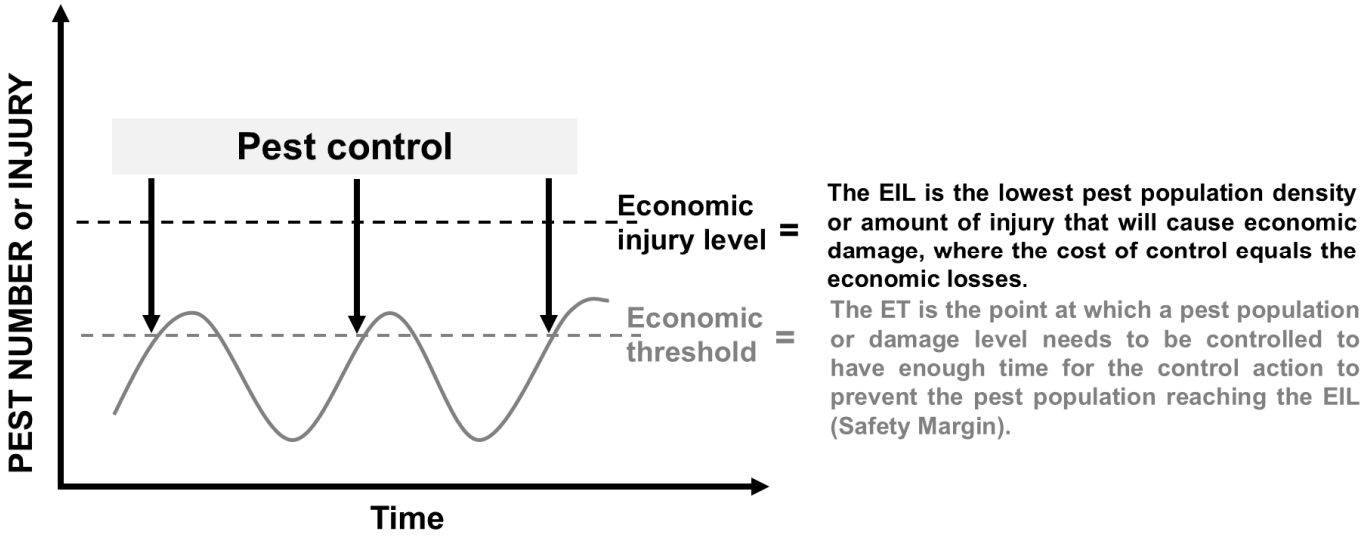


Figure 1. The relation between Economic Injury Level (EIL) and economic threshold (ET) within the Integrated Pest Management (IPM) decision process.

Despite decades of research on ETs, their practical adoption remains limited and fragmented across regions. Moreover, current ET frameworks often fail to incorporate ecological complexity, such as multispecies interactions, biological control, and environmental costs of chemical control. Consequently, a comprehensive and critical synthesis of ET applications at the global scale is still lacking. The objective of this review is to critically evaluate the role of ETs in optimizing insecticide use in soybean production worldwide, identify key limitations, and outline future directions for improving their applicability in sustainable agriculture.

2. Different Economic Thresholds for Soybean Integrated Pest Management Around the World

Despite slightly varying around the world (Table 1), considering the top five soybean-producing countries in the world (Brazil, USA, Argentina, China, and India), soybean yield is threatened by different pest species. These pests can be classified as caterpillars (Lepidoptera); stink bugs (Pentatomidae) and related families (Hemiptera); and soybean aphid [more harmful in the United States of America (USA) and China].

Table 1. Most important economic thresholds (ETs) established for control decisions in Soybean Integrated Pest Management (Soybean-IPM).

Pests	ET(s)	References
Aphis glycines	273 ± 38 aphids/plant	[21]
Bemisia tabaci	(a) 1.5 insects per leaflet (b) Beginning of sooty mold formation	[22,23]
Crocidosema sp.	50% of plants damaged	[24]
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)	[25–27]
Helicoverpa zea	3.5 caterpillars/meter or sample cloth or 9 caterpillars/25 sweeps—USA	[28]
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	[29]
Pod feeders	25% of pods damaged	[30]
Spodoptera spp.	10 caterpillars (≥1.5 cm)/meter or sample cloth	[13]

Table 1. *Cont.*

Pests	ET(s)	References
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 bug (≥0.5 cm)/meter or sample cloth (soybean for seed production)—Brazil	[26,31,32]
Tetranychus	21.23 mites/leaflet	[33]

These variations among not only different countries but also different regions inside the same countries (Table 1) are associated with: (1) the use of different soybean cultivars, which have different pest tolerances; (2) different pest species occurring in each country, and variable pest control costs; (3) local environmental conditions; (4) availability and effectiveness of different control technologies in each region [34,35].

The global history of Integrated Pest Management (IPM) on soybean, with the proposals of the first ETs for the most important pests, is linked to a change in the perception of pest control that occurred in the late 1960s and early 1970s. At that time, the world was alerted to the danger of the abusive use of synthetic chemical insecticides [36] and persuaded to preserve natural enemies through minimum insecticide use [37–39].

ET adoption significantly reduced insecticide uses in the countries where such thresholds were adopted in soybean production (Table 2). By limiting insecticide use to only when required, ET adoption has provided better pest control management, higher profits, and stronger environmental preservation.

Table 2. Reduction in insecticide use in the first (Brazil) and second (USA) major soybean producers in the world due to the adoption of economic thresholds within Soybean Integrated Pest Management.

Country	Soybean Season	Reduction in Insecticide Use (%)	Increased Profits [1] (kg/ha)	Reference
USA	From 2000 to 2006	40.0 to 50.0	Not informed	[40]
Brazil	2013/14	54.0	186	[13]
	2014/15	55.3	276	
	2015/16	44.7	264	
	2016/17	46.0	150	
	2017/18	55.9	258	
	2018/19	50.0	210	
	2019/20	43.3	138	
	2020/21	50.0	96	
	2021/22	69.2	72	
	2022/23	66.7	228	
	2023/24	48.5	438	[41]
	2024/25	69.6	258	[42]
	Average	54.4	214.5	

[1] Increased profit = (Yield of IPM Adopters—Yield of Non-Adopters) + (Pest Control Costs of Non-Adopters—Pest Control of IPM Adopters) transformed into the equivalent of the value of kilograms of soybean, for each season, to avoid any depreciation of the currency due to possible effects of inflation (Paraná State, Brazil).

Starting in the USA in the late 1960s and early 1970s [37], the establishment and adoption of ETs within Soybean-IPM then spread to the most important countries cultivating this crop in the world. Influenced by the US entomologists, Brazil started adapting the ETs for soybean pests recommended in the USA to the Brazilian reality in the mid-1970s. Years later, Brazil successfully reduced the use of insecticides at a rate of 50% or higher where the technology was adopted [36].

The results reporting insecticide reduction due to ET adoption within IPM are restricted to limited years and fields where experiments were conducted. However, in Brazil, soybean farmers have been carefully monitored over more than 12 years, and farmers adopting ETs for IPM decisions have been consistently reaching impressively positive results compared to farmers not adopting ETs (Table 2).

Despite these results being exclusively from Brazil, they are important indicators and contrast with the overall common farmers' perception that improved pest control (improved profits) requires increased insecticide use. On the contrary, excessive insecticide applications can paradoxically exacerbate pest problems through mechanisms such as pest resurgence following the removal of natural enemies [43,44], secondary pest outbreaks (eliminating primary pests allows others to thrive) [45], and development of insecticide resistance (pests are selected to survive chemicals) [46]. Unfortunately, this creates a cycle where the overuse of insecticides leads to even worse pest outbreaks and a greater need to use more and stronger chemicals more frequently [47]. Changing the common and misleading perception of farmers that more insecticide use provides better crop protection is one of the most important challenges for higher Soybean-IPM, and adoption of ETs plays a crucial role in this process. Nevertheless, more experimentation in other countries besides Brazil, under different weather conditions and variable soybean cultivation systems, is needed.

An insect becomes a pest only when it becomes too numerous, causing financial harm by reducing the yield or quality of a product, at higher values than the control costs associated with chemical use. Moreover, the aim of any pest management program, including Soybean-IPM, must not be to eradicate pest species in the field, but rather to maintain their populations below EILs [48]. The controlled presence of insect populations (even of the species considered pests) below pest status, as defined by EILs, improves crop health (sustainability) because such insects will serve as food and hosts for biocontrol agents, conserving those that are beneficial in the area [44]. The conservation of natural enemies in fields is essential for naturally regulating pest populations [49]. This is crucial to food security, since insect pests reduce between 5% and 20% of the yield of major grain crops around the world [50]. For instance, in the USA, China, and Brazil, soybean yield losses from pests have reached around 1.7, 3.1, and 4.3 million tons of soybean, respectively, each year [51–53]. However, this review affirms that this yield loss will not be efficiently mitigated with more insecticide use but with a more precise use of insecticides through the adoption of ETs within the IPM context. Overall, despite regional variability, ETs consistently lead to reduced insecticide use without compromising yield; however, their adoption remains uneven across countries due to differences in farming systems, monitoring capacity, and farmer perception.

3. Discussion About the Importance, Challenges, and Opportunities of Adopting Economic Thresholds in Soybean Cultivation Around the World

3.1. Benefits of Adopting Economic Thresholds

The reduction in production costs is usually regarded as one of the most important benefits of adopting ETs [13], which is achieved due to the reduction in insecticide use [22].

In addition, ETs provide higher preservation of natural biological control, which also helps to naturally keep pests under control [54]. Therefore, the adoption of ETs in soybean fields has generated substantial economic returns. For example, estimated benefits from ET adoption by U.S. farmers reached U$ 2.6 billion per year in soybean [15]. Comparable economic gains associated with ET adoption within Soybean-IPM have also been recorded in other countries, including Brazil [13], Argentina [16], China [51], India [55], and Indonesia [56]. Brazil is one of the few places where IPM adoption with the use of ETs for economic decisions has been monitored for long periods (12 years), and benefits equivalent to 214.5 kg of soybean per hectare have been reported [13] (Table 2). However, for these reported benefits to be translated into widespread on-farm adoption of ETs, the prevailing assumption that the presence of any pest is inherently detrimental to crop production must be changed. Excessive insecticide use not only imposes additional economic costs and environmental risks but can also reduce overall crop productivity by increasing pest outbreaks due to reducing natural biocontrol [44].

Under conditions with high natural enemy abundance, ETs should even be adjusted upward, allowing fewer insecticide applications [57]. This approach, referred to as dynamic thresholds, enables producers to better exploit existing biological control interactions, resulting in improved pest management, higher yields, and lower production costs compared to calendar-based or prophylactic insecticide applications [57].

Mitigating insecticide use (adopting ETs) is also essential to preserve pollinators [56] and the whole environment [58]. Conservation strategies involve changes to the crop environment to favor the abundance and pest-suppression activity of native or introduced natural enemies [54]. Thus, as previously discussed in this review, the adoption of ETs is an effective strategy to reduce insecticides in soybean by up to 40–50% (USA) [15,40] and 69% (Brazil) when compared to traditional farming practices. Consequently, adopting ETs can be regarded as an effective Conservation Biological Control and Pollinator (CBCP) strategy.

There are different problems associated with the misuse (or overuse) of pesticides, the most important being health risks, environmental damage, and selection of resistant pest populations [59]. Furthermore, pesticides can spread throughout the environment by leaching and runoff [60,61] and can remain in the soil for years as products with a long half-life [59], confirming the importance of adopting mitigation strategies. The large inputs of contamination from pesticides are growing sources of concern in the world today for environmental health and sustainable food production [62].

3.2. Ecological Implications

The preservation of beneficial organisms, especially biocontrol agents and pollinators, is one of the most important ecological implications of adopting ETs. Although the economic value of their action is still understudied, scientists have recently tried to assign economic value to natural biological control [63] and pollination [64]. For instance, conservation biological control provides an estimated value of US$ 1500 to US$ 2000 per hectare/year, varying accordingly to the pest and crop system being considered [65]. In soybean, the importance of adopting ETs as a CBCP strategy is still understudied, despite the common biocontrol agents found in soybean fields having a well-known capacity of naturally reducing populations of insects that can become pests. For instance, egg parasitoids are considered the most important stink bug biocontrol agents [66,67], and stink bugs are the most important pests requiring harmful insecticide sprays in the Neotropics [13]. Each female *Telenomus podisi* Ashmead, 1893 (Hymenoptera: Scelionidae) wasp can parasitize more than 100 eggs of *Euschistus heros* (Fabricius, 1798) [68] or *Diceraeus melacanthus* (Dallas, 1851) (Hemiptera: Pentatomidae) [69] during its lifespan [52,70]. Similar results have also been reported in different regions of the world. The percentage of parasitized stink bug

eggs found in soybean across the USA ranged from 7.5 to 63.4%, with *Telenomus podisi* being the most abundant parasitoid species [71]. In addition, *Anastatus* spp. have demonstrated high parasitism capacity of *Halyomorpha halys* (Stål) (Hemiptera: Pentatomidae) eggs, one of the most important stink bugs of soybean in the USA and China, in addition to eggs killed by the adult parasitoid feeding [72].

Predators and entomopathogens also play an important role in keeping not only stink bug but also lepidopterous pest populations below the EIL in soybean fields. For example, *Geocoris* sp. (Hemiptera: Geocoridae) and *Nabis* spp. (Hemiptera: Nabidae), which are frequently recorded in soybean agroecosystems in different countries [73], can consume between 9 and 21.1 eggs of the velvetbean caterpillar, *Anticarsia gemmatalis* Hübner (Lepidoptera: Erebidae), per day, respectively [74]. Similarly, larvae of ground beetles, *Callida* sp., consume around 65 caterpillars to reach the adult stage [75]. Furthermore, the natural occurrence of entomopathogens is responsible for up to 17.9% of the mortality of *Helicoverpa armigera* in soybean fields [13]. Although pest mortality caused by natural biological control does not necessarily result in the reduction in pest populations below ETs, it certainly helps to reduce the risks of pest outbreaks [76]. Furthermore, in augmentative biological control, conservation approaches may help improve the performance (e.g., longevity, fecundity, and searching ability) of the mass-released biocontrol agent, maximizing farmers' investment in purchased biological control agents [77]. Conserving those biological control agents in soybean fields is both economically and ecologically beneficial [13,78]; nevertheless, this value is often not recognized or incorporated into ETs and, consequently, into routine farm management decisions.

Pollinators play an important role in the functioning of all terrestrial ecosystems [79] and are essential for food security [80]. Despite being an autogamous plant, soybean yields are enhanced by insect pollination [81]. The average soybean yield increased by 13% for caged plots with honeybees and 5.6% for open plots, compared to caged plots without honeybee hives [82], highlighting the importance of conserving this ecosystem service for increased profits while ensuring the successful management of pests [83]. Therefore, beyond successful pest control and cost reduction, the adoption of IPM, including ETs, can increase the overall resilience of the farm and help increase natural capital and ecosystem services [84].

3.3. Limitations of Current Economic Threshold Frameworks

Despite the well-documented benefits of ETs for IPM decisions, IPM has not reached its expected success, and its adoption is still partial and not widespread [85]. Farmers still perceive IPM as too complex, time-consuming, and difficult to be implemented, providing lower and unpredictable economic advantages compared to the traditional insecticide-based agriculture [86]. Consequently, ETs and IPM have not been as widely adopted by soybean farmers [13] as they should be.

A primary barrier to ET adoption is the need for regular and precise monitoring of pest populations [40]. Pest detection and monitoring are considered one of the biggest challenges for IPM [87], requiring farmers and crop consultants to invest additional labor and develop specialized expertise, thereby increasing monitoring costs [88]. Multiple pest species [13] and diseases occurring together in the field associated with other variables, including weather conditions and nutritional development status of the plants, make the control decision more complex and difficult for IPM practitioners [89]. Consequently, IPM is less adopted by farmers [40].

While multiple pests are common in soybean fields, predators, parasitoids, and other biocontrol agents are also present. Although pest–plant and pest–biocontrol agent interactions occur and impact pest outbreaks, these factors have not yet been incorporated into

more dynamic ETs. This oversimplicity of ETs increases the risks of its adoption triggering distrust among farmers [90].

3.4. Future Directions of ETs

Most ET models are still based on simplified assumptions that do not reflect real agroecosystem complexity, particularly under multi-pest conditions. These simplified assumptions increase the risks of under- or overestimating pest pressure, as well as reduce farmer confidence in ET-based decisions. Hence, future directions of ETs must focus on reducing those limitations. Therefore, more complex and dynamic ETs that encompass complex scenarios, including multiple species of pests, biocontrol agents present, and environmental costs, must be developed.

The literature on multiple-species ETs is still sparse. An ET model for a two-pest/two-pesticide situation on spring barleys was initially developed [91]. Later, an injury equivalency system converting larval size to leaf consumption to develop a multispecies economic injury equivalency for determinate soybean was proposed [92]. Despite the proposal of multispecies EILs, ET use is still limited [93]. The central requirements for adopting a multiple-species EIL are (a) injuries by the different species of interest that produce a homogeneous physiological response in the plant; (b) the determination of the relationship between yield loss and injury; and (c) the determination of injury per individual (or stage) for each species in the guild [92]. Consequently, developing a single EIL for pests that cause different injury types is unlikely because they will impact crop physiology and growth differently [93].

In addition, the development of EILs and ETs in IPM valorizing the natural environment inside IPM decisions is needed [94]; however, defining values to protect and sustainably manage agroecosystems is very difficult due to their complexity. The procedures to calculate environmental costs and to determine Environmental EILs are detailed in the literature, adding the environmental costs of each insecticide into the EIL formula [95], making the use of EILs and ETs even more complex [95].

The required higher complexity of ETs to make them more precise and better reflect real agroecosystem complexity may not be attractive, compared to the convenience and simplicity of prophylactic pest management strategies, including not only insecticides but also the use of *Bacillus thuringiensis* (*Bt*) transgenic crops. Simplicity has driven a widespread adoption of *Bt* crops or insecticide-based agriculture over recent decades, often hindering the implementation of more sustainable insect pest management approaches [48]. Therefore, making the complexity of decision-making easier for farmers must also be a future direction for ETs. Innovations in remote sensing, unmanned aerial vehicle surveillance, and IoT-enabled smart traps further strengthen pest monitoring and intervention strategies. Computer programs and/or cell phone apps using artificial intelligence (AI) that analyze multiple input variables and summarize them into a simple output with a direct and easy-to-follow decision will help make future complex ETs more user-friendly for farmers to adopt. For realistic and easily adoptable ETs, both their complexity to better reflect a complex agroecosystem and ways (e.g., AI programs) to translate them into simple, friendly decisions are also essential. AI has shown the potential to revolutionize pest management by integrating the right pest identification, method selection, control timing, and action taken; optimizing control timing; and suggesting tools for selecting and applying pest control measures. Therefore, future research should focus on scalable AI solutions, interdisciplinary collaborations, and real-world validation to enhance AI-driven pest management in field crops [96].

3.5. New Global Scenario: Opportunities for Higher Adoption of Economic Thresholds Within Integrated Pest Management

Resistance to both chemical insecticides [97] and transgenic crops [98] has been increasingly recorded under field conditions. At the same time, the frequency of extreme climatic events has risen [99], affecting both rural and urban populations. These have intensified governmental efforts toward environmental sustainability worldwide [100]. Thus, agriculture around the world faces an increasing demand to reduce pesticide use and increase sustainable agricultural alternatives, which favors the adoption of biological control. More than 15% annual growth in the global biological control market has been recorded, reaching a value of US$ 3.3 billion in 2017 [101]. However, for biological control to succeed, the overuse of harmful insecticides must be mitigated with a more rational use of chemicals, which can only be achieved by adopting ETs [13] in addition to the selection of less harmful pest control strategies. Furthermore, despite the evident benefits of replacing several synthetic chemical insecticides with biocontrol agents [102], their total safety cannot be taken for granted. There is an increasing concern that the excessive release of natural enemies in agroecosystems could negatively affect the genetic structure of resident biocontrol populations [103], highlighting the urgent need to study and develop specific ETs for biological control adoption. Within this emerging context, IPM strategies and, consequently, the adoption of ETs have gained renewed relevance as viable and resilient approaches to crop protection in food production.

4. Conclusions and Final Remarks

Conventional ETs for IPM decisions are well established individually for the most important soybean pests. However, their success depends on careful pest monitoring, which can be too complex and time-consuming when facing a multiple-species scenario, against which most common ETs are not well adapted to confront. In addition, there is an increasing adoption of biological control in modern agriculture, while most of the established ETs have been developed for chemical insecticide use. Therefore, future progress in IPM will depend on transforming static ETs into adaptive decision-support systems for chemical, biological, or other control strategies, integrating ecological, economic, and technological dimensions. Future proposed ETs must include not only different pest species that injure plants at the same time, but also the presence of other plant stressors, including nutritional, environmental, and pathogenic stresses, as well as the presence of beneficial organisms such as biocontrol agents and pollinators. Furthermore, specific ETs for each control strategy must be studied, especially for different control tools such as chemical and biological control. Those improvements will lead to more complex and dynamic ETs, better representing the real agroecosystem complexity found in the field. To be able to translate this complexity into easier recommendations, AI will play an important role in integrating the complex plant response to different stressors with the right control method selection as well as the right control timing through easy-to-follow ETs.

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