# PLOS ONE

RESEARCH ARTICLE

# Sublethal effects of imidacloprid on the fitness of two species of wheat aphids, *Schizaphis graminum* (R.) and *Rhopalosiphum padi* (L.)

Xiang Ji[1], Yu-Tai Jiang[2☯], Tian-Xin Guo[3☯], Pei Zhang[2], Xin-an Li[2], Fan-Bin Kong[2]*, Bai-Zhong Zhang●[1,2]*

1 Hebi Institute of Engineering and Technology, Henan Polytechnic University, Hebi, P.R. China, 2 College of Resources and Environment, Henan Engineering Research Center of Biological Pesticide & Fertilizer Development and Synergistic Application, Henan Institute of Science and Technology, Xinxiang, P.R. China, 3 Department of Entomology, China Agricultural University, Beijing, P.R. China

☯ These authors contributed equally to this work.
* baizhongok@163.com (BZZ); 251315415@qq.com (FBK)

## Abstract

Imidacloprid is a neonicotinoid insecticide that efficiently controls piercing-sucking mouthparts pests. However, the impact of low lethal concentration of imidacloprid on key demographic parameters of wheat aphids, *Schizaphis graminum* (R.) and *Rhopalosiphum padi* (L.) has been scarcely studied. In this study, we used the age stage, two-sex life table approach to investigate the sublethal effects of imidacloprid on the biological traits of *S. graminum* and *R. padi*. Bioassays showed that imidacloprid possesses high toxicity to adult *S. graminum* and *R. padi*, with $LC_{50}$ of 3.59 and 13.78 mg $L^{-1}$ following 24 h exposure. A low lethal concentration of imidacloprid ($LC_{25}$) significantly decreased adult longevity and total longevity of progeny generation aphids ($F_1$) of *S. graminum*. Nevertheless, imidacloprid ($LC_{25}$) had no significant effects on the fecundity and longevity of directly exposed parental parental *S. graminum* and *R. padi* ($F_0$). Our results showed that the low lethal concentration of imidacloprid affected the demographic parameters that ultimately impact on the population of *S. graminum*. This study provides detailed information about the overall effects of imidacloprid on *S. graminum* and *R. padi* that might help to manage these two key pests.

## Introduction

Wheat aphids are the main agricultural pests in grain-growing areas of the world [1, 2]. *Schizaphis graminum* (R.)(Sg)and *Rhopalosiphum padi* (Rp)(L.) are important pests in wheat fields in China. They can cause severe damage to wheat crops, and they can also spread barley yellow dwarf virus, resulting in a large yield reduction and serious economic losses [3–6]. At present, chemical insecticides are the main method of controlling wheat aphids in the field, but long-term unscientific use of insecticides can lead to the development of wheat aphid resistance [7,

8]. In addition, insecticides gradually degrade to low lethal or sublethal concentrations after field application, resulting in sublethal effects on pests [9–12].

Sublethal effects are defined as impacts on the physiology and/or behaviour of individuals that survived exposure to insecticides at low lethal or sublethal concentrations [13]. Insecticides may have sublethal effects on insect physiology and behaviour [14], such as insect survival [15, 16], developmental duration [17–20], and fecundity [21–23].

Santos et al. [15] found that females of the Neotropical brown stink bug *Euschistus heros* had reduced rates of survival but higher fecundity and fertility rates under sublethal imidacloprid conditions. Chen et al. [18] found that exposure of *Aphis gossypii* Glover to imidacloprid at a low lethal concentration ($LC_{25}$) significantly increased the duration of their preadult stage and total preoviposition period as well as their mean generation time. Yuan et al. [22] found that the adults of cotton aphids.

(*Aphis gossypii* Glover) treated with a low lethal concentration ($LC_{10}$) and a lethal concentration ($LC_{40}$) of cycloxaprid had lower adult fecundity and net productive rates than controls.

Therefore, evaluating the sublethal effects of insecticides on pests provides better understanding of the response of pests to insecticides and has positive practical importance for guiding rational insecticide use in the field [9, 24, 25].

Imidacloprid acts on the acetylcholinesterase receptor in the nervous system of pests, interfering with the normal transmission of signals in their central nervous system and causing accumulation of high levels of acetylcholine; this causes a state of continuous excitation until paralysis and death. Therefore, it has high insecticidal activity and is characterized by high efficiency, low toxicity and a wide insecticidal spectrum [26–28]. Imidacloprid has a variety of effects on pests. It can be quickly absorbed by plants after application, so it has high control effects on piercing-sucking pests [29, 30], and it has been widely used to control wheat aphids in China.

Low or sublethal concentrations of insecticide typically occur due to field degradation and plant growth after the initial insecticide application [31]. Therefore, under field conditions, wheat aphids may be exposed to low lethal or sublethal concentrations of insecticides and exhibit sublethal effects on behaviour and physiology, with potential transgenerational transmission to the offspring of these surviving individuals [13, 32]. Xiao et al. [25] found that *Sitobion avenae* and *R. padi* have different responses exposure to pirimicarb. He et al. [33] found that sublethal concentrations of imidacloprid and bifenthrin significantly reduced phloem feeding, honeydew excretion and reproductive ability in *Bemisia tabaci*, while sublethal concentrations of chlorpyrifos and carbosulfan did not exert these harmful effects. Cui et al. [34] found that a sublethal concentration of cycloxaprid had a negative impact on the phloem-feeding behaviour and growth rate of *Sitobion avenae* in contact activity and root activity tests of cycloxaprid. Lashkari et al. [35] found that exposure of *Brevicoryne brassicae* to sublethal concentrations of imidacloprid and pymetrozine significantly reduced the intrinsic rate of increase ($r_m$) and the average fecundity of each female aphid and increased the mean generation time.

The construction and analysis of life tables can comprehensively describe population dynamics and help to clarify the sublethal effects of insecticides on pests [36]. Therefore, to evaluate the sublethal effects of imidacloprid on *S. graminum* and *R. padi*, life tables were constructed and analysed. This study is expected to guide scientific and rational insecticide use in the field and optimize the management of two important wheat aphids.

## Materials and methods

### Insects and insecticides

*S. graminum* and *R. padi* were fed fresh seedlings of Zhoumai 18 wheat and were reared under laboratory conditions with a temperature of 23–25°C, a relative humidity of 50%-65%, and a

photoperiod of 14 h:10 h (L:D). During this period, they were kept from contact with any chemicals. Imidacloprid (95% active ingredient, w/w) was obtained from Dow AgroSciences Inc. (USA).

## Insecticide bioassays

The lethal concentration of imidacloprid for aphids was determined by the aphid-dipping method as described previously [37]. The original imidacloprid (95%) was weighed, and then a certain amount of acetone was added to prepare a 1000 mg/L stock solution. The 5 concentrations (0.4-, 0.8-, 1.6-, 3.2-, and 6.4 mg $L^{-1}$ for *S. graminum*; 5-, 10-, 15-, 20-, and 25 mg $L^{-1}$ for *R. padi*) tested in the current study were created by dilution with 0.05% (v/v) TX-100 (surfactant) water.

Three repetitions of 25 aphids received treatment with one of these concentrations. Healthy wingless adult aphids raised on wheat seedlings were gently picked up with a writing brush, placed on fresh leaves, and then immersed in the imidacloprid solution for 10 s. After that, the leaves and aphids were removed with filter paper. The aphids were placed into a marked glass tube (1.5 cm in diameter, 7 cm in length) that was sealed with cotton. Surfactant was additionally used as a control treatment. After treatment, the aphids were reared under normal room conditions (temperature of 23–25°C, relative humidity of 50%-65%, photoperiod of 14 h:10 h (L:D). After 24 h, the aphids in each treatment were observed and recorded. The standard for judging the death of aphids is that only one leg moves or no movement is observed [38]. The $LC_{25}$ values of imidacloprid for *S. graminum* and *R. padi* were estimated using the bioassay results of imidacloprid; these concentrations were used in the experiments to determine the sublethal and transgenerational effects of imidacloprid. The obtained data were regarded as effective if the mortality rate of the control group was less than 5%, and PoloPlus software was used to carry out statistical analysis to determine the $LC_{25}$ and $LC_{50}$ values of imidacloprid on *S. graminum* and *R. padi*.

## Sublethal and transgenerational effects of imidacloprid on *S. graminum* and *R. padi*

The sublethal and transgenerational effects of imidacloprid on two wheat aphids were investigated based on the experimental design of the life table. Wheat seedlings (Zhoumai 18) were placed on the bottom of disposable cups (top: 7.5 cm in diameter, bottom: 5.0 cm in diameter, 4.2 cm in height) lined with moist filter paper to maintain the humidity level. The imidacloprid stock solution was diluted to $LC_{25}$ with distilled water containing 0.05% surfactant (Triton X-100). The *S. graminum* and *R. padi* adults on wheat seedlings were immersed in the $LC_{25}$ of imidacloprid for 10 s. Mortality was calculated at 24 h after treatment, and 40 surviving aphids were collected and reared in plastic dishes containing new wheat seedlings (Zhoumai 18), labelled $LC_{25}\_Sg\_F_0$ and $LC_{25}\_Rp\_F_0$. The control group was treated with 0.05% surfactant (Triton X-100) in distilled water and an equal volume of acetone; these groups were labelled $CK\_Sg\_F_0$ and $CK\_Rp\_F_0$. Therefore, four groups ($LC_{25}\_Sg\_F_0$, $CK\_Sg\_F_0$, $LC_{25}\_Rp\_F_0$ and $CK\_Rp\_F_0$) were established over 40 repetitions. The adult longevity of the $F_0$ generation aphids and the number of new nymphs produced in each replicate were recorded every 12 h until the adults died. After daily counts, $F_1$ generation nymphs were removed from the disposable cups.

New nymphs of the $F_1$ generation (age<24 h) were selected from each group, and replicates in the $F_1$ generation of the treatment and control groups were reared in disposable cups containing new wheat seedlings (Zhoumai 18). Forty repetitions were established for the four groups ($CK\_Sg\_F_1$, $LC_{25}\_Sg\_F_1$, $CK\_Rp\_F_1$, and $LC_{25}\_Rp\_F_1$). Thereafter, observations were

made every 12 h to record the developmental time in each growth stage of the $F_1$ generation, the duration and longevity of the spawning period, and the number of offspring produced by each $F_1$ adult. During the breeding period, new-born nymphs were counted and removed from disposable cups daily. The data obtained were used to construct the age-stage two-sex life tables.

## Life table analysis

The life history data for both *S. graminum* and *R. padi* were analysed according to age-stage two-sex life table theory [39] and the method described by Chi [40]. TWOSEX-MS Chart software [41–44] was used to analyse the data and calculate the intrinsic rate of increase ($r_m$), net reproductive rate ($R_0$), mean generation time ($T$), finite rate of increase ($\lambda$) and other curve data of life table parameters. GraphPad Prism (version 3.02, GraphPad Software, San Diego, CA) was used to construct survival rate, reproductive rate, life expectancy and reproductive rate curves. Student's t test was used to compare the developmental duration, longevity and aphid yield between the treatment and control groups, with a significance threshold of $p < 0.05$.

The life table parameters were calculated as follows:

Net reproductive rate:

$$R_0 = \sum l_x m_x$$

Finite rate of increase:

$$\lambda = e^{r_m}$$

Intrinsic rate of increase:

$$r_m = \ln R_0 / T$$

Mean generation time:

$$T = \sum (x l_x m_x) / \sum l_x m_x$$

In the above formula, $x$ is the time interval (1 day), $l_x$ is the survival rate of any individual during period $x$, and $m_x$ is the average number of aphids produced per female aphid during period x.

## Results

### Lethal concentrations

The $LC_{50}$ values of imidacloprid for *S. graminum* and *R. padi* were 3.59 and 13.78 mg $L^{-1}$, and the $LC_{25}$ concentrations of imidacloprid for *S. graminum* and *R. padi* were 1.13 and 7.43 mg $L^{-1}$, respectively. *R. padi* was more sensitive to imidacloprid ($LC_{50}$ = 3.59 mg $L^{-1}$) than *S. graminum* ($LC_{50}$ = 13.78 mg $L^{-1}$) (Table 1).

### Sublethal effects of imidacloprid on the longevity and fecundity of the $F_0$ generation of *S. graminum* and *R. padi*

*S. graminum* and *R. padi* were treated with their respective $LC_{25}$ of imidacloprid, and the mortality of the aphids was calculated after 24 h. The mortality rates of *S. graminum* and *R. padi* were 24.44% and 26.67%, respectively (Table 1). The surviving individuals of *S. graminum* and *R. padi* were selected and used as the $F_0$ generation for subsequent life table construction. The

**Table 1. The lethal and sublethal concentrations of imidacloprid for *Schizaphis graminum* and *Rhopalosiphum padi*.**

| Species | LC$_{50}$ (95% CI)(mg L$^{-1}$) | LC$_{25}$ (95% CI)(mg L$^{-1}$) | Concentrations in treatment | Mortality (%) |
|---|---|---|---|---|
| *R. padi* | 13.78 (11.70–16.41) | 7.43 (5.41–9.05) | 7.50 | 24.44 |
| *S. graminum* | 3.59 (2.32–1.83) | 1.13 (0.38–1.83) | 1.50 | 26.67 |

1) LC$_{50}$, 50% lethal concentration; CI, confidence interval; LC$_{25}$, 25% lethal concentration.

**Table 2. Sublethal effects of imidacloprid on the longevity and fecundity of the F$_0$ generation of *Schizaphis graminum* and *Rhopalosiphum padi*.**

| Aphid species | Life table parameter | Control[1] | Imidacloprid[2] | t | P value |
|---|---|---|---|---|---|
| *S. Graminum* (Sg) | Adult longevity | 11.88±0.46 a | 11.33±0.38 a | 0.923 | 0.359 |
| | Total fecundity | 21.03±0.83 a | 22.73±0.76 a | -1.512 | 0.134 |
| *R. Padi* (Rp) | Adult longevity | 13.52±1.08 a | 10.55±1.37 a | 1.697 | 0.095 |
| | Total fecundity | 20.10±2.68 a | 13.17±2.69 a | 1.826 | 0.073 |

[1] Treated without insecticide, including two groups: CK_Sg_F$_0$ for S. *graminum* and CK_Rp_F$_0$ for *R. padi*.

[2] Treated with the sublethal dose of imidacloprid, including two groups: LC$_{25}$_Sg_F$_0$ for *S. graminum* and LC$_{25}$_Rp_F$_0$ for *R. padi*. Data (mean±SE) in the same row followed by different letters are significantly different (P<0.05) from those of the controls according to Student's t test.

parameter data of aphids treated with the LC$_{25}$ of imidacloprid (the F$_0$ generation) are shown in Table 2. For the F$_0$ generation of *S. graminum* and *R. padi*, no significant differences were observed between the treatment and control groups in terms of longevity and fecundity (P>0.05).

## Transgenerational effects on life table parameters

In the F$_1$ generation of *S. graminum*, no significant difference was observed between the treatment and control groups in terms of the duration of the complete nymph stage (preadulthood), the duration of the adult preoviposition period (APOP), the duration of the total preoviposition period (TPOP), the reproductive period or the total longevity (P>0.05). However, the adult longevity and the total longevity of the treatment groups were significantly shorter than those of the control groups (P<0.05). In the F$_1$ generation of *R. padi*, there were no significant differences in any life table parameters between the treatment and control groups (P<0.05) (Table 3).

The age-stage specific survival rates ($S_{xj}$) of both *S. graminum* (CK_Sg_F$_1$ and LC$_{25}$_Sg_F$_1$) and *R. padi* (CK_Rp_F$_1$ and LC$_{25}$_Rp_F$_1$) are shown in Fig 1A and 1B. The curve in Fig 1 reflects the probability that the new-born nymph survive to age x and period j. The survival rate curve shows the differences in survival between the CK_Sg_F$_1$ group and LC$_{25}$_Sg_F$_1$ group and between the CK_Rp_F$_1$ group and LC$_{25}$_Rp_F$_1$ group. Due to differences in developmental rates, there is significant overlap between periods (Fig 1). The age-specific reproductive rate curve ($m_x$) showed that the LC$_{25}$_Sg_F$_1$ group began to reproduce on the 5th day, reproduction peaked on days 9 to 11, and the reproductive period ended on the 21st day. In the control group (CK_Sg_F$_1$), reproduction began on the 5th day, peaked from days 8 to 10, and ended on the 21st day (Fig 2A). The average reproductive period of the LC$_{25}$_Sg_F$_1$ group was 8.11 days, similar to that of the control group (8.44 days) (Table 3). Each female aphid in the LC$_{25}$_Sg_F$_1$ group produced 21.92 aphids on average, while each female aphid in the control group produced 22.28 aphids on average (Table 3). Therefore, the total fecundity of the LC$_{25}$_Sg_F$_1$ group was slightly lower than that of the CK_Sg_F$_1$ group, but the difference was

**Table 3. Sublethal effects of imidacloprid on the developmental duration and fecundity of the F₁ generation of *Schizaphis graminum* and *Rhopalosiphum padi*.**

| Parameter | *S. graminum* | | | *R. padi* | | |
|---|---|---|---|---|---|---|
| | CK_Sg_F$_1$ | LC$_{25}$_Sg_F$_1$ | P value | CK_Rp_F$_1$ | LC$_{25}$_Rp_F$_1$ | P value |
| L1 (d) | 1.92±0.073 | 1.85±0.062 | 0.473 | 1.72±0.057 | 1.70±0.056 | 0.837 |
| L2 (d) | 1.90±0.066 | 1.92±0.061 | 0.878 | 1.65±0.064 | 1.68±0.074 | 0.734 |
| L3 (d) | 1.82±0.069 | 1.85±0.074 | 0.785 | 1.72±0.057 | 1.57±0.079 | 0.128 |
| L4 (d) | 1.95±0.061 | 2.03±0.064 | 0.453 | 1.68±0.051 | 1.58±0.90 | 0.337 |
| Preadulthood (d) | 7.60±0.148 | 7.64±0.154 | 0.846 | 6.77±0.137 | 6.53±0.232 | 0.391 |
| APOP (d) | 0.15±0.044 | 0.17±0.045 | 0.825 | 0.18±0.051 | 0.18±0.050 | 0.816 |
| TPOP (d) | 7.75±0.162 | 7.81±0.159 | 0.807 | 6.93±0.143 | 6.70±0.237 | 0.403 |
| Oviposition period (d) | 8.44±0.440 | 8.11±0.425 | 0.588 | 8.15±0.938 | 8.70±0.980 | 0.687 |
| Adult longevity (d) | 12.33±0.532 | 10.61±0.574 | 0.031 | 10.43±0.949 | 10.80±1.041 | 0.795 |
| Total longevity (d) | 20.14±0.549 | 18.36±0.584 | 0.030 | 17.37±0.945 | 17.50±1.158 | 0.929 |
| Fecundity | 21.92±1.248 | 22.28±1.320 | 0.843 | 19.50±2.559 | 22.67±2.716 | 0.400 |

[1] L1, the first nymph stage; L2, the second nymph stage; L3, the third nymph stage; L4, the fourth nymph stage; Preadulthood, the duration of the complete nymph stage; APOP, the duration of the adult preoviposition period. TPOP, the duration of the total preoviposition period.
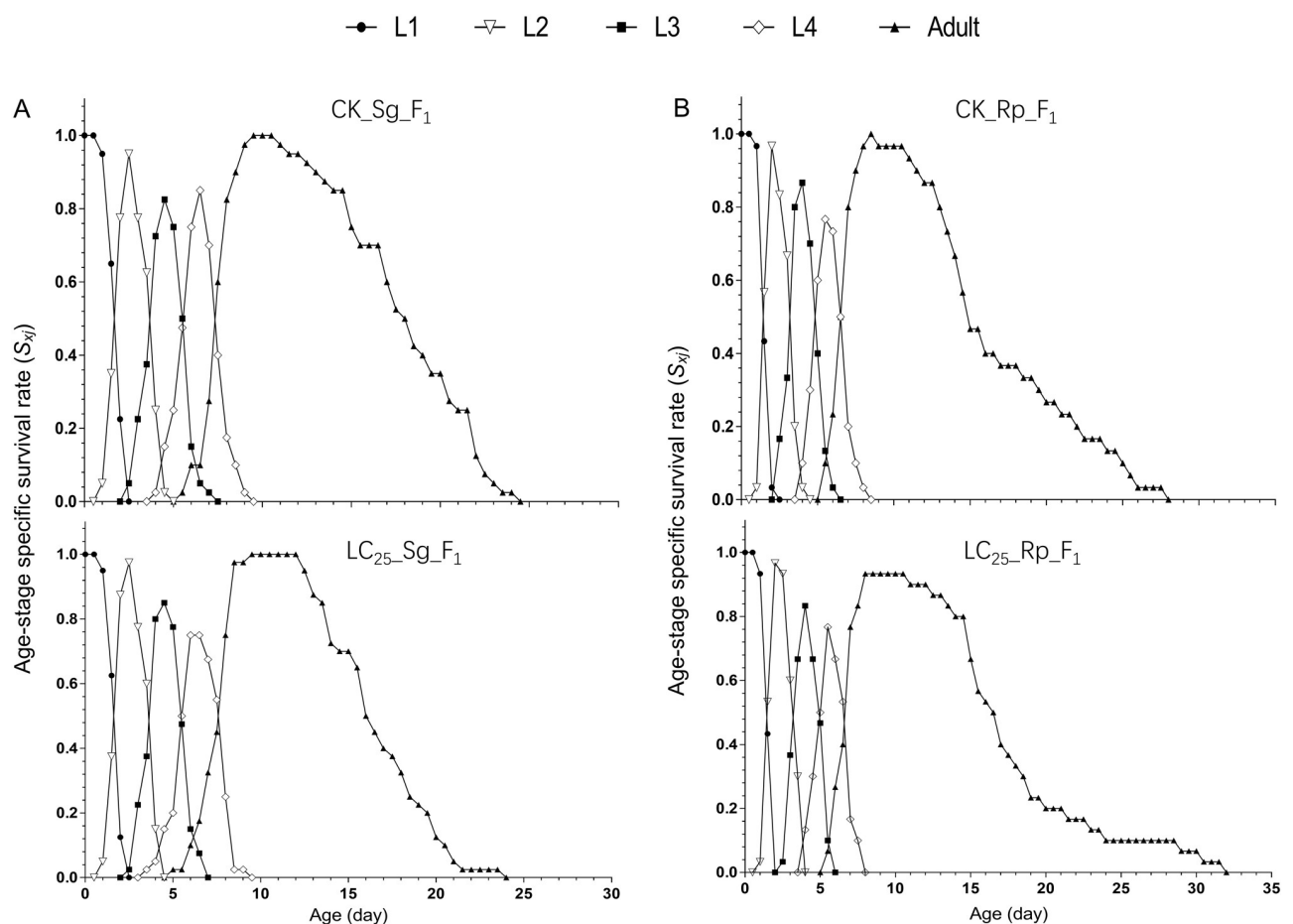
https://doi.org/10.1371/journal.pone.0294877.t003



**Fig 1. Age-stage-specific survival rates ($S_{xj}$) of the F₁ generation of *Schizaphis graminum* and *Rhopalosiphum padi*, with the control groups compared with the groups treated with sublethal concentrations of imidacloprid.** A, $S_{xj}$ of the F₁ generation of *Schizaphis graminum*. B, $S_{xj}$ of the F₁ generation of *Rhopalosiphum padi*. L1, the first nymph stage; L2, the second nymph stage; L3, the third nymph stage; L4, the fourth nymph stage.
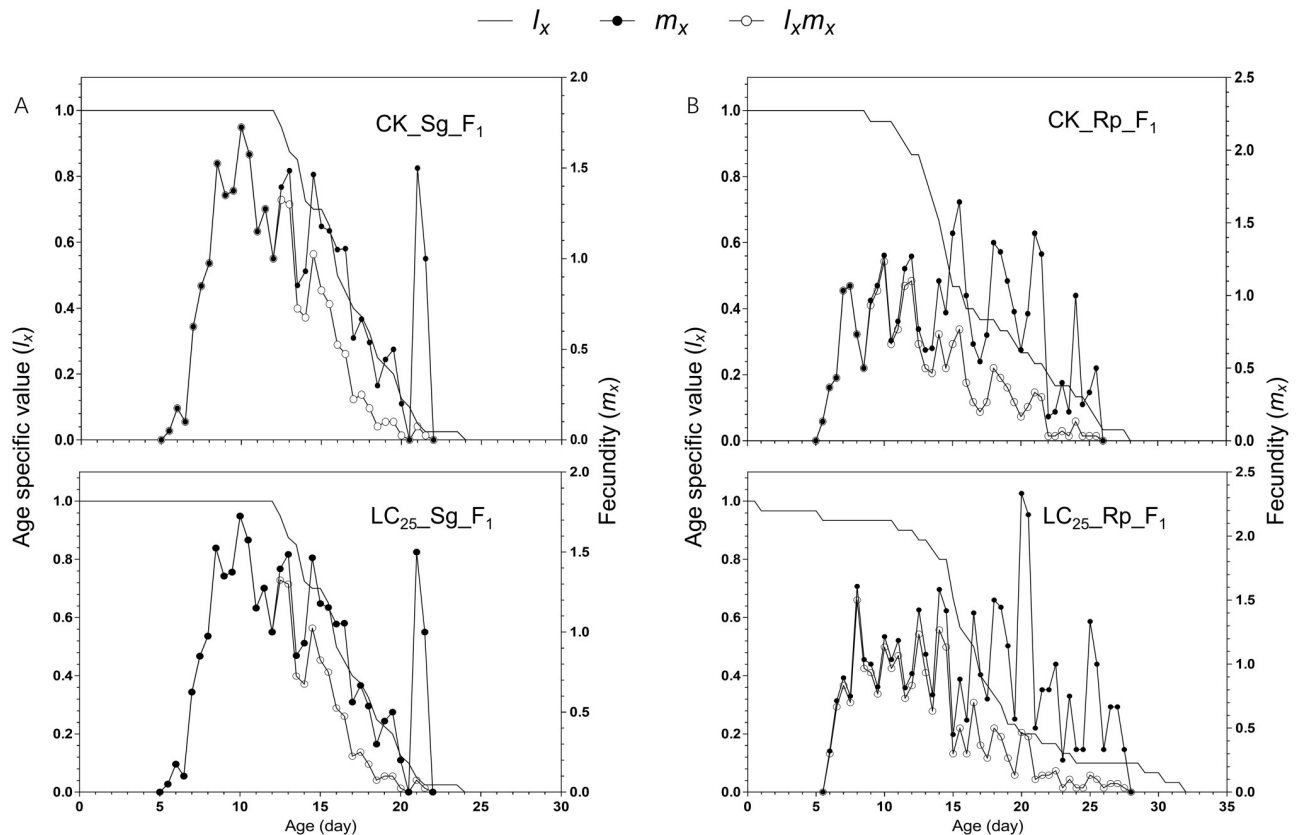
https://doi.org/10.1371/journal.pone.0294877.g001

**Fig 2. Age-specific survival rate ($l_x$), age-specific fecundity of the total population ($m_x$), and age-specific fertility ($l_x m_x$) of the $F_1$ generation of** *Schizaphis graminum* **and** *Rhopalosiphum padi*, **with the control groups compared with the groups treated with sublethal concentrations of imidacloprid.** A, $l_x$, $m_x$ and $l_x m_x$ of the $F_1$ generation of *Schizaphis graminum*. B, $l_x$, $m_x$ and $l_x m_x$ of the $F_1$ generation of *Rhopalosiphum padi*.

not significant. The age-specific reproductive rate curve ($m_x$) showed that the $LC_{25}$_Rp_$F_1$ group began to reproduce on the 7th day and stopped producing aphids on the 28th day, while the control group began to reproduce on Day 5.5 and stopped producing aphids on the 26th day. The fecundity of the $LC_{25}$_Rp_$F_1$ and CK_Rp_$F_1$ groups peaked from days 7 to 11. Females in the $LC_{25}$_Rp_$F_1$ and CK_Rp_$F_1$ groups produced an average of 19.5 and 22.7 aphids, respectively; this difference was not significant (Table 3). There was no evidence that imidacloprid had transgenerational effects on the age-specific survival rate ($l_x$) of *S. graminum* and *R. padi* (Fig 2).

Age-period life expectancy ($e_{xj}$) represents the length of time that an individual aphid of age x in period j is expected to survive. The life expectancies of new-born nymphs of *S. graminum* in the treated and control groups were 18.5 and 17.5 days, respectively (Fig 3A). The life expectancies of new-born *R. padi* nymphs in the treatment and control groups were 17.3 and 17.1 days, respectively (Fig 3B).

## Transgenerational effects on population parameters

The $LC_{25}$ of imidacloprid was used to treat the two wheat aphids. Subsequently, the life table parameters of the $F_1$ generation were assessed and are shown in Table 4. No significant differences in life table parameters were observed between the $LC_{25}$_Sg_$F_1$ and CK_Sg_$F_1$ groups (of *S. graminum)* or between the $LC_{25}$_Rp_$F_1$ and CK_Rp_$F_1$ groups (of *R. padi)* (Table 4).
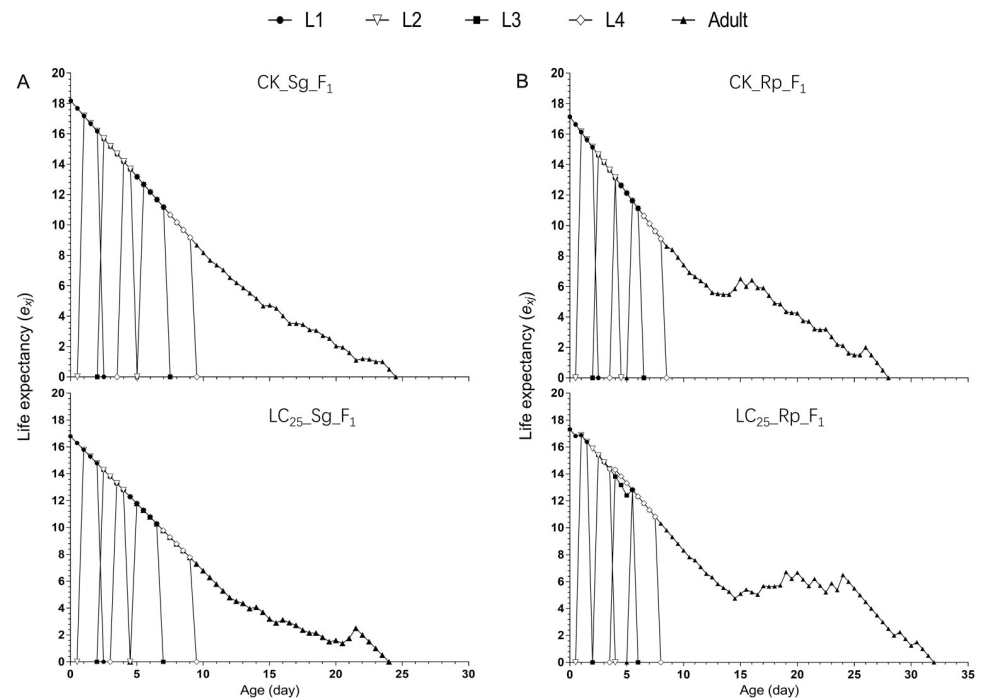
**Fig 3. Age-stage-specific life expectancy ($e_{xj}$) of the $F_1$ generation of *Schizaphis graminum* and *Rhopalosiphum padi*, with the control groups compared with the groups treated with sublethal concentrations of imidacloprid.** A, $e_{xj}$ of the $F_1$ generation of *Schizaphis graminum*. B, $e_{xj}$ of the $F_1$ generation of *Rhopalosiphum padi*.

The age-period reproductive rate ($V_{xj}$) represents the expected contribution of aphid individuals at age x and period j to the future population (Fig 4). The age-period reproductive rate ($V_{xj}$) trends of *S. graminum* and *R. padi* were similar in the treated and control groups.

## Discussion

In this study, we used age-stage, two-sex life table to investigate the transgenerational sublethal effects of imidacloprid on demographic parameters of *S. graminum* and *R. padi*. Bioassay results showed that imidacloprid is high toxicity to adult *S. graminum* and *R. padi*, with $LC_{50}$ of 3.59 and 13.78 mg $L^{-1}$ following 24 h exposure.

Applied insecticide concentrations typically degrade to low and sublethal concentrations due to field degradation and plant growth, resulting in frequent exposure of pests to low or sublethal concentration [31]. Low or sublethal concentration of insecticides ultimately affect

**Table 4. Sublethal effects of imidacloprid on the population parameters of the $F_1$ generation of *Schizaphis graminum* and *Rhopalosiphum padi*.**

| Life table parameter | *S. graminum* | | *R. padi* | |
|---|---|---|---|---|
| | CK_Sg_$F_1$ | LC$_{25}$_Sg_$F_1$ | CK_Rp_$F_1$ | LC$_{25}$_Rp_$F_1$ |
| Net reproductive rate | 20.700±1.863 a | 20.050±1.802 a | 19.500±2.121 a | 22.433±4.027 a |
| Mean generation time | 22.538±0.317 a | 22.284±0.713 a | 21.862±1.086 a | 22.010±0.553 a |
| Intrinsic rate of increase | 0.132±0.005 a | 0.134±0.007 a | 0.136±0.004 a | 0.136±0.006 a |
| Finite rate of increase | 1.143±0.005 a | 1.144±0.007 a | 1.145±0.005 a | 1.148±0.006 a |

Note: Data in the same row followed by different letters are significantly different at $P < 0.05$ according to the Tukey–Kramer test.
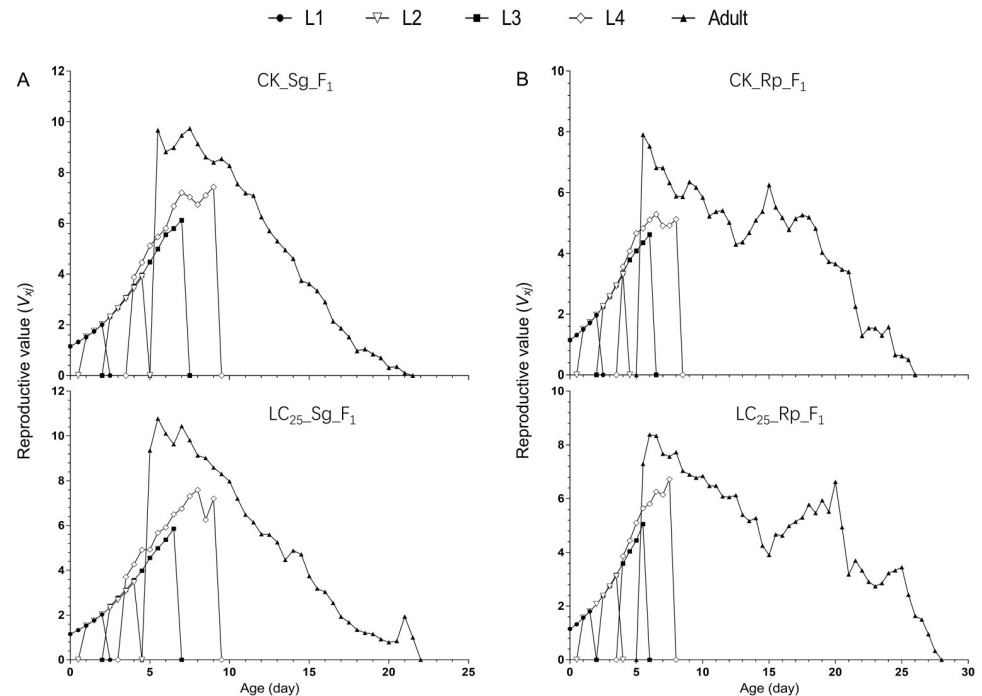
**Fig 4. Age-stage reproductive value ($v_{xj}$) of the $F_1$ generation of *Schizaphis graminum* and *Rhopalosiphum padi*, with the control groups compared with the groups treated with sublethal concentrations of imidacloprid.** A, $v_{xj}$ of the $F_1$ generation of *Schizaphis graminum*. B, $v_{xj}$ of the $F_1$ generation of *Rhopalosiphum padi*.

the physiological and behavioral traits of exposed individuals, such as lifespan, developmental period, fecundity, host finding, and feeding activity [13, 14, 45]. Therefore, indepth information about the impact of low or sublethal concentration of imidacloprid on the biological parameters might be crucial for managing *S. graminum* and *R. padi* under field contexts.

The findings demonstrated that low lethal concentration ($LC_{25}$) of imidacloprid had no significant effects on the fecundity and longevity of directly exposed parental parental *S. graminum* and *R. padi* ($F_0$). This is somewhat similar to the results that low lethal concentration of sulfoxaflor did not cause significant effects on the fecundity or the longevity of the parent generation ($F_0$ generation) of either *S. avenae* or *R. padi* [46]. However, Lu et al. [47] reported that both *S. avenae* and *R. padi* exhibited significantly decreased fecundity and longevity after pulse exposure to sublethal concentrations of imidacloprid for more than three generations. Ullah et al. [48] found that $LC_5$ and $LC_{15}$ of imidacloprid significantly decreased the longevity and fecundity of melon aphids. Likewise, a short lifespan and reduced fecundity were also reported in *M. persicae* when exposed to sublethal concentrations of flupyradifurone [49]. These findings demonstrated that along with lethal effects, the sublethal concentrations of chemical insecticides have detrimental effects on the lifespan and fecundity of surviving aphids.

In this study, low lethal concentration of imidacloprid ($LC_{25}$) significantly decreased the adult longevity and total longevity of progeny generation aphids ($F_1$) of *S. graminum*, while not of *R. padi*. Our results are consistent with those of Vakhide and Safavi [50] that the low lethal concentrations of acetamiprid substantially decreased the longevity and fecundity of *S. graminum*. Furthermore, Liang et al. [51] reported the decreased longevity of *A. gossypii* following exposure to the $LC_{25}$ of flupyradifurone. Similar effects have also been reported on *Sogatella furcifera* Horváth (Hemiptera: Delphacidae) and *Scolothrips longicornis* Priesner

(Thysanoptera: Thripidae) when treated with low lethal concentrations of buprofezin and abamectin [52, 53]. However, some studies reported that the developmental duration of $F_1$ generation insects was prolonged after the parent aphid ($F_0$) was exposed to sublethal and low lethal concentrations of pesticides. Ullah et al. [54] found that the developmental duration of 1st instar *A. gossypii* increased when treated with $LC_{15}$ of thiamethoxam. Likewise, Mostafiz et al. [11] reported that the low lethal concentrations of methyl benzoate extended the larval developmental time of $F_1$ generation *A. gossypii*. This could happen when insects devote energy to the detoxification of chemical insecticides and survive at the cost of development [55, 56].

In our study, the results show that there was no significant difference in the pre-adult stage, fecundity and key demographic parameters in $F_1$ individuals after exposure of parental *S. graminum* and *R. padi* ($F_0$) to imidacloprid. However, it should be noted that different sublethal concentration of insecticides have different effects on the fecundity and key demographic parameters of insects. James [57] found that the recommended concentration of imidacloprid could stimulate the population growth and spawning rate of *Amblyseius victoriensis*. Cutler et al. [58] exposed *Myzus persicae* to low concentrations of imidacloprid and found that they had no obvious effects on the reproductive rate of the parents, but the reproductive rate of the offspring was changed to some extent. Koo et al. [59] reported that the $LC_{30}$ of flonicamid significantly reduced the longevity, fecundity and net reproductive rate ($R_0$) of *A. gossypii*. Ma et al. [12] reported that key biological parameters including $R_0$, $r$, $\lambda$, and $F$ were decreased significantly, while T and TPRP were increased when *A. gossypii* were exposed to the sublethal concentration of afidopyropen. Therefore, the nonlethal negative effects of chemical insecticides on the demographic parameters of individuals might affect the population growth [60].

Together, imidacloprid ($LC_{25}$) significantly decreased the adult longevity and total longevity of progeny generation aphids ($F_1$) of *S. graminum*, while not of *R. padi*. Nevertheless, $LC_{25}$ of imidacloprid had no significant effects on the fecundity and longevity of directly exposed parental parental *S. graminum* and *R. padi* ($F_0$). Besides, there was no significant difference in the pre-adult stage, fecundity and key demographic parameters in $F_1$ individuals after exposure of parental *S. graminum* and *R. padi* ($F_0$) to imidacloprid. These results provides indepth information about the overall effects of imidacloprid on *S. graminum* and *R. padi* that might help to manage these two key pests.

## Supporting information

**S1 File.**
(ZIP)

## Author Contributions

**Conceptualization:** Pei Zhang.

**Data curation:** Xiang Ji, Tian-Xin Guo, Fan-Bin Kong.

**Formal analysis:** Tian-Xin Guo.

**Funding acquisition:** Fan-Bin Kong.

**Investigation:** Xiang Ji, Pei Zhang.

**Methodology:** Xiang Ji, Tian-Xin Guo.

**Project administration:** Yu-Tai Jiang, Pei Zhang.

**Resources:** Yu-Tai Jiang, Tian-Xin Guo, Pei Zhang.

**Software:** Yu-Tai Jiang, Xin-an Li, Fan-Bin Kong.

**Supervision:** Fan-Bin Kong.

**Validation:** Xin-an Li, Bai-Zhong Zhang.

**Visualization:** Xin-an Li, Bai-Zhong Zhang.

**Writing – original draft:** Tian-Xin Guo, Xin-an Li, Bai-Zhong Zhang.

**Writing – review & editing:** Bai-Zhong Zhang.

# References

1. Lu Y., Gao X., 2009. Multiple mechanisms responsible for differential susceptibilities of *Sitobion avenae* (Fabricius) and *Rhopalosiphum padi* (Linnaeus) to pirimicarb. *Bulletin of Entomological Research*, 99 (6), 611–617.

2. Lu Y. H., He Y. P., Gao X. W., 2013. Comparative studies on acetylcholinesterase characteristics between the aphids, *Sitobion avenae* and *Rhopalosiphum padi*. *Journal of Insect Science*, 13(1).

3. Zhang X. C., Zhou G. H., Shi M., Fang J. Z., Zhao Z. P., Li S. H., et al, 1985. The rules of long distance migration and virus transmission of wheat aphids. *Journal Plant Protection*, 12, 9–16.

4. Jiménez-Martínez E. S., Bosque-Pérez N. A., 2004. Variation in barley yellow dwarf virus transmission efficiency by *Rhopalosiphum padi* (Homoptera: Aphididae) after acquisition from transgenic and non-transformed wheat genotypes. *Journal of Economic Entomology*, 97(6), 1790–1796.

5. Tamborindeguy C., Bereman M. S., DeBlasio S., Igwe D., Smith D. M., White F., et al., 2013. Genomic and proteomic analysis of Schizaphis graminum reveals cyclophilin proteins are involved in the transmission of cereal yellow dwarf virus. *PLoS One*, 8(8), e71620. https://doi.org/10.1371/journal.pone.0071620 PMID: 23951206

6. Del Blanco I. A., Hegarty J., Gallagher L. W., Falk B. W., Brown-Guedira G., Pellerin E., et al., 2014. Mapping of QTL for tolerance to Cereal yellow dwarf virus in two-rowed spring barley. *Crop Science*, 54 (4), 1468–1475. https://doi.org/10.2135/cropsci2013.11.0781 PMID: 27212713

7. Bass C., Denholm I., Williamson M. S., Nauen R., 2015. The global status of insect resistance to neonicotinoid insecticides. *Pesticide Biochemistry and Physiology*, 121, 78–87. https://doi.org/10.1016/j.pestbp.2015.04.004 PMID: 26047114

8. Luo K., Zhao H., Wang X., Kang Z., 2021. Prevalent pest management strategies for grain aphids: Opportunities and challenges. *Frontiers in Plant Science*, 12. https://doi.org/10.3389/fpls.2021.790919 PMID: 35082813

9. Miao J., Du Z. B., Wu Y. Q., Gong Z. J., Jiang Y. L., Duan Y., et al., 2014. Sublethal effects of four neonicotinoid seed treatments on the demography and feeding behaviour of the wheat aphid *Sitobion avenae*. *Pest Management Science*, 70(1), 55–59.

10. Qu Y., Xiao D., Li J., Chen Z., Biondi A., Desneux N., et al., 2015. Sublethal and hormesis effects of imidacloprid on the soybean aphid *Aphis glycines*. *Ecotoxicology*, 24(3), 479–487.

11. Mostafiz M. M., Alam M. B., Chi H., Hassan E., Shim J. K., Lee K. Y., 2020. Effects of sublethal doses of methyl benzoate on the life history traits and acetylcholinesterase (AChE) activity of *Aphis gossypii*. *Agronomy*, 10(9), 1313.

12. Ma K.S., Tang Q. L., Liang P. Z., Li J. H., Gao X. W., 2022. A sublethal concentration of afidopyropen suppresses the population growth of the cotton aphid, *Aphis gossypii* Glover (Hemiptera: Aphididae). *Journal of Integrative Agriculture*, 21(7), 2055–2064.

13. Desneux N., Decourtye A., Delpuech J. M., 2007. The sublethal effects of pesticides on beneficial arthropods. *Annual Review of Entomology*, 52(1), 81–106. https://doi.org/10.1146/annurev.ento.52.110405.091440 PMID: 16842032

14. Gul H., Haq I., Ullah F., Khan S., Yaseen A., Shah S.H., et al., 2023. Impact of sublethal concentrations of flonicamid on key demographic parameters and feeding behavior of *Schizaphis graminum*. Ecotoxicology. https://doi.org/10.1007/s10646-023-02682-3 PMID: 37462788

15. Santos M. F., Santos R. L., Tomé H. V. V., Barbosa W. F., Martins G. F., Guedes R. N. C., et al., 2016. Imidacloprid-mediated effects on survival and fertility of the Neotropical brown stink bug *Euschistus heros*. *Journal of Pest Science*, 89(1), 231–240.

16. Zhen C., Miao L., Gao X., 2018. Sublethal effects of sulfoxaflor on biological characteristics and vitellogenin gene (AlVg) expression in the mirid bug, *Apolygus lucorum* (Meyer-Dür). *Pesticide Biochemistry and Physiology*, 144, 57–63.

17. Pan H., Liu Y., Liu B., Lu Y., Xu X., Qian X., et al., 2014. Lethal and sublethal effects of cycloxaprid, a novel cis-nitromethylene neonicotinoid insecticide, on the mirid bug *Apolygus lucorum*. *Journal of Pest Science*, 87(4), 731–738.

18. Chen X., Ma K., Li F., Liang P., Liu Y., Guo T., et al., 2016. Sublethal and transgenerational effects of sulfoxaflor on the biological traits of the cotton aphid, *Aphis gossypii* Glover (Hemiptera: Aphididae). *Ecotoxicology*, 25(10), 1841–1848.

19. Xu L., Zhao C. Q., Zhang Y. N., Liu Y., Gu Z. Y., 2016. Lethal and sublethal effects of sulfoxaflor on the small brown planthopper *Laodelphax striatellus*. *Journal of Asia-Pacific Entomology*, 19(3), 683–689.

20. Passos L. C., Soares M. A., Collares L. J., Malagoli I., Desneux N., Carvalho G. A. (2018). Lethal, sublethal and transgenerational effects of insecticides on *Macrolophus basicornis*, predator of *Tuta absoluta*. *Entomol Gen*, 38(2), 127–143.

21. Bao H., Liu S., Gu J., Wang X., Liang X., Liu Z., 2009. Sublethal effects of four insecticides on the reproduction and wing formation of brown planthopper, *Nilaparvata lugens*. *Pest Management Science*: *Formerly Pesticide Science*, 65(2), 170–174.

22. Zhang J., Yuan F., Liu J., Chen H., Zhang R., 2010. Sublethal effects of nitenpyram on life-table parameters and wing formation of *Nilaparvata lugens* (Stål)(Homoptera: Delphacidae). *Applied Entomology and Zoology*, 45(4), 569–574.

23. Yuan H. B., Li J. H., Liu Y. Q., Cui L., Lu Y. H., Xu X. Y., et al., 2017. Lethal, sublethal and transgenerational effects of the novel chiral neonicotinoid pesticide cycloxaprid on demographic and behavioral traits of *Aphis gossypii* (Hemiptera: Aphididae). *Insect Science*, 24(5), 743–752.

24. He Y., Zhao J., Zheng Y., Desneux N., Wu K., 2012. Lethal effect of imidacloprid on the coccinellid predator *Serangium japonicum* and sublethal effects on predator voracity and on functional response to the whitefly *Bemisia tabaci*. *Ecotoxicology*, 21(5), 1291–1300.

25. Xiao D., Yang T., Desneux N., Han P., Gao X., 2015. Assessment of sublethal and transgenerational effects of pirimicarb on the wheat aphids *Rhopalosiphum padi* and *Sitobion avenae*. *PLoS One*, 10(6), e0128936.

26. Oliveira E. E., Schleicher S., Büschges A., Schmidt J., Kloppenburg P., Salgado V. L., 2011. Desensitization of nicotinic acetylcholine receptors in central nervous system neurons of the stick insect (*Carausius morosus*) by imidacloprid and sulfoximine insecticides. *Insect Biochemistry and Molecular Biology*, 41(11), 872–880.

27. Kim Y. H., Issa M. S., Cooper A. M., Zhu K. Y., 2015. RNA interference: applications and advances in insect toxicology and insect pest management. *Pesticide Biochemistry and Physiology*, 120, 109–117. https://doi.org/10.1016/j.pestbp.2015.01.002 PMID: 25987228

28. Ihara M., D Buckingham S., Matsuda K., B Sattelle D., 2017. Modes of action, resistance and toxicity of insecticides targeting nicotinic acetylcholine receptors. *Current Medicinal Chemistry*, 24(27), 2925–2934. https://doi.org/10.2174/0929867324666170206142019 PMID: 28176635

29. Tomizawa M., Casida J. E., 2003. Selective toxicity of neonicotinoids attributable to specificity of insect and mammalian nicotinic receptors. *Annual Review of Entomology*, 48, 339–364. https://doi.org/10.1146/annurev.ento.48.091801.112731 PMID: 12208819

30. Kundoo A. A., Dar S. A., Mushtaq M., Bashir Z., Dar M. S., Gul S., et al., 2018. Role of neonicotinoids in insect pest management: A review. *Journal of Entomology and Zoology Studies*, 6(1), 333–9.

31. Desneux N., Fauvergue X., Dechaume-Moncharmont F. X., Kerhoas L., Ballanger Y., Kaiser L., 2005. *Diaeretiella rapae* limits *Myzus persicae* populations after applications of deltamethrin in oilseed rape. *Journal of Economic Entomology*, 98(1), 9–17.

32. Liu Y., Lu Y., Wu K., Wyckhuys K. A., Xue F., 2008. Lethal and sublethal effects of endosulfan on *Apolygus lucorum* (Hemiptera: Miridae). *Journal of Economic Entomology*, 101(6), 1805–1810.

33. He Y., Zhao J., Zheng Y., Weng Q., Biondi A., Desneux N., et al., 2013. Assessment of potential sublethal effects of various insecticides on key biological traits of the tobacco whitefly, *Bemisia tabaci*. *International Journal of Biological Sciences*, 9(3), 246.

34. Cui L., Sun L., Yang D., Yan X., Yuan H., 2012. Effects of cycloxaprid, a novel cis-nitromethylene neonicotinoid insecticide, on the feeding behaviour of *Sitobion avenae*. *Pest Management Science*, 68(11), 1484–1491.

35. Lashkari M. R., Sahragard A., Ghadamyari M., 2007. Sublethal effects of imidacloprid and pymetrozine on population growth parameters of cabbage aphid, *Brevicoryne brassicae* on rapeseed, *Brassica napus* L. *Insect Science*, 14(3), 207–212.

36. Chi H., You M., Atlıhan R., Smith C.L., Kavousi A., Özgökçe M.S., et al., 2020. Age- Stage, two-sex life table: an introduction to theory, data analysis, and application. *Entomologia Generalis*, 40, 102–123.

37. Zhang B. Z., Hu G. L., Lu L. Y., Hu S. F., Li Y. S., Su X., et al., 2021. Identification of differentially expressed microRNAs under imidacloprid exposure in *Sitobion miscanthi*. *Pesticide Biochemistry and Physiology*, 177, 104885.

38. Moores G. D., Gao X., Denholm I., Devonshire A. L.,1996. Characterisation of insensitive acetylcholin-esterase in insecticide-resistant cotton aphids, *Aphis gossypii* glover (homoptera: Aphididae). *Pesticide Biochemistry and Physiology*, 56(2), 102–110.

39. Chi H. S. I. N., Liu H. S. I.,1985. Two new methods for the study of insect population ecology. *Bulletin of the Institute of Zoology*, *Academia Sinica*, 24(2), 225–240.

40. Chi H.,1988. Life-table analysis incorporating both sexes and variable development rates among individuals. *Environmental Entomology*, 17(1), 26–34.

41. Dunnett C. W.,1980. Pairwise multiple comparisons in the homogeneous variance, unequal sample size case. *Journal of the American Statistical Association*, 75(372), 789–795.

42. Chi, H., 2015. TWOSEX-MSChart: a computer program for the age-stage, two-sex life table analysis. http://140.120, 197.

43. Chi H., Güncan A., Kavousi A., Gharakhani G., Atlihan R., Özgökçe MS., et al., 2022a. TWOSEX-MSChart: the key tool for life table research and education. *Entomologia Generali*s, 42: 845–849.

44. Chi H., Kara H., Özgökçe MS., Atlihan R., Güncan A & Rişvanlı MR, 2022. Innovative application of set theory, Cartesian product, and multinomial theorem in demographic research. *Entomologia Generalis*, 42: 863–874.

45. Aeinehchi P., Naseri B., Rafiee Dastjerdi H., Nouri-Ganbalani G., & Golizadeh A., 2021. Lethal and sublethal effects of thiacloprid on *Schizaphis graminum* (Rondani)(Hemiptera: Aphididae) and its predator *Hippodamia variegata* (Goeze)(Coleoptera: Coccinellidae). Toxin Reviews, 40(4), 1261–1271.

46. Xin J. J., Yu W. X., Yi X. Q., Gao J. P., GAO X. W., & Zeng X. P., 2019. Sublethal effects of sulfoxaflor on the fitness of two species of wheat aphids, *Sitobion avenae* (F.) and *Rhopalosiphum padi* (L.). *Journal of Integrative Agriculture*, 18(7), 1613–1623.

47. Lu Y.H., Zheng X.S., Gao X.W., 2016. Sublethal effects of imidacloprid on the fecundity, longevity, and enzyme activity of *Sitobion avenae* (Fabricius) and *Rhopalosiphum padi* (Linnaeus). *Bulletin of Entomological Research*, 106, 551–559.

48. Ullah F., Gul H., Desneux N., Gao X., Song D., 2019. Imidaclopridinduced hormesis effects on demographic traits of the melon aphid, *Aphis gossypii*. *Entomologia Generalis*, 39(3–4),325–337.

49. Tang Q., Ma K., Chi H., Hou Y., Gao X., 2019. Transgenerational hormetic effects of sublethal dose of flupyradifurone on the green peach aphid, *Myzus persicae* (Sulzer)(Hemiptera: Aphididae). *PLoS One* 14(1), e0208058.

50. Vakhide N., Safavi S.A., 2014. Lethal and sublethal effects of direct exposure to acetamiprid on reproduction and survival of the greenbug, *Schizaphis graminum* (Hemiptera: Aphididae). Arch Phytopathol Plant Prot 47(3), 339–348.

51. Liang P.Z, Ma K.S., Chen X.W., Tang C.Y., Xia J., Chi H., et al., 2019. Toxicity and sublethal effects of flupyradifurone, a novel butenolide insecticide, on the development and fecundity of *Aphis gossypii* (Hemiptera: Aphididae). *Journal of Economic Entomology*, 112(2),852–858.

52. Ali E., Liao X., Yang P., Mao K., Zhang X., Shakeel M., et al., 2017. Sublethal effects of buprofezin on development and reproduction in the white-backed planthopper, *Sogatella furcifera* (Hemiptera: Delphacidae). Scientific Report, 7(1),16913.

53. Pakyari H., Enkegaard A., 2015. Sublethal and transgenerational effects of abamectin on the biological performance of the predatory thrips *Scolothrips longicornis* (Thysanoptera: Thripidae). *Journal of Economic Entomology*, 108(2),559–565.

54. Ullah F, Gul H, Tariq K, Desneux N, Gao X, Song D, 2020. Thiamethoxam induces transgenerational hormesis effects and alteration of genes expression in *Aphis gossypii*. Pesticide Biochemistry and Physiology, 165,104557.

55. Jager T, Barsi A, Ducrot V., 2013. Hormesis on life-history traits: is there such thing as a free lunch? Ecotoxicology, 22(2),263–270. https://doi.org/10.1007/s10646-012-1022-0 PMID: 23179410

56. Mallqui K.V., Vieira J., Guedes R., Gontijo L., 2014. Azadirachtin induced hormesis mediating shift in fecundity-longevity trade-off in the Mexican bean weevil (Chrysomelidae: Bruchinae). Journal of Economic Entomology, 107(2), 860–866.

57. James D. G.,1997. Imidacloprid increases egg production in *Amblyseius victoriensis* (Acari: Phytoseiidae). *Experimental & Applied Acarology*, 21(2), 75–82.

58. Christopher, Cutler G., Ramanaidu K., Astatkie T., Isman M. B., 2009. Green peach aphid, *Myzus persicae* (Hemiptera: Aphididae), reproduction during exposure to sublethal concentrations of imidacloprid and azadirachtin. *Pest Management Science*: *formerly Pesticide Science*, 65(2), 205–209.

**59.** Koo H.N., Lee S.W., Yun S.H., Kim H.K., Kim G.H., 2015. Feeding response of the cotton aphid, *Aphis gossypii*, to sublethal rates of flonicamid and imidacloprid. *Entomologia Experimentalis et Applicata*, 154(2),110–119

**60.** Stark J.D., Banks J.E., 2003. Population-level effects of pesticides and other toxicants on arthropods. *Annual Review of Entomology*, 48(1), 505–519. https://doi.org/10.1146/annurev.ento.48.091801.112621 PMID: 12221038