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Field Evolution of Insecticide Resistance against *Sogatella furcifera* (Horváth) in Central China, 2011–2021

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Abstract: The white-backed planthopper *Sogatella furcifera* (Horváth) is an important pest on rice plants throughout Asia. The application of chemical insecticides is still the main approach to suppressing the field population of *S. furcifera*. However, misuse of chemical insecticides has promoted the development of insecticide resistance in this insect pest. Thus, in the present study, dose responses of 58 field populations of *S. furcifera* to 7 insecticides were analyzed by rice-stem dipping from 2011 to 2021 in Central China. The results indicated that field populations of *S. furcifera* showed moderate levels of resistance to nitenpyram (RR = 1.7–17.8-fold), thiamethoxam (RR = 1.4–25.8-fold), dinotefuran (RR = 1.5–25.3-fold), clothianidin (RR = 2.1–12.5-fold), chlorpyrifos (RR = 1.1–56.6-fold), etofenprox (RR = 1.1–14.8-fold) and isoprocarb (RR = 1.4–11.5-fold). The results presented here will be beneficial to improve our ability to identify and predict insecticide resistance, make better control recommendations and prevent further insecticide resistance development.

Keywords: white-back planthopper; neonicotinoid insecticides; organophosphorus insecticides; carbamate insecticides; pyrethroid insecticides; insecticide resistance

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1. Introduction

Rice is a major grain crop in China, with a planting area of about 30 million hectares each year in recent years [1–3]. It is one of the most important sources of income for farmers [4]. At the same time, rice is also the staple food of more than 65% of the population of China [5–8]. Therefore, rice production plays an important role in national grain production and food security maintenance [9].

The white-back planthopper (WBPH), *Sogatella furcifera* (Horváth) (Homoptera: Delphacidae) is a destructive insect pest on rice crops in rice-growing countries [10,11]. This pest causes severe damage to rice plants through direct sucking, oviposition and virus disease transmission [11,12]. Since the 1980s, the population size of the white-back planthopper steadily increased year by year, the outbreaks of *S. furcifera* became more frequent, and the damage to rice plants caused by *S. furcifera* was severe [13]. In addition to the prevalence of *S. furcifera*, the southern rice black-streaked dwarf virus (SRBSDV), in the genus *Fijivirus*, which is transmitted by *S. furcifera*, has also become epidemic in China since 2009 [14]. So far, chemical insecticide spraying continues to be the main approach for efficiently controlling the population of *S. furcifera* due to its overlapping generations, complex immigration sources, high growth rate, dispersal capacity and high outbreak frequency [11,15,16].

The rapid development of resistance to multiple insecticide classes has become a major problem and a limiting factor to manage *S. furcifera*. According to the available literature reports, *S. furcifera* has developed resistance to 15 conventional insecticides, including buprofezin, carbaryl, chlorpyrifos, clothianidin, dinotefuran, fenitrothion, fenobucarb, fenvalerate, fipronil, imidacloprid, isoprocarb, malathion, pymetrozine, thiamethoxam and carbamates (unspecified in the literature), with 216 reported cases of insecticide resistance of *S. furcifera* [15–24]. Currently, many scientists are devoted to the study of *S. furcifera's* resistance to insecticides, trying to find an effective new strategy for the management of its resistance. To be specific, Jin et al. (2017) showed that *S. furcifera* from five regions in Guizhou developed different levels of resistance to isoprocarb, thiamethoxam, imidacloprid, chlorpyrifos, pymetrozine and buprofezin [20]. Li et al. (2020) measured the susceptibility of eight populations to thirteen insecticides and assessed the control failure likelihood of insecticides in field populations of *S. furcifera* [10]. A more recent study by Ruan et al. (2021) also demonstrated that *S. furcifera* from eight different areas of Sichuan Province developed different resistance levels against thiamethoxam, imidacloprid, chlorpyrifos, pymetrozine and buprofezin [25]. Another more recent study demonstrated that *S. furcifera* developed high levels of resistance to chlorpyrifos and buprofezin, low to moderate levels of resistance to imidacloprid, thiamethoxam, dinotefuran, clothianidin, sulfoxaflor, isoprocarb and etofenprox, and susceptible or low levels of resistance to nitenpyram [22]. Although the development of insecticide resistance in *S. furcifera* is inevitable due to the continuous and exclusive application of insecticides in rice paddy fields, chemical control still is the primary means of managing *S. furcifera* in China. This is due to the lack of resistant varieties and weak natural regulation in intensive rice ecosystems [26]. Furthermore, insecticides are still preferred by farmers because of their significant application efficiency. Thus, it is important to understand the status of resistance of the field population of *S. furcifera* to various insecticides.

Thiamethoxam, nitenpyram, clothianidin, dinotefuran, chlorpyrifos and isoprocarb are the most frequently used insecticides for managing rice planthoppers in China [18,27,28]. Etofenprox has also gained registration for rice crop applications in China and has been used for many years [27]. Although previous reports on the resistance of *S. furcifera* to these insecticides in China can be found throughout the literature, resistance levels can significantly vary from year to year due to different doses and a variety of insecticide applications in each region. Therefore, the yearly resistance levels to these insecticides in different districts of China remain unclear. In this study, the objective was to monitor the resistance levels of field populations of *S. furcifera* against thiamethoxam, nitenpyram, dinotefuran, clothianidin, chlorpyrifos, etofenprox and isoprocarb by rice-stem dipping. The data have been collected in Central China (Anhui Province, Henan Province, Hubei Province, Hunan province) from 2011 to 2021.

2. Materials and Methods

2.1. Insect Populations

Eight populations of *S. furcifera* were collected annually from rice paddy fields of Gong'an, Tianmen, Wuxue, Tongcheng, Zaoyang, Jianli, Xiaogan and Wuhan in the Hubei Province of China from 2011 to 2014; nine populations of *S. furcifera* were collected from rice paddy fields of Gong'an, Tianmen, Wuxue, Tongcheng, Zaoyang, Xiaogan, Wuhan, Changsha and Xinyang in 2015; and nine populations of *S. furcifera* were collected from rice paddy fields of Gong'an, Tianmen, Wuxue, Zaoyang, Xiaogan, Changsha, Xinyang Nanchang and Lu'an in 2016. Furthermore, four populations of *S. furcifera* were collected annually from rice paddy fields of Xiantao, Qianjiang, and Songzi in Hubei Province and Changde in the Hunan province of China from 2020 to 2021 (Table 1). Approximately 1000–3000 adults and nymphs were collected from each site and reared on rice seedlings under standard conditions of 27 $\pm$ 1 °C and 70–80% relative humidity with a 16-h light/8-h dark photoperiod. The third-instar nymphs of the first (F_1) or second (F_2) generation were used for a bioassay to assess the susceptibility to a range of different insecticides.

Table 1. Sampling sites, dates and developmental stages of *S. furcifera* collected from fields.

Population	Location	Collection Date	Geographical and Coordinates	Insect Stage
GA-2011	Hubei, Gongan	12 July 2011	30.05° N, 112.19° E	nymph and adult
GA-2012	Hubei, Gongan	22 July 2012	30.05° N, 112.19° E	nymph and adult
GA-2013	Hubei, Gongan	1 August 2013	30.05° N, 112.19° E	nymph and adult
GA-2014	Hubei, Gongan	3 August 2014	30.05° N, 112.19° E	nymph and adult
GA-2015	Hubei, Gong'an	2 August 2015	30.05° N, 112.19° E	nymph and adult
GA-2016	Hubei, Gong'an	9 August 2016	30.05° N, 112.19° E	nymph and adult
TM-2011	Hubei, Tianmen	13 August 2011	30.43° N, 113.46° E	nymph and adult
TM-2012	Hubei, Tianmen	1 August 2012	30.43° N, 113.46° E	nymph and adult
TM-2013	Hubei, Tianmen	4 August 2013	30.43° N, 113.46° E	nymph and adult
TM-2014	Hubei, Tianmen	25 July 2014	30.43° N, 113.46° E	nymph and adult
TM-2015	Hubei, Tianmen	20 July 2015	30.43° N, 113.46° E	nymph and adult
TM-2016	Hubei, Tianmen	25 July 2016	30.43° N, 113.46° E	nymph and adult
WX-2011	Hubei, Wuxue	10 August 2011	30.11° N, 115.59° E	nymph and adult
WX-2012	Hubei, Wuxue	18 August 2012	30.11° N, 115.59° E	nymph and adult
WX-2013	Hubei, Wuxue	28 July 2013	30.11° N, 115.59° E	nymph and adult
WX-2014	Hubei, Wuxue	21 August 2014	30.11° N, 115.59° E	nymph and adult
WX-2015	Hubei, Wuxue	1 August 2015	30.11° N, 115.59° E	nymph and adult
WX-2016	Hubei, Wuxue	15 July 2016	30.11° N, 115.59° E	nymph and adult
TC-2011	Hubei, Tongcheng	5 August 2011	29.26° N, 113.84° E	nymph and adult
TC-2012	Hubei, Tongcheng	4 August 2012	29.26° N, 113.84° E	nymph and adult
TC-2013	Hubei, Tongcheng	30 July 2013	29.26° N, 113.84° E	nymph and adult
TC-2014	Hubei, Tongcheng	15 August 2014	29.26° N, 113.84° E	nymph and adult
TC-2015	Hubei, Tongcheng	8 August 2015	29.26° N, 113.84° E	nymph and adult
ZY-2011	Hubei, Zaoyang	19 August 2011	31.98° N, 112.76° E	nymph and adult
ZY-2012	Hubei, Zaoyang	7 August 2012	31.98° N, 112.76° E	nymph and adult
ZY-2013	Hubei, Zaoyang	12 August 2013	31.98° N, 112.76° E	nymph and adult
ZY-2014	Hubei, Zaoyang	3 August 2014	31.98° N, 112.76° E	nymph and adult
ZY-2015	Hubei, Zaoyang	27 July 2015	31.98° N, 112.76° E	nymph and adult
ZY-2016	Hubei, Zaoyang	18 August 2016	31.98° N, 112.76° E	nymph and adult
JL-2011	Hubei, Jianli	25 July 2011	29.91° N, 112.77° E	nymph and adult
JL-2012	Hubei, Jianli	10 August 2012	29.91° N, 112.77° E	nymph and adult
JL-2013	Hubei, Jianli	9 August 2013	29.91° N, 112.77° E	nymph and adult
JL-2014	Hubei, Jianli	25 July 2014	29.91° N, 112.77° E	nymph and adult
XG-2011	Hubei, Xiaogan	29 July 2011	31.27° N, 113.84° E	nymph and adult
XG-2012	Hubei, Xiaogan	13 August 2012	31.27° N, 113.84° E	nymph and adult
XG-2013	Hubei, Xiaogan	11 August 2013	31.27° N, 113.84° E	nymph and adult
XG-2014	Hubei, Xiaogan	7 August 2014	31.27° N, 113.84° E	nymph and adult
XG-2015	Hubei, Xiaogan	9 August 2015	31.27° N, 113.84° E	nymph and adult
XG-2016	Hubei, Xiaogan	21 August 2016	31.27° N, 113.84° E	nymph and adult
WH-2011	Hubei, Wuhan	27 July 2011	30.47° N, 114.35° E	nymph and adult
WH-2012	Hubei, Wuhan	3 August 2012	30.47° N, 114.35° E	nymph and adult
WH-2013	Hubei, Wuhan	26 July 2013	30.47° N, 114.35° E	nymph and adult
WH-2014	Hubei, Wuhan	30 September 2014	30.47° N, 114.35° E	nymph and adult
WH-2015	Hubei, Wuhan	10 August 2015	30.47° N, 114.35° E	nymph and adult
CS-2015	Hunan, Changsha	29 July 2015	20.18° N, 112.57° E	nymph and adult
CS-2016	Hunan, Changsha	18 July 2016	20.18° N, 112.57° E	nymph and adult
XY-2015	Henan, Xinyang	11 August 2015	32.14° N, 113.53° E	nymph and adult
XY-2016	Henan, Xinyang	26 July 2016	34.08° N, 111.04° E	nymph and adult
LA-2016	Anhui, Lu'an	15 August 2016	31.53° N, 116.71° E	nymph and adult
NC-2016	Jiangxi, Nanchang	23 August 2016	28.64° N, 115.57° E	nymph and adult
QJ-2020	Hubei, Qianjiang	2 August 2020	30.44° N, 112.98° E	nymph and adult
QJ-2021	Hubei, Qianjiang	21 July 2021	30.39° N, 112.66° E	nymph and adult
SZ-2020	Hubei, Songzi	8 August 2020	30.01° N, 111.90° E	nymph and adult
SZ-2021	Hubei, Songzi	7 July 2021	30.01° N, 111.90° E	nymph and adult
SS-2020	Hubei, Shishou	23 July 2020	29.68° N, 112.40° E	nymph and adult
SS-2021	Hubei, Shishou	4 July 2021	29.68° N, 112.40° E	nymph and adult
CD-2020	Hunan, Changde	19 July 2020	29.62° N, 111.78° E	nymph and adult
CD-2021	Hunan, Changde	7 July 2021	29.63° N, 111.74° E	nymph and adult

2.2. Insecticides

The seven insecticides used in this study are technical-grade compounds. Chlorpyrifos (98%) were supplied by Hebei VeYong Bio-Chemical CO., LTD, Shijiazhuang, China. Thiamethoxam (95%), nitenpyram (96%), dinotefuran (91%) and clothianidin (96%) were supplied by Hubei Kangbaotai Fine-Chemicals CO., LTD, Wuhan, China. Isoprocarb (98%) was supplied by Jiangsu Changlong Chemicals CO., LTD, Changzhou, China. Etofenprox (95%) was supplied by Suzhou ATL Chemical CO., LTD, Suzhou, China. The insecticides were dissolved in acetone as a stock solution and diluted to 5–7 series of varying concentration gradients using water containing 0.1% of Triton X-100 (laboratory grade) (Sigma-Aldrich, St. Louis, MO, USA).

2.3. Bioassays

Rice-stem dipping was used to monitor the resistance of *S. furcifera* against various insecticides using a previously described method by Su et al. (2013), Zhang et al. (2016, 2017) and Li et al. (2020) [10,11,15,18]. To be specific, rice from tillering to the early booting stage was pulled out from the soil, washed thoroughly, cut into an approximately 10 cm long rice stem with roots and air-dried. Three rice stems were grouped and dipped into appropriate insecticide solutions for 30 s and then air-dried at room temperature. The rice stems with roots were wrapped with water-impregnated cotton and put into 500 mL plastic cups. Three replicates were created for each concentration, and 5–7 concentrations were generated for each insecticide. The third-instar nymphs were collected with a homemade sucking device and twenty nymphs were transferred onto the rice stems in a plastic cup. This was performed for each replicate. The control system was treated with 0.1% of Triton X-100 water solution. The plastic cups containing the treated insects were kept at a temperature of 27 ± 1 °C and 70–80% relative humidity with a 16 h light/8 h dark photoperiod. Mortalities for isoprocarb, chlorpyrifos and etofenprox were recorded after 96 h, and for nitenpyram, thiamethoxam, dinotefuran and clothianidin the mortalities were recorded after 72 h to match the experimental conditions of the reference strains in the studies of Su et al. (2013), Zhang et al. (2016, 2017) and Li et al. (2020) [10,11,15,18]. The nymphs were considered dead if they were unable to move after a gentle prodding with a fine brush. The rice plants for bioassays were grown in white plastic pots (400 mm $\times$ 315 mm $\times$ 110 mm) containing soil and water under controlled conditions. Additionally, they were not exposed to any kind of insecticide. When they are at tillering to the early booting stage, these rice plants are used for bioassay.

2.4. Data Analysis

The mortality data were corrected using Abbott's formula. The LC_{50} values and 95% confidence interval values were calculated by probit analysis using the POLO-Plus software (Version 1.0) [29,30]. The resistance ratio (RR) was calculated by dividing the LC_{50} value of a field population by the corresponding LC_{50} value of the susceptible baseline (Table 2). Classification of resistance levels was done according to Shao et al. (2013). Resistance with an RR $\leq$ 5-fold was classified as susceptible, RR = 5–10-fold as a low resistance level, RR = 10–100-fold as a moderate resistance level and RR >100-fold as a high resistance level [31].

Table 2. The LC_{50} values of the reference susceptible strains of *S. furcifera*.

Insecticide Group	Insecticide	LC_{50} [a] (95% CI [b]) mg/L	Reference
Neonicotinoids	Thiamethoxam	0.096 (0.04–0.17)	[18]
	Clothianidin	0.15 (0.09–0.21)	[11]
	Dinotefuran	0.12 (0.08–0.17)	[11]
	Nitenpyram	0.13 (0.08–0.18)	[11]
Organophosphates	Chlorpyrifos	1.36 (1.05–1.71)	[11]
Carbamates	Isoprocarb	11.46 (9.44–13.87)	[11]
Pyrethroids	Etofenprox	25.08 (16.03–35.17)	[11]

[a] Median lethal concentration; [b] 95% confidence interval.

3. Results

3.1. Resistance to Neonicotinoid Insecticides

The field populations of *S. furcifera* collected from different sites in the Hubei, Hunan and Henan provinces annually from 2011 to 2021 were assayed for their susceptibility to seven insecticides (Table 1). The results show that all field populations of *S. furcifera* continued to be susceptible to nitenpyram from 2011 to 2014 (RR = 1.7–3.5-fold), except for WH-2014, which demonstrates a moderate level of resistance to nitenpyram (RR = 10.9-fold). However, all field populations from 2015 to 2021 developed low and moderate levels of resistance to nitenpyram (RR = 5.5–17.8-fold) (Table 3).

Table 3. The resistance to four neonicotinoid insecticides in *S. furcifera* field populations from 2011 to 2021.

Populations	Nitenpyram			Thiamethoxam			Dinotefuran			Clothianidin		
	LC_{50} [a] (95% CI) mg/L	χ^2 (df)	RR [c]	LC_{50} (95% CI [b]) mg/L	χ^2 (df)	RR	LC_{50} (95% CI) mg/L	χ^2 (df)	RR	LC_{50} (95% CI) mg/L	χ^2 (df)	RR
TM-2011	0.30 (0.22–0.37)	1.76 (3)	2.3	0.23 (0.16–0.33)	1.64 (3)	2.4	0.22 (0.17–0.28)	1.11 (3)	1.8	0.53 (0.43–0.65)	1.18 (4)	3.5
TM-2012	0.34 (0.23–0.50)	4.96 (4)	2.6	0.24 (0.16–0.35)	0.66 (3)	2.5	0.18 (0.16–0.20)	0.23 (3)	1.5	0.73 (0.65–0.81)	1.78 (3)	4.9
TM-2013	0.33 (0.22–0.47)	2.38 (3)	2.5	0.66 (0.44–0.97)	5.87 (4)	6.9	0.46 (0.35–0.61)	3.48 (3)	3.8	0.38 (0.28–0.49)	1.96 (4)	2.5
TM-2014	0.44 (0.29–0.79)	4.95 (4)	3.4	0.86 (0.60–1.35)	0.86 (3)	9.0	0.42 (0.31–0.54)	1.83 (3)	3.5	0.60 (0.52–0.69)	0.58 (4)	4.0
TM-2015	0.81 (0.55–1.15)	2.70 (3)	6.2	1.51 (0.91–2.25)	0.76 (2)	15.7	1.50 (0.95–2.29)	1.38 (2)	12.5	1.01 (0.81–1.59)	1.66 (3)	6.7
TM-2016	0.90 (0.62–1.24)	1.19 (2)	6.9	1.21 (0.68–1.29)	1.39 (3)	12.6	2.04 (0.89–2.15)	-	17.0	1.87 (0.76–6.12)	-	12.5
JL-2011	0.27 (0.20–0.33)	0.86 (4)	2.1	0.27 (0.22–0.33)	0.84 (3)	2.8	0.95 (0.72–1.24)	0.85 (3)	7.9	0.47 (0.27–0.69)	1.95 (3)	3.1
JL-2012	0.37 (0.26–0.59)	0.98 (3)	2.9	0.31 (0.21–0.46)	2.03 (4)	3.2	0.54 (0.45–0.66)	0.94 (4)	4.5	0.45 (0.35–0.57)	0.32 (4)	3.0
JL-2013	0.33 (0.23–0.46)	0.72 (4)	2.5	0.58 (0.41–0.84)	1.24 (3)	6.0	0.61 (0.52–0.72)	1.15 (4)	5.1	0.49 (0.41–0.59)	0.74 (4)	3.3
JL-2014	0.45 (0.30–0.63)	7.36 (3)	3.5	0.61 (0.44–0.87)	8.12 (4)	6.4	0.73 (0.61–0.87)	0.69 (3)	6.1	0.31 (0.18–0.47)	4.71 (3)	2.1
WH-2011	0.22 (0.17–0.31)	0.52 (3)	1.7	0.13 (0.10–0.16)	1.25 (4)	1.4	0.67 (0.57–0.80)	0.94 (3)	5.6	0.33 (0.26–0.41)	2.00 (3)	2.2
WH-2012	0.37 (0.25–0.56)	0.99 (4)	2.9	0.25 (0.18–0.36)	1.90 (3)	2.6	0.27 (0.23–0.32)	0.38 (4)	2.3	0.66 (0.46–0.92)	3.13 (4)	4.4
WH-2013	0.46 (0.33–0.62)	3.25 (4)	3.5	0.25 (0.16–0.35)	4.16 (3)	2.6	0.22 (0.15–0.30)	5.45 (3)	1.8	0.35 (0.26–0.49)	3.25 (3)	2.3
WH-2014	1.42 (0.73–5.37)	4.53 (3)	10.9	1.46 (0.97–2.47)	2.57 (3)	15.2	0.33 (0.29–0.38)	0.30 (4)	2.8	0.73 (0.44–1.16)	5.26 (4)	4.9
WH-2015	1.54 (1.04–2.30)	0.95 (2)	11.8	1.89 (1.42–2.39)	3.08 (2)	19.7	1.32 (0.91–1.31)	0.38 (2)	11.0	0.78 (0.76–0.99)	0.60 (2)	5.2
CS-2016	1.41 (1.27–1.57)	0.29 (3)	10.8	1.82 (1.40–2.40)	2.68 (4)	19.0	1.91 (1.51–2.17)	-	15.9	0.80 (0.64–0.98)	-	5.3
XY-2016	0.71 (0.51–0.96)	2.92 (3)	5.5	1.05 (0.75–1.47)	1.87 (3)	10.9	2.50 (1.57–3.85)	-	20.8	0.43 (0.26–0.66)	-	2.9
LA-2016	1.15 (0.96–1.37)	0.49 (2)	8.8	2.04 (1.61–2.59)	1.61 (4)	21.3	2.22 (1.93–2.54)	-	18.5	1.31 (0.93–1.77)	-	8.7
NC-2016	1.18 (0.91–1.58)	1.65 (3)	9.1	1.34 (1.10–1.66)	0.79 (3)	14.0	2.34 (2.11–2.59)	-	19.5	0.87 (0.70–1.06)	-	5.8
QJ-2020	1.06 (0.79–1.51)	0.08 (3)	8.2	2.48 (1.84–3.43)	0.19 (2)	25.8	2.32 (1.71–3.17)	0.16 (2)	19.3	0.90 (0.63–1.18)	0.10 (2)	6.0
QJ-2021	1.37 (1.02–2.00)	0.30 (2)	10.5	1.37 (1.03–1.95)	0.27 (2)	14.3	1.57 (1.18–2.37)	0.11 (2)	12.1	0.61 (0.37–0.82)	0.01 (1)	4.1

Table 3. *Cont.*

Populations	Nitenpyram			Thiamethoxam			Dinotefuran			Clothianidin		
	LC_{50} [a] (95% CI) mg/L	χ^2 (df)	RR [c]	LC_{50} (95% CI [b]) mg/L	χ^2 (df)	RR	LC_{50} (95% CI) mg/L	χ^2 (df)	RR	LC_{50} (95% CI) mg/L	χ^2 (df)	RR
SZ-2020	0.72 (0.53–1.07)	0.36 (2)	5.5	1.22 (0.87–1.77)	0.06 (2)	12.7	0.91 (0.65–1.18)	0.08 (2)	7.6	0.68 (0.41–0.93)	0.07 (2)	4.5
SZ-2021	1.28 (0.88–1.74)	0.23 (3)	9.8	1.71 (1.20–2.24)	0.16 (2)	17.8	1.60 (1.17–2.18)	0.18 (3)	13.3	1.00 (0.69–1.32)	0.76 (3)	6.7
SS-2020	2.32 (1.73–3.13)	0.22 (2)	17.8	1.24 (0.93–1.71)	0.08 (2)	12.9	1.01 (0.74–1.33)	0.10 (2)	8.4	1.13 (0.81–1.58)	0.01 (2)	7.5
SS-2021	1.62 (1.17–2.25)	0.32 (3)	12.5	0.85 (0.63–1.17)	0.47 (3)	8.9	1.88 (1.34–2.47)	0.34 (2)	15.7	0.87 (0.60–1.15)	0.19 (2)	5.8
CD-2020	1.29 (0.93–1.89)	0.02 (2)	9.9	1.70 (1.09–2.33)	0.25 (2)	17.7	2.41 (1.72–3.19)	0.14 (3)	20.1	1.66 (1.07–2.26)	0.09 (2)	11.1
CD-2021	1.56 (1.09–2.02)	0.19 (2)	12.0	2.26 (1.66–3.08)	0.12 (2)	23.5	3.03 (2.01–3.99)	0.12 (2)	25.3	0.99 (0.73–1.29)	0.28 (2)	6.6

[a] median lethal concentration; [b] 95% confidence interval; [c] resistance ratio. χ^2, chi-square value; df, degrees of freedom.

The monitored results of 2011 and 2012 showed that all *S. furcifera* populations were susceptible to thiamethoxam (RR = 1.4–3.2-fold) (Table 3). However, a low level of resistance to thiamethoxam (RR = 6.0–9.0-fold) has been discovered in all collected populations from Tianmen (TM-2013 and TM-2014) and Jianli (JL-2013 and JL-2014) in 2013 and 2014, except for the populations of WH-2013 and WH-2014 (Table 3). WH-2013 was susceptible to thiamethoxam (RR = 2.6-fold). In contrast, WH-2014 developed a moderate level of resistance to thiamethoxam (RR = 15.2-fold) (Table 3). Nevertheless, other populations collected from 2015 to 2021 have developed moderate levels of resistance to thiamethoxam (RR = 10.9–25.8-fold), except for a population of SS-2021, which shows a low level of resistance to thiamethoxam (RR = 8.9-fold) (Table 3).

All populations from 2011 to 2014 were susceptible to dinotefuran (RR = 1.5–4.5-fold), except for JL-2011, WH-2011, JL-2013 and Jl-2014 populations, which have a low level of resistance to dinotefuran (RR = 5.1–7.9-fold) (Table 3). However, the dinotefuran resistance was rising continuously, and a moderate level of resistance to this insecticide (RR = 11.0–25.3-fold) has been discovered in all populations from 2015 to 2021, except for two populations of SZ-2020 and SS-2020, which have a low level of resistance to dinotefuran (RR = 7.6–8.4-fold) (Table 3).

The results of the biological assay also reveal that all populations from 2011 to 2014 remained susceptible to clothianidin (RR = 2.1–4.9-fold) (Table 3). However, all populations from 2015 to 2021 developed low and moderate levels of resistance to clothianidin (RR = 5.2–12.5-fold), except for XY-2016, QJ-2021 and SZ-2020, which remain susceptible to this insecticide (RR = 2.9–4.5-fold) (Table 3).

3.2. Resistance to Carbamate Insecticides

The field populations of ZY-2011, ZY-2015, WX-2015, WH-2015, GA-2016, TM-2016, ZY-2016, CS-2016, LA-2016, NC-2016, CD-2020, QJ-2020, SS-2020, CD-2021, SS-2021 and SZ-2021 have developed low levels of resistance to isoprocarb (RR = 5.4–9.2-fold). Only the SZ-2020 population has developed moderate levels of resistance to isoprocarb (RR = 11.5-fold) (Table 4). Other field populations of *S. furcifera* from 2011 to 2021 still maintained susceptibility to isoprocarb (RR = 1.4–4.7-fold) (Table 4). Furthermore, no clear resistance increase tendency against isoprocarb can be seen (Table 4).

Table 4. The resistance to 3 groups of insecticides in *S. furcifera* field populations from 2011 to 2021.

Populations	Isoprocarb			Etofenprox			Chlorpyrifos		
	LC_{50} [a] (95% CI [b]) mg/L	χ^2 (df)	RR [c]	LC_{50} (95% CI) mg/L	χ^2 (df)	RR	LC_{50} (95% CI) mg/L	χ^2 (df)	RR
GA-2011	25.59 (20.45–32.00)	1.75 (4)	2.2	49.27 (42.15–57.57)	0.64 (3)	2.0	5.33 (4.80–5.92)	0.29 (3)	3.9
GA-2012	21.59 (16.81–27.93)	1.36 (3)	1.9	79.34 (70.56–89.20)	0.69 (4)	3.2	3.75 (3.37–4.71)	0.25 (2)	2.8
GA-2013	22.88 (14.46–33.68)	2.69 (2)	2.0	77.30 (54.2–114.6)	3.32 (4)	3.1	4.54 (2.99–6.50)	5.48 (4)	3.3
GA-2014	36.51 (27.76–52.21)	1.59 (3)	3.2	55.07 (37.74–88.67)	4.31 (4)	2.2	4.58 (3.06–6.88)	1.41 (3)	3.4
GA-2015	53.15 (42.09–67.17)	3.88 (1)	4.6	62.80 (25.76–149.05)	2.90 (2)	2.5	28.71 (24.31–33.86)	0.22 (2)	21.1
GA-2016	63.38 (41.81–95.97)	-	5.5	259.10 (197.56–339.87)	-	10.3	19.97 (16.42–24.29)	1.62 (3)	14.6
TM-2011	29.26 (24.30–35.22)	1.30 (3)	2.6	52.25 (43.83–62.22)	1.36 (3)	2.1	2.30 (1.73–2.99)	1.00 (3)	1.7
TM-2012	16.81 (12.59–22.05)	2.66 (3)	1.5	35.07 (26.53–46.18)	2.60 (4)	1.4	2.89 (1.69–4.66)	3.05 (2)	2.1
TM-2013	38.07 (27.08–53.12)	1.48 (2)	3.3	72.93 (62.16–85.55)	1.02 (4)	2.9	4.64 (4.17–6.14)	0.37 (2)	3.4
TM-2014	33.96 (26.12–44.85)	5.91 (4)	3.0	46.77 (34.34–67.48)	5.77 (4)	1.9	6.88 (5.21–9.64)	1.23 (3)	5.1
TM-2015	27.10 (21.95–33.41)	1.69 (1)	2.4	314.14 (217.85–454.28)	1.93 (3)	12.5	23.10 (20.89–25.54)	5.28 (1)	17.0
TM-2016	85.86 (68.51–107.62)	-	7.5	-	-	-	18.71 (15.63–22.38)	1.56 (3)	13.4
WX-2011	45.24 (33.11–61.63)	2.65 (4)	4.0	33.07 (27.80–39.31)	0.96 (3)	1.3	5.31 (4.69–6.01)	0.42 (2)	3.9
WX-2012	25.97 (19.98–33.52)	1.74 (3)	2.3	42.97 (31.85–57.81)	2.78 (2)	1.7	4.01 (3.36–4.79)	0.98 (3)	3.0
WX-2013	32.32 (21.49–46.97)	8.56 (3)	2.8	46.20 (31.40–66.80)	4.76 (3)	1.8	6.71 (4.55–9.68)	8.11 (3)	4.9
WX-2014	21.34 (16.42–29.25)	2.70 (4)	1.9	48.60 (34.48–72.39)	1.63 (4)	1.9	9.09 (6.65–13.67)	8.45 (3)	6.7
WX-2015	90.27 (64.54–126.08)	1.87 (2)	7.9	72.15 (41.32–124.78)	2.41 (3)	2.9	52.56 (33.18–83.28)	2.88 (2)	38.6
WX-2016	21.34 (16.42–29.25)	-	1.9	48.60 (34.48–72.39)	-	1.9	21.72 (17.59–21.87)	1.28 (3)	16.0
TC-2011	28.61 (23.09–35.39)	1.97 (4)	2.5	79.83 (57.58–110.61)	2.89 (3)	3.2	2.18 (1.94–2.44)	0.21 (3)	1.6
TC-2012	28.06 (22.48–36.20)	4.48 (3)	2.5	56.57 (44.16–72.40)	1.59 (4)	2.3	2.77 (2.31–3.33)	0.66 (2)	2.0
TC-2013	37.93 (25.42–56.51)	0.59 (1)	3.3	51.10 (32.90–79.01)	2.63 (3)	2.0	8.93 (5.99–13.56)	2.67 (3)	6.6
TC-2014	31.93 (23.02–47.36)	3.57 (3)	2.8	37.52 (27.11–53.50)	4.44 (4)	1.5	7.24 (4.91–11.58)	7.64 (3)	5.3
TC-2015	49.94 (26.77–92.24)	2.61 (2)	4.4	55.93 (43.15–72.30)	0.73 (3)	2.2	20.44 (10.12–40.29)	1.79 (2)	15.0
ZY-2011	61.91 (49.18–77.84)	1.30 (4)	5.4	34.58 (26.96–44.23)	1.28 (3)	1.4	7.11 (5.88–8.58)	0.91 (3)	5.2
ZY-2012	38.13 (28.92–55.95)	0.77 (2)	3.3	48.55 (35.46–66.28)	2.22 (3)	1.9	4.33 (2.81–6.56)	4.29 (3)	3.2
ZY-2013	16.48 (9.95–24.24)	0.68 (2)	1.4	31.50 (21.90–42.80)	1.19 (3)	1.3	5.60 (3.84–7.87)	5.60 (4)	4.1
ZY-2014	29.75 (22.74–40.94)	1.45 (4)	2.6	77.39 (53.79–132.09)	5.36 (3)	3.1	15.29 (10.89–23.77)	11.88 (4)	11.2
ZY-2015	67.48 (49.15–92.49)	3.28 (3)	5.9	196.92 (166.13–233.55)	0.30 (3)	7.9	45.08 (35.31–57.55)	0.49 (2)	33.1
ZY-2016	71.77 (51.13–100.69)	-	6.3	369.72 (286.31–478.37)	-	14.7	30.24 (20.21–45.34)	3.03 (2)	22.2
JL-2011	31.54 (26.21–37.95)	1.71 (2)	2.8	43.61 (39.15–48.95)	0.28 (3)	1.7	1.46 (1.28–1.65)	0.15 (2)	1.1
JL-2012	18.35 (14.56–22.97)	4.30 (4)	1.6	57.42 (48.12–68.46)	0.35 (3)	2.3	4.26 (2.65–2.77)	2.28 (3)	3.1
JL-2013	25.34 (17.13–35.67)	2.79 (3)	2.2	67.56 (57.93–78.89)	0.60 (3)	2.7	6.56 (5.74–7.49)	0.41 (3)	4.8

Table 4. *Cont.*

Populations	Isoprocarb			Etofenprox			Chlorpyrifos		
	LC_{50} [a] (95% CI [b]) mg/L	χ^2 (df)	RR [c]	LC_{50} (95% CI) mg/L	χ^2 (df)	RR	LC_{50} (95% CI) mg/L	χ^2 (df)	RR
JL-2014	18.45 (14.25–24.75)	3.87 (4)	1.6	38.50 (28.50–53.80)	5.81 (1)	1.5	7.98 (5.76–12.07)	5.90 (3)	5.9
XG-2011	23.98 (16.54–34.54)	2.47 (3)	2.1	27.61 (21.95–34.64)	1.71 (2)	1.1	8.00 (6.31–10.10)	1.64 (3)	5.9
XG-2012	18.54 (15.09–22.62)	2.13 (3)	1.6	88.78 (65.24–120.29)	1.43 (3)	3.5	5.25 (3.41–8.03)	6.78 (4)	3.9
XG-2013	27.27 (18.35–38.68)	1.70 (3)	2.4	62.80 (41.81–95.56)	4.94 (2)	2.5	7.28 (4.91–10.72)	7.28 (3)	5.4
XG-2014	42.96 (31.04–66.71)	2.70 (3)	3.8	50.95 (33.99–82.84)	13.01 (4)	2.0	8.08 (5.90–12.21)	8.47 (3)	5.9
XG-2015	42.68 (28.08–64.52)	1.31 (2)	3.7	115.86 (76.17–175.67)	1.96 (3)	4.6	20.09 (17.88–22.56)	3.23 (1)	14.8
XG-2016	42.96 (31.04–66.71)	-	3.7	50.95 (33.99–82.84)	-	2.0	27.64 (20.19–37.98)	3.15 (3)	20.3
WH-2011	18.15 (14.14–23.22)	1.09 (4)	1.6	35.44 (31.59–39.74)	0.29 (2)	1.4	2.80 (1.55–4.73)	9.04 (2)	2.1
WH-2012	36.81 (27.82–53.07)	1.69 (3)	3.2	53.32 (48.04–59.77)	0.39 (3)	2.1	4.16 (1.58–9.59)	0.43 (1)	3.1
WH-2013	41.23 (29.15–58.56)	3.17 (3)	3.6	96.50 (60.30–166.51)	3.31 (3)	3.9	9.95 (6.90–14.80)	8.46 (3)	7.3
WH-2014	27.33 (20.32–38.13)	0.36 (4)	2.4	86.24 (55.88–154.24)	6.31 (4)	3.4	23.08 (14.44–43.44)	0.60 (4)	17.0
WH-2015	87.43 (55.95–136.20)	2.55 (2)	7.6	115.21 (81.67–162.23)	0.81 (3)	4.6	42.00 (27.34–64.39)	2.08 (2)	30.9
CS-2015	53.31(33.52–84.65)	2.73 (2)	4.7	103.54(66.63–160.49)	3.01 (3)	4.1	28.84 (18.03–45.80)	1.97 (2)	21.2
CS-2016	81.14(64.19–102.49)	-	7.1	194.65(147.31–257.33)	-	7.8	36.79 (27.83–48.62)	1.18 (2)	27.1
XY-2015	39.57 (29.93–52.18)	0.47 (2)	3.5	57.36 (46.93–70.04)	0.20 (2)	2.3	19.62 (16.56–23.24)	3.87 (3)	14.4
XY-2016	-	-	-	371.42 (268.95–513.18)	-	14.8	76.93 (56.44–104.73)	1.81 (4)	56.6
LA-2016	89.37 (76.43–104.48)	-	7.8	269.16 (221.10–327.59)	-	10.7	40.15 (34.76–46.37)	0.97 (3)	29.5
NC-2016	73.12 (62.77–85.16)	-	6.4	124.08 (82.80–186.29)	-	4.9	45.25 (38.36–53.37)	0.58 (2)	33.3
QJ-2020	61.84 (44.64–81.23)	0.99 (3)	5.4	96.70 (65.22–133.68)	0.03 (2)	3.9	21.24 (16.27–27.29)	0.07 (2)	15.6
QJ-2021	52.64 (37.84–71.33)	0.001 (2)	4.6	113.07 (82.11–155.66)	0.18 (2)	4.5	17.74 (13.26–25.46)	0.04 (1)	13.0
SZ-2020	132.01 (95.92–194.89)	0.12 (2)	11.5	107.96 (79.19–144.85)	0.03 (2)	4.3	17.52 (12.18–23.17)	0.22 (2)	12.9
SZ-2021	80.00 (53.48–119.68)	0.01 (1)	6.9	157.91 (114.41–216.00)	0.01 (1)	6.3	26.28 (19.24–38.21)	0.01 (2)	19.3
SS-2020	90.26 (61.23–121.69)	0.20 (2)	7.9	168.15 (126.25–230.92)	0.09 (1)	6.7	31.64 (22.29–54.50)	0.22 (2)	23.1
SS-2021	105.21 (75.83–142.22)	0.32 (2)	9.2	154.02 (115.37–231.75)	0.28 (2)	6.1	43.25 (31.90–57.73)	0.59 (2)	31.8
CD-2020	92.06 (55.87–133.77)	0.08 (2)	8.0	148.60 (108.05–195.86)	0.002 (1)	5.9	33.49 (22.83–51.62)	0.0003 (1)	24.6
CD-2021	103.06 (72.54–159.09)	0.71 (3)	9.0	115.70 (87.59–153.87)	0.04 (2)	4.6	43.12 (31.13–58.64)	0.61 (2)	31.7

[a] median lethal concentration; [b] 95% confidence interval; [c] resistance ratio. χ^2, chi-square value; df, degrees of freedom.

3.3. Resistance to Pyrethroid Insecticides

Resistance to etofenprox has been recorded in *S. furcifera* field populations since 2015. Specifically, etofenprox resistance in field populations of ZY-2015, CS-2016, CD-2020, SS-2020, SS-2021 and SZ-2021 shows a low level of resistance (RR = 5.9–7.9-fold), and resistance against etofenprox in field populations of GA-2016, TM-2015, ZY-2016, XY-2016 and LA-2016 has developed moderate levels of resistance (RR = 10.3–14.8-fold) (Table 4).

The rest of the *S. furcifera* field populations still maintained susceptibility to etofenprox (RR = 1.1–4.9-fold) (Table 4) from 2011 to 2021.

3.4. Resistance to Organophosphorus Insecticides

All populations collected from 2011 to 2014 maintained a low level of resistance to chlorpyrifos (RR = 1.1–7.3-fold), except for the WH-2014 and ZY-2014 populations, which showed a moderate level of resistance to chlorpyrifos (RR = 11.2–17.0-fold) (Table 4). However, resistance to chlorpyrifos in the GA-2015, GA-2016, TM-2015, TM-2016, WX-2015, WX-2016, ZY-2015, ZY-2016, XG-2015, XG-2016 and WH-2015 field populations increased significantly in 2015 and 2016 compared to the previous four years (Table 4). All populations (CS, XY, LA, NC, QJ, SZ, SS, and CD) that were collected from 2015 to 2021 showed moderate levels of resistance to chlorpyrifos (RR = 12.9–56.6-fold) (Table 4). The resistance ratio of XY-2016 was as high as 56.6-fold in 2016 (Table 4).

4. Discussion

Thiamethoxam has been used widely to control rice planthopper populations since the early 2000s in China and plays an important role as chemical control methods [11,15,27,28,32–36]. The studies of Su et al. (2013) and Zhang et al. (2014) showed that field populations of *S. furcifera* remained sensitive or developed low levels of resistance to thiamethoxam. However, our findings showed that low and moderate levels of resistance to thiamethoxam were detected in Central China in this study from 2013 to 2021 (Table 3). Our present study was similar to the studies of Jin et al. (2017), Zhang et al. (2017), Li et al. (2020), Zhang et al. (2020), Li et al. (2021) and Ruan et al. (2021) [10,11,15,20,22,25]. This means that the increasing thiamethoxam resistance was associated with increasing uses of this insecticide against rice planthoppers in China. Therefore, monitoring of the resistance to thiamethoxam should be strengthened, as it is one of the primary insecticides used to control rice planthoppers [25]. Additionally, to reduce selection pressure for this insect pest, thiamethoxam should be in rotational use with other insecticides (which do not show positive cross-resistance with thiamethoxam) by applicators of pesticide and rice growers.

Nitenpyram, dinotefuran and clothianidin are the most common insecticides used for controlling rice planthoppers. All field populations collected from 2011 to 2014 in this study were susceptible to nitenpyram, dinotefuran and clothianidin. Similarly, no obvious resistance to nitenpyram, dinotefuran and clothianidin was found in *S. furcifera* in recent studies from 2011 to 2014 [11,15,17]. However, in other recent studies from 2018, resistance to nitenpyram, dinotefuran and clothianidin in field populations of *S. furcifera* has been reported [10]. This is in agreement with the findings in this study, which demonstrate that most field populations collected from 2015 to 2021 developed low and moderate levels of resistance to these insecticides, with the exception of the XY-2016, SZ-2020 and QJ-2021 populations, which remain sensitive to clothianidin. The wide use of these neonicotinoid insecticides in China and other Southeast Asian countries may be the reason for the increase in neonicotinoid insecticide resistance in *S. furcifera* in recent years [25,27]. However, careful monitoring of these neonicotinoid insecticides' susceptibility is also necessary to maintain control efficiency and successful resistance management.

Chlorpyrifos and isoprocarb have also been widely used to control rice planthopper populations in China [18,27,28]. Isoprocarb resistance against *S. furcifera* was first reported in China in 1990 [37]. It was demonstrated that the field populations from the Guangdong province developed 8-fold resistance to isoprocarb [38]. Then, a moderate level of resistance (RR = 10.3–19.5-fold) was detected in field populations of *S. furcifera* in the Zhejiang province from 1991 to 1992, and four field populations were collected in Hainan, Guangxi, Yunnan and Zhejiang in 1997 [37–40]. Moreover, *S. furcifera* LD_{50} values against carbamates were determined in Japan from 2005 to 2012. The results indicate that a moderate level of resistance (10.6–21.7-fold) to isoprocarb has been developed [28]. A recent study by Li et al. (2020) also discovered that field populations of *S. furcifera* have low and moderate levels of resistance to isoprocarb [10]. Similarly, in the study presented here, field populations of *S. furcifera* developed a low level of resistance to isoprocarb from 2016 to 2021, with the exception of the WX-2016, XY-2016 and QJ-2021 populations (RR = 1.9–4.6-fold). By contrast, our results show that field populations of *S. furcifera* maintained to be susceptible from 2011 to 2015 except for the XY-2011 and XY-2015 populations (RR = 5.4–5.9-fold). This difference in resistance levels may be due to a higher risk of failure to control *S. furcifera* with isoprocarb [10]. In addition, this difference in resistance levels may be caused by different people conducting the experiments, death standards and conditions during observation of the bioassay [25]. However, low to moderate levels of resistance to isoprocarb in seven of eight field populations of *S. furcifera* from 2020 to 2021 can be attributed to the common use of isoprocarb and other similar insecticides in these regions.

Chlorpyrifos resistance against *S. furcifera* was first reported in China in 2011 [19]. With chlorpyrifos' increased application, some field populations of *S. furcifura* in China developed moderate to high levels of resistance to it in 2018 [10]. Another study also discovered that the resistance level to chlorpyrifos in *S. furcifera* field populations from 2012 to 2013 is ranging from low to high [19]. However, our results indicate that *S. furcifera* is susceptible to chlorpyrifos, with low and moderate levels of resistance. Our results furthermore demonstrate that the LC_{50} values against chlorpyrifos in 2015–2021 significantly increased in comparison with LC_{50} values of *S. furcifera* obtained in 2011, suggesting a high risk of a further increase in resistance to chlorpyrifos. Thus, resistance management tactics including rotation and mixture with other insecticides should be undertaken.

Etofenprox has been registered for rice planthopper control in China due to its low toxicity to aquatic organisms and high insecticidal activity against sucking insect pests. Matsumura et al. (2014) monitored the resistance of the Japanese field population of *S. furcifera* to etofenprox for eight consecutive years (2005–2012), and the monitored results show that *S. furcifera* field populations did not produce resistance to etofenprox and were still in the susceptible stage [24]. Subsequently, Li et al. (2020) showed that field populations of *S. furcifera* in Hubei, Hunan, Anhui and Jiangxi were susceptible to etofenprox or developed low to moderate levels of resistance in 2018 [10]. Similarly, in this study, most populations of *S. furcifera* in Central China remained susceptible to etofenprox, while a few populations developed low to moderate levels of resistance. Given the high toxicity of etofenprox to the field population of *S. furcifera*, etofenprox could be used as a rotation insecticide for the control of *S. furcifera*. However, Li et al. (2020) reported a higher risk of failure to control *S. furcifera* with etofenprox, and conclude that etofenprox should be avoided for the control of *S. furcifera* [10]. Therefore, monitoring the development of etofenprox resistance in field populations in different regions is critical.

5. Conclusions

Our findings demonstrate that field populations of *S. furcifera* have developed low and moderate levels of resistance to neonicotinoid, pyrethroid and organophosphate insecticides. However, *S. furcifera* resistance against insecticides is not serious compared with the levels of resistance to insecticides in *N. lugens* [18,26–28,40–44]. Although intensive use of insecticides can kill natural enemies and cause serious environmental damage for a long time, rice planthopper control still relies heavily on the application of chemical insecticides. By monitoring the *S. furcifera* population's resistance development, we can determine if and when resistance management tactics are warranted. Thus, insecticide resistance monitoring of white-backed planthoppers should be carried out continuously in Central China. However, insecticide resistance monitoring has only been tested for the development of resistance in *S. furcifera*. Therefore, strategies and tactics of resistance management (such as the application of alternations, a mixture of insecticides, cultural practices, crop rotation, and biological control) must be implemented to avoid further susceptibility decline in the white-backed planthopper. The results presented here provide the knowledge required to implement insecticide resistance management in the white-backed planthopper.

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