REVISTA TÓPICOS
ISSN 2965-6672 | Qualis A2

PEST MANAGEMENT IN STRAWBERRY CULTIVATION: REGISTERED PESTICIDES IN ESPÍRITO SANTO, BRAZIL, AND BIOLOGICAL CONTROL ALTERNATIVES

CONTROLE DE PRAGAS NA CULTURA DO MORANGUEIRO: PRODUTOS REGISTRADOS NO ESPÍRITO SANTO E ALTERNATIVAS DE CONTROLE BIOLÓGICO

Ciências Agrárias • 02/11/2026

REGISTRO DOI: 10.70773/revistatopicos/793464141

Josimar de Souza Andrade[1]

Andréa Ferreira da Costa[2]

Girlaine Pereira Oliveira[3]

João Pedro de Barros Reicao Cordido[4]

Ismael Lourenço de Jesus Freitas[5]

Leandro de Castro Silva[6]

João Paulo Silva Borges Scarpini[7]

Igor Vasconcellos Pellegrini[8]

Hélcio Costa[9]

Cátia Oliveira de Paula Morais[10]

Laerciana Pereira Vieira Santos[11]

ABSTRACT

The sustainability of pest management in strawberry production depends on the functional diversity of available control strategies. This study analyzed pesticide products registered for strawberry cultivation in Espírito Santo, Brazil, identifying 36 commercial products containing 19 active ingredients distributed across 11 IRAC mode-of-action groups. Despite this apparent diversity, a substantial concentration of registrations was observed in groups 6, 13, and 3A, particularly for products containing abamectin and chlorfenapyr, indicating dependence on a limited number of biochemical targets. Previous studies have documented high levels of abamectin resistance in *Tetranychus urticae* populations. Frequent harvesting and restrictions associated with pre-harvest intervals may favor repeated applications of certain pesticides, thereby increasing selection pressure. Additionally, the literature review highlights the potential of biological control agents to expand the functional diversity of pest management by providing complementary alternatives to registered chemical pesticides. The findings indicate that a high number of commercial registrations does not necessarily ensure effective diversity in pest management. Therefore, integrated strategies emphasizing rotation among different modes of action and the systematic incorporation of biological control are essential to reduce selection pressure, delay resistance development, and enhance the resilience of strawberry production systems.

Keywords: Integrated pest management; Insecticide resistance.*Tetranychus urticae*; Mode of action; Selection pressure.

RESUMO

A sustentabilidade do manejo fitossanitário no morangueiro depende da diversidade funcional das estratégias de controle disponíveis. Este estudo analisou os produtos fitossanitários

registrados para a cultura do morangueiro no Espírito Santo, identificando 36 produtos comerciais contendo 19 ingredientes ativos distribuídos em 11 grupos de modo de ação segundo a classificação do IRAC. Apesar dessa aparente diversidade, observou-se expressiva concentração dos registros nos grupos 6, 13 e 3A, especialmente de produtos contendo abamectina e clorfenapir, indicando dependência de um número limitado de alvos bioquímicos. Estudos anteriores documentaram elevados níveis de resistência à abamectina em populações de *Tetranychus urticae*. A frequência das colheitas e as restrições associadas aos intervalos de segurança podem favorecer aplicações repetidas de determinados produtos, aumentando a pressão seletiva. Adicionalmente, a revisão bibliográfica evidencia o potencial dos agentes de controle biológico para ampliar a diversidade funcional do manejo, oferecendo alternativas complementares aos produtos químicos registrados. Os resultados indicam que um elevado número de registros comerciais não garante, necessariamente, diversidade efetiva nas opções de manejo de pragas. Portanto, estratégias integradas que priorizem a rotação entre diferentes modos de ação e a incorporação sistemática do controle biológico são essenciais para reduzir a pressão seletiva, retardar o desenvolvimento da resistência e aumentar a resiliência dos sistemas de produção de morango.
Palavras-chave: Manejo integrado de pragas; Resistência a inseticidas; Tetranychus urticae; Modo de ação; Pressão seletiva.

1. INTRODUCTION

Espírito Santo is an important strawberry-producing state in Brazil. In 2024, approximately 32,884 metric tons of strawberries were harvested from an area of 297 hectares distributed across 15 municipalities. This production corresponded to an average yield

exceeding 110 metric tons per hectare, highlighting the productivity and economic importance of strawberry cultivation in the state (Portal Jornal do Norte, 2025). Strawberry production represents an important opportunity for agricultural diversification and income generation, particularly for family farmers. Furthermore, the crop contributes to the development of regional agritourism, creating economic opportunities and supporting rural development.

In 2010, the "Morango Mais Saudável" ("Healthier Strawberry") project was implemented to improve product quality, promote food safety, and encourage the adoption of good agricultural practices. The initiative supported the implementation of integrated production systems in suitable strawberry-growing areas and promoted production traceability. These actions contributed to establishing Espírito Santo as a national reference in strawberry production in terms of quality, food safety, and sustainability (Galeano *et al.*, 2022).

Strawberry cultivation is characterized by intensive production systems and substantial biotic pressure throughout the crop cycle. During different phenological stages, strawberry plants are exposed to arthropod pests, pathogens, and weeds that can compromise fruit yield and quality. At the same time, strawberry agroecosystems harbor beneficial organisms, including predators, parasitoids, and entomopathogens, which play an important role in the natural regulation of pest populations.

In current strawberry production systems, chemical control has been a major strategy for pest management. However, frequent pesticide applications may cause undesirable ecological effects, including the reduction of natural enemy populations and the disruption of biological interactions (Altieri, 2012; Gullan; Cranston,

2017). Such ecological disturbances may increase dependence on chemical inputs and reduce agroecosystem resilience. Furthermore, repeated applications of insecticides and acaricides with the same mode of action exert selection pressure on target pest populations, accelerating the development of resistance (IRAC, 2026). This process can progressively reduce pesticide efficacy, potentially increasing the frequency of applications, production costs, and environmental impacts.

The consequences of intensive pesticide use extend beyond agricultural production and may affect environmental quality and human health. Soil and water contamination, as well as adverse effects on non-target organisms, including soil microorganisms involved in nutrient cycling and soil fertility, have been widely documented (Pimentel, 2005). Pesticide residues in fruits are also an important concern regarding food safety (ANVISA, 2025). In addition, agricultural workers may be exposed to occupational hazards during pesticide preparation and application, particularly when recommended safety procedures and personal protective equipment are not properly used (World Health Organization, 2022).

In this context, detailed knowledge of pesticides registered for strawberry cultivation, including their active ingredients, modes of action, pre-harvest intervals, and operational restrictions, is essential for developing more sustainable pest management strategies. The appropriate use of these products, based on the principles of Integrated Pest Management (IPM), can help minimize environmental impacts, reduce risks to human health, and delay the development of pesticide resistance.

Nevertheless, the availability of numerous commercial pesticide registrations does not necessarily indicate effective diversity in pest management options. A high concentration of registered products within a limited number of mode-of-action groups may represent a structural vulnerability in production systems. Therefore, this study aimed to critically analyze pesticide products registered for strawberry cultivation in Espírito Santo, Brazil, and to identify biological control agents with potential for integration into pest management strategies, thereby contributing to the sustainability of strawberry production systems.

2. METHODOLOGY

This study consisted of a qualitative and quantitative documentary analysis of pesticide products registered for strawberry cultivation in Espírito Santo, Brazil, complemented by a literature review of biological control agents with potential applications in strawberry pest management.

Data on registered pesticide products were collected between November 2025 and March 2026 from the pesticide registration database of the Instituto de Defesa Agropecuária e Florestal do Espírito Santo (Idaf, 2026). The information obtained was organized in Microsoft Excel® spreadsheets and included the following variables: commercial product name, target pest, active ingredient, pesticide class, mode of action according to the Insecticide Resistance Action Committee (IRAC) classification, chemical group, toxicological classification, environmental hazard classification, re-entry interval after application, maximum number of applications, interval between applications, and pre-harvest interval.

The literature review on biological control agents was conducted using Google Scholar, including studies addressing biological control in strawberry cultivation and research focusing on the management of major strawberry pests, particularly *Tetranychus urticae*. The selected publications were used to identify biological control agents with potential applications in strawberry production and to discuss their contribution to integrated pest management strategies, including the diversification of control methods and the reduction of dependence on chemical pesticides.

3. RESULTS AND DISCUSSION

According to the pesticide registration database of Idaf (2026), 36 commercial products were identified for pest control in strawberry cultivation in Espírito Santo, comprising 19 distinct active ingredients or pesticide components associated with 11 numbered IRAC mode-of-action groups and additional unclassified or separately classified products (Table 1). Although these numbers suggest a relatively broad range of available products, their distribution reveals a substantial concentration within a limited number of chemical groups. Products containing abamectin (10 registrations), chlorfenapyr (5 registrations), and lambda-cyhalothrin (4 registrations) collectively accounted for 52.8% of the commercial registrations, indicating a strong concentration of available chemical control options within a few modes of action.

According to the IRAC classification, the occurrence of 11 numbered mode-of-action groups contrasts with the concentration of commercial registrations in groups 6 (avermectins), 13 (uncouplers of oxidative phosphorylation), and 3A (pyrethroids). Furthermore, the availability of multiple commercial products containing the same

active ingredient may create an overestimated perception of the diversity of pest control options. From an insecticide resistance management perspective, products containing the same active ingredient or belonging to the same IRAC mode-of-action group should not be considered effective alternatives for mode-of-action rotation, as their repeated use may maintain selection pressure on the same physiological targets and favor the development of resistant populations (Georghiou, 1990).

The predominance of abamectin, present in approximately 28% of the registered commercial products in Espírito Santo, is particularly relevant from an insecticide resistance management perspective. Resistance to this compound has been widely documented in different arthropod species and has been associated with enhanced detoxification mechanisms involving glutathione S-transferases (GSTs) and cytochrome P450 monooxygenases (Pu *et al.*, 2010; Su *et al.*, 2026). In the citrus red mite, *Panonychus citri*, abamectin resistance has been characterized as autosomal, partially recessive, and polygenic (Liu *et al.*, 2024), demonstrating the complexity of resistance inheritance in this species. Although these findings provide relevant information on potential resistance mechanisms, their applicability to Tetranychus urticae should be considered in light of species-specific differences.

Table 1. Active ingredients, modes of action, and chemical groups of pesticide products registered for strawberry pest control in Espírito Santo, Brazil.

Commercial product®	Active ingredient(s)	Mode of action	Chemical group
Abadin 72 EC;	Abamectin	IRAC 6 – Glutamate-gated chloride channel	Avermectins

Abamectin 72 EC Nortox; Abamectin Nortox; Abamectin Prentiss; Abamex; Abamex Maxx; Acarigen; Potenza Sinon; Potenza Sinon Plus 36 EC; Vertimec 18 EC		allosteric modulators	
Adver 240 SC; Clorfenapir Nortox; Kanopus; Pirate; Trigger 240 SC	Chlorfenapyr	IRAC 13 – Uncouplers of oxidative phosphorylation via disruption of the proton gradient	Pyrrole analogue
Danimen 300 EC; Sumirody 300	Fenpropathrin	IRAC 3A – Sodium channel modulators	Pyrethroids
Karate Zeon 250 CS; Karate Zeon 50 CS; Samurai Bushi; Sparviero 50	Lambda-cyhalothrin	IRAC 3A – Sodium channel modulators	Pyrethroids
Actara 250 WG	Thiamethoxam	IRAC 4A – Nicotinic acetylcholine receptor competitive modulators	Neonicotinoids

Azamax	Azadirachtin	IRAC UN – Compounds with unknown or uncertain modes of action	Tetranortriterpenoids
Delegate	Spinetoram	IRAC 5 – Nicotinic acetylcholine receptor allosteric modulators	Spinosyns
Fujimite 50 SC; Ortus 50 SC	Fenpyroximate	IRAC 21A – Mitochondrial complex I electron transport inhibitors	Pyrazoles
Hangar; Rimon Supra	Novaluron	IRAC 15 – Inhibitors of chitin biosynthesis affecting CHS1	Benzoylureas
Imunit	Alpha-cypermethrin + teflubenzuron	IRAC 3A – Sodium channel modulators; IRAC 15 – Inhibitors of chitin biosynthesis affecting CHS1	Pyrethroid + benzoylurea
Krypto	Methomyl + bifenthrin	IRAC 1A – Acetylcholinesterase inhibitors; IRAC 3A – Sodium channel modulators	Carbamate + pyrethroid
Kumulus	Sulfur	Multisite contact activity (FRAC M02)	Inorganic compounds
Matrine	*Sophora flavescens* extract	Mode of action not specified in the source data	Quinolizidine alkaloids
Omite 720 EC	Propargite	IRAC 12C – Inhibitors of mitochondrial ATP synthase	Sulfite esters
Polo 500 SC	Diafenthiuron	IRAC 12A – Inhibitors of mitochondrial ATP synthase	Thioureas

Sanmite EW	Pyridaben	IRAC 21A – Mitochondrial complex I electron transport inhibitors	Pyridazinones
Sivanto Prime 200 SL	Flupyradifurone	IRAC 4D – Nicotinic acetylcholine receptor competitive modulators	Butenolides

Source: Prepared by the authors based on pesticide registration data from the Instituto de De-fesa Agropecuária e Florestal do Espírito Santo (Idaf, 2026).

The two-spotted spider mite (*Tetranychus urticae*), one of the major pests of strawberry cultivation, exhibits a high capacity for adaptation and resistance development. Sato *et al.* (2009) reported resistance frequencies of up to 81.3%, while Vassiliou and Kitsis (2013) documented resistance ratios exceeding 3,000 in populations collected from protected crops. Khajehali *et al.* (2011) also identified resistance to relatively recently introduced acaricides, highlighting that the development of new chemical compounds alone does not ensure sustainable pest control.

Among the products registered for *T. urticae*, 42% contain abamectin and 21% contain chlorfenapyr, indicating a concentration of available chemical control options (Figure 1). Vanzela (2022) observed a tendency toward an increased frequency of abamectin-resistant individuals following chlorfenapyr applications in *T. urticae* populations, suggesting that the use of different acaricides may influence resistance dynamics. Furthermore, although IRAC groups 12A, 12C, 13, and 21A affect mitochondrial or respiratory processes through distinct mechanisms, the possibility of shared metabolic resistance mechanisms cannot be entirely excluded. However, the

occurrence of cross-resistance among these groups cannot be inferred solely from their effects on mitochondrial processes.

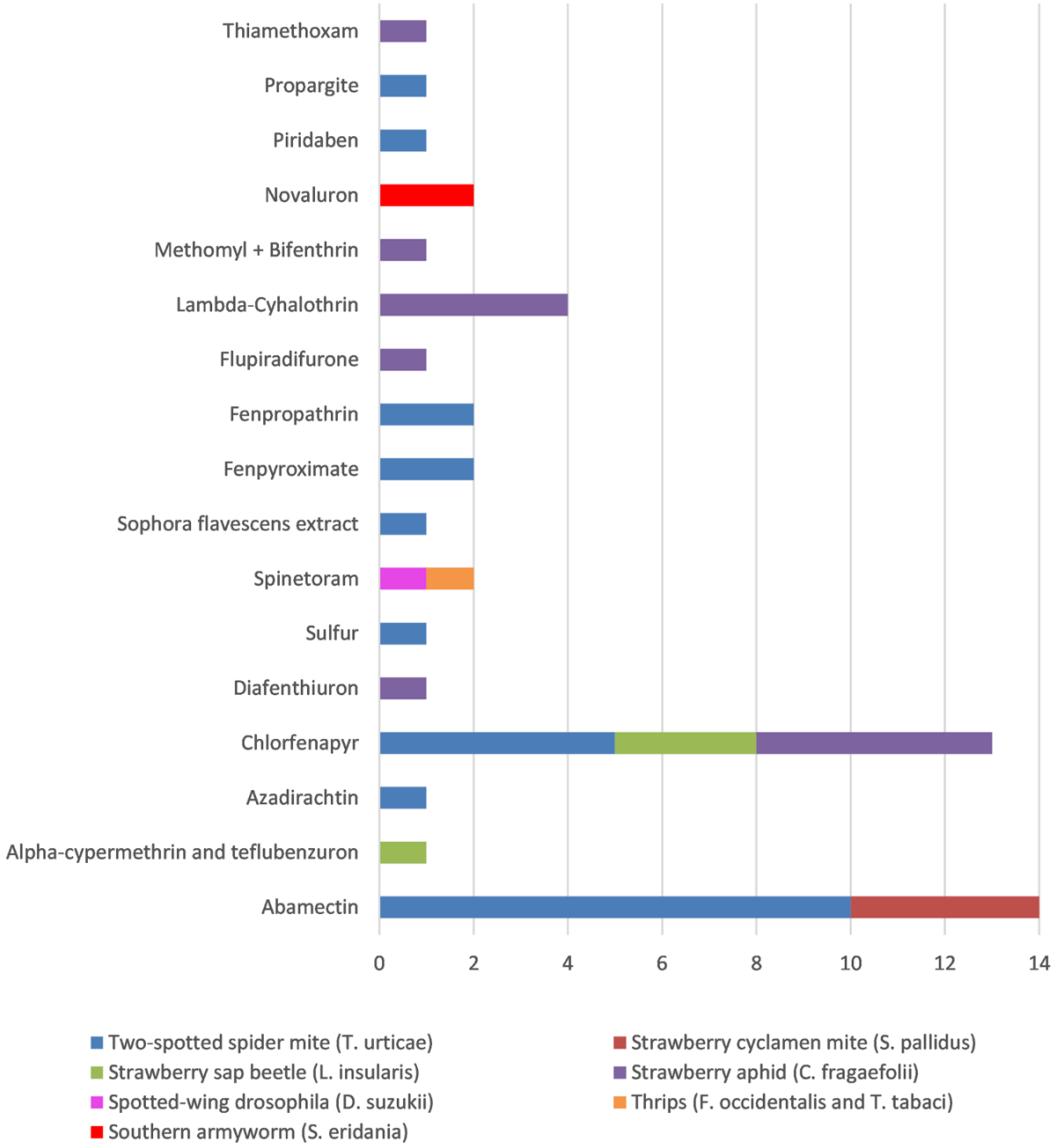
The availability of registered pesticides is even more limited for other important strawberry pests (Figure 1). For the strawberry cyclamen mite (*Steneotarsonemus pallidus*), registrations are restricted to abamectin-based products. For spotted-wing drosophila (*Drosophila suzukii*) and thrips (*Frankliniella occidentalis* and *Thrips tabaci*), only one spinetoram-based product is registered. Similarly, a single diafenthiuron-based product is available for the silverleaf whitefly (*Bemisia tabaci*). For the southern armyworm (*Spodoptera eridania*), two novaluron-based products are registered, while chlorfenapyr predominates among the products available for the strawberry sap beetle (*Lobiopa insularis*). These limitations restrict the implementation of effective mode-of-action rotation strategies for several important strawberry pests.

Among the major strawberry pests analyzed, aphids represented the second group with the greatest diversity of registered pesticide active ingredients, surpassed only by the two-spotted spider mite. A total of 13 commercial products were identified for aphid control, comprising six different active ingredient compositions and seven distinct active ingredients (Figure 1). However, despite this apparent diversity, the available products are concentrated in a limited number of modes of action, particularly pyrethroids and nicotinic acetylcholine receptor modulators. This concentration may restrict the effective diversity of options available for resistance management.

Another important factor is the considerable variation in pre-harvest intervals (PHIs), defined as the minimum period required between

the last pesticide application and harvest. Some registered products have PHIs of up to 28 days, whereas others have considerably shorter intervals (Table 2). This characteristic is particularly relevant to strawberry production because harvesting may occur daily or at intervals of up to three days, depending on environmental and production conditions (Cantillano, 2021). In production systems characterized by frequent harvesting, pesticides with longer PHIs may present operational limitations, potentially favoring the repeated use of products with shorter PHIs and increasing selection pressure on pest populations. Among the registered products, Polo 500 SC, containing diafenthiuron, has a PHI of 28 days; Krypto, containing methomyl and bifenthrin, has a PHI of 14 days; chlorfenapyr-based products have a PHI of 7 days; and abamectin-based products have a PHI of 3 days.

Figure 1. Number of registered pesticide products by active ingredient and target pest in strawberry cultivation in Espírito Santo, Brazil.



Source: Prepared by the authors based on pesticide registration data from Idaf (2026).

Some registered products have short pre-harvest intervals (PHIs) of only one day, including formulations containing thiamethoxam, lambda-cyhalothrin, and flupyradifurone, which may facilitate their use in strawberry production systems characterized by frequent harvesting. Other products have no specified harvest restrictions or have undetermined PHIs, as reported for formulations containing azadirachtin, *Sophora flavescens* extract, and sulfur (Table 2). Although these characteristics may favor their practical use, pesticide selection should not be based solely on PHIs but should

also consider toxicity, selectivity, resistance risk, and environmental impacts.

Table 2. Toxicological classification, environmental hazard classification, and pre-harvest intervals of pesticide products registered for strawberry pest control in Espírito Santo, Brazil.

Commercial product®	Toxicological classification	Environmental hazard classification	Pre-harvest interval (days)
Abadin 72 EC	Category 3 – Moderately toxic	Class II – Highly hazardous	3
Abamectin 72 EC Nortox	Category 3 – Moderately toxic	Class II – Highly hazardous	3
Abamectin Nortox	Category 5 – Unlikely to cause acute harm	Class III – Hazardous	3
Abamectin Prentiss	Category 3 – Moderately toxic	Class III – Hazardous	3
Abamex	Category 4 – Slightly toxic	Class III – Hazardous	3
Abamex Maxx	Category 3 – Moderately toxic	Class II – Highly hazardous	3
Acarigen	Category 4 – Slightly toxic	Class III – Hazardous	3
Actara 250 WG	Category 5 – Unlikely to cause acute harm	Class III – Hazardous	1
Adver 240 SC	Category 5 – Unlikely to cause acute harm	Class II – Highly hazardous	7

Azamax	Category 5 – Unlikely to cause acute harm	Class IV – Slightly hazardous	No restriction
Clorfenapir Nortox	Category 5 – Unlikely to cause acute harm	Class II – Highly hazardous	7
Danimen 300 EC	Category 3 – Moderately toxic	Class II – Highly hazardous	3
Delegate	Category 5 – Unlikely to cause acute harm	Class II – Highly hazardous	3
Fujimite 50 SC	Category 4 – Slightly toxic	Class II – Highly hazardous	5
Hangar	Category 5 – Unlikely to cause acute harm	Class II – Highly hazardous	3
Imunit	Category 4 – Slightly toxic	Class II – Highly hazardous	7
Kanopus	Category 5 – Unlikely to cause acute harm	Class II – Highly hazardous	7
Karate Zeon 250 CS	Category 5 – Unlikely to cause acute harm	Class I – Extremely hazardous	1
Karate Zeon 50 CS	Category 4 – Slightly toxic	Class II – Highly hazardous	3
Krypto	Category 3 – Moderately toxic	Class II – Highly hazardous	14
Kumulus	Category 5 – Unlikely to cause acute harm	Class III – Hazardous	No restriction

Matrine	Category 5 – Unlikely to cause acute harm	Class IV – Slightly hazardous	Not determined
Omite 720 EC	Category 4 – Slightly toxic	Class II – Highly hazardous	4
Ortus 50 SC	Category 4 – Slightly toxic	Class II – Highly hazardous	5
Pirate	Category 5 – Unlikely to cause acute harm	Class II – Highly hazardous	7
Polo 500 SC	Category 2 – Highly toxic	Class II – Highly hazardous	28
Potenza Sinon	Category 4 – Slightly toxic	Class III – Hazardous	3
Potenza Sinon Plus 36 EC	Category 4 – Slightly toxic	Class III – Hazardous	3
Rimon Supra	Category 5 – Unlikely to cause acute harm	Class II – Highly hazardous	3
Samurai Bushi	Category 3 – Moderately toxic	Class II – Highly hazardous	1
Sanmite EW	Category 3 – Moderately toxic	Class III – Hazardous	3
Sivanto Prime 200 SL	Category 4 – Slightly toxic	Class III – Hazardous	1
Sparviero 50	Category 4 – Slightly toxic	Class II – Highly hazardous	1
Sumirody 300	Category 3 – Moderately toxic	Class II – Highly hazardous	3
Trigger 240 SC	Not classified	Class II – Highly hazardous	7

Vertimec 18 EC	Category 3 – Moderately toxic	Class II – Highly hazardous	3

Source: Prepared by the authors based on pesticide registration data from the Instituto de Defesa Agropecuária e Florestal do Espírito Santo (Idaf, 2026).

This distinction is particularly important because products with short PHIs may be perceived as safer or more suitable for strawberry production. However, a short PHI does not necessarily indicate lower toxicological or environmental risks. For example, lambda-cyhalothrin-based products, such as Karate Zeon 250 CS, Samurai Bushi, and Sparviero 50, have a PHI of only one day but belong to the pyrethroid group and are associated with relatively high environmental hazard classifications (Table 2). Similarly, thiamethoxam and flupyradifurone also have short PHIs, but both act on nicotinic acetylcholine receptors, although they belong to different IRAC subgroups (4A and 4D, respectively). Therefore, pesticide selection should consider not only the operational advantages associated with PHIs but also selectivity, resistance management, toxicity, and potential effects on non-target organisms (Desneux *et al.*, 2007; Simon-Delso *et al.*, 2015).

Furthermore, 23 of the 36 registered products (63.9%) were classified as Class II (highly hazardous to the environment), indicating a predominance of pesticides with considerable potential environmental hazards (Table 2). Lethal and sublethal effects on natural enemies may disrupt ecological interactions and compromise the natural regulation of pest populations (Desneux *et al.*, 2007). Differences between toxicological classifications and environmental hazard classifications also demonstrate that products

with relatively low acute toxicity to humans may still present considerable environmental risks.

In this context, products containing compounds of biological or natural origin, such as azadirachtin, *Sophora flavescens* extract, and sulfur, represent a relatively small proportion of the registered products. These compounds may contribute to diversifying pest management strategies by providing alternatives with characteristics that differ from those of conventional synthetic insecticides and acaricides. Azadirachtin, for example, can interfere with insect growth, feeding, and reproduction through multiple physiological effects. In addition, spinetoram, a spinosyn classified in IRAC group 5, provides a distinct mode of action that may contribute to pesticide rotation strategies when registered for the target pest. Nevertheless, the effective contribution of these products to resistance management depends on their specific modes of action, appropriate use, and integration with other pest management practices.

In addition to the pesticide products identified in the Idaf registration database, the literature review revealed several biological control agents with potential applications in strawberry pest management (Table 3). Predatory mites such as *Phytoseiulus macropilis* and *Neoseiulus californicus* have been investigated for the management of the two-spotted spider mite (*Tetranychus urticae*) and may contribute to maintaining pest populations below economically damaging levels when appropriately introduced and managed. Similarly, *Amblyseius swirskii* has demonstrated potential for controlling thrips and whiteflies, particularly in protected cultivation systems. Entomopathogenic fungi, including *Beauveria bassiana* and *Metarhizium anisopliae*, may provide additional control

options for different insect pests, while entomopathogenic nematodes can contribute to the management of soil-dwelling insects.

The diversity of biological control agents identified in the literature indicates opportunities to expand the functional diversity of strawberry pest management beyond conventional chemical control. Reviews of strawberry production systems in Europe have shown that predatory mites, predatory insects, parasitoids, and entomopathogens can act against different pest groups, contributing to ecological interactions that support natural pest regulation (Solomon *et al.*, 2001). From this perspective, biological control should not be considered merely a direct substitute for chemical insecticides and acaricides, but rather an important component of integrated pest management strategies aimed at improving agroecosystem stability.

Unlike conventional pesticides, which frequently act on specific biochemical targets, biological control agents can suppress pest populations through different ecological and biological mechanisms, including predation, parasitism, and infection. Their integration into pest management programs may reduce the frequency of chemical applications and consequently decrease selection pressure on target pest populations. This approach is particularly relevant to the present study, considering the high concentration of commercial pesticide registrations in a limited number of IRAC mode-of-action groups. In particular, the use of predatory mites such as *P. macropilis* and *N. californicus* may help reduce reliance on acaricides for *T. urticae* management, provided that their establishment and effectiveness are supported by appropriate monitoring and compatible management practices.

Table 3. Biological control agents and their potential applications in strawberry pest management.

Biological control agent	Functional group	Main target pests	Reference
Phytoseiulus macropilis	Predatory mite	*Tetranychus urticae* (two-spotted spider mite)	Oliveira *et al.*, 2009
Neoseiulus californicus	Predatory mite	*Tetranychus urticae* (two-spotted spider mite)	Sato *et al.*, 2007
Amblyseius swirskii	Predatory mite	Thrips and whitefly	Calvo *et al.*, 2015
Beauveria bassiana	Entomopathogenic fungus	Thrips, whiteflies, and other susceptible insects	Alves, 1998; Faria; Wraight, 2007
Metarhizium anisopliae	Entomopathogenic fungus	Soil-dwelling pests and other susceptible insects	Alves, 1998; Zimmermann, 2007
Steinernema spp. / *Heterorhabditis* spp.	Entomopathogenic nematodes	Soil-dwelling insect larvae	Kaya; Gaugler, 1993

Source: Prepared by the authors based on the literature review of biological control agents with potential applications in strawberry pest management.

Beyond the introduction of biological control agents, their conservation and persistence within the production system are

essential for the long-term success of biological pest management. Fitzgerald and Jay (2013) highlighted that alternative food resources, such as pollen, nectar, and alternative prey, may favor the persistence of predators during periods of low target pest abundance. The availability of these resources can help maintain natural enemy populations and facilitate their response to subsequent pest outbreaks. In this context, conservation biological control strategies, including flowering plants, vegetated strips, and refuge areas, may promote the establishment and persistence of beneficial organisms in strawberry agroecosystems.

Evidence supporting this ecological approach has also been reported in commercial strawberry production in Mexico. Salas-Araiza *et al*. (2020) investigated the use of natural enemies associated with coriander strips established around strawberry fields and reported increased abundance of beneficial arthropods, including lacewings and predatory lady beetles, as well as reduced *Tetranychus urticae* populations compared with conventional management. The authors also reported that insecticide applications were not required during the evaluated production cycle. These findings suggest that conservation biological control may contribute to reducing pesticide dependence and supporting ecological stability under suitable management conditions.

Another relevant aspect is the functional complementarity among biological control agents. The combined use of different natural enemies may improve pest suppression compared with the use of individual species, depending on their biological characteristics and environmental conditions. In a study of thrips management in protected strawberry cultivation, Markkanen (2025) reported that the combination of the predatory mite *Neoseiulus cucumeris* and

the predatory bug *Orius laevigatus* provided favorable pest control performance and cost-effectiveness. Such complementarity may result from differences in prey preferences, feeding behavior, and the pest developmental stages targeted by each predator, contributing to more consistent biological control throughout the production cycle.

Despite the potential of biological control agents to expand the functional diversity of strawberry pest management, their adoption in commercial production systems may face practical limitations. These include producers' expectations of rapid pest suppression, the introduction of biological control agents only after pest populations have reached high densities, the need for regular monitoring of pest and natural enemy populations, and limited familiarity with the ecological principles of Integrated Pest Management (IPM). Unlike many conventional insecticides and acaricides, biological control strategies often rely on gradual pest population regulation, requiring preventive planning, appropriate timing, and continuous technical monitoring. Consequently, perceived limitations in biological control effectiveness may sometimes result from inadequate implementation rather than from the inherent inability of natural enemies to suppress pest populations.

In recent years, the Brazilian biological control sector has expanded, supported by technological developments and the increasing availability of registered biological products. According to Revista Cultivar (2026), 162 bioinput products were registered in Brazil in 2025, representing a record annual number of registrations. This expansion of the registered product portfolio may facilitate the incorporation of biological control into IPM programs, although

access to appropriate products, technical assistance, and adequate implementation practices remains essential for successful adoption.

The use of biological control agents in strawberry production extends beyond the direct replacement of chemical pesticides. Integrating predators, entomopathogens, bioinsecticides, and natural enemy conservation practices may enhance the functional diversity of pest management strategies, reduce reliance on specific chemical modes of action, and contribute to delaying resistance development. From the ecological and evolutionary perspective adopted in this study, biological control represents an important component of more resilient and sustainable strawberry production systems.

Overall, the findings indicate that the relatively high number of pesticide registrations for strawberry cultivation in Espírito Santo does not necessarily correspond to a broad diversity of effective modes of action. The concentration of commercial products within a limited number of IRAC groups, combined with operational restrictions associated with pre-harvest intervals, may increase dependence on certain chemical control options. In this context, integrating biological control agents identified through the literature review with appropriate pesticide rotation and regular pest monitoring may contribute to reducing selection pressure and improving the long-term sustainability of strawberry pest management.

4. CONCLUSION

The diversity of commercial pesticide products registered for strawberry cultivation in Espírito Santo does not necessarily translate

into effective functional diversity in pest management. The substantial concentration of registrations in a limited number of IRAC mode-of-action groups, particularly those represented by abamectin, chlorfenapyr, and pyrethroids, indicates a restricted range of chemical control options and potential vulnerability to the development of pesticide resistance.

The availability of effective alternatives for rotating pesticides with different modes of action remains limited for several important strawberry pests, including *Tetranychus urticae*, *Steneotarsonemus pallidus*, and *Lobiopa insularis*. Furthermore, operational restrictions associated with pre-harvest intervals may contribute to the repeated use of certain pesticide groups, potentially increasing selection pressure on pest populations.

The literature review identified biological control agents with potential applications in strawberry pest management. Their integration into pest management programs may expand the functional diversity of control strategies, reduce dependence on specific chemical modes of action, and contribute to delaying resistance development. However, successful implementation requires appropriate technical knowledge, regular pest monitoring, and management practices compatible with the establishment and persistence of natural enemies.

Overall, the findings highlight the importance of transitioning from pest management strategies predominantly based on chemical control toward integrated approaches that combine ecological, evolutionary, and agronomic principles. Structured rotation among different pesticide modes of action, conservation of natural enemies, planned incorporation of biological control, and continuous

monitoring of pest populations represent important strategies for reducing selection pressure and improving the long-term resilience and sustainability of strawberry production systems.

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Acknowledgment to FAPES for their financial support. Project: N° FAPES 081/2026 - P: 2026-VD873

[1] Pesquisadora do Instituto Capixaba de Pesquisa, Assistência Técnica e Extensão Rural. E-mail: acesse o artigo original para visualizar o e-mail

[2] Pesquisadora do Instituto Capixaba de Pesquisa, Assistência Técnica e Extensão Rural. E-mail: acesse o artigo original para visualizar o e-mail

[3] Pesquisadora do Instituto Capixaba de Pesquisa, Assistência Técnica e Extensão Rural. E-mail: acesse o artigo original para visualizar o e-mail

[4] Pesquisador do Instituto Capixaba de Pesquisa, Assistência Técnica e Extensão Rural. E-mail: acesse o artigo original para visualizar o e-mail

[5] Pesquisador do Instituto Capixaba de Pesquisa, Assistência Técnica e Extensão Rural. E-mail: acesse o artigo original para visualizar o e-mail

[6] Pesquisador do Instituto Capixaba de Pesquisa, Assistência Técnica e Extensão Rural. E-mail: acesse o artigo original para visualizar o e-mail

[7] Técnico de Laboratório do Instituto Capixaba de Pesquisa, Assistência Técnica e Extensão Rural. E-mail: acesse o artigo original para visualizar o e-mail

[8] Bolsista do Instituto Capixaba de Pesquisa, Assistência Técnica e Extensão Rural. E-mail: acesse o artigo original para visualizar o e-mail

[9] Pesquisador do Instituto Capixaba de Pesquisa, Assistência Técnica e Extensão Rural. E-mail: acesse o artigo original para visualizar o e-mail

[10] Analista em Ciência e Tecnologia do Instituto Nacional de Pesquisas da Amazônia. E-mail: acesse o artigo original para visualizar o e-mail

[11] Bióloga. E-mail: acesse o artigo original para visualizar o e-mail