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Review

Future of Insecticide Seed Treatment

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Abstract: Seed treatment as a method of local application of pesticides in precise agriculture reduces the amount of pesticides used per unit area and is considered to be the safest, cheapest and most ecologically acceptable method of protecting seeds and young plants from pests in the early stages of their development. With the introduction of insecticides from the neonicotinoid group in the mid-1990s, the frequency of seed treatment increased. Due to suspected negative effects on pollinators, most of these insecticides are banned in the European Union. The ban has therefore led to a reduction in the number of active substances approved for seed treatment and to an increased re-use of active substances from the group of pyrethroids as well as other organophosphorus insecticides, which pose potentially very serious risks, perhaps even greater than those of the banned neonicotinoids. The objective of this review is to analyze the advantages and disadvantages of seed treatment and the potential role of insecticide seed treatment in reducing the negative impact of pesticides on the environment. The main disadvantage of this method is that it has been widely accepted and has become a prophylactic protective measure applied to almost all fields. This is contrary to the principles of integrated pest management and leads to an increased input of insecticides into the environment, by treating a larger number of hectares with a lower amount of active ingredient, and a negative impact on beneficial entomofauna. In addition, studies show that due to the prophylactic approach, the economic and technical justification of this method is often questionable. Extremely important for a quality implementation are the correct processing and implementation of the treatment procedure as well as the selection of appropriate insecticides, which have proven to be problematic in the case of neonicotinoids. The ban on neonicotinoids and the withdrawal of seed treatments in oilseed rape and sugar beet has led to increased problems with a range of pests affecting these crops at an early stage of growth. The results of the present studies indicate good efficacy of active ingredients belonging to the group of anthranilic diamides, cyantraniliprole and chlorantraniliprole in the treatment of maize, soybean, sugar beet and rice seeds on pests of the above-ground part of the plant, but not on wireworms. Good efficacy in controlling wireworms in maize is shown by an insecticide in the naturalites group, spinosad, but it is currently used to treat seeds of vegetable crops, mainly onions, to control onion flies and flies on other vegetable crops. Seed treatment as a method only fits in with the principles of integrated pest management when treated seeds are sown on land where there is a positive prognosis for pest infestation.

Keywords: seed treatment; cyantraniliprole; chlorantraniliprole; spinosad; neonicotinoids

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1. Introduction

According to the World Food Program [1], it is projected that 840 million people worldwide will go hungry by 2030 if current trends continue.

To increase the production of food in sufficient quantity for the growing world population, and to ensure the production of agricultural products and other economic needs (livestock feeding, production of medicinal plants, production of biofuels, fibers and building materials), the use of synthetic chemicals in agriculture and the accumulation of their toxic residues in food and the environment has increased [2].

Although pest control is as old as agricultural production, Bažok and others [3] point out that it was not until the 20th century, with the advent of the first pesticides, that the revolutionary development of the chemical method of crop protection began. They also point out that with the knowledge of the facts about the toxicity of pesticides and their harmful effects on humans, the environment and non-target organisms, there has been a growing concern about the consequences. All this has led to an evolution of chemical pest management, i.e., a reduction in the dosage of pesticides used, more ecological studies in the approval process and the introduction of pesticides with reduced toxicity and improved biodegradability.

In a review of scientific studies, Müller [4] points out that pest control also exposes non-target organisms to insecticides that, while not lethal to them, can affect their development, physiology, behavior and communication.

The seriousness of the problem of contamination of soils and living organisms with pesticides is shown by the results of a study conducted in France [5]. It detected the presence of at least one pesticide in all soil samples and in 92% of earthworms sampled, both in treated crops and in untreated habitats. The vulnerability of earthworms is reflected in the fact that a mixture of at least one insecticide, one herbicide and one fungicide was found in 90% of soil samples and 54% of earthworm samples. In Germany, pesticide residues in pollen were investigated [6] and it was found that almost 90% of the analyzed pollen samples contained between one and thirteen different pesticides, with the highest concentrations found in 29 pesticides (up to 4500 ng pesticide/g pollen).

The improvement of existing plant protection methods and the development of new ones aim at reducing the negative impact of agriculture on the environment. One of the more modern methods is the production of genetically modified crops that are resistant to certain pests. By sowing these crops, the amount of insecticides used is again reduced [7]. A more recent method is gene silencing by RNA interference [8,9]. This method is constantly being improved and shows good efficacy in controlling some types of pests [10]. As both methods rely on genetic manipulation, there are some public concerns, so their implementation is limited in some countries, including EU countries.

Micropesticides and nanomaterial-based pesticides are also among the formulations considered as suitable alternatives to pesticides [11]. Nanocapsulation achieves controlled release of the active ingredient over a long period of time, thus preventing premature degradation under adverse environmental conditions, which is crucial for reducing active ingredient doses [12]. In addition to synthetic active ingredients, naturally derived active ingredients can also be encapsulated, such as essential oils, which are insecticidal, have low toxicity and are environmentally friendly [13].

One of the methods that provides effective protection with reduced use of pesticides is seed treatment. Therefore, seed treatment with insecticides to control soil pests is mentioned as one of the most ecologically and economically justifiable measures [14,15]. Although seed treatment as a method was known earlier, more intensive development and application of this method began in the mid-1990s after the discovery of insecticides from the group of neonicotinoids. Neonicotinoids proved to be particularly acceptable for application by seed treatment because they do not cause phytotoxic effects, which were often a limiting factor for the use of insecticides from other groups. In addition, the distinct systemic nature of neonicotinoids allowed the extension of the spectrum of action from soil pests to above-ground pests at an early stage of plant development. For example, according to Jeschke et al. [16], 60% of the total neonicotinoids produced were used either for seed treatment or in the form of granules. Compared to other insecticides, neonicotinoids are more selective for pests, less toxic to mammals and more biodegradable, but their use is associated with losses in bees and other non-target organisms [17]. Precisely because of the suspicion that they negatively affect bees and other pollinators, the use of four active substances from the group of neonicotinoids (imidacloprid, clothianidin, thiamethoxam and thiacloprid) has been permanently banned at the level of EU member states [18–21].

As the method of seed treatment is mostly based on the application of neonicotinoids, this ban will again restrict seed treatment. This could have a significant impact on crop protection technology, which is crucial for economically and environmentally sustainable crop production [22].

The aim of this review is therefore to analyze the advantages, disadvantages and role of seed treatment in reducing the negative impact of pesticides on the environment and to consider potential insecticides that have the perspective of application through seed treatment.

2. Advantages and Disadvantages of Insecticide Seed Treatment

Insecticidal seed treatment is carried out to control soil pests such as wireworms (*Agriotes* spp.), white grubs (*Melolontha* spp.) and pests that attack plants in their early stages of development such as flea beetles, aphids, etc. Sowing treated seeds is a measure of good and rational agricultural practice as it reduces the negative impact of insecticides on the environment [23].

Control of stored-product pests by treating stored seeds with insecticides [24] dates back to 60 AD. Vines and shredded cypress leaves were used for seed treatment. In the middle of the last century, the insecticide lindane was developed from the chlorinated hydrocarbon group, mainly to control wireworms. Aldrin, dieldrin and heptachlor were also developed from the same group. At the same time, the systemic insecticide disulfoton was developed from the group of organophosphorus insecticides. Disulfoton was used extensively to treat cotton seed.

In the United States, the percentage of corn seed treated with neonicotinoids ranges from 71% to nearly 100% (Douglas and Tooker, 2015, cited in Gurian-Sherman, [25]). Until the ban on neonicotinoid use in Croatia and other European Union countries, neonicotinoid-treated seeds were sown on about 30% of the cultivated area [22].

2.1. Advantages of Insecticide Seed Treatment

The available literature [14,15] states that seed treatment as a method of protection against pests has several advantages, namely:

1. Lower amount of insecticides used

Sowing insecticide-treated seeds reduces the amount of active ingredient per unit area compared to other types of insecticide application. For example, when sowing sugar beet, strip application of a carbofuran-based granular insecticide applies 1250 g of active ingredient/ha, compared to 52.5 g/ha for seed treatment. The tefluthrin-based products are applied at a dose of 50 g active ingredient/ha when applied in foliar strips and 3.6 g active ingredient/ha when applied as seed treatment [15]. A lower amount means less insecticide residues in the environment. If we add the fact that some of the foliar treatments can be avoided after seed treatment with systemic insecticides, we arrive at a reduction in the total amount of insecticides applied to a given crop. Bažok et al. [26] state that before the introduction of seed treatment of sugar beet as a regular measure, the maximum amount of active ingredient for the control of wireworms, flea beetles and aphids was 2.3 kg/ha treated and 1.64 kg/ha sown area. According to the same authors, 0.05 to 0.1 kg of active ingredient of the insecticide/ha of cultivated area was used to control the same pests in 2008–2010, which can certainly be considered a great change.

Another advantage of seed treatment is the smaller area to which the insecticides are applied. If the entire area of an acre of land is treated, 10,000 m^2 will come into contact with the insecticides. Row application exposes 500 m^2 of soil to the insecticides, while the smallest area affected by insecticides when sowing treated seeds is only 58 m^2 of soil [27]. This information is very important from the point of view of the possible negative effect of insecticides on beneficial insects in the soil. Springtails (order Collembola), ground beetles (family Carabidae, order Coleoptera) and rove beetles (family Staphylinidae, order Coleoptera) are groups of insects that live in the soil layer and shallowly below the surface. They are mainly useful either as natural enemies of pests or for maintaining soil fertility [28].

2. Reduced protection costs

The economic advantage of this method comes from the fact that smaller amounts of the active ingredient are used for seed treatment and therefore the price is lower. Another economic advantage is that no additional equipment is required for sowing treated seeds, as is the case with strip application of granulated insecticides. For this application, applicators for granules must be attached to the seeder as an optional accessory. Seed treatment with systemic insecticides provides additional protection against pests that attack above-ground organs in the early stages of plant development, so foliar treatment is often not required. This reduces the overall cost of protecting individual plants.

3. Reduced risk for farmers

There is a much lower risk of poisoning to the farmer when sowing treated seeds than when handling pesticides. Seed treatment is carried out during seed processing in specialized and well-equipped factories. Farmers only come into contact with treated seeds when filling the seed tanks. The absence of foliar application of insecticides against above-ground pests further increases farmers' safety.

2.2. Disadvantages of Insecticide Seed Treatment

The disadvantages of this method relate to the process of seed preparation and handling, the sowing equipment, the insecticides used and the fact that the insecticides are applied preventively by seed treatment, which is not always in accordance with the principles of integrated pest management.

1. Seed treatment, handling and sowing

High-quality seed treatment is a prerequisite for achieving satisfactory pest control results [27], and includes high-quality seed material, insecticide and seed treatment formulation as well as seed treatment equipment. The design of seed treatment equipment must be a closed system to avoid hazards to personnel and possible poisoning from dusts. Although seed treatment manufacturers and seed processors strive to ensure the highest quality seed treatment possible, damage can occur and insecticide particles can fall when handling treated seeds. By regulation, the amount of waste particles must be less than 1.5% of the total amount of pesticide applied. This is verified by the Heubach test [27]. Waste insecticide particles are very small, so they are easily dispersed by air.

Mechanical seeders do not generate air flow during seeding. For positive pressure pneumatic seeders, the air flow must be directed towards the soil. In pneumatic negative pressure seeders, the air flow generated by the fan is directed through the outlet at an angle of 45° to 100° to the surroundings, so that potentially hazardous waste particles can be blown out of the flow in an uncontrolled manner. It is therefore important that the air streams are directed towards the ground or that the exhaust pipes are equipped with filters to avoid the risk of insecticide dust entering the environment, especially in flowering plants.

2. Insecticides for seed treatment

The first insecticides used for seed treatment were insecticides belonging to the group of chlorinated hydrocarbons (lindane), organophosphorus insecticides (diazinon, chlorpyrifos, acephate ...) and carbamates (furatiocarb, carbofuran and methiocarb). Later, pyrethroids (bifentrin and tefluthrin) and GABA synaptic receptor inhibitors (fipronil) appeared on the market [15]. Some of these insecticides showed phytotoxic effects on the plant that developed from the treated seeds [29]. Since the development of a new class of insecticides from the group of neonicotinoids in the early 1990s, which manifest as neurotoxins with high toxicity to most arthropods [30], their more significant use for seed treatment has begun (Elbert et al. 2008., cited in Jeschke et al. [16]). As a large number of laboratory and field trials confirmed the heavy exposure and negative effects of neonicotinoids on bees and other pollinators [31,32], as well as on other environmental components (neonicotinoid residues in the environment, pollen, water and soil), an initiative for a permanent ban of the most commonly used active ingredients for seed treatment, imidacloprid, thiamethoxam and clothianidin, was launched in the European Union. In

2018, the initiative resulted in a permanent ban on the use of these three active substances from the neonicotinoid group (imidacloprod, clothianidin and thiamethoxam) [18–20]. The approval of another active ingredient, thiacloprid, which was also used in seed treatment, was not renewed in the EU in 2020 [21].

3. The actual need for seed treatment and the ultimate effect on harmful and beneficial fauna

Integrated pest management means that the decision to control pests is made solely on the basis of an identified need, i.e., a positive prediction of infestation by specific pests. Since the seed is treated by the conditioner, the decision to sow the treated seed is made when the seed is purchased. Although the decision should be made solely on the basis of an identified need (based on prediction and determination of the number of pests in the soil), as emphasized by many authors [14,15,33,34], this is usually not the case. In this way, seed treatment with insecticides becomes a prophylactic measure, which is not good at all. Neonicotinoid seed treatments are applied to every acre of corn sown in the U.S. [35], and the amounts of active ingredients used for corn seed treatments doubled between 2011 and 2014 [36]. It is also noted that seed treatments are used primarily on soybeans, cotton and other species [37,38]. According to Kyntec [39], from 2012 to 2014, treated seeds were sown on 90% of corn, 76% of soybean, 62% of cotton, and 56% of winter wheat acres in the United States. Hitaj et al. [40] point out that it is very difficult to collect accurate information on the amounts of insecticides used in seed treatments because farmers already purchase treated seeds and do not feel that they have actually used insecticides by sowing those seeds.

It is reasonable to assume that on such a large agricultural area there is no real need to sow treated seeds. Indeed, this would imply that the population of soil pests (wireworms, white grubs, western corn rootworm, vegetable maggots, cutworms . . .) is above the threshold, or that the population of pests attacking a given crop in the early stages of development is above the decision threshold. According to the research results of numerous authors from around the world (Canada, France, Italy, USA . . .), the percentage of fields where the soil pest population exceeds the critical number is very low [33,35,41–43], suggesting that the use of insecticides for seed treatment is mainly a prophylactic measure or, as some refer to this type of protection, "insurance pest management" [35].

At the same time, a large number of authors note that there is no clear evidence of reduced pest incidence and increased yield, i.e., economic benefits, in crops whose seeds have been preventively treated with neonicotinoids [33,43–47]. According to Hauer et al. [48], sowing neonicotinoid-treated sugar beet seed is not necessary in one-third of experimental fields, but is used as a preventive measure due to the difficulty in predicting pest emergence. A study conducted in Quebec, Canada [33], found that seed treatment with neonicotinoids in field crops was beneficial less than 5% of the time. Similar results were provided by a study conducted in the Ontario region on 129 corn fields and 31 soybean fields under conditions of heavy wireworm infestation [43]. It was found that only 8% of corn fields and 6% of soybean fields had higher yields in variants where the seeds were treated with fungicides and insecticides. It should be noted that these studies included seeds treated with neonicotinoids and chlorantraniliprole. At the same time, seed treatments with insecticides were found to be economically viable in 23% of the fields. It follows that most applications of neonicotinoid-treated seeds are not justifiable under the principles of integrated pest management because the target species are opportunistic pests and there is no economic benefit [36]. The sowing of treated seeds not only contradicts the principles of integrated pest management as it is prophylactic, but also because it has undesirable effects on biodiversity. Although a significantly lower amount of active ingredient is applied per unit area when sowing treated seeds [15,27] than when applying granulated insecticides, the treated area is significantly larger due to the prophylactic application. There is a growing body of research showing that sowing treated seeds consequently has a negative impact on beneficial entomofauna [35,49,50]. Research by Dubey et al. [50] showed that seed treatments with neonicotinoids can affect arthropod communities, including important natural enemies, even when environmental persistence and active ingredient concentrations are low. The arthropod community on the above-ground parts of winter wheat has shown that in some cases these effects can persist for several months after sowing.

4. Possible human health risk of insecticide seed treatment

In general, neonicotinoids, as the most commonly used insecticides for seed treatment, are considered safe for humans at low concentrations and are considered less toxic to mammals compared to other groups of insecticides (e.g., organophosphates). However, several studies have shown that there are human health concerns [51]. These concerns relate to the effects of acute poisoning and possible chronic effects. Poisoning with neonicotinoids can result in respiratory, cardiovascular, and neurological symptoms, and even death [52–54]. Poisoning with neonicotinoids from food consumption (residues in plant tissue) has been documented, but there are insufficient data to definitively link neonicotinoids to potential health risks [51]. Due to the very low doses applied as seed treatments [55] and the fact that uptake of neonicotinoids by plants is generally very low [32], as well as the fact that only low levels of neonicotinoids could be recovered from plants 27 days after sowing [55], it is difficult to believe that subacute intoxication from consumption of food grown from treated seeds is likely.

2.3. Consequences of the Ban on Neonicotinoids for Seed Treatment

The ban on the use of neonicotinoids, which came into force in the EU first as a temporary ban in 2013 and then as a full ban in 2018 [22], has, according to some reports, led to an increase in the use of organophosphorus insecticides, which have potentially more serious risks than the banned neonicotinoids [56]. This suggests an increased use of chlorpyrifos, which has also been banned since the beginning of 2020 [57].

The biggest problems related to the ban of neonicotionides for seed treatment occur in crops that are attacked by a large number of pests, such as oilseed rape and sugar beet [58]. Recent research in the UK [59] shows that after the ban on the use of neonicotinoids for seed treatment of oilseed rape, there were yield losses and a reduction in the area under oilseed rape, as well as increased foliar application of insecticides from the pyrethroid group, to which the pests developed resistance.

The situation is similar in Poland [60], where oilseed rape and maize are grown on 1 million hectares each. In that year, no insecticides were available for oilseed rape seed dressing. At the same time, only one insecticide was available for corn seed treatment with the active ingredient methiocarb.

Since the ban on neonicotinoids, these are no longer approved for seed treatment in the European Union, and the question arose of replacement candidates, i.e., insecticides that can adequately replace neonicotinoids while being safer for the environment.

3. Candidates for the Replacement of Neonicotinoids

Insecticides from the groups known so far can be used as alternatives to neonicotinoids for seed treatment in the EU if they are still allowed on the market.

Data published by Virić Gašparić and Bažok [61] show that in the Republic of Croatia in the period from 1987 to 2018, the number of active substances of insecticides decreased by 40% and the number of insecticide products by 50%, while at the same time 12 new groups of insecticides with a new mode of action were introduced to the market. The same source shows that in 2018, pyrethroids were the most represented group of insecticides on the market, accounting for 28% of the total number of insecticide products. Although insecticides with a different mechanism of action have entered the market, their application is often specific and limited to individual crops, and they tend to be less affordable. Therefore, foliar application of pyrethroids is very common, which according to Dewar (2017) is a very common cause of increased resistance development in a wider range of pests.

In the Republic of Croatia, the number of approved products for protection against soil pests is constantly decreasing. In 1987 [62], 29 insecticidal products from the group of organophosphorus insecticides for the control of soil pests were registered on the market, but none of them were an insecticide for seed treatment. The only registered seed treatment insecticide was methiocarb from the carbamate group. In 2013, seven active substances were registered for seed treatment [63], based on which 13 products were on the market. Of these active substances used in 2013, six products based on three active substances are approved today, according to the list of registered plant protection products [64] (Table 1). Although a larger number of active ingredients are approved for seed treatment, only one active ingredient, the insecticide telfutrin from the pyrethroid group, is approved without specific restrictions (Table 1). Formally, insecticides from the group of neonicotinoids, imidacloprid, thiamethoxam and clothianidin, are also on the list, but with the restriction that seeds treated with these insecticides may only be used in permanent greenhouses [57].

Table 1. Comparison of registered active ingredients of insecticides for seed treatment in the Republic of Croatia, 2013/2021. (According to Bažok, 2013 [63] and FIS portal, 2021 [64]).

Group	Active Ingredient	Preparation	Crops on Which It Was Allowed		Restrictions 2021
			2013	2014	
Carbamates	Methiocarb	Mesurol FS 500	Sunflower, oilseed rape and corn	No permission	
Pyrethroids	Tefluthrin	Force 20 SC	Corn and sugar beet	Corn, sugar beet, sunflower, wheat and barley	
Neonicotinoids	Imidacloprid	Macho 70WS	Corn and potatoes	No permission	
		Gaucho FS 600 Macho 60 FS	Corn and sugar beet	No permission	
		Gaucho FS 600 Rot	Potatoes, corn, sunflower and cereals	Potatoes and winter cereals;	Treated seeds and tubers may only be sown (planted) in a protected area that is a permanent greenhouse, and the crop must remain in a protected area that is a permanent greenhouse throughout its life *
	Imidacloprid + pencycuron	Prestige FS 290	Potatoes	No permission	
	Thiamethoxam	Cruiser 70 WS	Sugar and fodder beet	Sugar and fodder beet	Treated seeds may only be sown (planted) only in a protected area that is a permanent greenhouse, and the crop must remain in a protected area that is a permanent greenhouse throughout its life
		Cruiser FS 350	Sugar beet, corn, sunflower, winter wheat and winter barley	Sugar beet, winter wheat and winter barley	
	Thiamethoxam + metalaxyl + fludioxonil	Cruiser OSRMaxim Top	Oilseed rape	Oilseed rape	
	Clothianidin	Poncho FS 600 Rot	Corn and sugar beet	Sugar beet	
Neonicotinoids + pyrethroids	Imidacloprid + eta-cyfluthrin	Chinook FS 200	Oilseed rape	No permission	
Phenylpyrazoles	Fipronil	Cosmos 50 FS	Corn and sunflower	No permission	

* The license for GAUCHO FS 600 ROT is valid until 1 March 2021, the cutoff date for stock sales is 1 September 2021 and the deadline for application of the stock is 1 June 2022.

A good candidate for replacement should be a systemic insecticide whose action protects young plants from pests. Tefluthrin, the only insecticide currently on the market, is not a systemic insecticide [57] and therefore cannot be considered an adequate substitute for neonicotinoids.

Newer insecticides, which entered the market after neonicotinoids, show some effect on pests. From the group of insecticides that act by modulating the ryanodine receptor, according to the Insecticide Resistance Action Committee (IRAC) (Group 28), the group of compounds known as diamides includes three active ingredients, namely chlorantraniliprole, cyantraniliprole and flubendiamide [57]. Two of these, cyantraniliprole and chlorantraniliprole, are already registered for seed treatment in some markets outside the EU [65]. Both active ingredients are approved for use in the European Union [60]. According to Bažok [57], they are insecticides that act in muscle tissue by stimulating the loss of calcium ions from muscle tissue cells. The release and depletion of intracellular calcium stored in the sarcoplasmic reticulum of muscle cells leads to impaired muscle regulation, paralysis and eventual death of the insect [66]. Comparative studies have shown that the sensitivity of ryanodine receptors in insect cells is 350 times higher than the sensitivity of the same receptors in mammalian cells [57].

Besides foliar application, cyantraniliprole is also approved for seed treatment [56], so Du Pont in its promotional leaflet [67] refers to a new product, Lumiposa, with the active ingredient cyantraniliprole for seed treatment of oilseed rape in the European Union. It is not registered in our country [64], but it is possible that rapeseed treated with this product is imported to Croatia from some EU countries. According to Bažok [57], chlorantraniliprole is a contact and stomach insecticide with translaminar and systemic activity. It has ovicidal and larvicidal activity on insects. Due to its systemic nature, the fact that it has a low potential for bioconcentration, is slightly toxic, shows selectivity towards beneficial arthropods and is considered suitable for use in integrated pest management, it is a good candidate for neonicotinoid replacement. The negative side of this active ingredient is its moderate toxicity to fish and high toxicity to aquatic invertebrates [57].

Cyantraniliprole is a stomach insecticide with systemic effects [68]. It is highly to moderately mobile in soil [69]. It has low toxicity (LD_{50} 5000) and low potential for bioconcentration [68]. The research results of Kolupaeva et al. [70] show that the insecticide product leaches into the soil one and a half years after application and that under certain climatic conditions there is a risk of accumulation of cyantraniliprole in groundwater. This characteristic certainly limits the potential of this active ingredient to be a suitable candidate for neonicotinoid replacement.

Studies on the treatment of corn, soybean and rice seeds with chlorantraniliprole and cyantraniliprole have shown their good efficacy in pest control. The active ingredient cyantraniliprole applied at a dosage of 2 and 4 g a.i./kg seed in the treatment of maize seed resulted in 92% efficiency in controlling *Agrotis ipsilon* L. cutworms, and the percentage of maize plants damaged by cutworms was less than 24% [71].

The active ingredient chlorantraniliprole is registered for corn seed treatment in some US states [72] as well as in Ontario and Quebec in Canada [73]. The trade name of the compound is Lumivia. Table 2 shows the results of research on the use of insecticides from the group of diamides in seed treatment.

Table 2. Overview of part of the research results on the efficacy and possibility of using chlorantraniliprole (Ch) and cyantraniliprole (Cy) in seed treatment.

Active Ingredient	**Treated Crop**	**Targeted Pest**	**Experimental Design (Laboratory—L, Field—F)**	**Results Achieved**	**Source**
Ch, Cy	Soybean	Fall armyworm *Spodoptera frugiperda* (J.E.Smith)	L	Insecticides resulted in rapid death of caterpillars, which reduced the leaf area eaten by the caterpillars and thus increased soybean yields	Triboni et al., 2019 [23]
Ch	Wheat	Wireworms *Agriotes* spp.	L	Treatment of wheat seed with chlorantraniliprole did not result in satisfactory efficacy on wireworms	van Herk et al., 2015 [74]
Cy	Wheat	Sugar beet wireworm *Limonius californicus* (Mannerheim)	F	Cyantraniliprole, applied at a dosage of 10 to 40 g a.i./ha, provided initial crop density protection but did not protect plants over a prolonged period and had no effect on population reduction	van Herk et al., 2018 [75]

Table 2. *Cont.*

Active Ingredient	Treated Crop	Targeted Pest	Experimental Design (Laboratory—L, Field—F)	Results Achieved	Source
Ch	Sugar beet	Sugar beet weevil *Bothynoderes punctiventris* (Germar); sugar beet flea beetle *Chaetocnema tibiallis* (Illiger)	L	Chlorantraniliprole, administered at doses of 0.2, 0.4 and 0.6 mg/seed, did not provide adequate protection against the sugar beet weevil (maximum effect of the highest dose less than 40%); the same doses provided satisfactory protection against the sugar beet flea beetle.	Bažok et al., 2018 [76]
Ch	Rice	*Scirpophaga incertulas* (Walker); *Cnaphalocrocis medinalis* (Guenee)	F	The applied dose of 90 g a.i./ha effectively suppressed pests up to 70 days after sowing rice under direct sowing conditions	Rani et al., 2020 [77]
Ch, Cy	Rice	*Lissorhoptrus oryzophilus* (Kuschel); *Eoreuma loftini* (Dyar)	F	Seeds treated with chlorantraniliprole and the combination of cyantraniliprole with thiamethoxam gave the best protection against L. *oryzophilus*; only the treatment of seeds with chlorantraniliprole gave satisfactory protection against E. *loftini*	Wilson et al., 2021 [78]
Ch	Rice	Rice water weevil *Lissorhoptrus oryzophilus* (Kuschel)	L	Reduced oviposition was noted after adults were exposed to treated plants, which is considered a sublethal effect; no effect on adult survival was noted even four days after feeding	Lanka et al., 2013 [79]
Ch	Rice	Rice water weevil *Lissorhoptrus oryzophilus* (Kuschel); fall armyworm *Spodoptera frugiperda* (J.E.Smith); sugarcane borer *Diatraea saccharalis* F.	F	Rice seed treated with chlorantraniliprole may provide adequate protection against these pests even at reduced doses	Vilegas et al., 2019 [80]
Cy	Maize	Black cutworm *Agrotis ipsilon* (Hufnagel)	F	Seed treatment with cyantraniliprole at a dose of 2 g a.i./kg seed significantly reduced infestation compared with seed treatment with chlorantraniliprole and clothianidin in corn fields; the effect of cyantraniliprole was more sustained in spring than in summer; and residues of cyantraniliprole and the metabolite J9Z38 in maize stalks and soil were degraded more slowly in spring than in summer	Zhang et al., 2019 [71]
Ch	Maize	Wireworms *Agriotes* spp.	L	Chlorantraniliprole, administered at doses of 0.2, 0.4 and 0.6 mg/seed, did not provide adequate protection	Bažok et al., 2018 [76]
Ch, Cy	Maize	Fall armyworm *Spodoptera frugiperda* (J.E.Smith)	L	Better protection of young, higher leaves compared to foliar insecticides	Pes et al., 2020 [81]

From the results presented, it is evident that seed treatment with the studied active ingredients provides adequate protection against pests of the above-ground plant organs, such as fall armyworm in maize and soybean, rice pests and sugar beet flea beetle in sugar beet. This means that fewer insecticides need to be applied as foliar treatment, resulting in lower costs and reduced impacts on non-target species and the environment. At the same time, apart from the good effect of cyantraniliprole on black cutworm, other studies have not shown satisfactory efficacy of these insecticides on wireworms [74,75]. This means that seed treatments with cyantraniliprole provide some initial maintenance of plant density, but do not reduce wireworm populations and do not provide protection for the entire vegetation [75]. Most authors agree that susceptibility to wireworms can vary greatly between species, so studies should be conducted on different species. Although numerous studies indicate that wireworm populations rarely exceed critical numbers and the use of soil insecticides to control them is often unnecessary [33,43], it is difficult to imagine that insecticides that have no effect on wireworms could be considered good substitutes for neonicotinoids. As for insecticides from the anthranilic diamides group and all their good properties shown in the cited research, which could be a future in seed treatment, chlorantraniliprole, like other systemic insecticides, could contaminate pollen and nectar and pose a potential risk to beneficial insects, so a long-term assessment of the impact of pesticides on beneficial arthropods is needed [82]. Insecticides from the naturalite group, such as spinosad, are registered in the European Union [65], as well as in the Republic of Croatia [64]. Two insecticides from this group are registered in Croatia, Laser (contact and stomach insecticide containing 24 g/l of spinosad for pest control on potatoes and vines) and Success Bait (Spinosad-based insecticide bait with attractant for pest control on olives and citrus fruits). None of these insecticides are registered for seed treatment.

Seed treatment with spinosad is mainly used on onions, and good results are obtained in the control of onion flies (*Delia antiqua* L.) [83]. When spinosad is used, adverse effects on bee communities [84] and bumblebees [85] are minimal when exposed to real concentrations of insecticides that would be expected in the environment. Van Herk et al. [74] state that treatment of wheat seeds with spinosad under laboratory conditions resulted in transient morbidity of larvae, which later recovered after treatment. Another laboratory experiment showed that spinosad at doses of 3.5 and 5 mg/kg of seed applied to maize seed achieved an efficacy on wireworms of about 70% [76]. In the same study, the application of spinosad by seed treatment did not show satisfactory efficacy against sugar beet weevil, while the results for sugar beet flea beetle were much better. Application of 0.2 and 0.4 mg a.i./seed (corresponding to 40 mg/ha) resulted in more than 95% efficacy on the fourth day. Bažok et al. [86] state that spinosad is effective against sugar beet weevil under laboratory conditions. After foliar application of spinosad at a dose of 72 g a.i./ha, 80% efficacy was achieved on the fifth day after treatment. At the same time, an efficiency of more than 90% in maintaining leaf area was achieved [87]. A possible candidate to replace neonicotinoids could be the botanical insecticide azadirachtin, the effect of which was studied by Bažok et al. [76]. In the laboratory trials conducted, no satisfactory efficacy was found on wireworms in maize and on sugar beet weevil in sugar beet. However, efficacy on sugar beet flea beetle on the fourth day of the trial was relatively high and close to 100% at all three applied doses of azadirachtin (4.3, 8.6 and 12.9 mg a.i./seed).

Given the reduction in pesticide use and frequent withdrawal of pesticides from the market, as well as the development of pest resistance, biological control is becoming an important component of an integrated production method [88]. In this sense, biological seed treatment is expected to be one of the fastest growing sectors of seed treatment in the near future and play a key role in sustainable crop production, also because biological agents are easier to register due to their lower toxicity [89]. Biological control agents, biopesticides, can be a good alternative and provide safer management of pest populations. Compounds of plant origin can be very effective, with multiple mechanisms of action while having low toxicity to non-target organisms [2], and can be an alternative to commercial pesticides, especially where availability and access to synthetic pesticides is limited [90]. However, biopesticides are not suitable for widespread use due to their limitations, such as short shelf life, photosensitivity and volatility [91]. To date, biopesticides account for only 2% of the total amount of pesticides, and of these, 90% are biopesticides derived from the entomopathogenic bacterium *Bacillus thuringiensis* [92]. The market presence of biopesticides is still extremely low. Additionally, the cultivation of GMO crops is not allowed in the countries of the European Union, i.e., such crops (maize MON 810) are only sown in Spain and Portugal, (ISAAA, 2017, cited in Hundleby and Harwood, [93]), and it should be noted that the practical application of RNAi technology remains questionable [94].

The main negative consequences of the ban on neonicotinoids for seed treatment are seen in the production of oilseed rape and sugar beet due to heavy infestation by pests on above-ground plant organs. It could be concluded that seed treatment should be used as a protective method to control pests during the early growth of these crops, for which insecticides from the group of anthranilinic diamides, chlorantraniliprole and cyantraniliprole could be used according to the results published so far. In any case, it would be very important to further investigate not only the efficacy of these agents, but also their environmental behavior and possible effects on beneficial insects. For the control of wireworms, which are less common and less affected by insecticides, alternative strategies should be sought, as indicated by Veres et al. [34].

4. Conclusions

The results of many studies point to the harmfulness of neonicotinoids, a group of insecticides most commonly used for seed treatment. There is also no clear evidence of pest reduction and yield increase, i.e., economic benefit, in crops whose seeds have been treated with neonicotinoids as a precaution. Following the ban on the use of four insecticidal active ingredients from this group in the European Union, there is a shortage of insecticides available for seed treatment. In addition, the acreage of certain crops is being reduced and foliar applications of insecticides from the pyrethroid group, to which pests have developed resistance, have been increased.

Much research is being done to find new active ingredients of insecticides suitable for seed treatment of important crops. The results of the present studies generally indicate good efficacy of active ingredients belonging to the group of anthranilic diamides (cyantraniliprole and chlorantraniliprole) in the treatment of maize, soybean, rice and sugar beet seeds for pest control of above-ground plant organs and wireworms. Good efficacy in controlling wireworms in maize is shown by an insecticide from the naturalites group, spinosad, which is currently used for seed treatment of vegetable crops, especially onions, and is effective against vegetable (fruit) fly. Seed treatment with azadirachtin does not give satisfactory results against either wireworms or pests of the above-ground plant organs.

Because of their good pest control properties, these insecticides should be used more widely for seed treatment, with particular attention to the effects on beneficial insects. However, it is extremely important for the future of seed treatment that seed treatment is no longer used as a preventive measure, but that the decision to sow dressed seeds is based on an actual need determined by a pest forecast.

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