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REVIEW

Toxicity, residue, degradation and detection methods of the insecticide triazophos

Fang-Wei Yang[1] · Yi-Xuan Li[1] · Fa-Zheng Ren[1,2] · Ran Wang[1] · Guo-Fang Pang[1,3]

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Abstract

Organophosphorus pesticides were widely used in agricultural production and in public health as insecticides and acaricides. Triazophos, an organophosphorus insecticide widely used in developing countries, has been found in agricultural products and the environment. Additionally, triazophos is toxic for aquatic organisms and poses a risk of dietary exposure. This article reviews the toxicity, the residues in agricultural products, water and soil, exposure risk, metabolism, microbial degradation, hydrolysis, and photolytic and detection methods of triazophos. Commonly used methods for triazophos detection include chromatography-mass spectrometry and rapid methods based on antigen–antibody reactions. China had made many advances in studying triazophos-degrading bacteria and rapid detection methods of triazophos residues. We also found that triazophos causes oxidative stress, cell damage and tissue injury in animals through neurotoxicity, hepatotoxicity, nephrotoxicity, reproductive toxicity and genotoxicity.

Keywords Triazophos · Organophosphorus insecticide · Toxicity · Exposure risk · Degradation

Introduction

The use of chemical pesticides, including insecticides, was still the mainstay in the large-scale control of most insects, pest mites, fungi and other pests, and it was important for ensuring the quality of agricultural products, food safety and public health safety (Cooper and Dobson 2007; Food and Agriculture Organization 2015). Triazophos/Triazofos/Hostathion/Phentriazophos (O,O-diethyl-O-(1-phenyl-1H-1,2,4-triazol-3-yl) phosphorothioate, CAS Registry No. 24017-47-8, chemical formula $C_{12}H_{16}N_3O_3PS$) (Fig. 1) was an efficient broad-spectrum organophosphorus pesticide widely used as insecticide, nematicide and acaricide in Asian agriculture to protect various crops such as cotton, rice, wheat, tea, fruits, oil seeds and vegetables (Bhandari et al. 2019; Chen et al. 2009; Duan et al. 2016; Fang et al. 2015; Kumari and John 2019; Hong et al. 2019). However, the widespread application of triazophos presented a risk to human health and to the environment due to its high chemical and photochemical stability (http://sitem.herts.ac.uk/aeru/iupac/Reports/653.htm). According to the classification standards of the World Health Organization (WHO), triazophos was a Class Ib toxic organophosphorus insecticide (World Health Organization 2010). The toxicity of triazophos had attracted considerable public attention in recent decades. It was reported that triazophos had fairly high toxicity to aquatic creatures and threatens the aquatic ecosystem (Wu et al. 2018; Zhang et al. 2017; Wang et al. 2010). Recent studies have also shown that triazophos induces oxidative stress and histomorphological changes in rats (Jain et al. 2011, 2013; Sharma and Sangha 2014; Sharma et al. 2015b). Zhang et al. (2011) found that chronic dietary intake of triazophos resulted in a risk of elderly persons and that an acute nutritional intake risk of triazophos residues in apple, cabbage, rice and wheat meal reached an

✉ Ran Wang
wangran8609@126.com

✉ Guo-Fang Pang
gfpang@163.com

[1] Beijing Advanced Innovation Center for Food Nutrition and Human Health, College of Food Science and Nutritional Engineering, China Agricultural University, Beijing 100083, China

[2] Key Laboratory of Functional Dairy, Co-constructed by Ministry of Education and Beijing Government, and Beijing Laboratory of Food Quality and Safety, China Agricultural University, Beijing 100083, China

[3] Chinese Academy of Inspection and Quarantine, Beijing 100176, China

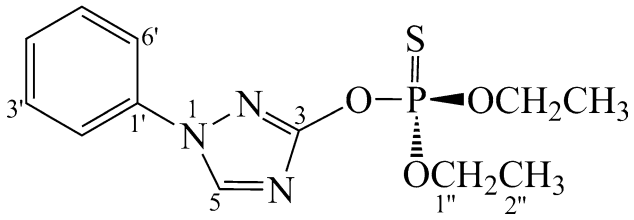

Fig. 1 Chemical structure of Triazophos

unacceptable range in China. Therefore, the wide application of triazophos raised concerns about environmental pollution and the potential risk to human health.

To date, reviews on triazophos toxicity, residues, degradation and detection methods were still limited. We extracted data from different government departments, published literature in research journals and reports from international organizations. The aim of this review was to summarize triazophos studies in the global context and provide a clear picture of its detrimental effects on nontarget organisms, including but not limited to human beings and aquatic organisms and the environment. It will also contribute to the implementation of further plans of action in pesticide research in developing countries.

Toxicity of triazophos against living organisms

An overview of the toxicity and hormesis of triazophos

The effects of triazophos applied at levels of no observed adverse effect (0.15 mg kg^{-1} body weight (bw) per day) and the lowest observed adverse effect (1.3 mg kg^{-1} bw per day) were only available on erythrocyte acetylcholinesterase (AChE) inhibition in a 2-year study of toxicity and carcinogenicity, for this was the most critical effect in laboratory animals (JMPR 2002). The acceptable daily intake (ADI) of triazophos for humans was 0.001 mg/kg bw per day (JMPR 2002). Triazophos was a moderately toxic, broad-spectrum, nonsystemic and contact organophosphorus insecticide. Animals administered triazophos at acute doses showed a sequence of signs of toxicity, viz. acute cholinergic symptoms due to the inhibition of AChE activity, chewing, licking, salivation, writhing, arching and rolling, lacrimation, occasional pawing or burrowing, hyperactivity to sound/touch, abnormal gait pattern, incoordination, imbalance, difficulty breathing, anxiety, ataxia, depression of respiration and circulation and convulsions (Chandra et al. 2014).

The general population was exposed to triazophos through food products and drinking water, but human exposure to acute oral doses of triazophos was mostly accidental or suicidal (Rani et al. 2001). Triazophos might harm nontarget organisms because it was an AChE inhibitor and a neurotoxicant, potentially threatening human health through the food chain (Xiao et al. 2010). Triazophos also damaged mRNA transcription and membrane proteins of nontarget organisms (Zhong et al. 2009). Mammary gland fibroadenoma was overwhelming in all tumors (63.2%) in rats fed triazophos; among the tumors, those of the female reproductive system accounted for 82.1%, and the others were tumors of the endocrine and genetic system (22.9%). Tumor incidence increased in rats exposed to high concentrations of triazophos for a long period (Ma et al. 2007).

From an ecotoxicological point of view, excessive usage of triazophos was detrimental to aquatic organisms and previous research had shown that triazophos had adverse effects on aquatic organisms. Table 1 showed the data of acute toxicity of triazophos to aquatic organisms, including amphibians, crustaceans, fish, molluscs, phytoplankton and zooplankton (Chen et al. 2011a; Liu et al. 2015; Wu et al. 2018). It is seen from Table 1 that crustaceans, plankton and some fish had strong sensitivity to triazophos, among which *Penaeus chinensis* post-larva was the most sensitive species to triazophos, followed by *Penaeus vannamei*, *Liza haematocheila*, *Apocyclops borneoensis*, etc. Correspondingly, species such as amphibians, algae, shellfish and higher fishes showed strong tolerance to triazophos. Triazophos could enter aquatic environments (Mahboob et al. 2015) and cause teratogenicity in fish embryos and larvae (Zhu et al. 2014). Triazophos was likely a risk to the early development of fish. *Gobiocypris rarus* embryos and larvae were exposed to various concentrations of triazophos (0.1–15 mg L^{-1}) for 72 h. Increased malondialdehyde (MDA) and decreased heart rate and body length occurred in a gradual concentration-dependent pattern. Enzyme activities and mRNA levels were significantly changed, even at low concentrations (Zhu et al. 2014).

In addition, female rats suffered from blood, kidney and liver toxicities, as well as changed in hormone levels, after long-term exposure to low concentrations of triazophos (Sharma et al. 2015b). The *erα* transcript was a sensitive biomarker of endocrine-disrupting chemicals. Triazophos could affect fish *erα* expression, with the potential to cause endocrine disruption and possibly affected development (Zhu et al. 2014).

Repeated oral administration of triazophos affected the intestinal absorption of nutrients in rats. Triazophos caused 14% and 18% increase in intestinal glucose absorbance after 7 and 14 days of exposure, respectively, at the 5.8 mg kg^{-1} dose level. Tyrosine uptake, however, decreased drastically by 20% and 26% at the same dose level. Hyperglycemia was observed following 7 and 14 days of exposure to both low and high doses (Sharma et al. 2002).

Table 1 Acute toxicity data of triazophos on aquatic organisms

Biological name	Species name	Median effective concentration EC_{50} (mg L^{-1})	
		48 h	96 h
Anabaena	*Anabaena flos-aquae*	–	12.6200
Japanese eel elver	*Anguilla japonica*	0.0900	–
Apocyclops	*Apocyclops borneoensis*	0.0068	–
Artemia	*Artemia salina*	0.8000	–
Mudskipper	*Boleophthalmus pectinirostris*	0.0090	–
Bufo gargarizans tadpoles	*Bufo gargarizans*	5.0900	5.0900
Bufo melanostictus tadpoles	*Bufo melanostictus*	3.0700	1.7000
Bullacta exarata	*Bullacta exarata*	0.8760	0.3680
Goldfish	*Carassius auratus*	–	1.1000
Chlorella	*Chlorella vulgaris*	0.0240	–
Cirrhinus mrigala juvenile	*Cirrhinus mrigala*	0.0650	0.0500
Black pacu	*Colossoma brachypomum*	–	0.0600
Grass carp juvenile	*Ctenopharyngodon idella*	1.7300	1.5000
Carp	*Cyprinus carpio*	1.5502	0.9930
Zebrafish embryonic	*Danio rerio*	–	0.5800
Zebrafish larval	*Danio rerio*	–	0.4900
Zebrafish juvenile	*Danio rerio*	–	4.9900
Zebrafish adult	*Danio rerio*	–	1.6600
Daphnia magna	*Daphnia magna*	13.8100	–
Exopalaemon carinicauda	*Exopalaemon carinicauda*	0.0089	0.0010
Fejervarya multistriatu tadpole	*Fejervarya multistriata*	8.0000	6.4300
Perch	*Lateolabrax japonicus*	0.0820	0.0310
Mullet	*Liza haematocheila*	0.0044	0.0029
Macrophthalmus japonicus	*Macrophthalmus japonicus*	0.5200	0.2700
Microcystis aeruginosa	*Microcystis aeruginosa*	–	13.4700
Loach	*Misgurnus dabrvanus*	4.8510	3.7710
Moerella iridescens	*Moerella iridescens*	1.1850	1.0490
Monopterus albus larvae	*Monopterus albus*	0.4200	0.2500
Monopterus albus	*Monopterus albus*	0.4400	0.3200
Mytilus coruscus larval	*Mytilus coruscus*	103.5180	97.1500
Myxocyprinus asiaticus juvenile	*Myxocyprinus asiaticus*	0.0750	0.0490
Fenneropenaeus chinensis nauplii	*Penaeus chinensis*	1.2500	–
Penaeus chinensis post-larva	*Penaeus chinensis*	0.0016	–
Penaeus penicillatus	*Penaeus penicillatus*	0.0530	0.0086
Penaeus vannameiv	*Penaeus vannamei*	0.0032	0.0011
Pseudorasbora parva	*Pseudorasbora parva*	–	0.0080
Rana zebra tadpoles	*Rana limnocharis*	7.5087	5.5589
Mud clam	*Tegillarca granosa*	21.0000	10.2000
Tigriopus japonicus	*Tigriopus japonicus*	0.0163	–
Nile tilapia	*Tilapia nilotica*	0.0400	0.0350

– indicates that data were not available

A previous study has shown that triazophos exposure generally promoted enzyme activity (Hackenberger et al. 2008), a phenomenon that could be regarded as a type of hormesis characterized by conversion from low-dose stimulation to high-dose inhibition (Chapman 2002). A dose-dependent induction of oxidative stress, as evidenced by increased MDA levels and compromised antioxidant defense, including glutathione S-transferase (GST) activity, glutathione (GSH) content and ferric-reducing ability of plasma (FRAP) in blood, tissues and organs, following chronic exposure to triazophos (Jain et al. 2011; Zhu et al. 2014). However, the results can be regarded as a type of hormesis characterized

by conversion from low-dose stimulation to high-dose inhibition for AChE, SOD and GST activities (Zhu et al. 2014).

Triazophos-induced oxidative stress and liver and kidney injury

Triazophos exposure could lead to oxidative stress in the liver and kidney tissues of rats, resulting in tissue injury (Table 2). An earlier study showed that triazophos caused oxidative stress in rat tissues after chronic doses (Jain et al. 2011). Acute oral toxicity of triazophos caused oxidative stress in experimental animals, and its exposure significantly increased the level of MDA in the liver, kidney and brain at doses of 18.4 mg kg^{-1} bw and 21.73 mg kg^{-1} bw (Mohineesh et al. 2014). In the brain, high lipid peroxidation was observed, which might be due to the high susceptibility of the brain to oxidative insult. Triazophos caused oxidative damage by two possible mechanisms: (a) increasing the production of free radicals and subsequent peroxidation of membrane lipids and (b) in parallel reducing protective antioxidants such as GSH (Jain et al. 2011).

Neurotoxicity of triazophos

The study indicated that young rats were more sensitive to triazophos toxicity than adult rats and that the neurobehavioral effects were correlated well with AChE inhibition both in the brain and in the plasma of young and adult rats (Singh and Rishi 2005).

Researchers also found that chronic exposure to triazophos significantly impaired the learning and memory function of rats. Wistar male albino rats were orally administered triazophos at 8.2 mg kg^{-1} bw daily for 30 days. Significantly decreased mRNA expression ($p < 0.01$) and protein levels ($p < 0.001$) of brain-derived neurotrophic factor (BDNF), increased MDA and reduced GSH levels were observed in triazophos-treated rats (Jain et al. 2013).

Reproductive toxicity of triazophos

It has been reported that triazophos has a significant stimulating effect on the oviposition of *Nilaparvata lugens* and *Laodelphax striatellus* (Zhang et al. 2014). The juvenile hormone titers and the expression of vitellogenin in adult worms were significantly increased with triazophos exposure concentrations (Azzam et al. 2009), indicating that triazophos had a certain environmental estrogen effect. The upregulation of gene expression by triazophos might be associated with *N. lugens* female reproduction or resistance to triazophos. Although it was not clear, these candidate genes might have the potential to induce resurgence via increasing female reproduction or resistance to triazophos (Bao et al. 2010).

A significantly altered male/female sex ratio was observed in all of the triazophos-treated groups of rats. Clinical signs such as hyperactivity, impaired gait, forelimb and hindlimb paralysis and increased head elevations were observed in pups born to female rats treated with 1/10th of the LD_{50} of triazophos (8.2 mg kg^{-1} bw). Reduced body weight of the pups was observed in the groups treated with 1/10th and 1/20th of the LD_{50} of triazophos (8.2 and 4.1 mg kg^{-1} bw) during 30 days postnatal development. Therefore, triazophos exposure preconception might affect reproductive performance (Sharma et al. 2015a).

Triazophos-induced oxidative stress through elevated lipid peroxidation and differentially altered activity of endogenous antioxidants had the potential to interfere with estrogen/progesterone balance and could potentially affect fertility. Follicular atresia in corroboration with granulosa cell apoptotic observations was also more prominent in all the triazophos-treated rats, suggesting the impact of severe oxidative stress in ovaries (Sharma et al. 2015b). Increased ovarian surface epithelium height also reflected the susceptibility of the ovary to a number of pathophysiological conditions with triazophos exposure (Sharma et al. 2015b). In addition, an unsettling discovery by Bhanot and Sangha (2018) was that in utero and lactational exposure to ADI level of triazophos could influence testis development and

Table 2 Oxidative stress in rats induced by triazophos exposure

Doses and time	Results	References
8.2, 4.1, 2.05 mg kg^{-1} bw; 30 days	↓CAT,SOD,GST,GR,GPx,LPO; ↑estradiol; ↓progesterone; ↑Follicular atresia, ovarian surface epithelial height, granulosa cell apoptosis and necrosis	Sharma et al. (2015b)
8.2, 4.1, 2.05 mg kg^{-1} bw; 30 days	↓CAT,SOD,GST,GR,GPx,LPO; ↑liver tissue infiltration, vacuoles, sinusoids and necrosis	Sharma and Sangha (2014)
8.2 mg kg^{-1} bw; 30 days	↑MDA; ↓GSH	Jain et al. (2013)
1.64, 3.2, 8.2 mg kg^{-1} bw; 90 days	↑MDA; ↓GST,GSH,FRAP;↑MDA: FRAP;↑liver damage	Jain et al. (2011)
1.64, 3.2, 8.2 mg kg^{-1} bw; 30 days	↑MDA; ↓GST,GSH,FRAP; severe degenerative disease of liver tissue	Jain et al. (2011)
10.87, 18.11, 21.73 mg kg^{-1} bw; 24 h	↑MDA; ↓GSH,SOD,AChE; hepatic medullary congestion and hepatic cell degeneration	Mohineesh et al. (2014)

function in male offspring, and triazophos exposure had a transgenerational effect.

Triazophos treatment also induced various testicular changes, including the admixture of necrotic cells, the arrest of spermatogenesis and decreased seminiferous tubule diameter, germinal epithelial height and number of seminiferous tubules with normal sperm in birds (Ghaffar et al. 2015).

Triazophos disrupted energy metabolism and osmotic regulation in ovaries. However, in the testes, triazophos only caused disturbances in energy metabolism. Therefore, triazophos, which might be an endocrine-disrupting chemical, was more likely to exhibit gender-specific toxic effects in the gonads of mussel *Perna viridis* (Zhang et al. 2017).

Genotoxicity of triazophos

The expression of 26 genes related to oxidative stress, cellular apoptosis, the immune system and the hypothalamic–pituitary–thyroid and hypothalamic–pituitary–gonadal axis at the mRNA level revealed that zebrafish embryos were affected by triazophos, imidacloprid or their joint pesticides, and greater changes in the expression of six genes (*Mn-sod, CXCL-CIC*, *Dio1*, *Dio2*, *tsh* and *vtg1*) were observed when exposed to joint pesticides compared with that when exposed to individual pesticides. Triazophos treatment significantly increased caspase3 and caspase9 activity, while CAT activity was significantly decreased, and the expression of *Mn-sod* was significantly downregulated. Triazophos treatment could affect the T3 and T4 levels in embryos and the expression of *TRα*, *TRβ*, *Dio1*, *Dio2*, *tsh*, *ERα*, *ERβ1*, *ERβ2* and *vtg1* in embryos (Wu et al. 2018).

Seven miRNAs were differentially expressed in zebrafish after treatment with triazophos, of which miR-135c, miR-30b and miR-365 showed decreased expression and miR-21, miR-31, miR-203b and miR-455 showed increased expression (Wang et al. 2010). Among the differentially expressed miRNAs induced by triazophos, miR-30b, miR-21 and miR-31 have been implicated in tumorigenesis (Wang et al. 2010). In addition, triazophos could cause DNA damage in amphibian tadpoles in a dose-dependent manner (Zhong et al. 2009).

Residues of triazophos

Triazophos and its active ingredients were registered mainly in some countries in Asia, Africa and Central America, such as China, India, Pakistan, Thailand, Indonesia, Egypt, South Africa, Panama, Ecuador and Costa Rica. The USA, Canada, Brazil, Argentina, Australia, South Korea and Malaysia did not register triazophos and its active ingredients. Triazophos was included in the list of banned pesticides in the European Union (EU), mainly on the basis of residues, health and ecological environment (Dai et al. 2017).

Approximately 20 years ago, triazophos was a broad-spectrum nonsystemic contact insecticide approved in developed countries for the treatment of a broad array of crops, including apples, cereals, sweet corn, beans, carrots and parsnips (Holden et al. 2001). Triazophos has been found to reside in a wide variety of foods as part of European and US food monitoring schemes. The residues of triazophos were therefore important in determining the risk to consumers of triazophos residue-containing food and agricultural products, such as fruits and vegetables.

Thence, triazophos was evaluated under Directive 91/414/EEC, repealed by Regulation (EC) No 1107/2009 in 2002, and a decision did not to be approved was made (Commission Directive 2002/2076/EU15). Then, in 2014, the European Food Safety Authority (EFSA) reported that the estimated triazophos theoretical maximum daily intakes (TMDI) were below the ADI; the TMDI ranges in percentage of triazophos ADI minimum–maximum were 10–79%, and a long-term intake of residues of triazophos was unlikely to present a public health concern in EU countries (Table 3) (EFSA 2014).

Thus, EU residents' dietary exposure to triazophos was mainly through milk and dairy products, grain cereals and fruits and vegetables. However, because triazophos was never assessed at the EU level, no agreed-upon European toxicological reference values were available. For triazophos, no EFSA conclusion and no MRL (maximum residual limit) applications were available. It was noted that in 2010, the JMPR (Joint FAO/WHO Meeting on Pesticide Residues) concluded that without animal livestock metabolism studies, a residue definition for animal products could not be derived. Therefore, the JMPR did not consider the residues in animal products resulting from the usage of triazophos in rice and soybeans (JMPR 2010). No new information was provided regarding the animal products. Therefore, the EFSA held that the codex maximum residue limit proposal was not acceptable since the impact on food of animal origin was not assessed. No data on the stability of triazophos under processing conditions were available. Further clarifications regarding the residue trials assessed in 2010 JMPR were required to conclude whether the MRL and the STMR have been calculated correctly (clarification was needed as to whether the results refer to husked rice or rough rice).

As the largest developing country, China was no exception. In recent years, most high-toxicity and high-residual organophosphorus insecticides, such as parathion, methyl parathion and methamidophos, have been banned in crops, fruits and vegetables by the Ministry of Agriculture of China. As a good alternative to the above pesticides, triazophos was widely used on a variety of crops and was one of the most important insecticides for controlling bollworms

Table 3 Calculations of consumer exposure to triazophos with Pesticide Residues Intake Model

Highest calculated TMDI values in percentage of ADI (%)	MS diet	Highest contributor to MS diet (in percentage of ADI) (%)	Commodity/group of commodities	Second contributor to MS diet (in percentage of ADI) (%)	Commodity/group of commodities	Third contributor to MS diet (in percentage of ADI) (%)	Commodity/group of commodities
78.7	UK infant	38.7	Milk and cream	10.1	Sugar beet (root)	7.6	Rice
76.1	NL child	29.3	Milk and cream	9.5	Wheat	6.3	Apples
74.1	FR toddler	39.6	Milk and cream	5.2	Wheat	5.1	Potatoes
73.2	UK toddler	22.9	Sugar beet (root)	20.7	Milk and cream	7.8	Wheat
64.6	WHO Cluster diet B	17.1	Wheat	6.3	Rice	4.9	Maize
61.6	DE child	14.3	Milk and cream	12.1	Apples	8.2	Wheat
52	DK child	12.6	Milk and cream	11	Wheat	8.8	Rye
46.3	FR infant	25.7	Milk and cream	4.1	Potatoes	2.6	Carrots
46.1	IE adult	4.6	Maize	4.6	Maize	3.5	Sweet potatoes
45.8	ES child	12.5	Milk and cream	8.9	Wheat	5.8	Rice
42.4	WHO cluster diet D	13	Wheat	6.6	Rice	5	Milk and cream
40.3	SE general population 90th percentile	12.4	Milk and cream	6.4	Wheat	4.8	Rice
38.1	WHO cluster diet E	7.9	Wheat	3.8	Potatoes	3	Milk and cream
34.1	WHO Cluster diet F	7.2	Wheat	4	Milk and cream	3.4	Potatoes
33.9	PT general population	9.4	Rice	7.8	Wheat	5.3	Potatoes
33.5	WHO regional European diet	5.9	Wheat	4.8	Milk and cream	4	Potatoes
27.4	NL general	6.6	Milk and cream	4.1	Wheat	2.7	Potatoes
26.7	IT kids/toddler	13.3	Wheat	3	Other cereal	2.3	Rice
25.7	ES adult	5	Milk and cream	4.7	Wheat	2.9	Rice
24.1	UK vegetarian	4.6	Rice	4.1	Wheat	3.8	Sugar beet (root)
22.9	FR all population	6.6	Wheat	4	Wine grapes	2.7	Milk and cream
22	UK adult	4.4	Rice	4	Sugar beet (root)	3.4	Wheat
21	LT adult	4	Milk and cream	3.2	Potatoes	2.6	Rice
21	DK adult	5.4	Milk and cream	4	Wheat	1.5	Potatoes
19	IT adult	8.3	Wheat	2.1	Rice	1.4	Other cereal
17.5	FI adult	5.7	Milk and cream	2	Wheat	1.4	Rye
9.7	PL general population	3.4	Potatoes	2	Apples	0.9	Tomatoes

DE Germany, *DK* Denmark, *ES* Spain, *FI* Finland, *FR* France, *IE* Ireland, *IT* Italy, *MS* Member States, *NL* Netherlands, *PL* Poland, *PT* Portugal, *SE* Sweden, *TMDI* theoretical maximum daily intakes, *UK* the United Kingdom, *WHO* World Health Organization

in paddy fields in China (Jin et al. 2012). In 2012, China's annual output of triazophos original drugs and preparations reached more than 10,000 tons (Guo et al. 2018).

In addition, it was noteworthy that since the late 1980s, China's Zhejiang and Fujian coastal areas widely used triazophos as pond cleaning agent, greatly improving shellfish farming production. However, due to the increasing range and intensity of triazophos in aquaculture, coupled with its nonstandard application, the damage to marine biological resources and aquaculture organisms cannot be ignored. The pollution by triazophos of estuaries, bays and aquaculture products has attracted increasing attention in China. The

potential threat of coastal water pollution by triazophos was raising concern regarding its misuse in intertidal aquiculture, and mainly because of triazophos contamination, fish kill accidents sporadically occurred in coastal areas of China (Sun et al. 2016).

Exposure levels of triazophos in humans

Kumar et al. (2015) found that in some areas of India, the prevalence of triazophos poisoning was high. It also indirectly illustrated that the usage of triazophos in these areas was large and/or that the frequency of usage was high. Naksen et al. (2016) used a previously developed method for determining organophosphorus insecticides in plasma samples from Thailand farmworkers and found that among 63 plasma samples, the detection rate of triazophos was 19%, and the triazophos concentration of %DNQ was 17.4 ng mL^{-1}.

The residues of triazophos in agricultural products

Fruits and vegetables

Triazophos was one of the most important residues in cowpea (*Vigna unguiculata* L. Walp) in Hainan, and the estimated daily intake (EDI) of triazophos was 72.89% of the ADI. A relative potency factor method was employed to ascertain whether exposure to triazophos was a cause for concern (Duan et al. 2016). In Kazakhstan, the most critical commodity was triazophos in tomatoes, contributing 70.8% to the acute hazard index (Lozowicka et al. 2015). However, triazophos was not registered in Kazakhstan. Similarly, a study found that triazophos had high residues in Chinese celery (Fang et al. 2015). Additionally, residues of triazophos found in the samples of fruits and vegetables from the study area indicated a potential threat to human health, especially in children in the western Indian Himalayan Region (Kumari and John 2019). In Nepal, of all the pesticides and vegetables tested, the consumption of tomatoes could carry the highest risks (both short-term risk and long-term risk) for both adolescents and adults due to the high amounts of triazophos found in these vegetables (Bhandari et al. 2019). According to the exposure risk assessment of pesticide residues in vegetables from Xinjiang Uygur Autonomous Region of China during 2010–2014, triazophos was easily spot checked, and the number of times triazophos exceeded the MRLs was higher than that for other pesticides (Wu et al. 2017). The half-life of triazophos was 20.6–22.8 days in apple and 10.7–15.4 days in soil, and the residues of triazophos increased with the concentration and frequency with which it was applied and decreased with time (Zhang and Dai 2007). Chen et al. (2011b) reported that the average EDI of triazophos for fruit and vegetable consumption in Xiamen City, China, was 0.0110 μg kg^{-1} bw day^{-1}. Due to the fact that triazophos was prone to excessive residues, triazophos was no longer suggested to be used on vegetables and was prohibited in China after December 31, 2016. Therefore, more efforts were currently focused on monitoring the usage of prohibited pesticides.

Rice and wheat

In 2010, the JMPR reported that the proposed draft codex MRLs on rice posed an acute risk for consumers (JMPR 2010; EFSA 2014). In milled rice (*Oryza sativa*) on the Chinese market, triazophos was the most frequent pesticide in the samples (4.60%), followed by methamidophos (3.41%) and chlorpyrifos (1.67%) (Chen et al. 2009). When water and soil samples from rivers in rice cultivation areas in Jiangsu were analyzed, the detection rate of triazophos was 3.7%, and the detection rate of triazophos in the soil was 1.4%. Compared with the soil samples, water was contaminated more seriously (Shen et al. 2012). Li et al. (2008) investigated the persistence, dissipation and kinetics of triazophos residues in wheat crops and the soil in which they were grown and found that the maximum final residues of triazophos in wheat grain, stems and leaves and soil were 1.865, 44.506 and 0.973 mg kg^{-1}, respectively. The residual levels of triazophos in rice and wheat might pose risks to the health of humans and other animals.

Tea

Excessive and careless usage of organophosphorus insecticides could also lead to high residues in tea and subsequent toxic effects on human health. Triazophos was an organophosphorus insecticide with detectable residue, and the detectable rate was 17.4%. The average residual concentration of triazophos was 44 μg kg^{-1}, whereas the maximum concentration was 675 μg kg^{-1}. The corresponding average daily intake of triazophos by tea drinking was 0.0022 μg kg^{-1} bw day^{-1}. The high exposure of triazophos was 0.0095 μg kg^{-1} bw day^{-1} (Chen et al. 2016).

As the requirements of triazophos residues in tea in developed countries were increasingly stringent, triazophos residue had become a prominent problem, especially for tea exported to Japan. Japan's Ministry of Health, Labor and Welfare announced on August 9, 2006, and December 27, 2007, that it had ordered the inspection of triazophos in Chinese-made oolong tea and its products and green tea on the Chinese market. In the last 5 years, Japan's Ministry of Health, Labor and Welfare has continuously banned the import to Japan from China of tea contaminated with triazophos (as according to Japan's notification in 2010, China's triparagine tea failed nine batches; four batches failed in 2011), and this ban had not yet been lifted. Moreover, Japan

would revise the limit of triazophos in tea to 0.01 mg kg^{-1}. Once in effect, it would be increasingly difficult for China to export oolong tea and green tea. There was also the risk that Japan adopting the policy of "importing self-sufficiency" or "banning imports" (Tong 2012). Since the EU announced a new entry measure to China's tea in October 2011, China's export to the EU of jasmine tea was reported as triazophos unqualified by the EU RASFF in January 2012 (Miao and Zhou 2014).

The residues of triazophos in the environment

Water

Organophosphorus insecticides have become significant pesticides and should be considered in aquatic ecosystem risk management. It was worth mentioning that triazophos was found above 100 ng L^{-1} in five sampling sites, and its maximum concentration reached 1055 ng L^{-1} in the Jiulong River and Estuary in Fujian Province, southeastern China. Triazophos showed the highest risk in river water for consumption and was the main pesticide contributing to the ecological risk to fish (Zheng et al. 2016). In the East China Sea, the estimated water concentration of triazophos (8530.50 ng L^{-1}) was higher than the toxicological endpoint for fish and very close to that for aquatic invertebrates; therefore, the ecotoxicological risk of triazophos was higher than that of other pesticides (Lan et al. 2019).

Pesticide pollution of surface waters in agriculture usage has been well-documented worldwide in recent years. Mahboob et al. (2015) found that the highest concentration of triazophos in the River Ravi of Pakistan was 0.41 ± 0.07 µg L^{-1}, but triazophos was not detected in the sediment samples. The highest concentration of triazophos was 2.64 ± 0.18 µg g^{-1} lipid-normalized weight in the muscle tissues of fish from the river. The minimum and maximum concentrations of the contaminant triazophos fluctuated between 0.005 and 0.41 µg L^{-1} in the river water samples.

In the prediction of the dissipation behavior of triazophos in a paddy crop where the toxicant was recommended for controlling soil-borne insect pests, the half-life values of triazophos in canal water under Indian climatic conditions observed were 24.87 days in 0.25 µg a.i. mL^{-1} and 25.44 days in 0.5 µg a.i. mL^{-1} (Rani et al. 2001). Kinetic studies revealed that dissipation of triazophos residues followed first-order kinetics at both spiking levels.

Triazophos was most frequently detected in the Egyptian Nile River. In the Nile estuaries, the highest concentration of organophosphorus insecticide detected in water was 1.488 µg L^{-1} for triazophos (Dahshan et al. 2016). These results agree with the study (Zheng et al. 2016) conducted in the Jiulong River in South China, as triazophos was the main organophosphorus insecticide detected in the estuary river water. Furthermore, triazophos was considered highly hazardous to fish and other aquatic organisms.

Soil

As paddy was one of the most important crops on which triazophos was used and its yield was better under flooded or submerged conditions, assessing the fate of triazophos under various soil moisture conditions was important. Moreover, soil was vulnerable to triazophos pollution. Rani and Sud (2015a) showed that triazophos degradation followed first-order kinetics (biphasic), with half-life $t1/2$ varying significantly (2–87 days) under different soil moisture and light conditions. Compared to that in dry and field-capacity soil, triazophos degradation was faster in submerged soil.

Adsorption–desorption processes help us understand the mechanism and extent of triazophos movement through soil and waterbodies. Thermodynamic analysis showed that triazophos adsorption onto soil was spontaneous and exothermic and might have occurred through chemisorption, hydrogen bonding or ligand-exchange interactions. Triazophos had the potential to contaminate surface and ground water at higher temperatures due to weak adsorption on tested soils and the release of more adsorbed pesticides during desorption with water. Due to its greater mobility in soil at higher temperatures and under greenhouse conditions, the usage of triazophos should be strictly controlled to avoid groundwater contamination (Rain and Sud 2015b). A lower K_{oc} value of triazophos (358) indicated its weak sedimental absorbability (Lan et al. 2019).

Bajeer et al. (2016) investigated the dissipation, adsorption and degradation of triazophos in different soils from Pakistan. The dissipation rate of triazophos in three different soils was 90% over 30 days, with an average half-life of 9.059 days. Dissipation studies inferred that the rate was variable in each soil due to climatic changes, soil nature and soil-pesticide interactions.

Degradation of triazophos in living organisms and the environment

Effects of triazophos on insect CYP450

Organophosphorus insecticides mainly experienced oxidation, hydrolysis and conjugation in organisms. The degradation enzymes of organophosphorus insecticides mainly involve AChE, glutathione S-transferases (GSTs), carboxylesterase (CarE) and multifunctional oxidase (multifunction oxidases, MFOs). CYP450 was an important component of MFOs that plays an important role in the metabolism of

insecticides and other substances in organisms (Wang et al. 2015).

NlCYP303A1 gene expression was dramatically upregulated upon triazophos treatment, and transcript levels increased more than eightfold compared to those under no treatment (Lao et al. 2015). Gene overexpression or higher activity of CYP450 s was related to the improved metabolism of organophosphorus insecticides and contributed to the metabolic resistance to organophosphorus insecticides in insects (Bao et al. 2010; Lao et al. 2015).

Absorption, distribution and metabolism of triazophos in experimental rats

The excretion patterns and tissue residues were determined after single and repeated oral dosing of rats with triazophos-^{14}C; within 4 days, after a single oral dose, 76.3% of the ^{14}C was excreted in urine and 21.0% in feces. After daily application for 12 days, 69.5–83.4% of the label was eliminated in urine and 30.9–18.1% in feces. Unchanged triazophos and 1-phenyl-3-hydroxy-1,2,4-triazole-3-^{14}C were excreted in feces. Renewed release of other metabolites into the gastrointestinal tract apparently did not take place. The following metabolites were detected in the urine: urea-^{14}C (approximately 85% of the radioactivity excreted with the urine) and three compounds as conjugates with glucuronic acid, i.e., 1-phenyl-3-hydroxy-1,2,4-triazole-3-^{14}C (approximately 3%), l-phenylsemicarbazide-3-^{14}C (approximately 5%) and semicarbazide-^{14}C (approximately 5%) (Fig. 2) (Bock and Thier 1976).

The maximal triazophos concentrations in blood were attained after approximately 4 h, and the mean half-life of radioactivity triazophos in the blood was 3.8 h in rats. The recovery rate of 98% after 96 h indicates that excretion was relatively complete. The predominant route of excretion was urinary, with > 90% of the administered radioactive triazophos excreted within 48 h. Pooled urine contained three identifiable metabolites: 1-phenyl-3-hydroxy-1,2,4-triazole

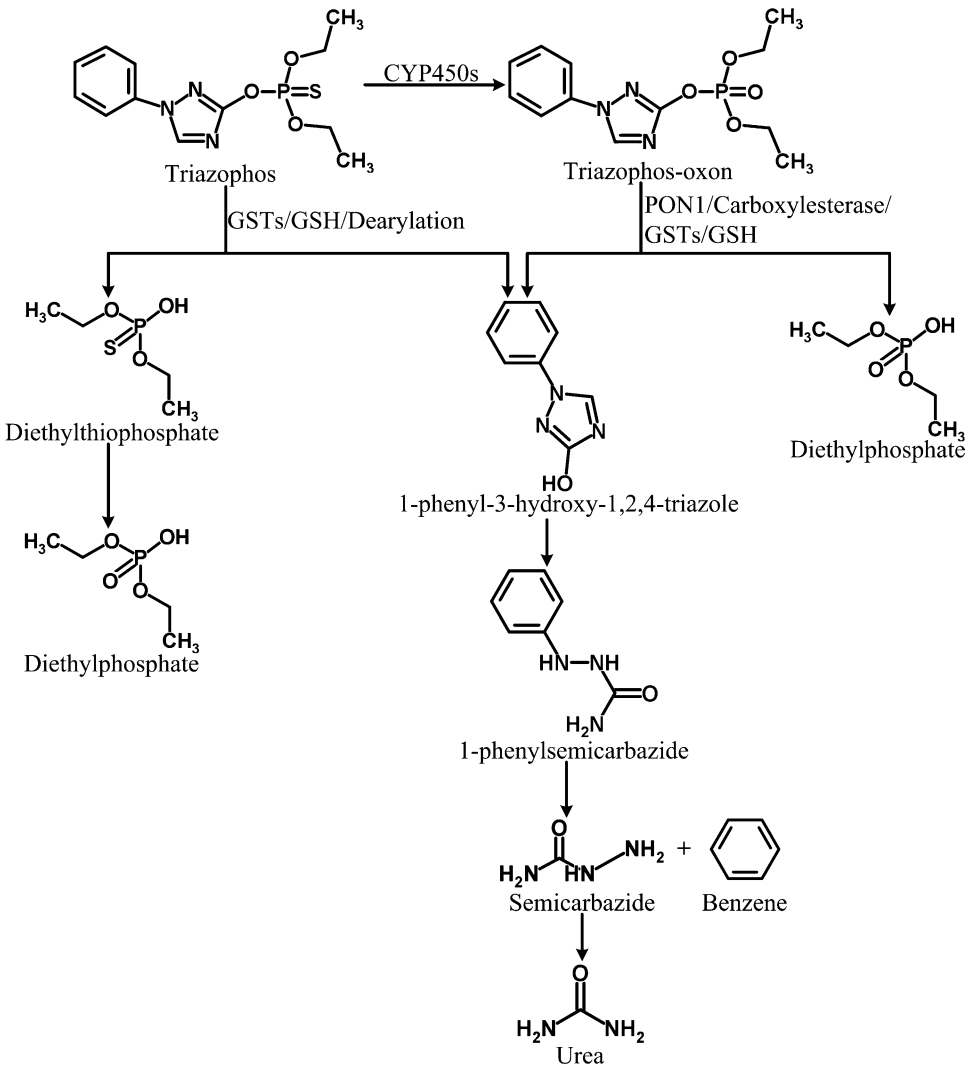

Fig. 2 Possible metabolites of triazophos in vivo (Bock and Thier 1976; Wang et al. 2015). CYP450, Cytochromes P450; GSH, Glutathione; GST, Glutathione S-transferase; PON, Paraoxonase

(43% of the administered dose) and its glucuronide (36%) and sulfate (13%) conjugates. The glucuronide was unstable and was apparently converted to the parent compound at room temperature. Unchanged triazophos was not detected in urine (Schwalbe-Fehl and Schmidt 1986).

Biodegradation of triazophos by bacteria

For the past several years, the overuse of triazophos in China has severely polluted surface water, soil, food and biota (Dai et al. 2017). Therefore, it was important to raise concern about its environmental behavior and to develop an effective and feasible method for removing triazophos residues. Bioremediation was an attractive alternative to the classic treatment of organophosphorus insecticide pollution by taking advantage of microbial metabolism (Upadhyay and Dutt 2017). Studies on the biodegradation of triazophos have been performed previously. Several bacterial strains such as *Bacillus amyloliquefaciens* YP6 (Meng et al. 2019), *Burkholderia sp*. SZL-1 (Zhang et al. 2016), *Klebsiella oxytoca* TDB-1 (Li et al. 2012), *Bacillus sp*. triazophos-1 (Tang and You 2012), *Diaphorobacter sp*. TPD-1 (Yang et al. 2011), *Bacillus subtilis*. CY106 (Chen et al. 2010), *Diaphorobacter sp*. GS-1 (Guo et al. 2009a), *Klebsiella sp*. E6 (Wang et al. 2005), and *Ochrobactrum sp*. mp-4 (Dai et al. 2005) have been reported to be capable of degrading triazophos.

An alkaline phosphatase (AP3) from *Bacillus amyloliquefaciens* YP6 was characterized and utilized to test the potential for new applications in the biodegradation of triazophos. The degradation of triazophos was 96.3% after treatment with AP3 for 1 h, and after treatment with triazophos for 8 h, AP3 activities remained at more than 80% (Meng et al. 2019).

A triazophos-degrading bacterium, *Burkholderia sp*. SZL-1, was isolated from long-term triazophos-polluted soil. Strain SZL-1 could hydrolyze triazophos to 1-phenyl-3-hydroxy-1,2,4-triazole, which was further utilized as the carbon source for growth. In addition, strain SZL-1 could degrade 100 mg L^{-1} triazophos within 4 h (Zhang et al. 2016).

The bioremediation of OPs was recognized as an economical and reliable method. A triazophos-degrading bacterial strain, *Klebsiella oxytoca* TDB-1, which could use triazophos as the sole carbon source, was isolated by enrichment culture technology. Strain TDB-1 was very promising in triazophos biodegradation due to its extreme pH tolerance (pH 4 and 10). The kinetics of strain TDB-1 in degrading triazophos followed a first-order model under optimal growth conditions. Strain TDB-1 had high hydrophobicity when grown on high concentrations of triazophos (Li et al. 2012).

A novel triazophos-degrading *Bacillus sp*., triazophos-1, was isolated from sewage sludge in a wastewater treatment system of organophosphorus insecticide produced by Funong Group Co., in Jianou, Fujian, southeastern China. Triazophos-1 could degrade triazophos through co-metabolism. When fed with nutrients such as yeast extract, peptone and glucose, triazophos-1 could degrade 98.5% of triazophos in the medium (100 mg L^{-1}) within 5 days. *Bacillus sp*. Triazophos-1 could tolerate and degrade relatively high concentrations of triazophos (50–400 mg L^{-1}) (Tang and You 2012).

The bacterial strain *Diaphorobacter sp*. TPD-1, capable of using triazophos and its intermediate, 1-phenyl-3-hydroxy-1,2,4-triazole, as its sole carbon source for growth, was isolated from triazophos-contaminated soil in China. The first step involved in the degradation of triazophos was the hydrolysis of its P-O ester bond to form 1-phenyl-3-hydroxy-1,2,4-triazole and O, O-diethyl phosphorothioic acid. Then, the triazole ring of 1-phenyl-3-hydroxy-1,2,4-triazole was subsequently cleaved to form (E)-1-formyl-2-phenyldiazene. Subsequently, (E)-1-formyl-2-phenyldiazene was transformed to 2-phenylhydrazine carboxylic acid by adding one molecule of H_2O. Finally, the carboxyl group of 2-phenylhydrazine carboxylic acid was decarboxylated to form phenylhydrazine (Fig. 3) (Yang et al. 2011).

Strain C-Y106 was identified as *Bacillus subtilis*. Strain CY106 could grow in mineral salt medium with 40 mg L^{-1} triazophos as the sole source of carbon, nitrogen and phosphorus. The triazophos degradation rate was the highest, at 76.8%, in the mineral salt medium with 40 mg L^{-1} triazophos as the sole source of phosphorus after being incubated at 31 °C, pH 8.0 and 150 r/min for 60 h (Chen et al. 2010).

A strain designated GS-1, capable of efficiently degrading triazophos, was isolated from the sludge in an organophosphorus insecticide wastewater treatment plant. Strain GS-1 was identified preliminarily as *Diaphorobacter sp*. based

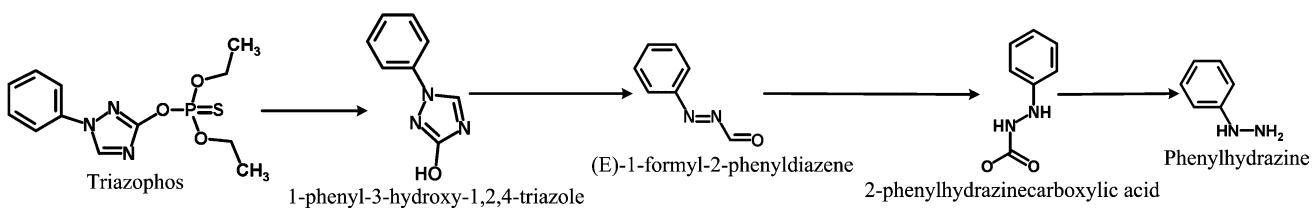

Fig. 3 Proposed degradation pathway of triazophos by *Diaphorobacter* sp. TPD-1

on its physiological and biochemical characteristics and the result of the 16S rDNA homologue sequence analysis. Strain GS-1 could grow with triazophos as its sole carbon source and degrade 100 mg L^{-1} triazophos to a nondetectable level within 12 h (Guo et al. 2009a).

A triazophos-degrading strain, *Klebsiella sp*. E6, was isolated by enrichment from soil that had been exposed long term to triazophos. Strain E6 showed that it utilized triazophos more effectively when triazophos was supplied as the sole nitrogen source as opposed to an additional carbon source. The metabolic products of triazophos degradation, diethylthiophosphate and 1-phenyl-3-hydroxy-1,2,4-triazole, were formed through the hydrolysis of triazophos. Based on the above experimental evidence, an initial pathway of triazophos degradation was proposed (Fig. 4). *Klebsiella sp*. E6 was capable of degrading triazophos and therefore would be beneficial for the exploration of new bioremediation strategies for triazophos-contaminated sites (Wang et al. 2005).

A triazophos-degrading bacterium designated mp-4 was isolated from soils that have long been subjected to organophosphorus pollution. Strain mp-4 was identified as *Ochrobactrum sp*. based on its biochemical–physiological characteristics and the result of 16S rDNA homologue sequence analysis. Strain mp-4 could grow with triazophos as its sole carbon source and degrade it at a rate of 98.3%. At 27–32 °C and pH 7.5–8.8, mp-4 could significantly degrade triazophos. Field test showed that mp-4 could decrease the residue of triazophos in rice husk and brown rice by 91.9 and 100%, respectively (Dai et al. 2005).

Hydrolysis and photolysis of triazophos

The proposed mechanism for the base-catalyzed hydrolysis of triazophos is shown in Fig. 5a. In a basic solution of pH 10, the polarization of the O-P bond in triazophos results from the differing electronegativities of the oxygen atom and phosphorus atom. Therefore, there was an electron deficiency at the phosphorus atom. The nucleophile, a hydroxide ion, approaches the phosphorus atom in triazophos and displaces H-I, which acted as the leaving group to form H-I. The other product, H-II, was further attacked by the hydroxide ion and again undergoes similar nucleophilic reactions to form the products H-III, H-IV and ethyl alcohol (Lin et al. 2004a). Figure 5b illustrated the mechanism of acid-catalyzed hydrolysis. In solution at pH 4, the protonation of the P–S bond was the first step in the hydrolysis of triazophos. The protonated inter-I was attacked by water. Loss of a proton gives a pentahedral inter-II, which could be further converted to form inter-III. By attacking water, inter-III was finally deprotonated to produce H-II. H-II underwent similar reactions to give H-III and H-IV (Lin et al. 2004a). Thus, triazophos was relatively stable in acidic and neutral solutions and easily hydrolyzes in basic solutions. The base-catalyzed and acid-catalyzed hydrolyses occurred possibly through two different pathways; however, they produced the same products.

The UV-Fenton degradation products of triazophos could be tentatively identified as the corresponding trimethylsilyl derivatives of O,O-diethyl phosphorothioic acid, monoethyl phosphorothioic acid, phosphorothioic acid, 1-phenyl-3-hydroxy-1,2,4-triazole, and 1-phenyl semicarbazine. Based on the products detected, a possible degradation pathway of triazophos with the UV-Fenton process is proposed in Fig. 6. Triazophos in aqueous solution was relatively stable in response to irradiation from the sun and a mercury lamp. However, the photo-Fenton process could degrade triazophos effectively. With the optimized parameters, the degradation of triazophos using UV-Fenton and solar-Fenton processes followed the first-order reaction model. The solar-Fenton process offered a promising method to remove triazophos in water (Lin et al. 2004b).

The degradation of triazophos was maximum under UV light ($t1/2$ 2.01 ± 0.02 days), followed by enhanced sunlight (twice the normal sunlight flux density, $t1/2$ 2.95 ± 0.065 days), normal sunlight ($t1/2$ 8.22 ± 0.24 days) and dark conditions ($t1/2$ 36.7 ± 0.86 days). Furthermore, exposure of the thin film of triazophos to different light conditions revealed that the pesticide was photolabile and highly unstable under UV light ($t1/2$ 2.92 ± 0.09 days), followed by enhanced sunlight ($t1/2$ 3.89 ± 0.46 days), normal sunlight and dark conditions (Rani and Sud 2015a).

Detection methods of triazophos

Classic analytical techniques, such as high-performance liquid chromatography and gas chromatography coupled with different detection modes, were carefully used to

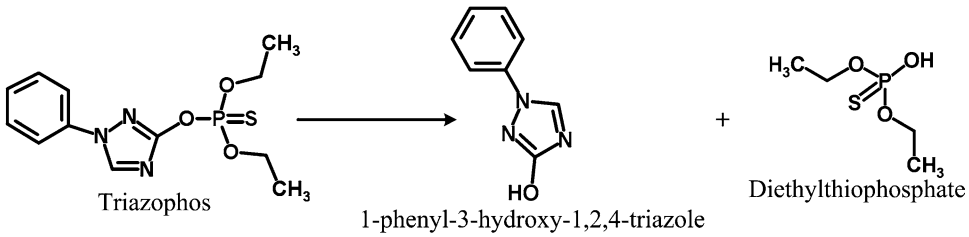

Fig. 4 Triazophos degradation pathway in *Klebsiella sp*. E6

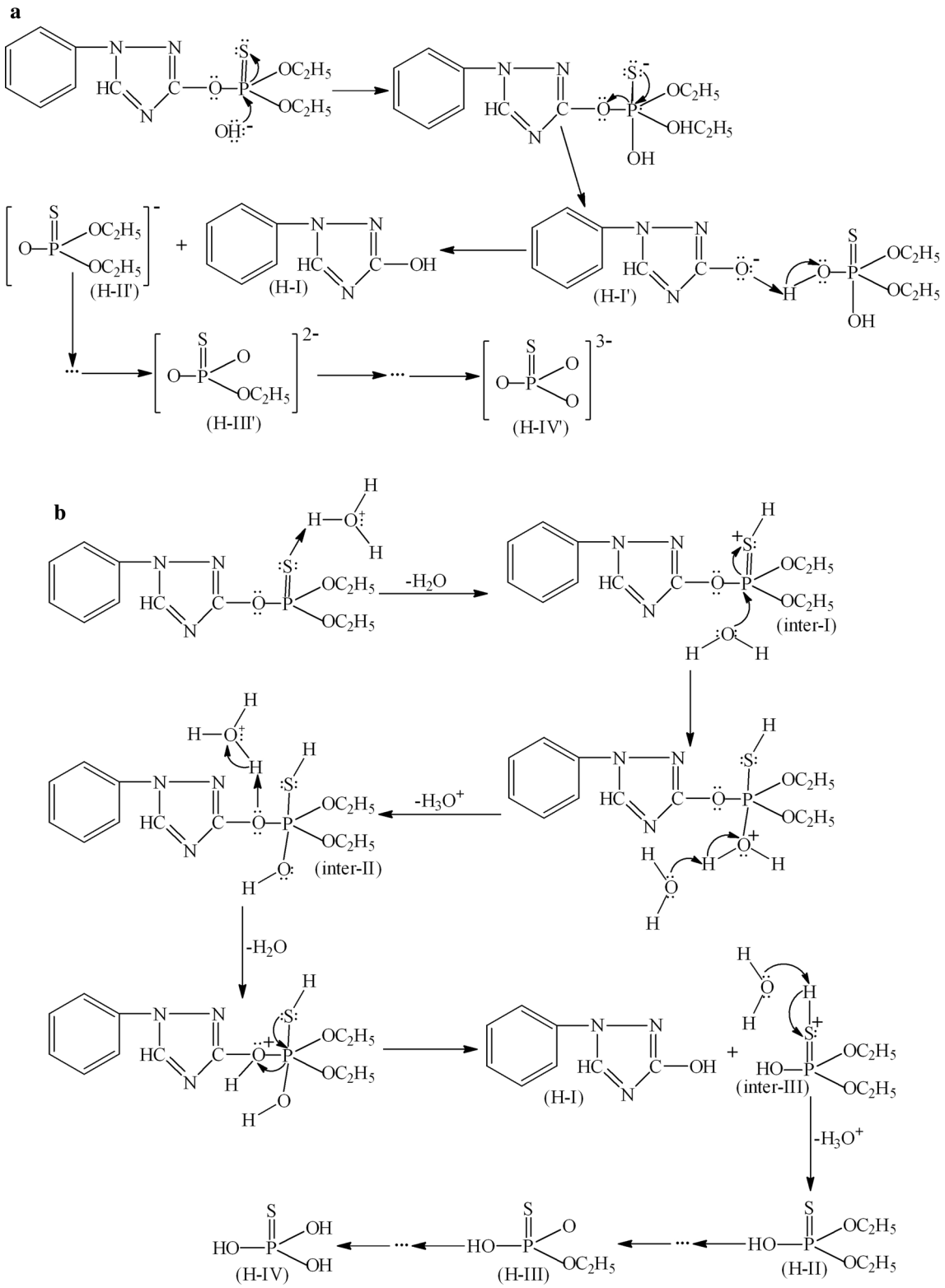

Fig. 5 Possible hydrolytic pathways for triazophos in (a) pH 10 and (b) pH 4 solutions, respectively (Lin et al. 2004a)

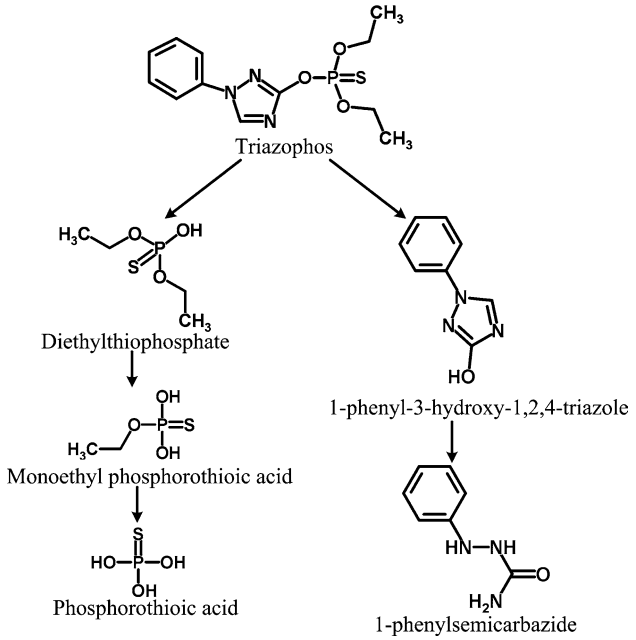

Fig. 6 Proposed degradation pathway of triazophos with the UV-Fenton process (Lin et al. 2004b)

determine triazophos residues in various samples (Fu et al. 2009; Zhao et al. 2014; Andrade et al. 2015; Hayward et al. 2015). These methods were accurate and reliable but require skilled technicians, sophisticated instrumentation, high consumption of organic solvent and complicated sample pretreatment. Studies using mass spectrometry tools to detect triazophos were often studies that specifically investigated the degradation of triazophos to determine the degradation products of triazophos and to speculate the corresponding degradation pathways (Aungpradit et al. 2007; Lin et al. 2004a, b). However, it was noteworthy that there were few studies that simply determine one of the organophosphorus pesticides in foods, agricultural products or environmental samples with mass spectrometry technology. Researchers often used mass spectrometry to detect a large number of organophosphorus pesticides in samples, and triazophos was one of the detected organophosphorus pesticides (Guo et al. 2019; Huang et al. 2019; Lehotay 2019). For example, determination of multi-pesticide residues in green tea with the high-performance liquid chromatography-tandem mass spectrometry, the linear range of triazophos was 2–50 μg L^{-1}, the limit of detection of triazophos was 0.5 μg L^{-1} (Huang et al. 2019). Or it was related to the rapid detection of triazophos, the researchers compared the results of mass spectrometry with the results of rapid detection to prove the feasibility and applicability of their rapid detection technology (Guo et al. 2018; Hong et al. 2019).

Nanosensors and nanobiosensors were alternative classical quantification methods in food and agricultural products (Srivastava et al. 2018). AChE-based biosensors for triazophos (Ju et al. 2015; Du et al. 2007) were rapid and easy to use but lack high specificity, as AChE could be inhibited by both organophosphorus and carbamate pesticides. As a popular screening methodology, immunodiagnostics of different formats, such as enzyme-linked immunosorbent assay (ELISA) (Liang et al. 2007; Gui et al. 2006, 2010; Jin et al. 2008), microbead-based immunoassay (Du et al. 2015; Liang et al. 2013; Guo et al. 2013), chemiluminescent enzyme immunoassay (CLEIA) (Jin et al. 2012; Chen et al. 2015), gold immunochromatographic strip test (Guo et al. 2009b; Gui et al. 2008) and fluorescence polarization immunoassay (Liu et al. 2016), had been successfully developed for the rapid detection of triazophos residues in food and environmental samples, with detection limits lower than 0.01 mg L^{-1} (Table 4).

To date, only a non-competitive rapid piezoelectric immunosensor for the direct determination of triazophos has been reported (Huang et al. 2010), but the detection limit (0.04 mg L^{-1}) and working range (0.1–100 mg L^{-1}) cannot reach the MRL requirements. A competitive assay using novel CdSe/Zns quantum dot fluorescence based on molecularly imprinted sensitive membranes showed good sensitivity, steady and fast response and excellent anti-interference ability compared to those of conventional fluorescence-quenching methods, and the proposed methodology was successfully applied for the detection of triazophos in real samples and met the

Table 4 Rapid immunoassays for detection of triazophos in buffer

Assay format	LOD (ng mL^{-1})	Linear range (ng mL^{-1})	Assay time	References
Antibody-coated ELISA	0.07 (IC_{10})	0.12–3.58	75–80 min per run	Jin et al. (2008)
Antibody-coated enhanced CLEIA	0.063 ($S/N=3$)	0.12–6.45	60–65 min per run	Jin et al. (2012)
An immunomagnetic bead-based assay	0.1 (IC_{10})	0.19–6.37	40–45 min per run	Du et al. (2015)
A one-step immunogold strip test	4 (By naked eye)	Not determined	10 min per strip	Du et al. (2015)
Fluorescence polarization immunoassay	0.29 (IC_{10})	1.25–10.48	10 min per run	Liu et al. (2016)
Non-competitive piezoelectric immunosensor	40 ($S/N=3$)	100–100,000 (Undefined)	40–45 min per cycle	Huang et al. (2010)
Non-competitive direct SPR immunosensor	0.096 ($S/N=3$)	0.98–8.29 (EC_{20}–EC_{80})	7 min per cycle	Guo et al. (2018)

requirement for detecting its level below the stipulated MRL (MRL = 0.05 mg kg^{-1}) set by China (Hong et al. 2019).

Conclusion

Triazophos has been widely used in large-scale popularization worldwide for more than 40 years. The issues of its excessive usage, excessive residues, aquatic organism poisoning, pest resistance and pest resurgence have been gradually exposed. In recent years, some researchers have successively conducted in-depth studies on triazophos detection technology, dietary exposure, environmental risks, toxicity characteristics, pest resistance mechanisms and re-rampancy mechanisms. The authors suggest that reliable monitoring, assessment and reporting procedures should be implemented in accordance with appropriate risk assessment of dietary exposure, environmental policies, laws and regulations to minimize triazophos exposure.

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Compliance with ethical standards

Conflict of interest The authors declare they have no conflict of interest.

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