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Review

Prospects of the Application of Garlic Extracts and Selenium and Silicon Compounds for Plant Protection against Herbivorous Pests: A Review

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Abstract: Protection of plants against herbivorous pests is an important aspect that guarantees agricultural efficiency, i.e., food provision to populations. Environmental, water and foodstuff pollution by toxic pesticides, along with climate changes, highlight the necessity to achieve intensive development of ecologically safe methods of herbivory control. This review discusses modern methods of plant protection against insect pests: the biofortification of plants with selenium, treatment of plants with bulk and nano-silicon, and utilization of garlic extracts. The peculiarities of such methods of defense are described in relation to growth stimulation as well as increasing the yield and nutritional value of products. Direct defense methods, i.e., mechanical, hormonal, through secondary metabolites and/or mineral element accumulation, and indirect defense via predator attraction are discussed. Examples of herbivorous pest control during plant growth and grain/seed storage are emphasized. A comparison of sodium selenate, silicon containing fertilizer (Siliplant) and garlic extract efficiency is analyzed on *Raphanus sativus* var. lobo infested with the cruciferous gall midge *Contarinia nasturtii*, indicating the quick annihilation of pests as a result of the foliar application of garlic extract or silicon-containing fertilizer, Siliplant.

Keywords: herbivory; selenium; silicon; garlic extracts

1. Introduction

Approximately 40% of crop harvest is lost every year due to herbivory attacks, diseases, weeds and grain infestation [1–3]. Insect pests are known not only to decrease plant growth and development, causing crop death in extreme cases, but also to act as vectors of pathogens [4]. These facts result not only in great economical losses but also stimulate insecticide production, thus increasing the pollution of the environment, water and food products with toxic compounds. At present, worldwide insecticide production reaches more than 3 million tons per year. Russian statistics reveal that, during 2016–2020, the production of these compounds increased by 1.8 times and reached 131 thousand tons. Taking into account that insect activity is directly affected by temperature as they are poikilothermic organisms, a temperature increase will induce increased herbivory occurrence in agricultural crops in the near future, a phenomenon connected with the increase in reproduction, survival and geographical expansion [5,6]. These facts highlight the urgent necessity to revise the existing methods of pest control, abandon the utilization of chemical insecticides and develop new, safe and highly efficient methods of plant protection against herbivory [7]. In this respect, the utilization of environmentally friendly pesticides, such as essential oils, plant extracts, special microelements demonstrating growth stimulation effects and inert powders, may become the main method of herbivory control.

To be successful against herbivorous pests, natural plant defense should be encouraged, in order to develop ecologically safe and highly efficient methods of crop protection (Figure 1) [4,8,9]. Apart from mimicry (mimosa) and endophytes (mutualistic fungi), four approaches may be enhanced artificially: (1) mechanical protection, (2) mineral elements' hyperaccumulation, (3) increase in secondary metabolite production and (4) predator attraction. Taking these facts into consideration, we have chosen three topics to develop in this review: (i) the biofortification of plants with selenium, (ii) the utilization of an ionic form of silicon and its nanoparticles and (iii) garlic extracts. The last method was first described many years ago, whereas the utilization of Se and Si should be considered as one of the latest extremely promising approaches to solving this problem. Although neither of the mentioned methods has gained profound attention from commercial companies thus far, such ecofriendly and highly efficient supplements, which also show growth stimulation effects and the ability to protect plants against other biotic and abiotic stresses, may herald a new era of modern agriculture.

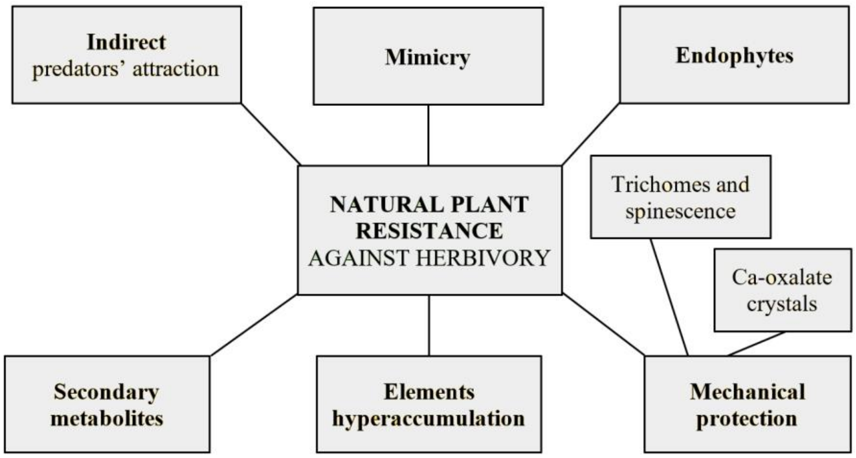

Figure 1. Natural methods of plant resistance against herbivories.

2. Selenium Compounds

To date, interest to selenium has mostly been connected with the worldwide problem of this element deficiency and the importance of agricultural crops' biofortification to optimize the human Se status and human immunity [10]. Indeed, besides the well-known, powerful protection of Se against cardiovascular diseases and cancer, valuable antioxidant properties and beneficial effects on human fertility and brain activity [11–13], the latest investigations in China indicated the high potential of Se utilization in COVID-19 prevention. Epidemiological investigations revealed statistically lower levels of COVID-19 morbidity and mortality among the population in Chinese provinces with high Se status [14]. On 11 March 2021, the lowest COVID-19 morbidity among the European population was recorded in Finland, the country where Se consumption levels have been optimized due to the wide utilization of Se-containing fertilizers [15]. On the contrary, Baltic countries, Slovenia and Great Britain, known as Se-deficient countries, demonstrate significantly higher levels of COVID-19 morbidity. Though the abundance of grain import from endemic regions of Canada and the USA with high Se content (500–600 μg Kg^{-1}), the exclusive utilization of wheat cultivars of native origin with relatively low Se levels (approximately 80 μg Kg^{-1}) in Russia resulted in a decrease in the human Se status [16], which may partially explain the high COVID-19 morbidity in this country. Furthermore, wide Se fertilizer utilization in Finland since 1980 led to an outstanding decrease in mortality caused by cancer and cardiovascular diseases among the population [15].

Against this background, the issue of protecting plants from insect pests using Se biofortification draws significantly less attention and, in particular, plant biofortification and reduction in pest attacks are discussed separately.

Situated in the sixth group of the periodic table, Se demonstrates similar properties to sulfur and is included in compounds with different valences: selenates (+6), selenites (+4), nano Se (0), selenides (−2) and organic derivatives [17]. Their toxicity to humans decreases according to: selenites > selenates > organic Se > nano Se. The same sequence of Se toxicity levels is also recorded for plants, while, for insects, only fragmental data are available. The investigations of Jensen et al. [18] on the toxicity of different Se derivatives' chronic application to *Megaselia scalaris* larvae revealed the lowest LC_{50} level for SeCys (83 μg g^{-1} f.w.), while SeMet, selenate (+6) and selenite (+4) LC_{50} values were 1.6, 3.1 and 4.7 times higher. Data related to *Spodoptera exigue* (Hubner) larvae revealed a decrease in LC_{50} levels from Se-Met and Se^{+6} (LC_{50} < 50 μg g^{-1} f.w.) to SeCystine (LC_{50} 15 μg g^{-1} f.w.) and Se^{+4} (LC_{50} 9.14 μg g^{-1} f.w) [19,20], which indicate significant species differences regarding diverse chemical forms of Se. Contrary to organic derivatives, the inorganic ones (especially selenates) generally have anti-feedant activity for insects [21]. Insects' inability to avoid organic Se forms results in toxic effects when feeding on Se-supplemented plants [19,20,22,23]. As far as Se nanoparticles are concerned, the information is rather scant. Indeed, the joint application of nano-Se and melatonin to wheat seedlings improved plant resistance to aphids via an increase in antioxidant levels and activation of the phenylpropane pathway [24].

Notably, among organic Se forms, methylated Se forms containing amino acids (SeMeSeCys, SeMeSeMet) are the most valuable ones in human society due to their high anticarcinogenic activity [25]. In plants and insects, the formation of methylated forms may be considered a protection against Se toxicity. Indeed, such derivatives usually accumulate in the flowers of Se hyperaccumulators and a few herbivories are able to tolerate high Se levels [26,27]. On the contrary, non-Se-accumulator plants concentrate Se predominantly in the leaves, either as inorganic forms or as Se-containing amino acids and proteins, with a much lower content of amino acids in methylated forms [28]. Volatile chemical forms of selenium are di- and tri-methyl selenides, which deter herbivories [29]. Observations of selenate supplementation to herbivories indicate both toxic and repelling effects [30]. The latter phenomenon was described on Se hyperaccumulator *Stanlea piñata* (447 mg Se Kg^{-1} d.w.) and secondary Se accumulator Indian mustard (230 mg Se Kg^{-1} d.w.) under Mizus persicae (larvae) [31], *Pieris rapae* (larvae) [32] and grasshopper and cricket infestation (adults) [33]. Se may decrease herbivories' survival and mobility and increase the duration of the immature stage of insect development.

Selenium may repel herbivories, slow down growth or cause toxicity, thus increasing plants' growth. The list of target insects under Se supplementation is rather large and includes weevils, aphids, white cabbage butterfly, beetles and caterpillars (Figure 2) [34,35]. Investigations of Prins on *S. pinnata* [36] revealed a protective effect of Se against nematodes. Broccoli supplemented with sodium selenate (50 mg L^{-1}) demonstrated anti-feedant properties towards *Delia radicum* larvae, which decreased thrice the survival of pupae [37]. In another observation, genetically modified potatoes stable against Colorado beetles contained extremely high levels of selenium in leaves without any artificial Se biofortification (approximately 1 mg Kg^{-1} d.w.) [38]. It is well known that grain with high selenium content is less damaged by pests during storage [35].

The repelling and toxic effects of Se compounds are recorded for herbivories of different taste preferences, such as cell disrupters and phloem and leaf feeders, which is extremely valuable in field conditions, where plants are subjected to numerous herbivory species [22,31–33,39,40]. The intensity of the beneficial effect of such treatment is closely connected to the Se dose applied. Indeed, selenium-biofortified *B. napus* plants with high Se concentrations (>800 mg Kg^{-1}) were less infected with a turnip aphid herbivory compared to plants with low Se levels (<100 mg Kg^{-1}), while feeding by red legged mites was reduced by 200% in selenium-biofortified plants [41]. In general, the Se dose should be adopted experimentally, taking into consideration the significant differences in resistance to high Se doses in both different plants and herbivory species. Indeed, according to literature data, aphids are more sensitive to Se than spider mint [32,40].

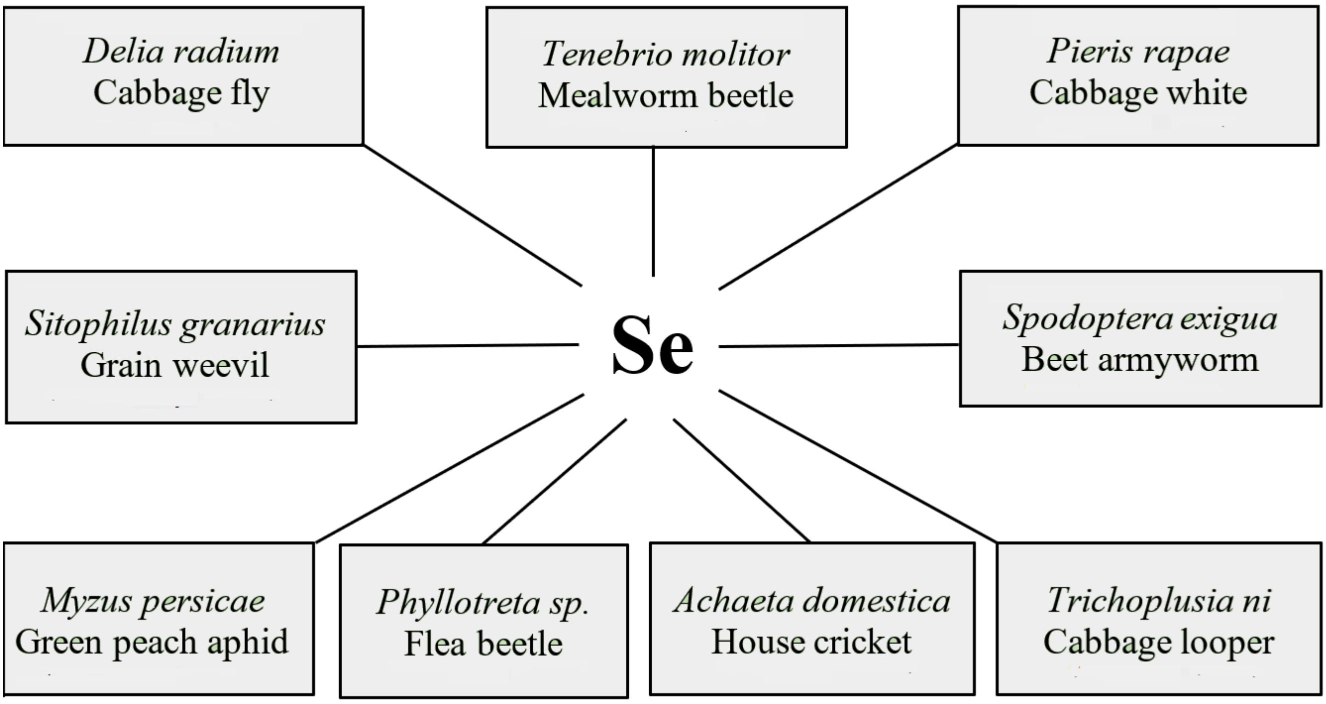

Figure 2. Examples of plant protection against herbivory using selenium [19,22,31–33,37,42–44].

Honey from seleniferous areas contains significant amounts of Se (0.4–1 µg Se g^{-1}), thus becoming a truly functional product enriched with microelements [32,45], though chronic exposure of bees to high Se levels may result in growth retardation and death [46].

3. Silicon

Similarly to Se, Si is not an essential element to plants and its growth stimulation properties are connected to its protective role under conditions of biotic and abiotic stress [47–51]. Its accumulation in plants is governed by soil characteristics, water availability and plants' evapotranspiration [52] and may vary considerably between Si accumulators (predominantly representatives of the Poaceae family, with Si concentration up to 10% per d.w.), intermediates (Brassicaceae, Fabaceae representatives, less than 1% content) and excluders (for instance, tomato plants).

Silicon provides plant protection against herbivories, improving morphological, biochemical and molecular protection and decreasing plant tissue disruption, insects' growth intensity and survival. This element causes significant biochemical changes in plants, activating the biosynthesis of photosynthetic pigments and increasing antioxidants, anti-stress proteins and phytohormone production [53]. The attraction of natural predators and parasitoids during a pest attack as a result of Si supplementation is caused by the emission of herbivore-induced plant volatiles, whose amounts increase in Si-treated plants [47]. Stimulation of plant hormone biosynthesis is considered the most pronounced effect of Si, inducing ethylene, salicylic and jasmonic acid production [52].

Silicon supplementation stimulates the additional formation of trichomes and wax accumulation on the surfaces of leaves, and it strengthens cell walls by improving lignin biosynthesis (Figure 3). Thus, while plant protection against herbivory pests by Se compounds takes place by direct (toxicity of Se derivatives applied) and indirect action (plants'

Se accumulation and emission of toxic volatiles), Si provides valuable protection of plants exclusively by changing plants' physical and biochemical characteristics.

Both ionic forms of Si and Si nanoparticles demonstrate protective effects against biotic stresses in the case of soil and foliar Si supplementation [47,53–59] and, in particular, inducing the production of herbivory-induced plant volatiles attracting predators [57]. Despite rather restricted reports on the nano Si effect on herbivories, it is supposed that the small size of nanoparticles promotes their penetration through cuticle layers, blocking feed digestion and causing changes in morphology. Numerous publications devoted to Si application have focused on the prospects of this approach, particularly the possibility to improve the growth and development of agricultural crops and increase yields. To date, some investigations have proven the ability of Si to increase plants' resistance to the attacks of different herbivory species: Lepidoptera (butterflies and moths) [50], Hemiptera (true bugs, such as cicadas, aphids, planthoppers) [51,60], Diptera (true flies) [61], Thysanoptera (thrips) [62] and others [44].

Several examples of silicon protection are presented below (Figure 3) [63].

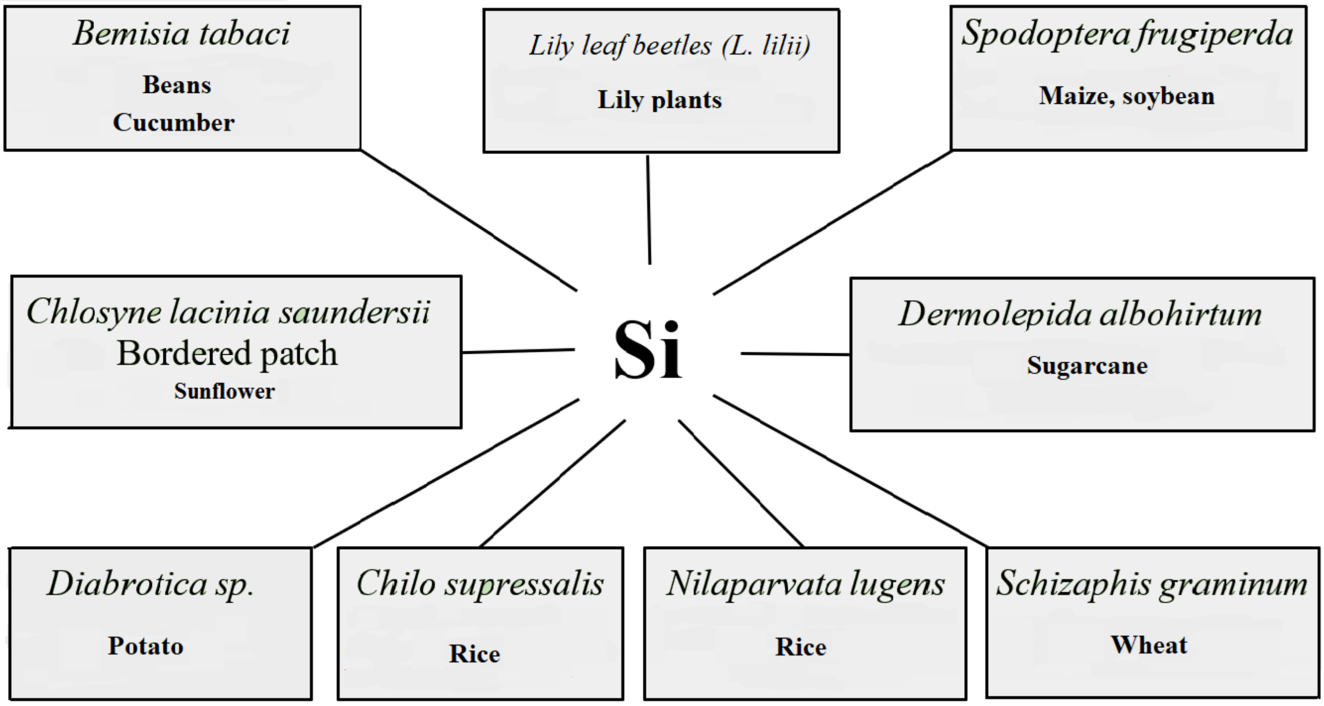

Figure 3. Si application against herbivory pests [64–74].

Among these examples, it is worth noting the three-fold decrease in *Bemisia tabaci* oviposition as a result of 1% silicic acid foliar application on bean and cucumber plants [64,65]; the intensive development of trichomes with high Si content under 1% silicic acid supply, leading to *Spodoptera frugiperda* larvae mortality in tomatoes, soybean and maize [67]; the possibility of AMF to increase root Si content, causing increased cane beetle larvae mortality [69]; the protective effect of wheat against *Schizaphis graminum* [73,74] and the significant protective effect of granite dust against lily leaf beetle [66]. It is significant that Si's beneficial effect takes place both in plant accumulators of Si and in Si excluders [67].

The information shown in Figure 3 indicates that Si may be effective for the protection of both vegetating plants and grain under storage.

4. Garlic Extracts

Garlic (*Allium sativum* L.) is one of the most valuable vegetables, in terms of outstanding health-promoting activity, including anti-tumor, cardio-protective, anti-microbial and anti-diabetic effects [75], high antioxidant activity (vitamins, polyphenols, flavonoids) and significant amounts of sulfur-containing derivatives [76]. It is known to possess growth stimulation properties and the ability to protect plants against pathogens [77]. In practice, the harvesting, storage and processing of garlic are usually accompanied by the formation of wastes, including partially damaged cloves, whose utilization in agriculture as a protection tool against biotic stresses may become highly valuable. The demonstrated insecticidal activity of garlic is determined by allicin, formed as a result of alliinase activity during clove crushing and other sulfur derivatives [78]. Interestingly, attacks by herbivorous pests, pathogens and animals, causing biotic stress, promote allicin biosynthesis [79].

Examples of garlic's protective effect against herbivories, shown in Table 1, indicate the high efficiency of this approach in combating caryopsis, scoop, whitefly, weevils, etc. Furthermore, the investigations of Hardiansyah et al. [80] demonstrated that the foliar supplementation of garlic extract significantly increased rice yield due to the prevention of grain losses connected with scaly finch (*Lonchura punctulata*) attacks.

Table 1. Examples of garlic utilization against insect attack.

Insects, Birds	Plant	Stage of Development	LC50 (mg L^{-1})	References
		Garlic oil		
Black cutworm (*Agrotis ipsilon*)	Rice, beet, cotton, blackberry	Eggs, Larvae, Pupae	60 190 90	[81]
Silverleaf whitefly (*Benisia tabaci*)	Tomato, cucumber, pumpkin, cotton, melon, *Brassica*	Imago	150	[82]
Cacopsylla chinensis	Plum	Imago	142	[83]
Cowpea weevil (*Calloso-bruchus maculatus*)	*Vigna chinensis*	Imago	0.25	[84]
Grasshopper (*Heteracris littoralis*)	Maize, rice, vegetables, cotton	First instar Larvae	670	[85]
Cabbage looper (*Trichoplusia ni*)	Cabbage	Larvae	3300	[86]
Rice weevil (*Sitophilus oryzae*)	Rice	Imago	0.017	[87]
		Garlic extracts		
Kelly's citrus thrips (*Pezothrips kellyanus*)	Citrus	Larvae	Low protection level	[88]
Cowpea weevil (*Callosobruchus maculatus*)	Chickpea seeds, *Vigna unguiculata*	Imago	0.11 g L^{-1}	[89]
red palm weevil *Rhynchophorus ferrugineus*	Palms	Larvae	* 44 μg mL^{-1}	[90]
Diamondback moth (*Plutella xylostella*), Cabbage aphid *(Brevicoryne brassicae)*, Cabbage webworm (*Hellula undalis*), *Cabbage looper (Trichoplusia ni)*	Cabbage (*Brassica oleracea*)	Larvae, imago	200 g L^{-1}	[91]
Coleoptera, *Bruchinae*	*Prosopis laevigata* seeds soaking in 5% during 3 days at 20 °C	Larvae, imago		[92]
Spontaneous herbivory attacks in field conditions	*Cucurbita pepo* (1% water extract)	-	**	[93]
		Garlic juice		
Maize weevil (*Sitophilus zeamais*)	Storage of maize grain	Imago	90% lethal mortality	[94]
Cabbage root fly (*Delium radicum*)		Eggs Larvae Imago	0.8 % (7 days) 6.8 % (4 days) 0.4 % (2 days)	[95]

Table 1. *Cont.*

Insects, Birds	Plant	Stage of Development	LC50 (mg L^{-1})	References
Housefly (*Musca domestica*)		Eggs Larvae Imago	1.6 % (7 days) 4.5 % (4 days) 2.2% (2 days)	[95]
		Diallyl polysulfides		
Cacopsylla chinensis	Plum	Imago	11.04 DADS 0.640 DATS	[83]
Sciarid fly (*Lycoriella ingénue*)	Mushrooms, herbs	Larvae	0.25 DAS 0.087 DADS 0.25 DATS	[96]
Maize weevil (*Sitophilua zeamais*)	Maize	Imago	5.54 DATS	[97]
Red flour beetle (*Tribolium castaneum*)	Cereals, flour	Imago	1.02 DATS	

DAS—diallyl sulfide; DADS—diallyl disulfide; DATS—diallyl trisulfide [98]; * onion/garlic extract was used; ** yield and photosynthetic pigments increase.

The powerful insecticidal properties of garlic and *Allium cepa* essential oil have been demonstrated. Furthermore, appropriate information has been recorded for sulfur compounds of these plants, allyl disulfides and allyl mercaptane, in the protection of plants against rice weevil [99]. Allyl mercaptane's insecticidal properties are based on the inhibition of insects' acetylcholine esterase.

Comparison between garlic juice's effects on two insect species, housefly (*Musca domestica*) and cabbage root fly (*Delia radiculus*), indicated the importance of the developmental stage and species differences in insects' tolerance [95]. Indeed, the lowest LD_{50} values were recorded at the egg and adult stages of development, accompanied by significantly higher LD_{50} values for *Musca domestica*. The opposite situation was demonstrated for LD_{50} values at the larvae stage of development (Table 1). In a cowpea seed storage experiment with *Callosobruchus maculatus* infestation [89], the authors demonstrated lower LD_{50} values associated to garlic extract (0.11 g L^{-1}) than to garlic powder (9.66 g Kg^{-1}) and emphasized the high potential of garlic extract utilization in the protection of chickpea against this very dangerous herbivory of legumes.

5. Comparative Evaluation of the Efficiency of *Raphanus sativus* var. Lobo Protection against Cruciferous Gall Midge (*Contariana nastirtii*) Using Foliar Application of Selenium, Silicon and Garlic Extract

Raphanus sativus var. Lobo, or margelan radish, belongs to the cruciferous family and, thanks to the low content of radish oil, demonstrates a pleasant taste. This crop suitably grows in most regions of Russia and is widespread in China and Korea.

Cruciferous gall midge, which lays eggs in inflorescences, causes significant damage to the seed yield of loba, thus preventing seed set.

Gall midges (Diptera: Cecidomyiidae), including more than 6000 species [100], form a large insect family with high speed of species formation compared to other Diptera insects [101]. Most of the gall midge species are herbivorous monophages [100] feeding on a single plant family, plant species or separate parts [102,103]. Most representatives of *Contarinia nasturtii* (Kieffer, Diptera: Cecidomyiidae) freely live in flower buds or in folded leaves or galls of leaf folds [100,104].

The productivity of lobo seeds is sharply reduced when infected by flower gall midge (Figure 4).

Figure 4. *Raphanus sativus* var. lobo infested by *Contarinia nasturtii*.

Single spraying of lobo plants during the period of active gall midge infestation by (a) sodium selenate solution (50 mg L^{-1}), (b) Siliplant fertilizer as a source of ionic silicon (5 mL L^{-1}) and (c) garlic extracts (5%) resulted in 100% larvae mortality only one week later in cases of Siliplant application, either singly or in combination with sodium selenate and garlic extract supplementation. The lack of a significant positive effect of sodium selenate supplementation may be connected both to the lower gall midge sensitivity to Se and/or the necessity for a longer period of exposure.

Among the biochemical parameters tested, a significant disaccharide content increase was recorded under all treatments, especially intensive in the case of garlic extract (Figure 5).

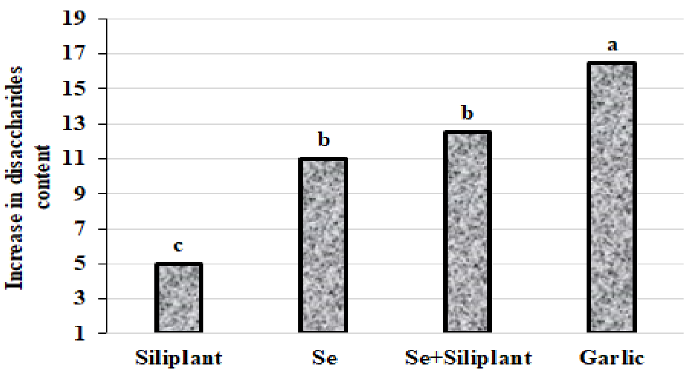

Figure 5. Changes in disaccharide content in *Raphanus sativus* var. lobo treated with Siliplant, Se and garlic extract.

The detected phenomenon is directly connected with the active participation of carbohydrates in plant protection [105] and may be highly significant for increasing the nutritional value of vegetables.

Other biochemical parameters (Table 2) indicate a statistically significant increase in polyphenol content in lobo upon garlic extract treatment, contrary to sodium selenate application, which demonstrated only a slight tendency to this increase. The detected beneficial effect of garlic extract on phenolic accumulation in lobo (1.22 times compared to control plants) was in agreement with a similar phenomenon described in tomato [106].

Table 2. Effect of foliar application of Si (Siliplant), sodium selenate and garlic extract on biochemical characteristics and infestation of *Raphanus sativus* var. lobo by *Contarinia nasturtii*.

Parameter	Control	Siliplant	Se	Se + Siliplant	Garlic
Presence of live larvae	++	−	+	−	−
Dry matter, %	12.29a	11.67a	11.25a	12.48a	11.56a
AOA *, mg GAE g^{-1} d.w.	46.1a	44.1a	48.6a	46.1a	50.5a
TP **, mg GAE g^{-1} d.w.	14.0b	15.0ab	16.0ab	16.1ab	17.1a
Se, µg Kg^{-1} d.w.	146d	213c	1080b	1295a	150d
Monosaccharides, %	17.0a	16.9a	12.6b	13.9b	16.5a
Disaccharides, %	0.2d	1.0c	2.2b	2.5b	3.3a
Total sugar, %	16.8bc	17.9ab	14.8c	16.4bc	19.8a
Water-soluble compounds TDS, mg g^{-1}	57.1b	72.8a	70.4a	56.3b	58.0b
Nitrates, mg Kg^{-1} d.w.	2968b	3112ab	3306a	2326c	2750bc
Ash, %	10.0a	10.9a	11.3a	9.1a	9.1a

* AOA—total antioxidant activity, ** TP—polyphenols. '++'—intensive infestation; '−'—100% mortality of larvae; '+'—50% reduction of live larvae. Along each line, values with the same letters do not differ statistically according to Duncan test at $p < 0.05$.

The lower efficiency of sodium selenate treatment compared to that of Siliplant and garlic extract, and the different intensities in biochemical changes (Table 2, Figure 4) indicate that Se's protective effects require more time than those of Si and garlic extracts.

6. Prospects and Constraints of Plant Protection against Herbivory Pests via Se, Si and Garlic Extract Application

In general, the comparison of Se, Si and garlic extracts' efficiency against herbivory attack reveals several peculiarities. First, active elements demonstrating significant toxicity to insects are Se in sodium selenate, Si in bulk and nano Si particles and sulfur compounds in garlic extracts. The resulting effect is either toxicity or repellent activity. In all living organisms, Se may substitute S in appropriate natural compounds as these elements are considered chemical analogs. In this respect, Se-fortified plants may lead to herbivory toxicity not only via a direct effect of inorganic derivatives and Se-containing amino acids, but also via the production of Se analogs of allicin, mono-, di- and tri-sulfides. The highest efficiency in Se biofortification is recorded for plants that are Se accumulators, which include *Allium, Brassica* species and garlic in particular [17].

Contrary to Se and S compounds, Si causes plant mechanical protection, which also causes toxicity or repellant activity against herbivories, such as: the formation of additional trichomes, an increase in wax accumulation on the leaves' surfaces and an abrasiveness increase in plant tissues, resulting in a reduction in palatability and digestibility for herbivores [107,108].

The strongest beneficial effect of Si supplementation is recorded in plant Si accumulators belonging predominantly to the *Poaceae* family, while *Brassica* and *Allium* representatives (typical accumulators of S and Se) are known to be non-Si accumulators [109].

Furthermore, the protective effects of the three mentioned supplements relate to the intensive emission of volatiles from the plant tissue of treated plants: di- and trimethyl selenides for Se, allicine and other mono- di- and tri-sulfides from garlic, and herbivore-induced plant volatiles upon Si supplementation. While the first two ones show repellent properties against herbivories, silicon causes biochemical changes in plants, where volatile production intensifies the attraction of herbivory animals [52].

The protection against herbivories and the growth stimulation effect of all three preparations relate to hormonal activity. Supplementation of Se and Si induces intensive hormonal changes in plants. Se actively affects the production of auxins, gibberellins, jasmonic (JA) and salicylic (SA) acids and ethylene (ET) [110]. Silicon supplementation results in changes in JA, SA, ET and auxins' biosynthesis [59]. On the contrary, the growth stimulation effect of garlic extracts is closely connected to their high content of phytohormones: SA, auxins and gibberellins [111].

Furthermore, all these treatments for plants' protection against herbivories are closely connected with the intensification of plant antioxidant status, either directly (Se and S antioxidant properties) or indirectly, improving the production of natural antioxidants.

The attractiveness of Se, Si and garlic extracts' utilization relates to the multiplicity of their beneficial effects, including pest management, protection against abiotic stress and an increase in crop yield and nutritional quality (Figure 6).

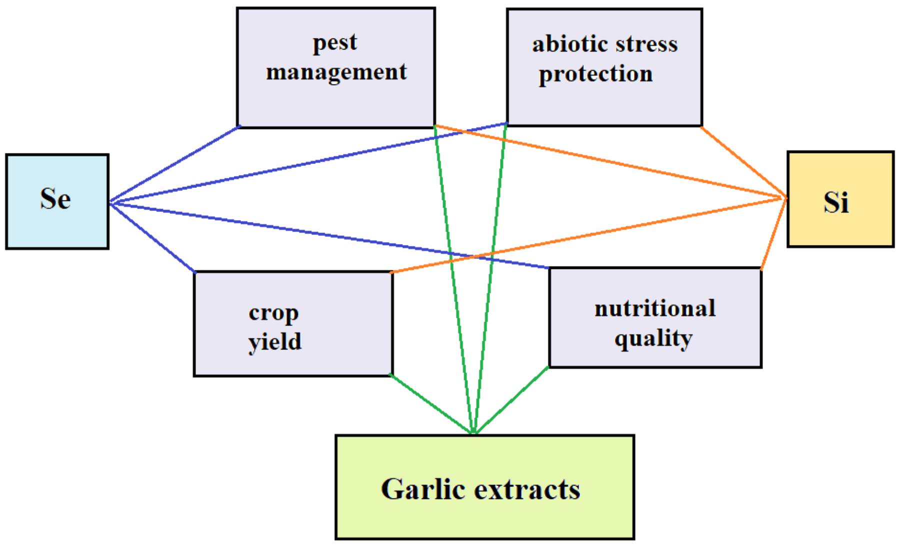

Figure 6. Beneficial effects of Se and Si compounds, and garlic extracts' utilization.

In this respect, the development of appropriate preparations is highly significant. To date, no appropriate registered products with active ingredients derived from garlic, selenium and silicon are known. Such a situation is connected with the complexity of Se, Si and garlic extracts' interaction with plants and insect pests, highlighting the necessity to find optimal concentrations that are sufficient to both demonstrate protection against pests and avoid toxicity. Notably, the beneficial protective effects of Se, Si and garlic extracts against insect pests are not ubiquitous and greatly depend on the plant and insect species, stage of pest development and supplement concentration. Indeed, silicic acid application resulted in the most pronounced protective effect against armyworms at the early time point in soybean and at early and late time points in maize [67]. Granite dust utilization was shown to be effective in the protection of lily but not squash and cabbage plants [66].

Theoretically, the supplementation of plants with selenium should result in variable protective effects against herbivorous pests, due to both variations in different Se chemical forms in fortified plants and differences in these compounds' toxicity to pests. At present, in most cases, we are not able to evaluate the composition of Se chemical derivatives present in plants upon Se supplementation.

As for garlic extract utilization, a serious problem exists in standardizing the preparations, whose activity will depend either on the concentration used or the chemical composition of garlic cloves. The allelopathic effect of garlic has been intensively studied [112,113] and an increase in extract concentration may lead to plant growth inhibition.

Taking into account the species differences in plants/insects' responses to Se, Si and garlic extract supply, further investigations will be performed on this topic.

Notably, to date, the joint application of Se, Si and garlic extracts has never been used in pest management. Literature reports indicate that this approach may become especially beneficial, providing a growth stimulation effect, improving crops' quality and protecting plants against biotic and abiotic stresses. Joint supplementation of plants with Se and Si is known to be highly efficient in increasing plants' tolerance to abiotic stresses [114–118] and improving yields [119]. Unfortunately, no data are available concerning the efficiency of plants' protection against insect pests under joint Se and Si treatments. The joint application of garlic extracts with Se and Si compounds, both for plant growth and development and pest management, is extremely attractive, but such an approach needs special investigations.

7. Conclusions

Global economic crisis and climate changes indicate the need for urgent decisions aimed to ecological equilibrium restoration, the utilization of highly efficient and safe methods of both plant protection against herbivories, without any harmful effect either on human health or on the environment, and plant growth stimulation. The present review covers three possible strategies to address the mentioned issues, and their practical application will promote sustainable agricultural development. Further investigations should unveil the interactions of Se, Si and garlic extract with plants and insect pests, which show remarkable complexity, and the connected effects of climate and soil, the genetic peculiarities of plants and different biologically active derivatives. However, the broad possibilities of Se, Si and garlic extracts' application, both for plant protection against pests and growth stimulation, suggest the necessity for the commercial production of appropriate supplements to successfully convert the mentioned innovative approaches into agricultural practice.

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