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Towards Integrated Pest Management of the Cereal Leafminer *Syringopais temperatella* Led. (Lepidoptera: Scythrididae): Status, Current and Future Control Options

Firas A. Al-Zyoud

Department of Plant Protection and Integrated Pest Management, Faculty of Agriculture, Mu'tah University, Karak, Jordan

Abstract The cereal leafminer, *Syringopais temperatella* Led. is a destructive insect pest of wheat and barley in the field, and causes economic damage to these crops in many countries including Jordan. The insect feeds on plant foliage and eventually leads to a sharp decline in production. Management of agricultural pests is undoubtedly considered one of the most important farming practices that should be taken by growers. Continuous use of chemical insecticides is neither economic nor sustainable, and poses risk to humans, animals, beneficials and their environment. One of the promising alternatives is the use of integrated pest management (IPM). IPM was proven to be a successful, sustainable, effective, economic and environmentally friendly control strategy for pests. However, to the best of our knowledge, no an integration published work was found to cover the status, biological and ecological aspects, current and future control options of *S. temperatella*. Therefore, this review paper was prepared to better understanding the biological and ecological aspects of *S. temperatella*, and to develop management strategies to successfully suppress its population. Also, this review aims to improve wheat and barley production in our region, through the introduction of IPM practices such as resistant plant cultivars, natural enemies, bio-insecticides and cultural practices to control *S. temperatella*, since this paper is the first to tackle some of IPM measures of this pest. However, in this review, the geographical distribution, host plant spectrum, life cycle and biology of the pest, susceptibility/resistance of hundreds of wheat and barley cultivars/accessions, role of oxalic acid, crop rotation, ploughing, right chemical and time, parasitoids, bio-insecticide and environmental factors were thoroughly discussed. All these aspects are fundamental components of IPM, and should be taken into account in any future IPM program to control *S. temperatella*.

Keywords Biology, Ecology, IPM, Host-plant resistance, Wheat, Barley

1. Introduction

Wheat and barley are the principal food crops for hundreds of millions of people in the predominantly mixed crop-livestock farming systems world-wide. The grain yield of these crops achieved by farmers in arid and semi-arid regions in West Asia and North Africa is low with large variability from year to year [1]. Low grain yield and even crop failure are common in Jordan [2]. Jordan is not self-sufficient in the production of wheat and barley, and the self-sufficiency ratio is only 1.8% and 6.1%, respectively. In 2010, the country imported 1,076,650 and 447,332 tons of wheat and barley, respectively [3] to cover the national needs. Both crops are classified as low-input crops to farmers, though, farmers can't accept much loss of their yield due to any causal agent. The demand on Jordanian agriculture to rapidly increase cereals' production should be effectively addressed through modifications in the present control measures, and adaption of proven newer protection measures.

In addition to the environmental stresses (mainly drought) which are main causes for low productivity of wheat and barley [4, 5], insect pests cause serious and yield loss to these crops [6]. Hundreds of insects have been monitored on wheat and barley worldwide. While most of these insects cause insignificant damage, others are considered major limiting factors that cause serious reduction in wheat and barley grains and forage production [7, 8, 9]. Some insect pests are specifically adapted to wheat and barley and their relatives and to the set of environmental conditions where wheat and barley are grown. As some agricultural practices eliminate natural regulating forces that would normally check their populations, many insect-pest populations have erupted into severe outbreaks wreaking near-total destruction on the crops they infest [6].

* Corresponding author:
firaszud@yahoo.com (Firas A. Al-Zyoud)
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The cereal leafminer, *Syringopais temperatella* Led. is considered one of the most serious insect pests of wheat and barley in the field, and causes economic damage to these crops in the countries of West Asia [10-18]. In Jordan, *S. temperatella* is endemic to the country, and has been reported more than 50 years ago [19]. The pest has been recognized since 2001 as the most destructive insect pest limiting the production of wheat and barley [20, 21]. Outbreaks of this pest have mostly occurred in the south of the country (Karak District) for the last twelve years [22]. Wheat and barley fields were almost damaged in Karak District, even though the infested fields were sprayed with insecticides [23]. The insect feeds on plant foliage, soon turning its leaves into yellow and eventually leads to a sharp decline in production. The pest infestation reduced grain yield by 72% and straw dry mass by 59% [24]. In Turkey, Kaya [12] estimated the damage to be around 40-60%. In Jordan, the infested areas are yearly increasing, where three areas were infested in 2001 as compared to eighteen areas in 2006, and this might be due to frequent occurrence of drought and lack of proper crop rotation [17].

Management of agricultural pests is undoubtedly considered as one of the most important farming practices that should be taken by farmers [6]. Due to the importance of wheat and barley production in Jordan and the surrounding countries, prevention and control measures of *S. temperatella* are of vital importance. However, rapid knock-down, high target mortality and ease of application rapidly led to the adoption of chemical pesticides [25], and the use of synthetic compounds soon became the predominant method of controlling crop pests and overshadowed programs of alternative methods of pest control [26]. Intensive application of chemical insecticides has been used to suppress *S. temperatella* in many countries [5, 16, 27, 28]. However, continuous use of chemical insecticides is neither economic nor sustainable, and poses risk to humans, animals, beneficial insects and their environment [29]. Moreover, the use of insecticides on wheat and barley has generally lagged due to cost constraints associated with these two crops as low-input crops [30], and the developed resistance by *S. temperatella* to many insecticides [31]. Increased public concerns about the adverse effects of indiscriminate use of chemical insecticides prompted search of alternative methods for pest control. One of the promising alternatives is the use of integrated pest management (IPM) [32]. IPM was proven to be a successful, sustainable, effective, economic and environ-mentally friendly control strategy for pests [33]. The use of resistant plant cultivars, biological control, biopesticides and cultural methods are main parts of IPM [20-22, 34, 35, 36].

Although considerable efforts have been made to develop IPM strategies over the past years, it is still unable to completely manage pests in an environmentally manner [37]. However, to date and to the best of our knowledge, no an integration published work was found to cover the status, biological and ecological aspects, control options of *S. temperatella* despite the outbreaks experienced over the last years in our region. This review paper was prepared to better understanding the status, biological and ecological aspects, current and future control options of *S. temperatella*. In addition, this review aims to improve wheat and barley production in our region, through the introduction of IPM technologies to control *S. temperatella*. Therefore, in this review, the pest geographical distribution and host plant spectrum, its life cycle and biology, susceptibility/resistance of hundreds of wheat and barley cultivars/accessions, role of oxalic acid, crop rotation, ploughing, right chemical and time, parasitoids, bio-insecticide and environmental factors were thoroughly discussed. It is hoped that the application of such IPM practices will play a central role in protecting cereal crops; thereby it will drastically replace, at least in part, some of the most dangerous insecticides currently used against *S. temperatella* in Jordan and neighboring countries. The final goal of this work is to encourage farmers to adopt these technologies in order to improve livelihoods, and to help in investigation, development and promotion of effective plant protection measures (i.e. IPM), compatible with environment and human health.

2. Geographical Distribution and Host Plant Spectrum

The cereal leafminer, S. *temperatella* is reported in Jordan [20, 21, 22, 27], Iraq [10, 38, 39], Iran [16, 40, 41], Turkey [12, 18], Cyprus [11, 42, 43, 44, 45], Greek [15], Israel [46], and Syria, Lebanon, Minor Asia and the Mediterranean riparian countries [13]. In Jordan, the infested areas were only three in 2001 as compared to eighteen areas in 2006, which proves that the areas are yearly expanding [17]. S. *temperatella* is known to attack wheat, barley and wild barley in Jordan [17], wild grasses and Egyptian clover in Israel [46], the common oats and the grass family of plants [47]. In Cyprus, S. *temperatella* was observed feeding on 37 species of weeds belong to 14 families [48].

3. Life Cycle and Biology

In order to control the cereal leafminer successfully, it is important to investigate its life cycle and biology, which are considered important features that should be taken into account. In Jordan, field observations indicate that *S. temperatella* larvae emerge from ground in early February and penetrate the leaf mesophyll of wheat and barley. The larvae live in the leaves about 1.5 months and gnaw mines between the two epidermal layers. After reaching a maximum growth in late March to early April, the larvae enter the ground and pupate. Later the adults begin to appear in flight in late April to early May. Eggs laying take place on the cereal plants or in soil cracks. After larvae hatching in late May to early June, they descended into the soil [49], and formed cysts in which they aestivated during summer, autumn and part of the winter as first-instar larvae [17]. In Iraq, the first infestation by larvae was recorded in January.

In mid March to early April, pupation took place inside cocoons in the soil. Adults appeared in late April, and females deposited eggs in end April. Hatchlings were first noticed in early May. They descended into the soil and formed cysts in which they aestivated from summer until part of the winter as first-instar larvae [5, 38]. In Cyprus, the adults are on the wing in the late spring or early summer. The eggs are laid in the soil, persisted through the hot weather, hatched during the winter, and the larvae attack the young wheat. Pupation takes place in the soil [42]. In Israel, the larvae emerge from ground in January and early February, and penetrate the leaf mesophyll. They live in the leaves from 2-2.5 months and gnaw mines between the two epidermal layers. Usually they begin mines from the upper tip of the blade, but during development they may change their position many times and commence fresh mines. After reaching maximum growth in March to early April, the larvae enter the ground and pupate in fine-threaded cocoons. The moths are abundant by April. The eggs are laid in the ground, which are resistant to desiccation and drought. The larvae hatch later, and after a week they hide in the ground [46]. In Turkey, larvae began to mine the leaves of young plants at the end of February to early March; about 2 months later they entered the soil to pupate. Adults began to appear in flight in mid May. Eggs laid on the cereal plants or in soil cracks. Larvae hatched at the beginning of June and entered summer diapose in the soil; they began feeding on cereals after the autumn rains [12]. In Iran, 8 months was spent as first instar larvae in diapose state in soil and the remaining life period is passed within 4 months as active larvae inside plant, pupae, adults and eggs in the soil. The active larval period inside leaves is approximately 75-100 days, from mid March gradually pupae forms. Adults appear in late March [41]. The insect has one generation a year [12, 17, 41].The pest has an egg stage, five larval instars, a pupal stage and an adult stage. Mean developmental periods of egg, larval and pupal stages on wheat at 20°C take 13, 19 and 12 days, respectively. The entire life cycle from egg to adult emergence takes 44 days [17]. Avidov and Harpaz [46] mentioned that the egg development last for 8-17. The pupal stage lasts for 10-15 days under laboratory conditions in Turkey [12], 10-14 days in field conditions in Iran [41] and 14 days in Iraq [5]. The mortality of the pests was 44%, 35% and 31% during egg, larval and pupal stages, respectively. Total mortality during development from egg to adult emergence is estimated at 74% [17]. The sex ratio (females: males) was estimated to be 1: 0.39 in the laboratory [17], and 1: 0.54 in the field [41]. Adult longevity of 11 and 14 days for females and males, respectively [17], 2-3 weeks [46], 4-10 days (males) and 6-13 days (females) [12] was recorded. The pre-oviposition period of females takes 4 days [17], and 3-7 days [46], and oviposition period lasts is 7 days. The pest fecundity is 26 eggs/female [17], 50-125 eggs [46], 29 eggs [5]), and 26-100 eggs [12]. In general, the high variability in temperatures, relative humidity, plant species and even plant cultivars used in the different studies might explain the discrepancy of the different findings.

4. Infestation and Crop Loss

Due to the increasing demand for wheat and barley crops and their products for humans and animals in much of the world, investigating *S. temperatella* infestation and predicting crop loss caused by the pest are important. Larvae of *S. temperatella* feed restrictly on leaf tissue, which affects plant vegetation growth and thereby, the production of grain yield and straw. In the Mediterranean area, *S. temperatella* causes yield and straw reduction of wheat and barley that depends on plant infestation level, plant cultivar, soil condition, rainfall, ploughing, predation, parasitism and sowing date [10, 16, 20, 22, 50, 51].

In Iraq, infestation of 49% and 53% in 2000 and 47% and 49% in 2001 in Abo-Ghrab and Al-Fedeleh were recorded, respectively [39], while in Jordan the infestation reached up to 70% [22]. In a screening of 34 wheat and barley accessions, the infestation reached 33% for wheat and 35% for barley [52]. Ghabeish *et al*. [24] have found a decreasing function between percentage of infestation and grain yield for 27 wheat and 15 barley accessions tested. They found that the overall yield reduction due to the pest is around 72% for both wheat and barley. In addition, Ghabeish *et al*. [24] found also a decreasing function between infestation percentage and straw dry mass and they stated that the average straw biomass reduction due to the pest is 72% for wheat and 59% for barley. A decreasing function was stated between the number of larvae that attack foliage and straw dry mass for wheat and barley [24]. There was a positive correlation between the consumed leaf area and number of pest attaches [22]. These results are in line with conclusion made by Abu-Yaman [10] in Iraq, who reported that larval density plays an important role, but not the only factor affecting damage. However, the capacity of the cereal leafminer to reduce yield has been documented by many researchers. In Turkey, the pest reduced the yield by 40-60% [12]. Later, Duran *et al*. [50] estimated the reduction in the field to be around 22%. While in Iraq, the crop loss was between 10% and 20% [10]. However, Kaya [12] stated that the economic threshold level (ETL) for *S. temperatella* when over 20% infestation is observed. So, the cereal leafminer requires control action in Jordan and surrounding countries since the infestation exceeded such a set threshold.

5. Preferences and Host Plan Resistance

Development of resistant cultivars of wheat and barley is of great importance for farmers, since these crops with relatively low financial return, therefore, control method of high cost is considered undesirable for farmers. The use of resistant cultivars against pests are desirable practice due to their effectiveness, safe to environment [33], durable and maintain natural balances within the ecosystem. Since wheat and barley growers have to spend much of inputs like applications of agrochemicals to control *S. temperatella*, it was considered viable to search the available germplasm for sources of resistance to the pest to be used in breeding insect resistant cultivars. Because of the relatively low emphasis on insect pests in wheat- and barley-based systems, cultivars possessing resistance to insect pests have for the most part lagged behind the development of high-yielding and pest-resistant cultivars [26]. Using of less preference or moderate resistance cultivars will reduce the reliance of farmers on chemical insecticides; provide farmers with a viable alternative to chemical control. Furthermore, oxalic acid accumulation in plants is considered to be one of the chemical mechanisms of pest resistance [53, 54]; therefore, the relation between infestation and oxalic acid level in the plant is discussed in this section. Such information can help to detect and monitor pest infestation, cultivar selection and crop breeding. Growing pest resistant cultivar is an ideal component of IPM strategy worldwide [21, 27, 55].

In regards to plant species, barley is more preferred than wheat (more leaf area was consumed) whether the crops were provided separately or together [20, 22]. In addition, when the larvae were provided with two different cultivars of each wheat and barley, the results indicated that the barley cultivars, Mutah and Athroh were attached around 2-fold more than the wheat cultivars, Sham and Acsad 65 [22]. Furthermore, yield and straw losses were greater 3.8 and 2.2-fold in barley than in wheat [49]. Concerning the preferences of *S. temperatella* to wheat and barley cultivars, many studies have been conducted. There were significant differences in the susceptibility of 6 cultivars of each wheat and barley offered separately to *S. temperatella* [20] or together [22]. In both studies, the wheat cultivars, Acsad 65 and Horani 27, and the barley cultivar, Athroh were the least preferred ones. In Jordan also, in a study conducted by Ghabeish *et al.* [56], it was found that the wheat cultivars; Acsad 1273, Acsad 1245 and Umkais, and the barley accession, 1614 were the most resistant ones. In Iraq, it was found that the wheat cultivar, Sham 6 is less susceptible to *S. temperatella* larvae [5]. Also, in Iraq in field trials, Ali *et al.* [39] found that the wheat cultivar, IPA99 is the least preferred by the pest. Although, no cultivar or accession tested in the different studies were immune to *S. temperatella*, it appears promising a type of resistance to *S. temperatella* that could be useful as a source of genetic material for future studies in breeding programs to produce *S. temperatella* - resistant cultivars. Statistically, the above mentioned cultivars showed low percentage of infestation, relatively high grain yield and straw biomass, and low larval population size attacking their foliage.

Madanat *et al.* [57] screened 546 accessions for their resistance to *S. temperatella* in Jordan under field conditions including 193, 308 and 45 barley, bread wheat and durum wheat, respectively. Of the 193 barley accessions, 24 accessions were resistant to *S. temperatella*, and the remaining accessions were susceptible. Of the 308 bread wheat accessions tested, 37 accessions had highly and moderately resistant and 271 accessions were susceptible. All durum wheat accessions were highly susceptible to *S. temperatella*. Some of the resistance wheat and barley accessions tested by Madanat *et al*. [57] had an additional resistance to other pest species such as the wheat stem sawfly and the cereal leaf beetle [7, 8, 9].

Al-Zyoud *et al*. [52] investigated the relation amonginfestation, oxalic acid level and moisture content of the leaves of 34 wheat and barley accessions to understand the precise correlation for the resistance to *S. temperatella*. They found a significant variation in the oxalic acid level among the accessions, and there was a significant inverse correlation of oxalic acid content with infestation percentage for both wheat and barley. Thus, leaf oxalic acid level is playing an opposite role in the pest infestation, thus, leaf oxalic acid may consider as a resistant factor against the pest attack. This might be confirmed by the results of Yoshida *et al.* [53], Sharma *et al*. [58] and Sarwar [37], in which the inhibition of *Helicoverpa armigera* (Hubner) larval growth by oxalic acid in the trichome exudate appears to be a component of host-plant resistance in chickpea; since there was a negative correlation between the oxalic acid level and larval density. However, the infestation in some of the wheat and barley accessions was low despite the low level of oxalic acid in the leaves. This observation indicates that, in addition to oxalic acid, other factors might also determine *S. temperatella* susceptibility in wheat and barley such as average rainfall [57], plant cultivar [20], and starting of leaves germination whether earlier or later among the different accessions tested which reflects the duration of exposure to the pest infestation. Another factor that might play a role in the infestation level is the moisture content of the leaves. The infestation correlated positively with leaf moisture content; normally, the mining larvae prefer more succulent plant tissues [52]. This finding is in full agreement with Wei et al. [59] where host feeding selection (number of feeding punctures) of the pea leafminer, *Liriomyza huidobrensis* (Blanchard) was positively correlated with the leaf moisture content. Moreover, one of the most conspicuous correlations between leaf moisture and larval growth is that found in *Bombyx mori* L., in which positive correlation between leaf moisture content and different larval parameters was resulted [60]. The preference of the cereal leafminer for a plant species (wheat or barley), cultivar or accession upon another might be due to physical factors such as hairiness, hardiness and thickness of the plant leaves [54], as well as to differences in chemical composition of the leaves [20]. Also, this might be due to morphological and physiological features of the cultivars [39]. Moreover, the genetic make-up of the accessions may stand behind the leafminer resistance, since the random amplified polymorphic DNA markers showed a high level of polymorphism among the accessions examined [56], which may explain the variation of susceptibility of the pest to the different accessions. In this regard, Maric *et al*. [61] and Sapna *et al*. [62] indicated that wheat and barley are highly polymorphic species. Nevertheless, it is unlikely that resistant accessions tested in the different studies will alone maintain pest populations at acceptable levels, and back-up chemical applications might be appropriate during the pest outbreak. Furthermore, farmers can start growing the resistant accessions to *S. temperatella*, and even moderate accessions resistance would likely be useful in reducing the number of sprays currently applied on wheat and barley to control *S. temperatella*.

6. Cultural Practices

Due to the uncountable number of adverse effects, hazards and problems of pesticides [30, 63], the interest in cultural methods for pest control is renewed, and now forms an important component of IPM. In many wheat- and barley-based systems, cultural control methodologies, where crop rotation and ploughing are used to maintain pest populations below the economic threshold, are of vital importance. Crop rotation is a good management practice because it reduces the carryover of pests between crops. In addition, crop rotation is effective for controlling pests that have narrow host plant spectrum. Small grain rotations can provide agronomic benefits that improve the long-term stability and performance of agricultural systems. Deep ploughing influences directly the survival of soil inhabiting pests. So, determining the soil depth at which *S. temperatella* larvae diapose will help in determining the right ploughing depth in order to bring up the pest from the soil to facilitate its control. It is to be noted that the pest will only be brought to the surface if the soil is ploughed at the right depth; otherwise the pest may remain undisturbed and lays in wait ready to attack the target crop. It is obvious that the majority of the cereals' farmers, at least in Jordan, have not ploughed their fields at the right depth under the pretext of conserving the soil moisture; therefore, the pest is infesting the cereal fields yearly.In regards to crop rotation, among five crop rotations Al-Zyoud [22] reported that the infestation percent (34%) is significantly the lowest in the crop rotation, wheat/chickpea/wheat, and the highest (68%) for barley/barley/barley. The mean number of *S. temperatella* larvae was also the lowest for wheat/chickpea/wheat (21 larvae/plot), and the highest for barley/barley/barley (70 larvae/plot) crop rotation. However, Duran et al. [50] reported that *S. temperatella* larvae could survive in the soil and the survival could be affected by the type of plant present (cereal crop or fallow). While larvae could survive in the soil for up to 54 months, it was found that the larval population began to decline if the intervals between sowing of susceptible crops were longer than 18 months. The finding of Duran *et al.* [50] agrees completely with the results of Al-Zyoud [22], since he found that when the fields were left for two years without growing any crop, then it followed by barley (fallow/fallow/ barley) the infestation was reduced from 68% to 52% and the number of larvae decreased from 70 to 39 larvae/plot.

Concerning the ploughing depth, in Jordan it was found that the number of diaposed larvae increased with increasing soil depth, and this result confirmed by percentage of plant infestation. The infestation percentage and larval population size were higher of both wheat and barley plants grown in soil taken from the deeper field soil depth (21-40 cm) than shallower one (0-20 cm) [49]. This agrees partially with the finding of Jemsi *et al*. [41] in Iran, who reported that *S. temperatella* larvae diapose at 15-30 cm depth of soil. Furthermore, in the same country,ploughing treatment done up to late August with disking was effective in decreasing the pest infestation, provided that the depth of ploughing must not be lower than 15 cm [16]. While in Cyprus it was found that a single deep ploughing in summer was not effective against larvae, but gave a slight reduction in the pest population [11]. Based on these results, ploughing at soil depth up to 40 cm will be of great benefit in the pest control; since it will bring up the maximum larval population from the soil, and they will be exposed to natural mortality factors such as predators, unfavorable environmental conditions and will disturb the niche of the diaposed larvae. It is worth to mention that larval population size in the soil could greatly affect plant's yield and straw biomass. Results indicated that larval population size is negatively correlated with grain yield and dry biomass, and positively correlated with plant infestation percentage. For wheat and barley, yield loss was 20% and 76%, respectively, while straw loss was 31% for wheat and 67% for barley [49]. These results are in line with the findings of Abu-Yaman [10] and Al-Zyoud [22], who reported a positive correlation between the infestation and larval population size, and also with Serghiou [11] who stated a negative correlation between the larval population size and grain yield. There are other cultural practices that might help positively in controlling the pest. In Iran, burning the stubble of cereals reduced the infestation by 100% as compared with the control [51]. In Turkey, changing the sowing time of cereals from autumn to spring, especially to after mid March, reduced the larval population considerably [50].

7. Biological Control

It is well known that continuous use of chemical insecticides [16, 28] against *S. temperatella* is neither economic nor sustainable, and has a negative impact on environment, natural enemies and human health [30]. Therefore, efforts are needed to develop IPM to suppress this pest through the use of biological control. Indigenous natural enemies of this pest, particularly parasitoids, are diverse within their native ranges and there is evidence that in pesticide free areas natural enemies can regulate this pest [18]. However, in Jordan Al-Zyoud [17] reported a total parasitism by the parasitoid, *Anilastus* sp. Förster (Hym., Ichneumonidae) reached up to 49%. It is to be noted that the parasitism percent found in his study is high enough to make a sufficient reduction in the pest population. Bodenheimer [64] stated that parasitoids of the Ichneumonid genus *Anilastus* are bred from bodies of *S. temperatella* larvae. In addition, in Turkey *S. temperatella* larvae were parasitized by *Bracon stabilis* Wesmael and *Apanteles* sp. (Hym., Braconidae) [18]. In Iran, *Diglyphus chabrias* Walker and

Necremnus tidius Walker (Hym., Eulophidae) [65], and *Sympiesis euspilapterygis* (Erdos) [66, 67] were found attacking *S. temperatella.* Therefore, almost care should be taken not to disturb the agro-ecosystem in order to give the chance for these parasitoids to build up their population successfully.Microbial control agents (pathogens) are effective and serve as alternatives to chemical insecticides [68]. The bacterium, *Bacillus thuringiensis* (Berliner) (*Bt*) has been known to be a reservoir of several insecticidal proteins that efficiently utilized to safely and effectively control a wide range of insect pests on vegetables, ornamentals, forest trees and stored grains [36, 69, 70] belongs to lepidopteran, coleopteran and dipteran [71]. Compared to chemical pesticides, *Bt* is highly toxic and specific to insects. Therefore, *Bt* is ideally suited for incorporation into IPM programs [69]. During the sporulation process, the bacteria produce large crystal proteins that are toxic to many insect pests [72]. However, adoption in Europe and many developing countries has been uneven [35].

In spite of *Bt* has been used in spray formulations for more than 40 years [69] against nearly 3,000 insect species [73], only few studies have evaluated its efficacy against *S. temperatella*. In Jordan, under laboratory conditions, Al-Zyoud *et al*. [21] indicated that *S. temperatella* larval mortality is affected by *Bt* concentration and time after bacterial application. After 3, 5 and 7 days of spraying, *Bt* var. *israelensis* caused 73%, 78% and 80% mortality to the pest on wheat, respectively. Also, after 3 and 5 days of application, the highest mortality was recorded for the high concentrations of *Bt* var. *kurstaki* with 54% and 71%, respectively [74]. Furthermore, Al-Dababseh *et al.* [75] investigated 22 *Bt* isolates and found that some isolates gave mortality reached up to 73% against the pest larvae. Under field conditions, one week after *Bt* spraying, the lowest infestation (61%) of barley plants was recorded for the high concentration of *Bt* var. *kurstaki* [74]. Comparing these results with another conducted by Al-Zyoud [27] on chemical control under the same laboratory conditions, *Bt* var. *kurstaki* and *Bt* var. *israelensis* caused higher mortality to *S. temperatella* larvae than methomyl (66%), lamda cyhalothrin (63%) and cypermethrin (48%). One of the most important factors affecting differences in *Bt* toxicity among the different studies is the *cry* gene content of the *Bt* strains used, in which the type of *cry* gene presents in a strain correlates to some extent with its insecticidal activity [76].

Daborn *et al*. [77] found that in an infected insect, the bacteria grow exponentially until the time of insect death, when the virulence factors are produced. In this regard, Al-Zyoud *et al*. [21] reported a gradual increase in the pest mortality at 3, 5 and 7 days post *Bt* spraying. It was found that all *Bt* isolates tested caused concentration related mortality, in which the highest mortality was recorded at the highest concentration that has the highest number of bacterial cells. Thus, both time and concentration play an important role in *Bt* efficacy. In the study of Al-Dababseh *et al*. [75], some isolates were found less effective (less than 40% mortality) against *S. temperatella* larvae. The reason behind this is that such isolates might not cause enough infection to the larvae as reported by Theunis and Aloali'i [78], in which they stated that *Bacillus popilliae* causes low pest mortality due to its inability to infect the beetle, *Papuana uninodis*. In addition, the same isolates investigated by Al-Dababseh *et al*. [75] were previously bio-assayed against *Ephestia kuehniella* by Meihiar *et al.* [79], and demonstrated that the most toxic isolates harbor different specific *cry* genes including *cryI* and *cryIV* which have insecticidal activity to Lepidoptera insects. This confirmed by Ammouneh *et al.* [76], in which the type of *cry* genes presents in the *Bt* strain was correlated to a certain extent with its insecticidal activity. It is to be mentioned that the number of bacterial cells is positively correlated with the amount of toxins they produced and the ability to cause death to the pest larvae [75]. Nevertheless, some *Bt* strains/isolates used in the different studies exhibit a toxic potential and, therefore, could be adopted for future control program to suppress the pest. It is expected that start applying *Bt* will drastically reduce and replace, at least in part, some of the most dangerous chemical insecticides currently used against the pest in Jordan and surrounding countries, making it an ideal component of IPM.

8. Chemical Control

It is unlikely that resistant cultivars, natural enemies or cultural control alone will maintain pest populations at acceptable levels, but through careful integration with pesticides it could represent a significant source of sustainable control, or back-up sprays may be appropriate during outbreaks of pests [80]. Because insecticides are likely to remain a major component of pest suppression, therefore, reduced rates of application, use of less persistent materials, temporal and spatial changes in application methods, changes in formulation, and application at right time are needed [81]. Concomitantly, it is necessary to present the results the efficacy of insecticides against this destructive pest to be able to help farmers to select the right insecticide and time in their control tactics, because until now there are no other control measures applying against the pest in Jordan and the surrounding countries.

Intensive application of chemical insecticides has been used to suppress *S. temperatella* in many countries [12, 15, 16, 27, 45, 51]. In Jordan, under laboratory conditions, Al-Zyoud [27] reported in a direct spray test that *S. temperatella* larval mortality was significantly affected by insecticide, time after application and concentration of the material. After three days of spray, most of insecticides caused significantly high mortality, and it reached 100% for diazinon, chlorpyrifos and fenitrothion. In a residual test, diazinon and chlorpyrifos caused larval mortalities of 69% and 64%, respectively [27]. In Jordan also under filed conditions, diazinon caused the highest mortality to *S. temperatella* on barley with 99.8%, followed by chlorpyrifos and fenitrothion (around 89%). When the plants were sprayed twice (early and late), diazinon, chlorpyrifos and fenitrothion caused 100% mortality. These three insecticides belong to the insecticidal group organophosphate, and it might be that this group is more toxic to the pest than the neonicotinoid group [28]. However, in Cyprus in a field test on barley, Serghiou [11] mentioned that mevinphos, fenitrothion, diazinon and chlorpyrifos were the best foliar-spray treatments. Later in Cyprus also, Melifronides [45] reported that diazinon, fenitrothion, phosphamidon, trichlorphon and mecarbam caused mortalities of 98, 97, 91, 92% and 90% to larvae after 4 days of application. In Turkey, Kaya [12] mentioned that diazinon proved effective against the larvae giving 96% mortality. Later, Koyuncu and Kurcman [82] showed that diazinon and azinphos-methyl applied at tiller formation in wheat and barley fields gave good results against *S. temperatella*. Moreover, in Turkey, the best rate of larval mortality was caused by chlorpyrifos (89% kill) [50]. In Iran, dursban caused only 50% mortality for the pest [51], while diazinon was effective against the pest [16]. In Iraq, chlordane gave the highest kill of larvae in the soil and prior to their entry into the plant when applied early in the season (January). Azinphos-methyl resulted in effective control of larvae [10]. In Iraq, spraying alpha cypermethrin and diazinon on wheat and barley was resulted in a decrease in the percentage of infested plants and number of live larvae, and live larvae were absent after 9-12 days in wheat and barley after treatment. Diazinon and cypermethrin showed some effects in reducing leafminer infestation [5]. Nevertheless, the above mentioned studies indicated that some insecticides caused high mortality to the pest (higher than 90%) and could be used against the pest.

It is important to be noted that the correct time of chemical control is very important. The infestation percentage was lower in an early spray rather than in a late spray [28]. Several workers reported that the best time for chemical treatment is when the crop at the 3-leaf stage, but it was not effective when done at the tillering stage [16, 31, 45, 82]. Chemicals applied early in the cropping period gave season-long control and results in greater yield increases than did an application made later [11]. It might be that the larvae in the early instars, which attack the crop in early growing stage, are more susceptible to insecticides than older larvae, and thus, they are killed by earlier applications of the insecticides. In addition, Kaya [12] mentioned that diazinon proved effective against the small larvae, giving up to 96% mortality, but timing of application was very important since mature larvae were more resistant to these compounds and suffered only 31% kill. However, in order to determine the correct time of chemical control, it is important to know the phenology of the pest in the field especially for the detective stage, which in this case is the larva. In this regards, in Jordan Al-Zyoud [17] reported that the larvae started feeding on plant leaves at early February until early April. In Israel, Avidov and Harpaz [46] reported that in January and early February the larvae penetrate the leaf mesophyll, and live in the leaves for about 2 months. In Iraq, the larvae start feeding on plants at late January until early April [5]. In Turkey, Kaya [12] reported that larvae began to mine the leaves at the end of February or beginning of March for 2 months. In conclusion, it seems that the best time of chemical control should be taken place from late February until early March, because the larvae are very active within this period and are more sensitive to insecticide applications.

Insecticides can be also sprayed on the soil or mixed with the seeds before sowing and not only applying them directly on the plants. In this regard, in Cyprus benzene hexachloride dust was broadcasted on the soil at the time of sowing, so that it is mixed with the soil surface when the seeds are covered and affects the aestivating first-stage larvae before they start attacking the crop [43]. Also, chlordane gave the highest kill of larvae in the soil and prior to their entry into the plant when applied early in the season [10]. In a wettable powder applied as a soil treatment, the best rates of larval mortality were afforded by chlorpyrifos (89% kill) and trichloronate (85%) [50]. Furthermore, granular diazinon was mixed with seeds of three wheat cultivars, and the results showed a low percentage of the infested leaves and larval population size [5].

9. Effect of Weather Conditions

The extent of the infestation by *S. temperatella* depends on the rainfall, if it is regularly over the season; the infested plants regain strength and continue to develop in spite of the insect damage [17]. Furthermore, rainfall and soil conditions play a part in determining susceptibility of cereal plants to *S. temperatella* infestation [10, 38]. In Iraq, environmental factors had an obvious influence on infestation intensity since the larval population size was associated with the environmental conditions, and it was found that drought during spring increased the infestation [39]. Madanat *et al.* [57] reported a variation in the susceptibility of the same wheat and barley accessions between two different cropping seasons, which could be mainly due to the high inter- and intraseasonal variation in terms of amount and distribution of rainfall during the different seasons. Since the plant capacity for compensation depends on the availability of moisture during the growing season, resistant accessions might compensate for insect infestation by producing more leaves and stems and, therefore, the infestation level was higher in the second cropping season than the first one [57], which agrees with a conclusion made by Duran *et al.* [50].

10. Conclusions

The cereal leafminer is distributed in Jordan, Iraq, Iran, Turkey, Cyprus, Greek, Syria and Lebanon, and attacks wheat, barley, wild barley, Egyptian clover, oats and the grass family. *S. temperatella* infestation reaches up to 70%, and causes yield reduction of 72% for wheat and barley, and straw biomass reduction of 72% for wheat and 59% for barley. Since the ETL for *S. temperatella* is 20% infestation, the pest requires control action since the infestation exceeded such a set threshold in all countries threatened. Barley is more preferred than wheat, and yield and straw losses were greater in barley than in wheat. The wheat cultivars, Acsad 65, Horani 27, Acsad 1273, Acsad 1245 and Umkais as well as the barley cultivars, Athroh and 1614 are the most resistant ones to the pest. These cultivars are promising, and could be useful as a source of genetic material for further studies in breeding programs for producing resistant cultivars. These cultivars showed low infestation, relatively high grain yield and straw biomass, and low larval population size attacking their foliage. Thus, farmers can start growing the resistant cultivars, and this would likely be useful in reducing the number of sprays currently applied against *S. temperatella*. Cultural methods of pest control form an important component of IPM. The infestation and pest population were the lowest in the crop rotation, wheat/ chickpea/wheat. Also, infestation and larval population were higher for plants grown in soil taken from an infested field at deeper depths (21-40 cm) than shallower ones (0-20 cm). Thus, ploughing should be done during August, provided that ploughing depth must reach up to 40 cm which will be of a great benefit to control the pest. In addition, changing the sowing time of cereals from autumn to spring might help positively in reducing the pest population. There are many natural enemies that can reduce the pest population, therefore, almost care should be taken not to disturb the agro-ecosystem in order to give the chance for these bio-agents to build up their population successfully. *Bt* var. *israelensis* and *kurstaki* caused mortality to the pest ranged from 72% to 80%, thus, it is expected that start applying *Bt* will reduce the pesticides usage, making it an ideal component of IPM. It is unlikely that alternative methods will maintain pest population at acceptable level, but through careful integration with insecticides it could represent a significant source of sustainable control. However, diazinon, chlorpyrifos and fenitrothion are the best foliar-spray treatments when the crop is at 3-leaf stage.More emphasis should be placed on regional and international cooperation. It appears that future studies should focus on producing plant cultivars which are immune to the pest, and rearing and releasing of natural enemies to increase their impact on the pest population. These future studies together with studies discussed in this review are expected to form the foundation of IPM for *S. temperatella* in Jordan and surrounding countries. Finally, it is hoped that the application of IPM practices will drastically replace, at least in part, the insecticides currently used against *S. temperatella* in the countries threatened.

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