horticulturae

MDPI

Article

Fruit Phenology of Two Hazelnut Cultivars and Incidence of Damage by *Halyomorpha halys* in Treated and Untreated Hazel Groves

Flavia de Benedetta [1,2], Matteo Giaccone [3,*], Feliciana Pica [1], Maria Tiziana Lisanti [4], Francesco Vinale [1,5,6], David Turrà [2,6], Gianpaolo Maria Giacca [7] and Umberto Bernardo [1]

1 National Research Council, Institute for Sustainable Plant Protection-IPSP-CNR, P.le E. Fermi, 1, 80055 Portici, Italy; flavia.debenedetta@ipsp.cnr.it (F.d.B.); feliciana.pica@ipsp.cnr.it (F.P.); frvinale@unina.it (F.V.); umberto.bernardo@ipsp.cnr.it (U.B.)
2 Department of Agricultural Sciences, University of Napoli Federico II, Via Università, 100, 80055 Portici, Italy; davturra@unina.it
3 National Research Council, Institute for Agriculture and Forestry Systems in the Mediterranean—ISAFOM-CNR, P.le E. Fermi, 1, 80055 Portici, Italy
4 Division of Vine and Wine Sciences, Department of Agricultural Sciences, University of Napoli Federico II, Viale Italia, 60, 83100 Avellino, Italy; mariatiziana.lisanti@unina.it
5 Department of Veterinary Medicine and Animal Production, University of Napoli Federico II, Via Federico Delpino, 1, 80137 Napoli, Italy
6 Center for Studies on Bioinspired Agro-Environmental Technology, Department of Agricultural Sciences, University of Napoli Federico II, Via Università, 100, 80055 Portici, Italy
7 Azienda Agricola Riccio, 81057 Teano, Italy; gianpaolo.giacca@gmail.com
* Correspondence: matteo.giaccone@cnr.it; Tel.: +39-06-499327570

Abstract: Over the past decade, *Halyomorpha halys* has become one of the main threats to hazelnut production. Its trophic activity makes kernels inedible due to strongly detrimental effects on the organoleptic quality. Its management in Italy is still tricky due to the lack of effective native biocontrol agents and authorized and effective insecticides. A field test was performed on San Giovanni (SG) and Tonda Romana (TR) cultivars (early and late ripening, respectively) to assess the intensity of cimiciato damage with different pest management approaches (no insecticide and integrated pest management, IPM). Moreover, phenological analysis of fruits and the monitoring of stink bug species by traps and plant beating were carried out. In the untreated plots, the SG cv showed a higher cimiciato incidence with respect to the late TR cv (40% SG–NI vs. 23% TR–NI). This was probably due to the different phenological phases in which stink bugs injured the fruits. In fact, stink bug bites provoke different kinds of injuries (blanks, shriveled, and cimiciato) according to the fruit's development period. Indeed, in the period of highest insect occurrence in the field, the fruits of the early cv (SG) were in kernel expansion, a phenological phase in which bug injuries are more likely in cimiciato defects. Lastly, the IPM did not provide sufficient fruit protection (19% SG–IPM vs. 11% TR–IPM). The interaction between the phenological development of hazelnuts and the brown marmorated stink bug represents a critical aspect in understanding and implementing effective strategies for controlling this key pest on hazelnut trees.

Keywords: brown marmorated stink bug; *Corylus avellana*; integrated pest management; invasive species; corked hazelnut

check for updates

Citation: de Benedetta, F.; Giaccone, M.; Pica, F.; Lisanti, M.T.; Vinale, F.; Turrà, D.; Giacca, G.M.; Bernardo, U. Fruit Phenology of Two Hazelnut Cultivars and Incidence of Damage by *Halyomorpha halys* in Treated and Untreated Hazel Groves. *Horticulturae* **2023**, *9*, 727. https://doi.org/10.3390/horticulturae9060727

Academic Editor: Luigi De Bellis

Received: 28 April 2023
Revised: 29 May 2023
Accepted: 15 June 2023
Published: 20 June 2023

1. Introduction

Climate change, resulting from human activities and natural variability, represents an increasing challenge for agriculture [1]. One of the main results of climate change is the variation in the ecological niche of different species [2,3], including agriculture and forestry insect pests [4,5]. In parallel, the spread of alien invasive species is promoted by the import–export of goods and the movement of people [6].

Italy is particularly vulnerable to insect and biological invasions due to its numerous entry points, such as harbors and airports [7,8]. Moreover, Mediterranean basin countries are characterized by favorable warm-temperate climates [9]. Climate change makes these areas warmer, smoothing the way for the establishment and acclimatization of invasive species [10,11]. The climatic conditions of the Italian territory, made more favorable by climate changes, permitted the invasion of *Halyomorpha halys* (Stål) (BMSB) (Hemiptera: Pentatomidae), which started in northern Italy in 2012 and then spread throughout the country [10,12].

Halyomorpha halys, also known as the brown marmorated stink bug, is a polyphagous pest native to East Asia that attacks up to 300 agricultural, horticultural, and ornamental host plants, including hazelnut (*Corylus avellana* L.) [13,14]. This is worrying because hazelnut cultivation has a strategic role in Turkey's and Italy's agricultural economies, as well as in the USA, Azerbaijan, and Georgia [15]. Turkey, indeed, manages to produce ∼72.9–85% of the hazelnut's world supply (about 684,000 t in 2021), followed by Italy (about 84,670 t in 2021) [15,16]. In Italy, the main regions contributing to hazelnut production are Piedmont (35% of the hazelnut national production in 2021), followed by Latium (29%), and Campania (28%) [17].

With the increase in the *H. halys* population, this species became a key pest for hazelnut management, spreading rapidly in Piedmont (2013), Latium (2015) [18], and Campania (2018) [19].

The fast growth and invasiveness of *H. halys* in the Italian territory are related to different factors: adequate average temperature, variety, and abundance of both spontaneous and cultivated host plants on the territory [20,21]. Additionally, the lack of effective native biocontrol agents and human influence (movement of people and commodities, overwintering sites) also contribute to the spread of *H. halys* [21,22].

The damage produced by *H. halys* on hazelnuts mainly concerns the fruits. In fact, it causes different kinds of injuries depending on the development phase of the fruit [23,24]. When the bite occurs during the shell expansion, the seed growth stops, inducing a kernel abortion (empty shells). In this stage, the "early fall", caused by native stink bugs, is common [25]. However, this kind of damage has not yet been associated with *H. halys* trophic activity. If the injury occurs during the kernel expansion, the seed becomes shriveled and/or malformed [23]. Differently, cimiciato (or corked) hazelnuts are formed if the bite occurs during both kernel expansion and fruit ripening [23]. This last kind of damage results in dry and necrotic tissues with a distinctive flavor called "cimiciato", resulting from secondary metabolites [16,26]. Cimiciato-infected hazelnuts are characterized by bitterness and astringency due to a pool of diarylheptanoids and a typical and unpleasant aroma. However, to the best of our knowledge, specific volatile compounds responsible for cimiciato's off-odor have not yet been identified [26,27]. Moreover, corked hazelnuts present various other alterations regarding the the lipid composition profile and the increase the sensibility in lipid oxidation [16,28,29]. These alterations affect the taste and shelf life of the product, making hazelnuts, in some cases, inedible and not marketable [16,26]. Similar damages on hazelnuts can be caused by other insect species, such as *Gonocerus acuteangulatus* (Goeze) (Hemiptera: Coreidae), *Nezara viridula* L. (Hemiptera: Pentatomidae), *Palomena prasina* L. (Hemiptera: Pentatomidae), *Piezodorus lituratus* (Fabricius) (Hemiptera: Pentatomidae), *Dolycoris baccarum* L. (Hemiptera: Pentatomidae), and *Rhaphigaster nebulosa* Poda (Hemiptera: Pentatomidae) [30–33]. Unfortunately, *H. halys* seems more harmful than native stink bugs; indeed, it provokes the highest percentages of total damaged kernels, more moldy and rotten hazelnuts, and more external symptoms [31]. Additionally, *H. halys* tends to quickly dominate the invaded ecosystem, prevailing over the other pentatomids [34,35]. Furthermore, the available insecticides are ineffective against *H. halys* due to their short residual activity and low initial knock-down effect [36,37].

The high polyphagy of this species determines that many specimens are also present in the surroundings of the treated crop, hence not undergoing the treatment directly and infesting the field later on [21]. This increases the necessity for pesticide applications, resulting in economic losses and negative environmental and health effects [38]. In this context, improving knowledge of *H. halys* in relation to specific agricultural environments and hazelnut cultivars is increasingly necessary.

In the present study, a field test was performed to collect useful information to improve sustainable pest management strategies in hazelnuts, with the following aims: (a) To evaluate the intensity of cimiciato damage caused by stink bugs in the hazel orchards of two different CVs (one early and one late ripening) in relation to kernel development; (b) to evaluate how the density of *H. halys* adults varies in hazelnut orchards up to the hazelnut harvest; (c) to evaluate the possible relationship between the density of stink bugs at a particular phenological stage of hazelnuts and the incidence of damaged fruits; (d) to evaluate whether the treatments normally carried out in hazelnut orchards can reduce the damage of the fruits to an acceptable level.

2. Materials and Methods

2.1. Experimental Design, Location, and Plant Materials

The experimental trial was conducted in 2022 in a commercial hazelnut (*Corylus avellana*) orchard (about 20 hm^2) located in Teano (CE), Campania region (southern Italy). The trial was performed in two plots, one for each cultivar, about 200 m apart. The cultivars were San Giovanni (planted in 2015) and Tonda Romana (planted in 1987). The tree spacing was 5 m between rows and 4 m across the row in both plots. The trees were trained to open a vase with four main branches.

Two pest management strategies were evaluated: integrated pest management (IPM) and no insecticide (NI). The application dates, the quantities per square hectometer, and the formulations of the insecticide treatments used in the trial are shown in Table 1.

Table 1. List of insecticide treatment, dosage, and date of application used in the experimental test. a.i.: active ingredient.

Date	Commercial Name and Manufacturer	Active Substance	Concentration of a.i. in the Formulate	Quantity of the Formulate/Hectare
2 May 2022	Kestrel® (Nufarm, Melbourne, Australia)	Acetamiprid	200 g/L	0.4 (L/hm^2)
6 June 2022	Sparviero® (Sipcam, Pero, Italy)	Lambda-cyhalothrin	100 g/L	0.125 (mL/hm^2)
21 July 2022	Kaimo® Sorbie (Nufarm, Melbourne, Australia)	Lambda-cyhalothrin	50 g/kg	0.3 (kg/hm^2)

In March 2022, 80 plants of each cultivar were selected for the test (10 plants in 8 different rows) in the central part of the corresponding plot, avoiding the bordering parts.

In each cultivar plot, the first two rows of trees were treated according to IPM principles (IPM–SG and IPM–TR theses). The remaining trees were not treated with insecticides. The samples for the NI thesis were collected only from the two central rows (5 and 6) (NI–SG, NI–TR theses), while the two rows on each side (3–4 and 7–8) formed a buffer zone to avoid contamination by the insecticide. One block of four trees (two plants from each row) was considered a replicate for the fruit phenology study (five replicates in total, two rows of twenty plants).

2.2. Brown Marmorated Stink Bugs Occurrence: Monitoring Activities

Three traps were placed around the experimental field on the 3 May 2022 (the 123rd day of the year, DOY). They were placed 250–400 m apart. The traps consisted of a black cylindrical polypropylene tube (tube diameter: 15 cm; tube length: 60 cm) [39,40] (Figure S1). One distal part of the tube was closed with a net to prevent insects from exiting. The opposite part consisted of a net funnel through which insects, once inside, could not exit. A plate was attached to the tube to allow the trap to rotate with the wind.

The traps were baited with Pherocon BMSB high-load lures (Trécé, Adair, OK, USA). Although this is a specific pheromone, it is based on aggregation pheromones that can also attract other pentatomids [41]. This can help determine the presence of local stink bugs [42]. Traps were checked every 6–8 days from the 130th to the 262nd DOY. During sampling, the specimens were collected from the traps and transported to the laboratory for morphological identification using the available taxonomic key [43]. The adult specimens of *H. halys* were sexed starting with the 145th DOY. The occurrence of BMSB was estimated by taking the average of the catches collected from the three traps. The data were expressed as a percentage of specimens per week relative to the total number of specimens caught during the entire monitoring period (% total catches, TC).

In addition to the traps, some plant beating monitoring was performed following the protocol of Bosco et al. (2018) because there are no commercially available lures specific to other pentatomids [31].

2.3. Fruit Growth and Phenological Classification

Twenty hazelnuts were randomly collected weekly (from San Giovanni from the 130th to the 236th DOY and Tonda Romana from the 130th to the 243rd DOY) from the five hazelnut blocks. This sample was used for the phenological study. The hazelnuts were collected from the four compass directions of each block: northeast, southeast, southwest, and northwest.

The main biometric measurements were collected using a digital caliper, as shown in Figure 1. The classification of fruit development was estimated by a method specifically developed based on the classification method proposed by [23]. The classification used in our study consisted of seven phases, mainly based on the percentage of the hazelnut volume occupied by the embryo/kernel. The kernel and in-shell hazelnut volumes were approximated to an ellipsoid. In particular, the pre-kernel expansion phase (Hedstrom classification) corresponded to phase 1 (Figure 2); the kernel expansion (Hedstrom classification) was divided into four phases 2–5 (Figure 2), while the complete kernel expansion (Hedstrom classification) was divided into two phases (6–7) (Figure 2). A numerical value corresponding to the previously described phenological stages was assigned to each collected sample fruit (twenty hazelnuts for each cultivar and thesis).

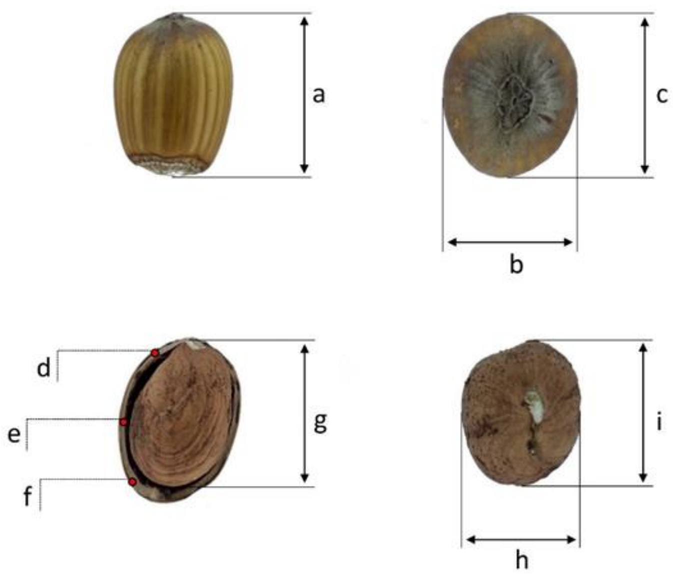

Figure 1. Biometric measurements were collected on hazelnuts and kernels. (**a**) hazelnut height; (**b**) minor hazelnut diameter at equatorial point; (**c**) hazelnut larger diameter at equatorial point; (**d**–**f**) measuring points of the shell (the value of the shell used was obtained from the average of these three values); (**g**) kernel height; (**h**) kernel minor diameter at equatorial point; (**i**) kernel larger diameter at equatorial point.

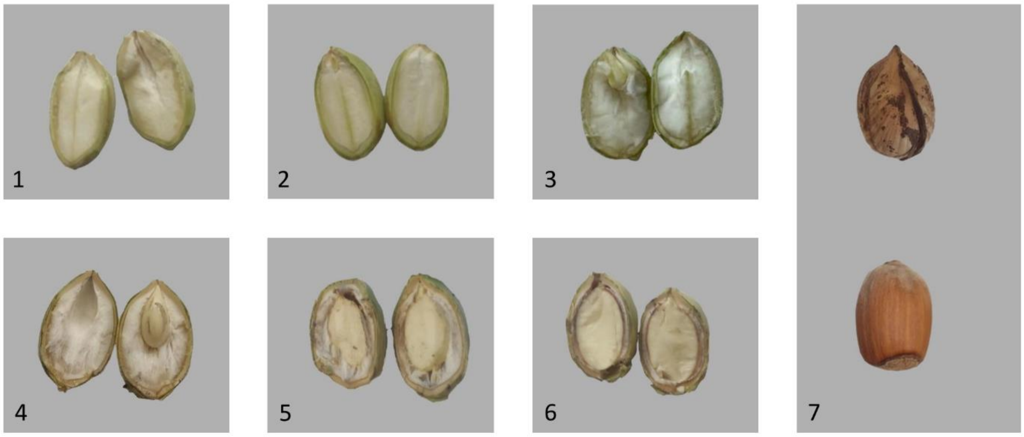

Figure 2. Phenological phases of the hazelnut fruit development in the San Giovanni cultivar. (**1**) Phase 1, shell expansion, no embryo present; (**2**) phase 2, embryo volume ≤ 5% of the internal hazelnut volume; (**3**) phase 3, 5% < embryo volume ≤ 25% of the internal hazelnut volume; (**4**) phase 4, 25% < embryo volume ≤ 50% of the internal hazelnut volume; (**5**) phase 5, 50% < embryo volume ≤ 75% of the internal hazelnut volume; (**6**) phase 6, embryo volume > 75% of the internal volume; (**7**) phase 7, shell color change, from green to brown.

2.4. Harvest and Hazelnut Damage Assessment

The DOY in which the hazelnuts started to fall, the DOY of the first commercial harvest (40% of the fallen fruits), and the DOY of the second commercial harvest (95% of the fallen fruits) were recorded. In order to assess the cimiciato incidence, a sample of 10 fruits per 10 trees (n = 100; of which 50 fruits were collected during the first commercial harvest and 50 fruits during the second commercial harvest) was randomly collected for each hazelnut thesis (IPM–SG; NI–SG; IPM–TR; NI–TR). These samples were dried up to a commercial humidity of 6% according to the United Nations Economic Commission for Europe (UNECE) guidelines for marketing hazelnuts in shell [44]. The hazelnuts were shelled and visually inspected to identify the damaged ones. The hazelnuts were inspected for stink bug damage, both externally (visible on the kernel's surface) and internally (inspection of the fruit by cutting the kernel into four parts).

Based on visual inspection, kernels were classified as healthy, shriveled, or cimiciato (external and/or internal damage). In addition, all hazelnuts were classified as cimiciato after two researchers tasted them to confirm the visual classification. The researchers involved in the study were expert tasters who recognized the typical cimiciato off-flavor. The four portions of each presumed cimiciato hazelnut, cut during the preliminary inspection, were randomly assigned to the two tasters (two portions each) by a third person. The evaluation was made independently, without any possibility of communication between the tasters. The blank nuts were not included because it is impossible to distinguish whether the damage has been caused by the action of the stink bugs or by climatic and physiological factors [45–47].

2.5. Statistical Analysis

GLM analysis evaluated the incidence of cimiciato and shriveled hazelnuts for the "cultivar" and "pesticide" variables and the interactions. The comparison of tree productions between the treated theses was evaluated by one-way ANOVA (α = 0.05) using the post hoc Tukey HSD test to separate means. The Kruskal–Wallis test (α = 0.05) was used to assess differences in the phenological stage between the different dates.

All statistical analyzes were performed using SPSS 28 (IBM, Chicago, IL, USA).

3. Results

3.1. Stink Bug Occurrence

The density of *H. halys* in the field, represented by the catches in the traps (%TC), is shown in Figure 3a. The highest density of *H. halys* in hazelnut fields was recorded during the interval between the 145th and the 159th DOY (Figure 3a). Approximately 20.5% of the total captured specimens (355) were recorded on the 152nd DOY.

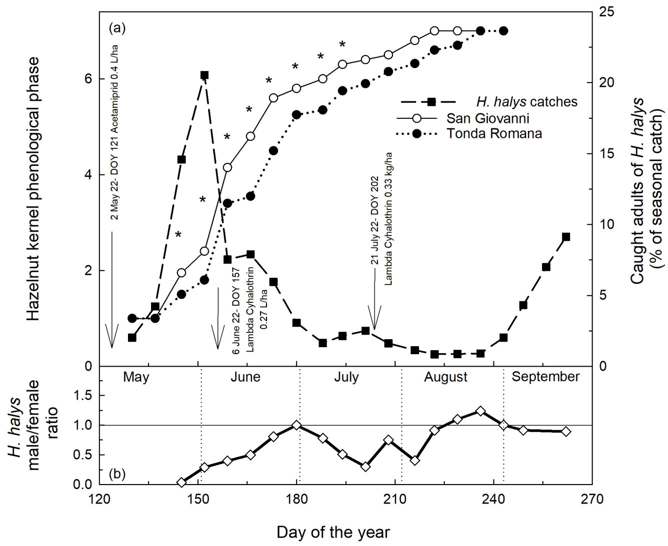

Figure 3. (**a**) Percentage of *Halyomorpha halys* adults, captured from the 130th to the 262nd of 2022, and hazelnut fruit growth represented the mean phenological phase of San Giovanni and Tonda Romana cultivars. Asterisks indicate significant differences between the hazelnut cultivars according to Kruskal–Wallis ($p < 0.05$) and (**b**) the pattern of the sex ratio of *H. halys* adults caught between days 145th and 262nd of 2022.

The sex ratio during the sampling period is shown in Figure 3b.

Plant-beating samplings showed a very low population of stink bugs other than *H. halys*. Occasionally, only a few specimens of *P. prasina* and *N. viridula* were recorded in traps and plant beating samples. Therefore, their presence can be considered irrelevant for the purposes of the present study.

3.2. Fruit Growth

Figure 3a shows the mean phenological phase for the two cultivars at each sampling date. The growth curves of both cultivars had a sigmoid shape, with the ascending part of the curve presenting an inflection point corresponding to an average phenological phase of 5.60 (173rd DOY) for San Giovanni and 5.25 (180th DOY) for Tonda Romana. After these inflection points, the growth rates slowed down.

On the first two sampling dates (130th and 137th DOY), the two cultivars were in phase 1, i.e., shell expansion with no embryo present (Figure 2(1), Figure 3a). From the third sampling date (145th DOY) onwards, the San Giovanni cultivar showed earlier fruit development than that of the Tonda Romana at each sampling (Figure 3a). Differences in phenological growth per date are shown in Figure 3a [the asterisks indicate significant differences according to Kruskal–Wallis results ($p < 0.05$)]. For both cultivars, pesticide application did not affect fruit/kernel size.

3.3. Harvest and Hazelnut Damage Assessment

The different fruit development trends of the two cultivars led to different ripening and harvesting dates, as shown in Table S1.

At the end of the harvest, the production (in-shell hazelnuts at 6% moisture) was approximately 2.8 t/ha (about 5.8 kg/tree) for the San Giovanni cultivar and 2.2 t/ha (about 4.5 kg/tree) for Tonda Romana. For both cultivars, no significant differences were detected in the production between IPM and NI treatment (in the comparison between NI and IPM for the SG cultivar, df = 1, F = 1.059, $p = 0.317$, while for the TR cultivar, df = 1, F = 0.734, $p = 0.403$).

Table 2 reports the incidence of cimiciato hazelnuts for both cultivars and theses (IPM and NI). During the damage assessment in the laboratory, the two tasters confirmed that all the hazelnuts judged as cimiciato by the visual examination had the typical cimiciato off-flavor. When insecticides were applied (SG–IPM vs. TR–IPM), no significant differences between the cultivars in terms of incidence of cimiciato and shriveled hazelnuts were found (Table 3). On the contrary, in the absence of insecticide treatments (SG–NI vs. TR–NI), the incidence of cimiciato damage was higher in the San Giovanni cultivar (Table 3). The pesticide treatments and the cultivar affected the cimiciato incidence; the interaction between these factors was insignificant (Table 3). No statistically significant differences in the incidence of shriveled hazelnuts were found between the cultivars for either of these (with or without insecticide) (Table 3).

Table 2. Mean number (+/−SE) of cimiciato hazelnuts on early San Giovanni and late Tonda Romana cultivars under NI (control) and IPM theses. For each of the four treatments, the incidence of cimiciato hazelnuts in every ten fruits was recorded, with five trees examined during the first and another five during the second commercial harvest.

Cultivar	Cimiciato Hazelnuts	
	NI	IPM
San Giovanni (SG)	4 ± 0.45	1.9 ± 0.35
Tonda Romana (TR)	2.3 ± 0.30	1.1 ± 0.28

Table 3. GLM analyzed the incidence of cimiciato and shriveled hazelnuts affected by cultivar, pesticide, their interaction, and different treatments. SG, San Giovanni cultivar; TR, Tonda Romana cultivar; NI, no pesticide; IPM, integrated pest management with pesticides.

Factors	Cimiciato Incidence			Shriveled Incidence		
	p	*df*	*F*	*p*	*df*	*F*
Cultivar	0.001	1	12.813	ns	1	0.671
Pesticide	<0.001	1	22.326	ns	1	0.953
Cultivar vs. Pesticide	ns	1	1.661	ns	1	0.106
SG–IPM vs. SG–NI	0.002	1	13.734	ns	1	0.600
TR–IPM vs. TR–NI	0.009	1	8.640	ns	1	0.360
SG–IPM vs. TR–IPM	ns	1	3.236	ns	1	0.600
SG–NI vs. TR–NI	0.005	1	9.966	ns	1	0.360

4. Discussion

Although stink bug damage to hazelnut is well known, few papers have scientifically assessed its incidence [31,47]. Our study pointed out that the intensity of cimiciato damage is considerable, reaching an average value in the absence of insecticide treatments of 23% for the cultivar Tonda Romana and 40% for the cultivar San Giovanni. The damage was greater than that observed by Bosco et al. (2018) (13.98% in 2015 and 14.58% in 2016) in a similarly managed orchard under the same conditions of the absence of insecticides [31]. The differences may be attributable to the different cultivar (Tonda Gentile delle Langhe), climate (NW vs. southern Italy), year (2015–2016 vs. 2022), and stink bug species [31]. The sampling in that orchard did not record any *H. halys* specimens [31].

As demonstrated by our monitoring (plant beating and trapping), the cimiciato damage observed during this study was determined almost exclusively by *H. halys* specimens. This finding is consistent with what has been recorded in previous studies on soy [35] and pome fruits [34]. It was observed that *H. halys* became the dominant stink bug species in the newly invaded territory after about three years [35]. This is consistent with the first detection of *H. halys* in Campanian 2018 [19]. Furthermore, *H. halys* appears to be the most harmful species, causing the greatest damage to kernels compared to other stink bug species [31].

The recorded percentages of cimiciato damage are economically unsustainable, especially if the reported values exclude the blank traumatic damage, which cannot be attributed with certainty to the trophic activity of the stink bugs [45,46].

As highlighted in Table 2, the greatest cimiciato damage was found in the early cultivar (SG). The study of fruit phenology showed that the two cultivars reached the same phenological stages at different times. Indeed, they were spaced about 12.5 days apart. The new phenological classification used in this paper permits the distinction of different phases during kernel expansion, unlike the classification used by Hedstrom et al. (2014) [23]. The choice of a greater number of phases was made to try to highlight more clearly if the fruit presented a different vulnerability and different intensities of cimiciato symptoms if stung at different stages of kernel growth. Further studies are needed to understand this feature [47]. Hitherto, there were no studies on the phenological stages of fruit development in Tonda Romana and San Giovanni.

As shown in Figure 3a, a large population of *H. halys* adults moved into hazelnut groves immediately after overwintering. This is consistent with other observations about the presence of a larger peak of emerging adults from experimental refugees between mid-May and early June [48,49]. This is also consistent with Bosco et al. (2018) [31], who reported that during monitoring activities in a hazelnut orchard in West Georgia, they recorded early captures from mid-June due to the overwintering population. This early recolonization was not observed in the other three orchards (one in NW Italy and two in West Georgia), where the largest occurrence happened in the late season [31]. Generally, high early peaks indicate a higher population for that year [50,51].

The sex ratio in the first part of the season after overwintering was biased toward females (Figure 3b). This is another variable to consider because females are more voracious than males in several Pentatomid species, for which a greater presence of females in a period could cause higher damage [24,52]. The sex ratio varied considerably over time according to the development of the different generations (two per year), tending toward parity when the adults of the first generation of the year arrived or developed in the groves.

The differences in the cimiciato incidence in the no insecticide thesis (SG–NI vs. TR–NI) may be due to several factors. However, the analysis of the phenological phases permits us to state that during the time of maximum density of *H. halys*, the early cultivar (SG) was in the kernel expansion stages. These are the most susceptible stages of fruit development for cimiciato defect occurrence, consistent with previous studies on *G. acuteangulatus*, *P. prasina* [24], and *H. halys* [23]. These studies indicated that the type of damage to the hazelnut kernel is strongly related to the moment of attack by stink bugs in relation to fruit development. Thus, the high incidence of cimiciato (40%) recorded in the SG cv should be due to the high *H. halys* density, with 42.65% of the total catches recorded between the 145th and 159th DOY. This period coincided with the phenological phase of kernel expansion, during which SG fruits were predominantly in stages two to four. Moreover, this period was also characterized by a higher presence of females.

Conversely, the high density of the *H. halys* population did not coincide with the phenological phase more susceptible to the TR kernel. Indeed, the fruits of this cv were up to the 152nd DOY in the shell expansion phase (fruits did not reach stage two, kernel presence).

This would explain the different levels of cimiciato damage recorded in the two cultivars grown in the same commercial orchard (Table 2).

The insecticide treatments affected the density of *H. halys* and the cimiciato incidence. However, the first treatment with Acetamiprid (Table 1, Figure 3a) was performed too early compared to both the presence of *H. halys* specimens and the presence of fruits for both cultivars (121st DOY). Differently, the second and third treatments with lamba-cyhalothrin (157th and 202nd DOY) caused an effective decrease in the *H. halys* population density. The effectiveness of lamba-cyhalothrin in controlling *H. halys* is at least partially consistent with previous results [53]. Nevertheless, the chemical treatments did not reduce the cimiciato damage incidence to an acceptable level (19% SG and 11% TR). On the other hand, the reduction in the percentage incidence of cimiciato in the treated SG plot was very high (from 40% to 19%), and this should be due to the first treatment carried out with acetamiprid. This systemic and persistent active ingredient may have protected the fruits during their vulnerable phenological stages [54,55].

The analysis of the presence of *H. halys* in the hazelnut orchards and the phenological stage of the fruits showed that the first two treatments were not carried out at the best moment to control the stink bug. The first should have been delayed, while the second should have been anticipated; hence, IPM strategy improvements must be made.

The *H. halys* population increased again after maturation and the first harvest. This is probably due to the absence of other treatments, the development of the second generation, and the fact that the area is a likely overwintering site.

Despite the strong reduction in cimiciato damage recorded for both cultivars, the results showed that the insecticide treatments carried out on IPM theses did not provide sufficient protection. The results of these research activities have strong implications for future IPM strategies. Results showed that to manage *H. halys*, it is essential to simultaneously analyze the density of the pest and plant phenology. In particular, it is very important to study the phenology of the fruits to identify when they are more vulnerable to damage. This study also highlights the importance of differentiating defense strategies according to the development of the cultivar. Finally, knowing the pest population density in the orchard is essential to identifying the best time to apply chemical treatments. This is particularly true in the early movement of the overwintering generation in hazelnut groves, indicating higher population years [51]. In such cases, as in this study, treatment with a persistent active ingredient is recommended at the beginning of the infestation. The treatments must aim to keep the density of the *H. halys* population very low during the more susceptible phenological phases (kernel development) of the fruit's development.

5. Conclusions

The overall damage analysis showed that: (1) the *H. halys* population, in some localities, arrives rapidly at hazelnut groves just after overwintering. It has the typical dynamic of two generations per year, besides the specimens of the second generation that overwinter; (2) the damage to the hazelnuts due to *H. halys* was very high; (3) the early cv (SG) in the absence of insecticide treatments was more damaged than the late one (TR); (4) major damage seems to be related, at least in Caserta, to an early attack of *H. halys*; (5) IPM treatments should be necessarily linked to the use of traps and monitoring of fruit phenology to obtain the maximum effectiveness.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/horticulturae9060727/s1, Figure S1: BMSB trap used in the trial; Table S1: harvest date for San Giovanni and Tonda Romana.

Author Contributions: Conceptualization, U.B. and M.G.; methodology, U.B. and M.G.; funding acquisition, U.B.; formal analysis, U.B. and M.G.; investigation, F.d.B., F.P. and G.M.G.; resources, U.B.; data curation, F.d.B. and M.G.; writing—original draft preparation, F.d.B.; writing—review and editing, U.B., M.T.L., F.V. and D.T.; visualization, F.P.; supervision, U.B.; project administration, U.B. and M.G. All authors have read and agreed to the published version of the manuscript.

Funding: The research was carried out as part of F.d.B.'s Ph.D. project. This Ph.D. was funded by V. Besana S.p.A., San Gennaro Vesuviano (Naples), Italy, and by the National Research Council of Italy (CNR), Rome, Italy.

Data Availability Statement: Almost all the data will be available upon publication of the manuscript as Supplementary Materials. Furthermore, all other data are deposited in the Institute for Sustainable Plant Protection—National Research Council (IPSP-CNR), P.le E. Fermi, 1-80055 Portici (NA), Italy, and are available on request to Dr. Umberto Bernardo, umberto.bernardo@ipsp.cnr.it.

Acknowledgments: The authors thank Simona Gargiulo for critically reviewing the manuscript draft, Raffaele Sasso for his valuable help in designing sampling activities, and Raffaele Di Biasi for his support during graphic and statistical design. The authors also thank SIPCAM Italia S.p.A. for providing the free lures used for the test.

Conflicts of Interest: The authors declare no conflict of interest. The funders had no role in the study's design; in the collection, analyses, or interpretation of data; in the writing of the manuscript; or in the decision to publish the results.

References

1. Intergovernmental Panel on Climate Change. *Climate Change 2007: The Physical Science Basis*; Intergovernmental Panel on Climate Change: Geneva, Switzerland, 2007; Volume 4, p. 333.
2. Wiens, J.A.; Stralberg, D.; Jongsomjit, D.; Howell, C.A.; Snyder, M.A.; Grinnell, J.; Elton, C. Niches, models, and climate change: Assessing the assumptions and uncertainties. *Proc. Natl. Acad. Sci. USA* **2009**, *106* (Suppl. S2), 19729–19736. [CrossRef]
3. De Benedetta, F.; Gargiulo, S.; Miele, F.; Figlioli, L.; Innangi, M.; Audisio, P.; Nugnes, F.; Bernardo, U. The spread of *Carpophilus truncatus* is on the razor's edge between an outbreak and a pest invasion. *Sci. Rep.* **2022**, *12*, 18841. [CrossRef]
4. Nugnes, F.; Russo, E.; Viggiani, G.; Bernardo, U. First record of an invasive fruit fly belonging to *Bactrocera dorsalis* complex (Diptera: Tephritidae) in Europe. *Insects* **2018**, *9*, 182. [CrossRef]
5. Sweeney, J.; Rassati, D.; Meurisse, N.; Hurley, B.; Duan, J.; Stauffer, C.; Battisti, A. Special issue on invasive pests of forests and urban trees: Pathways, early detection, and management. *J. Pest. Sci.* **2019**, *92*, 1–2. [CrossRef]
6. Gargiulo, S.; Nugnes, F.; de Benedetta, F.; Bernardo, U. *Bactrocera latifrons* in Europe: The importance of the right attractant for detection. *Bull. Insectology* **2021**, *74*, 311–320.
7. Capinha, C.; Essl, F.; Porto, M.; Seebens, H. The worldwide networks of spread of recorded alien species. *Proc. Natl. Acad. Sci. USA* **2023**, *120*, e2201911120. [CrossRef]
8. Pace, R.; Ascolese, R.; Miele, F.; Russo, E.; Griffo, R.V.; Bernardo, U.; Nugnes, F. The bugs in the bags: The risk associated with the introduction of small quantities of fruit and plants by airline passengers. *Insects* **2022**, *13*, 617. [CrossRef]
9. Encyclopedia Britannica. Available online: https://www.britannica.com/science/Mediterranean-climate (accessed on 23 February 2023).
10. Stoeckli, S.; Felber, R.; Haye, T. Current distribution and voltinism of the brown marmorated stink bug, *Halyomorpha halys*, in Switzerland and its response to climate change using a high-resolution CLIMEX model. *Int. J. Biometeorol.* **2020**, *64*, 2019–2032. [CrossRef]
11. Seebens, H.; Blackburn, T.M.; Dyer, E.E.; Genovesi, P.; Hulme, P.E.; Jeschke, J.M.; Pagad, S.; Pyšek, P.; Winter, M.; Arianoutsou, M.; et al. No saturation in the accumulation of alien species worldwide. *Nat. Commun.* **2017**, *8*, 14435. [CrossRef]
12. Streito, J.C.; Chartois, M.; Pierre, É.; Dusoulier, F.; Armand, J.M.; Gaudin, J.; Rossi, J.P. Citizen science and niche modeling to track and forecast the expansion of the brown marmorated stinkbug *Halyomorpha halys* (Stål, 1855). *Sci. Rep.* **2021**, *11*, 11421. [CrossRef]
13. Giovannini, L.; Mazza, G.; Chitarra, W.; Sabbatini-Peverieri, G.; Sonnati, C.; Roversi, P.F.; Nerva, L. New insights from the virome of *Halyomorpha halys* (Stål, 1855). *Virus Res.* **2022**, *316*, 198802. [CrossRef] [PubMed]
14. Chen, J.H.; Avila, G.A.; Zhang, F.; Guo, L.F.; Sandanayaka, M.; Mi, Q.Q.; Shi, S.S.; Zhang, J.P. Field cage assessment of feeding damage by *Halyomorpha halys* on kiwifruit orchards in China. *J. Pest. Sci.* **2020**, *93*, 953–963. [CrossRef]
15. FAOSTAT. Available online: https://www.fao.org/faostat/en/#data/QCL (accessed on 23 February 2023).
16. Singldinger, B.; Dunkel, A.; Hofmann, T. The cyclic diarylheptanoid asadanin as the main contributor to the bitter off-taste in hazelnuts (*Corylus avellana* L.). *J. Agric. Food Chem.* **2017**, *65*, 1677–1683. [CrossRef] [PubMed]
17. Istat. Available online: https://www.istat.it/ (accessed on 22 February 2023).
18. Cianferoni, F.; Graziani, F.; Dioli, P.; Ceccolini, F. Review of the occurrence of *Halyomorpha halys* (Hemiptera: Heteroptera: Pentatomidae) in Italy, with an update of its European and world distribution. *Biologia* **2018**, *73*, 599–607. [CrossRef]
19. *Regione Campania, Decreto Dirigenziale Numero 28 del 20 March 2019*; BURC Regione Campania: Napoli, Italy, 2019.
20. Cesari, M.; Maistrello, L.; Ganzerli, F.; Dioli, P.; Rebecchi, L.; Guidetti, R. A pest alien invasion in progress: Potential pathways of origin of the brown marmorated stink bug *Halyomorpha halys* populations in Italy. *J. Pest. Sci.* **2015**, *88*, 1–7. [CrossRef]
21. Maistrello, L.; Vaccari, G.; Caruso, S.; Costi, E.; Bortolini, S.; Macavei, L.; Foca, G.; Ulrici, A.; Bortolotti, P.P.; Nannini, R.; et al. Monitoring of the invasive *Halyomorpha halys*, a new key pest of fruit orchards in northern Italy. *J. Pest. Sci.* **2017**, *90*, 1231–1244. [CrossRef]
22. Costi, E.; Haye, T.; Maistrello, L. Surveying native egg parasitoids and predators of the invasive *Halyomorpha halys* in northern Italy. *J. Appl. Entomol.* **2019**, *143*, 299–307. [CrossRef]
23. Hedstrom, C.S.; Shearer, P.W.; Miller, J.C.; Walton, V.M. The effects of kernel feeding by *Halyomorpha halys* (Hemiptera: Pentatomidae) on commercial hazelnuts. *J. Econ. Entomol.* **2014**, *107*, 1858–1865. [CrossRef]
24. Hamidi, R.; Calvy, M.; Valentie, E.; Driss, L.; Guignet, J.; Thomas, M.; Tavella, L. Symptoms resulting from the feeding of true bugs on growing hazelnuts. *Entomol. Exp. Appl.* **2022**, *170*, 477–487. [CrossRef]
25. Tavella, L.; Arzone, A.; Miaja, M.L.; Sonnati, C. Influence of bug (Heteroptera, Coreidae and Pentatomidae) feeding activity on hazelnut in northwestern Italy. *Acta Hortic.* **2001**, *556*, 461–468. [CrossRef]

26. Singldinger, B.; Dunkel, A.; Bahmann, D.; Bahmann, C.; Kadow, D.; Bisping, B.; Hofmann, T. New taste-active 3-(O-β-d-Glucosyl)-2-oxoindole-3-acetic acids and diarylheptanoids in *cimiciato*-infected hazelnuts. *J. Agric. Food Chem.* **2018**, *66*, 4660–4673. [CrossRef] [PubMed]
27. Squara, S.; Stilo, F.; Cialiè Rosso, M.; Liberto, E.; Spigolon, N.; Genova, G.; Castello, G.; Bicchi, C.; Cordero, C. *Corylus avellana* L. Aroma blueprint: Potent odorants signatures in the volatilome of high quality hazelnuts. *Front. Plant Sci.* **2022**, *13*, 840028. [CrossRef]
28. Memoli, A.; Albanese, D.; Esti, M.; Lombardelli, C.; Crescitelli, A.; di Matteo, M.; Benucci, I. Effect of bug damage and mold contamination on fatty acids and sterols of hazelnut Oil. *Eur. Food Res. Technol.* **2017**, *243*, 651–658. [CrossRef]
29. Turan, A. Effect of the damages caused by the green shield bug (*Palomena prasina* L.) on the qualitative traits of hazelnuts. *Grasas Aceites* **2021**, *72*, 1135192.
30. Viggiani, G. *Nematodi, Acari e Insetti Dannosi al Nocciuolo*; Annali della Facoltà di Scienze Agrarie dell'Università di Napoli: Napoli, Italy, 1972; p. 6.
31. Bosco, L.; Moraglio, S.T.; Tavella, L. *Halyomorpha halys*, a serious threat for hazelnut in newly invaded areas. *J. Pest. Sci.* **2018**, *91*, 661–670. [CrossRef]
32. Pollini, A. *Manuale di Entomologia Applicata*; Edagricole-Edizioni Agricole: Bologna, Italy, 2013.
33. Ak, K.; Uluca, M.; Tunçer, C. Distribution and population density of *Halyomorpha halys* (Stål, 1855) (Hemiptera: Pentatomidae) in Black Sea Region of Türkiye. *Turk. J. Zool.* **2023**, *47*, 120–129. [CrossRef]
34. Nielsen, A.L.; Hamilton, G.C. Seasonal occurrence and impact of *Halyomorpha halys* (Hemiptera: Pentatomidae) in tree fruit. *J. Econ. Entomol.* **2009**, *102*, 1133–1140. [CrossRef] [PubMed]
35. Nielsen, A.L.; Hamilton, G.C.; Shearer, P.W. Seasonal phenology and monitoring of the non-native *Halyomorpha halys* (Hemiptera: Pentatomidae) in soybean. *Environ. Entomol.* **2011**, *40*, 231–238. [CrossRef]
36. Leskey, T.C.; Lee, D.; Short, B.D.; Wright, S.E. Impact of insecticides on the invasive *Halyomorpha halys* (Hemiptera: Pentatomidae): Analysis of insecticide lethality. *J. Econ. Entomol.* **2012**, *105*, 1726–1735. [CrossRef]
37. Leskey, T.C.; Short, B.D.; Lee, D. Efficacy of insecticide residues on adult *Halyomorpha halys* (Stål) (Hemiptera: Pentatomidae) mortality and injury in apple and peach orchards. *Pest. Manag. Sci.* **2014**, *70*, 1097–1104. [CrossRef]
38. Leskey, T.C.; Short, B.D.; Butler, B.R.; Wright, S.E. Impact of the invasive brown marmorated stink bug, *Halyomorpha halys* (Stål), in mid-Atlantic tree fruit orchards in the United States: Case studies of commercial management. *Psyche* **2012**, *2012*, 1–14. [CrossRef]
39. Suckling, D.M.; Levy, M.C.; Roselli, G.; Mazzoni, V.; Ioriatti, C.; Deromedi, M.; Cristofaro, M.; Anfora, G. Live traps for adult brown marmorated stink bugs. *Insects* **2019**, *10*, 376. [CrossRef] [PubMed]
40. Horner, R.; Roselli, G.; Sasso, R.; Cristofaro, M.; Chen, S.; Jermy, M.; Anfora, G. The tunnel trap: Aerodynamic Design Principles for Improved Brown Marmorated Stink Bug Trapping. In Proceedings of the International Congress on Biological Invasions, Christchurch, New Zealand, 1–4 May 2023.
41. Khrimian, A.; Zhang, A.; Weber, D.C.; Ho, H.Y.; Aldrich, J.R.; Vermillion, K.E.; Siegler, M.A.; Shirali, S.; Guzman, F.; Leskey, T.C. Discovery of the aggregation pheromone of the brown marmorated stink bug (*Halyomorpha halys*) through the creation of stereoisomeric libraries of 1-bisabolen-3-ols. *J. Nat. Prod.* **2014**, *77*, 1708–1717. [CrossRef] [PubMed]
42. Vandervoet, T.F.; Bellamy, D.E.; Anderson, D.; MacLellan, R. Trapping for early detection of the brown marmorated stink bug, *Halyomorpha halys*, in New Zealand. *N. Z. Plant Protect. Soc.* **2019**, *72*, 36–43. [CrossRef]
43. Wyniger, D.; Kment, P. Key for the separation of *Halyomorpha halys* (Stål) from similar-appearing pentatomids (Insecta: Heteroptera: Pentatomidae) occurring in Central Europe, with new Swiss records. *J. Swiss Entomol. Soc.* **2010**, *83*, 261–270.
44. UNECE, U.S. *DDP-04 Concerning the Marketing and Commercial Quality Control of Hazelnut Kernels*; United Nations: New York, NY, USA, 2010.
45. Silva, A.P.; Ribeiro, R.M.; Santos, A.; Rosa, E. Blank fruits in hazelnut (*Corylus avellana* L.) Cv. "Butler": Characterization and influence of climate. *J. Hortic. Sci.* **1996**, *71*, 709–720. [CrossRef]
46. Fattahi, R.; Mohammadzedeh, M.; Khadivi-Khub, A. Influence of different pollen sources on nut and kernel characteristics of hazelnut. *Sci. Hortic.* **2014**, *173*, 15–19. [CrossRef]
47. De Benedetta, F.; Pica, F.; Improta, A.; Turrà, D.; Vinale, F.; Giaccone, M.; Lisanti, M.T.; Bernardo, U. Relationship between *Halyomorpha halys* (Stål) Population Density, Its Damage, and Phenology of Three Hazelnut Cultivars (*Corylus avellana* L). In Proceedings of the XXVII Congresso Nazionale Italiano di Entomologia (CNIE), Palermo, Italy, 12–16 June 2023.
48. Ak, K.; Tuncer, C.; Baltaci, A.; Eser, U.; Saruhan, I. Incidence and severity of stink bugs damage on kernels in turkish hazelnut orchards. *Acta Hortic.* **2018**, *1226*, 407–411. [CrossRef]
49. Bergh, J.C.; Morrison III, W.R.; Joseph, S.V.; Leskey, T.C. Characterizing spring emergence of adult *Halyomorpha halys* using experimental overwintering shelters and commercial pheromone traps. *Entomol. Exp. Appl.* **2017**, *162*, 336–345. [CrossRef]
50. Leskey, T.C.; Agnello, A.; Bergh, J.C.; Dively, G.P.; Hamilton, G.C.; Jentsch, P.; Khrimian, A.; Krawczyk, G.; Kuhar, T.P.; Lee, D.H.; et al. Attraction of the invasive *Halyomorpha halys* (Hemiptera: Pentatomidae) to traps baited with semiochemical stimuli across the United States. *J. Econ. Entomol.* **2015**, *44*, 746–756. [CrossRef]
51. Weber, D.C.; Morrison, W.R., III; Khrimian, A.; Rice, K.B.; Leskey, T.C.; Rodriguez-Saona, C.; Nielsen, A.L.; Blaauw, B.R. Chemical ecology of *Halyomorpha halys*: Discoveries and applications. *J. Pest Sci.* **2017**, *90*, 989–1008. [CrossRef]
52. Smith, J.R.; Hesler, S.P.; Loeb, G.M. Potential impact of *Halyomorpha halys* (Hemiptera: Pentatomidae) on grape production in the finger lakes region of New York. *J. Entomol. Sci.* **2014**, *49*, 290–303. [CrossRef]

53. Preti, M.; Montanari, M.; Landi, M.; Cavazza, F.; Franceschelli, F.; Mirossevich, L.; Nannini, R.; Bortolotti, P.P. Screening in open field and laboratory condition of pyrethroids insecticide activity against *Halyomorpha halys*. In Proceedings of the Emilia-Romagna, Atti, Giornate Fitopatologiche, Chianciano Terme, Italy, 6–9 March 2018; Volume 1, pp. 403–414.
54. Yao, X.; Min, H.; Lü, Z.; Yuan, H. Influence of acetamiprid on soil enzymatic activities and respiration. *Eur. J. Soil Biol.* **2006**, *42*, 120–126. [CrossRef]
55. Al-Rajab, A.J.; Alhababy, A.M.; Alfaifi, T. Persistence of imidacloprid, acetamiprid and methomyl in qat leaves. *Hell. Plant Prot. J.* **2016**, *9*, 51–59. [CrossRef]