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LITERATURE REVIEW

Responses of Plants to Pesticide Toxicity: an Overview

Respostas de Plantas à Toxicidade de Pesticidas: Uma Visão Geral

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ABSTRACT - Pesticides are applied all over the world to protect plants from pests. However, their application also causes toxicity to plants, which negatively affects the growth and development of plants. Pesticide toxicity results in reduction of chlorophyll and protein contents, accompanied by decreased photosynthetic efficiency of plants. Pesticide stress also generates reactive oxygen species which causes oxidative stress to plants. To attenuate the negative effects of oxidative stress, the antioxidative defense system of plants gets activated, and it includes enzymatic antioxidants as well as non-enzymatic antioxidants. The present review gives an overview of various physiological responses of plants under pesticide toxicity in tabulated form.

Keywords: physiological responses, antioxidative defense system, oxidative stress.

RESUMO - Os pesticidas são aplicados no mundo todo para proteger as plantas contra as pragas. No entanto, essa aplicação também causa toxicidade às plantas, o que afeta de forma negativa o crescimento e o desenvolvimento delas. A toxicidade dos pesticidas resulta na redução dos teores de clorofila e proteína, acompanhada de menor eficiência fotossintética das plantas. O estresse causado por pesticidas também gera espécies reativas de oxigênio, que causam estresse oxidativo às plantas. Para atenuar os efeitos negativos do estresse oxidativo, o sistema de defesa antioxidante das plantas é ativado, e isso inclui antioxidantes enzimáticos e não enzimáticos. A presente revisão fornece uma visão geral de várias respostas fisiológicas de plantas sob toxicidade de pesticidas, em forma de tabela.

Palavras-chave: respostas fisiológicas, sistema de defesa antioxidante, estresse oxidativo.

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INTRODUCTION

A pesticide is a compound which is utilized to repel, kill or prevent any pest. On the basis of the target killed, pesticides are mainly classified as herbicides, fungicides and insecticides. The increased demand of food on account of population explosion has compelled man to use pesticides for better crop production (Tomer, 2013). Pesticides are used to protect crops in the field as well as during post-harvest storage to minimize crop damage. Crop plants are attacked by a variety of pests which include soil insects, cut worms, leaf rollers, aphids etc., and pesticides are mostly used to control these pests (Goh et al., 2011). Nowadays, there are other alternatives to control these insect pests which include the use of bio-pesticides and development of pest resistant

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transgenic varieties. However, the use of chemical pesticides is still the best and most widely applied strategy to protect crops from pests and results in high yield production of crops. It has been reported that approximately two million tonnes of pesticides are consumed annually throughout the world (De et al., 2014). Global pesticide consumption includes 47.55% of herbicides, 29.5% of insecticides, 17.5% of fungicides and 5.5% of other pesticides.

Transpiration pull helps in the absorption of water soluble pesticides and their entry into the plant system. Volatile pesticides indirectly come into the atmosphere via leaves through stomata during transpiration. Plants absorb pesticides via roots, leaf surface or roots. A number of factors are involved in pesticide uptake and its metabolism in the plant system which include external environmental factors (temperature, humidity and precipitation) and physiochemical properties of soil and pesticides (Finlayson and MacCarthy, 1973). Uptake of pesticides via the root system and their metabolism in the plant system is affected by factors such as mode of application, amount of pesticide, physiochemical and biochemical properties of pesticides and their reaction with soil and stage of plant development (Führ, 1991). Absorption of pesticides by plants is also determined by their degree of water solubility. Pesticide uptake takes place either by active absorption via the root system, or by passive absorption. Absorbed pesticides are either metabolized by the plant system or accumulate in plants, causing bio-magnification in the ecosystem (Mwevura, 2000).

Pesticide application also causes toxicity to plants, which can be seen in the form of necrosis, chlorosis, stunting, burns and twisting of leaves (Sharma et al., 2018a). The excessive use of pesticides is one of the major causes of reduction of the diversity of structural vegetation (Donald, 2004). Sensitive or stressed plants may be extra vulnerable to phytotoxicity. Toxicity depends upon many factors such as use of pesticides, rate of application, spraying technique, climate conditions, organization of flora, humidity and properties of soil such as moisture, temperature, pH, texture and microbial activity. It has been found that pesticide application negatively affects plant growth and development (Sharma et al., 2015, 2016a, Shahzad et al., 2018). Pesticide application causes oxidative stress to plants as a result of the generation of reactive oxygen species (ROS) Sharma et al., 2018b). This oxidative stress results in degradation of chlorophyll pigments and proteins and it ultimately causes a reduction in the photosynthetic efficiency of plants (Xia et al., 2006; Sharma et al., 2015). To cope up with oxidative stress, the antioxidative defense system of plants is activated, which involves enzymatic and non-enzymatic antioxidants (Xia et al., 2009; Sharma et al., 2015; 2016b,c,d). Activation of the antioxidative defense system aids with ROS scavenging and reduces the oxidative stress in plants caused by pesticide toxicity (Sharma et al., 2015, 2017a,b). The present review has been planned to give a detailed overview of various physiological changes in plants subjected to pesticide treatment. Physiological responses of plants to pesticide application have been summarized in tabulated form.

PHYSIOLOGICAL RESPONSES OF PLANTS TO PESTICIDE TOXICITY

Table 1, 2, and 3 show oxidative stress markers, enzymatic antioxidants and non-enzymatic antioxidants, respectively, whereas supplementary Tables 1, 2, and 3 give a detailed overview for growth parameters, pigment system, photosynthetic parameters and protein content, respectively, in plants against pesticide toxicity.

It has been concluded that pesticide application causes oxidative stress in plants by production of reactive oxygen species. This ultimately leads to retarded growth and photosynthetic efficiency of plants. Plants try to ameliorate pesticide toxicity by activation of their internal antioxidative defense system which includes antioxidative enzymes and non-enzymatic antioxidants.

Table 1 - Effect of pesticides on oxidative stress markers in plants

Type of pesticide	Pesticide name	Plant name	Mode of application	Concentration of pesticide	Time after treatment	Plant part analyzed	Effect of pesticide on oxidative stress markers		Reference
							Parameter	Effect	
Amide	Acetochlor	*Vitis vinifera* L. × *Vitis labrusca* L.	Soil	22460 g a.i. ha^{-1}	30 d	Leaves (upper node)	$O_2^{\cdot -}$ MDA	Increase Increase	Tan et al. (2012)
	Napropamide	*Brassica napus* L.	Seedling	8 mg L^{-1}	5 d	Leaves	TBARS	Increase	Cui et al. (2010)
						Root	TBARS	Increase	
	Rac-metolachlor	*Oryza sativa* L.	Culture solution	6.2 µM L^{-1}	5 d	Root	MDA	Increase	Liu et al. (2012)
		Zea mays L.	Culture solution	74.4 µM L^{-1}	5 d	Root	MDA	Increase	
	S-metolachlor	*O. sativa* L.	Culture solution	6.2 µM L^{-1}	5 d	Root	MDA	Increase	
		Z. mays L.	Culture solution	74.4 µM L^{-1}	5 d	Root	MDA	Increase	
Cyclohexene oxime	Clethodim	*Z. mays* L.	Soil	200 ppm	21 d	Leaves	H_2O_2 MDA	Increase Increase	Radwan (2012)
Dinitroaniline	Pendimethalin	*Vigna mungo* L. var. Shekhar	Soil	10 ppm	15 d	Leaves	MDA	Decrease	Singh et al. (2012)
Diphenyl ether	Fluoroglycofen	*V. vinifera* L. × *V. labrusca* L.	Soil	375 g a.i. ha^{-1}	30 d	Leaves (upper node)	$O_2^{\cdot -}$ MDA	Increase Increase	Tan et al. (2012)
Imidazolinone	Imazapic	*Nicotiana tabacum* L.	Spray	0.12 mM	9 d	Leaves	MDA	Increase	Kaya and Doganlar (2016)
	R (-)-imazethapyr	*Arabidopsis thaliana* L.	Culture solution	2.5 µg L^{-1}	28 d	Plantlets	$O_2^{\cdot -}$ H_2O_2 MDA	Increase Increase Increase	Qian et al. (2011)
	S (+)-imazethapyr	*A. thaliana* L.	Culture solution	2.5 µg L^{-1}	28 d	Plantlets	$O_2^{\cdot -}$ H_2O_2 MDA	Increase Increase No change	
Neonicotinoid	Imidacloprid	*Oryza sativa* L.	Sand	0.015%	12 d	Seedlings	$O_2^{\cdot -}$ H_2O_2 MDA	Increase Increase Increase	Sharma et al. (2015)
				0.02%	12 d	Seedlings	MDA	Increase	Sharma et al. (2013)
Organophosphorus	Chlorpyrifos	*O. sativa* L.	Sand	0.04%	12 d	Seedlings	$O_2^{\cdot -}$ H_2O_2 MDA	Increase Increase Increase	Sharma et al. (2015)
				0.06%	12 d	Seedlings	MDA	Increase	Sharma et al. (2012)
		Vigna radiata L.	Spray	15 mM	10 d	Leaves	TBARS	Increase	Parween et al. (2012)
	Dimethoate	*V. radiata* L.	Culture soln.	150 ppm	4 d	Leaves	$O_2^{\cdot -}$ H_2O_2 MDA OH^-	Increase Increase Increase Increase	Singh et al. (2014)
	Glyphosate	*Glycine max* L. var. DM48	Spray	0.94 %	24 h	Leaves	MDA	Increase	Moldes et al. (2008)
						Root	MDA	Increase	
		G. max L. var. DM4800RG	Spray	0.94 %	24 h	Leaves	MDA	Increase	
						Root	MDA	Decrease	
		G. max L. var. MSOY7501	Spray	0.94 %	24 h	Leaves	MDA	Increase	
						Root	MDA	Increase	
		G. max L. var. MSOY7575RR	Spray	0.94 %	24 h	Leaves	MDA	Increase	
						Root	MDA	Increase	
		Z. mays L. var. Kneza-640	Spray	10 mM	10 d	Leaves	H_2O_2 MDA Electrolyte leakage	Increase Increase Increase	Sergiev et al. (2006)
Phenoxy	Clodinafop-propargyl	*Secale cereale* L.	Spray	800 µg L^{-1}	7 d	Leaves	$O_2^{\cdot -}$	Increase	Lukatkin et al. 2013
		Triticum aestivum L.	Spray	800 µg L^{-1}	7 d	Leaves	$O_2^{\cdot -}$	Increase	
		Z. mays L.	Spray	800 µg L^{-1}	7 d	Leaves	$O_2^{\cdot -}$	Increase	
	Fluazifop-*P*-butyl	*Acanthospermum hispidum* DC.	Shoot immersing	10 µM	24 h	Leaves	MDA	Increase	Luo et al. (2004)
		Avena sativa L.	Shoot immersing	10 µM	24 h	Leaves	MDA	Increase	
	Fusilade	*Arachis hypogaea* L.	Spray	60 ppm	14 d	Leaves	H_2O_2 MDA	Increase Increase	Fayez et al. (2014)
	Quizalofop-*p*-ethyl	*Helianthus. annuus* L.	Spray	0.8 mM	15 d	Leaves	MDA	Increase	Bayram et al. (2015)
	R-diclofop-methyl	*A. thaliana* L.	Culture medium	1 mg L^{-1}	28 d	Plantlets	MDA	Increase	Zhang et al. (2012)
	S-diclofop-methyl	*A. thaliana* L.	Culture medium	1 mg L^{-1}	28 d	Plantlets	MDA	Increase	
Pyrethroid	Deltamethrin	*G. max* L. Merr.	Spray	0.20 %	10 d	Leaves	MDA	Increase	Bashir et al. (2007)
Pyridine	Fluroxypyr	*O. sativa* L.	Culture soln.	0.8 mg L^{-1}	6 d	Leaves	O_2^{-} H_2O_2 MDA	Increase Increase Increase	Wu et al. (2010)
Quaternary ammonium	Paraquat	*Papaver somniferum* L.	Spray	0.48 %	24 h	Leaves	MDA Electrolyte leakage	Increase Increase	Zhao et al. (2010)
Triazine	Atrazine	*Acorus calamus* L.	Culture soln.	8 mg L^{-1}	15 d	Leaves	MDA	Increase	Wang et al. (2015)
		Lythrum salicaria L.	Culture soln.	8 mg L^{-1}	15 d	Leaves	MDA	Increase	
		O. sativa L.	Hoagland medium	0.4 mg L^{-1}	6 d	Leaves	$O_2^{\cdot -}$ H_2O_2 TBARS	Increase Increase Increase	Zhang et al. (2014)

To be continued...

Table 1, cont...

Type of pesticide	Pesticide name	Plant name	Mode of application	Concentration of pesticide	Time after treatment	Plant part analyzed	Effect of pesticide on oxidative stress markers: Parameter	Effect of pesticide on oxidative stress markers: Effect	Reference
Triazine	Atrazine	*Pennisetum americanum* L.	Soil	10 mg kg^{-1}	38 d	Shoot	MDA	Increase	Jiang et al. (2016)
						Root	MDA	Increase	
		Scirpus tabernaemontani P.	Culture soln.	8 mg L^{-1}	15 d	Leaves	MDA	Increase	Wang et al. (2015)
		Vicia faba L.	Spray	1.79 kg a.i. ha^{-1}	12 d	Shoot	H_2O_2 MDA C=O	Increase Increase Increase	Hassan and Alla (2005)
		Z. mays L.	Spray	1.79 kg a.i. ha^{-1}	12 d	Shoot	H_2O_2 MDA C=O	Increase Increase Increase	
				78 mM	5 d	Leaves	MDA	Increase	Akbulut and Yigit (2010)
			Hoagland medium	10 mg L^{-1}	3 d	Shoot	MDA	No change	Li et al. (2012)
						Root	MDA	Increase	
		Z. mays L. Hybrid 351	Soil	1.79 kg ha^{-1}	8 d	Shoot	H_2O_2 MDA C=O	Increase Increase Increase	Alla and Hassan (2006)
		Z. mays L. Giza 2	Soil	1.79 kg ha^{-1}	8 d	Shoot	H_2O_2 MDA C=O	Increase Increase Increase	
	Prometryne	*T. aestivum* L.	Soil	12 mg kg^{-1}	10 d	Leaves	TBARS	Increase	Jiang and Yang (2009)
						Root	TBARS	Increase	
Urea	Chlorotoluron	*T. aestivum* L.	Soil	25 mg kg^{-1}	10 d	Leaves	$O_2^{\bullet -}$ H_2O_2 TBARS	Increase Increase Increase	Song et al. (2007)
	Chlorimuron-ethyl	*T. aestivum* L.	Soil	300 µg kg^{-1}	24 h	Leaves	MDA	Increase	Wang and Zhou (2006)
						Root	MDA	Increase	
	Fluometuron	*V. faba* L.	Spray	2.98 kg a.i. ha^{-1}	12 d	Shoot	H_2O_2 MDA C=O	Increase Increase Increase	Hassan and Alla (2005)
		Z. mays L.	Spray	2.98 kg a.i. ha^{-1}	12 d	Shoot	H_2O_2 MDA C=O	Increase Increase Increase	
	Granstar	*Avena fatua* L.	Spray	300 µg L^{-1}	3 d	Leaves	$O_2^{\bullet -}$ MDA	Increase Increase	Gar'kova et al. (2011)
		Secale cereale L.	Spray	300 µg L^{-1}	3 d	Leaves	$O_2^{\bullet -}$ MDA	Increase Increase	
			Leaf disk immersing	300 µg L^{-1}	3 h	Leaves	$O_2^{\bullet -}$	Increase	
		T. aestivum L.	Leaf disk immersing	300 µg L^{-1}	3 h	Leaves	$O_2^{\bullet -}$	Increase	
			Spray	300 µg L^{-1}	3 d	Leaves	$O_2^{\bullet -}$ MDA	Increase Increase	
		Z. mays L.	Leaf disk immersing	300 µg L^{-1}	3 h	Leaves	$O_2^{\bullet -}$	Increase	
			Spray	300 µg L^{-1}	3 d	Leaves	$O_2^{\bullet -}$ MDA	Increase Increase	
	Isoproturon	*P. sativum* L.	Sand	10 mM	15 d	Leaves	H_2O_2 MDA Electrolyte leakage	Increase Increase Increase	Singh et al. (2016)
		T. aestivum L.	Soil	2.5 L ha^{-1}	15 d	Shoot	H_2O_2 MDA	Increase Increase	Alla and Hassan (2014)
				4 mg kg^{-1}	10 d	Shoot	$O_2^{\bullet -}$ H_2O_2 TBARS	Increase Increase Increase	Liang et al. (2012)
						Root	TBARS	Increase	
						Leaves	H_2O_2	Increase	
				10 mg kg^{-1}	10 d	Leaves	TBARS	Increase	Yin et al. (2008)
						Root	TBARS	No change	
	Rimsulfuron	*V. faba* L.	Spray	0.015 kg a.i. ha^{-1}	12 d	Shoot	H_2O_2 MDA C=O	Increase Increase Increase	Hassan and Alla (2005)
		Z. mays L.	Spray	0.015 kg a.i. ha^{-1}	12 d	Shoot	H_2O_2 MDA C=O	Increase Increase No change	
Unclassified	Dichlorobenzene	*Z. mays* L.	Hoagland medium	80 mg L^{-1}	7 d	Root	H_2O_2	Increase	San Miguel et al. (2012)
						Leaves	H_2O_2	Decrease	
	Flurochloridone	*H. annuus* L.	Spray	11 mM	15 d	Leaves	MDA	Increase	Kaya and Yigit (2014)
	Monochlorobenzene	*Z. mays* L.	Hoagland medium	80 mg L^{-1}	7 d	Root	H_2O_2	Increase	San Miguel et al. (2012)
						Leaves	H_2O_2	No change	
	Trichlorobenzene	*Z. mays* L.	Hoagland medium	40 mg L^{-1}	7 d	Root	H_2O_2	Increase	
						Leaves	H_2O_2	Increase	

Table 2 **-** Effect of pesticides on enzymatic antioxidants in plants

Type of pesticide	Pesticide name	Plant name	Mode of application	Concentration of pesticide	Time after treatment	Plant part analyzed	Effect of pesticide on enzymatic antioxidants		Reference
							Parameter	Effect	
Amide	Acetochlor	*Vitis vinifera* L. × *Vitis labrusca* L.	Soil	22460 g a.i.ha^{-1}	30 d	Leaves (upper node)	APOX CAT POD SOD	Decrease Decrease Decrease Decrease	Tan et al. (2012)
	Alachlor	*Lactuca sativa* L.	Hoagland medium	2 µM	24 d	Leaves	CAT POD SOD	Increase Increase Increase	Stajner et al. (2003)
		Phaseolus vulgaris L.	Hoagland medium	2 µM	24 d	Leaves	CAT POD SOD	Increase Increase Increase	
		Pisum sativum L.	Hoagland medium	2 µM	24 d	Leaves	CAT POD SOD	Increase Increase Increase	
	Fomesafen	*Glycine max* L. Merr.	Spray	1000 g ha^{-1}	2 d	Leaves	GST	Increase	Andrews et al. (2005)
	Metolachlor	*L. sativa* L.	Hoagland medium	2 µM	24 d	Leaves	CAT POD SOD	No change Decrease Increase	Stajner et al. (2003)
		P. vulgaris L.	Hoagland medium	2 µM	24 d	Leaves	CAT POD SOD	Increase Increase Increase	
		P. sativum L.	Hoagland medium	2 µM	24 d	Leaves	CAT POD SOD	Decrease Increase Increase	
	Metosulam	*Vicia faba* L.	Seedling's root immersing	10^{-4} %	24 h	Leaves	APOX CAT POD	Increase Increase Decrease	Badr et al. (2013)
	Napropamide	*Brassica napus* L.	Seedling	8 mg L^{-1}	5 d	Leaves	APOX CAT GST POD SOD	Increase Increase Increase Increase Increase	Cui et al. (2010)
	Rac-metolachlor	*Oryza. sativa* L.	Culture solution	6.2 µM L^{-1}	5 d	Root	CAT POD	Decrease Decrease	Liu et al. (2012)
		Zea mays L.	Culture solution	74.4 µM L^{-1}	5 d	Root	CAT POD SOD	Decrease Decrease Decrease	
	S-metolachlor	*O. sativa* L.	Culture solution	6.2 µM L^{-1}	5 d	Root	CAT POD	Decrease Decrease	
		Z. mays L.	Culture solution	74.4 µM L^{-1}	5 d	Root	CAT POD SOD	Decrease Decrease Decrease	
Cyclohexene oxime	Clethodim	*Z. mays* L.	Soil	200 ppm	21 d	Leaves	APOX CAT POD SOD	Increase Decrease Increase Decrease	Radwan (2012)
Diphenyl ether	Fluoroglycofen	*V. vinifera* L. × *V. labrusca* L.	Soil	375 g ai ha^{-1}	30 d	Leaves (upper node)	APOX CAT POD SOD	Decrease Decrease Decrease Decrease	Tan et al. (2012)
	Oxyfluorfen	*G. max* L. Merr.	Spray	2500 g ha^{-1}	2 d	Leaves	GST	Increase	Andrews et al. (2005)
Imidazolinone	Imazapic	*Nicotiana tabacum* L.	Spray	0.12 mM	9 d	Leaves	APOX CAT GR GST	Increase Increase Increase Increase	Kaya and Doganlar (2016)
	R (-)-imazethapyr	*Arabidopsis thaliana* L.	Culture solution	2.5 µg L^{-1}	28 d	Plantlets	APOX CAT GPOX SOD	Decrease Decrease Increase Decrease	Qian et al. (2011)
	S (+)-imazethapyr	*A. thaliana* L.	Culture solution	2.5 µg L^{-1}	28 d	Plantlets	APOX CAT GPOX SOD	Increase Decrease Increase Decrease	
Neonicotinoid	Imidacloprid	*Brassica juncea* L.	Soil	300 mg kg^{-1}	65 d	Leaves	GR GST POD	Increase Increase Increase	Sharma et al. (2016b)
					80 d	Green pods	APOX GPOX GR GST POD	Increase Increase Increase Increase Increase	Sharma et al. (2017c)
		O. sativa L.	Sand	0.01%	12 d	Seedlings	APOX CAT DHAR GR MDHAR POD SOD	Increase Decrease Increase Increase Increase Decrease Increase	Sharma et al. (2013)

To be continued...

Table 2, cont...

Type of pesticide	Pesticide name	Plant name	Mode of application	Concentration of pesticide	Time after treatment	Plant part analyzed	Effect of pesticide on enzymatic antioxidants: Parameter	Effect of pesticide on enzymatic antioxidants: Effect	Reference
				0.015%	12 d	Seedlings	APOX CAT DHAR GR MDHAR POD SOD	Increase Increase Decrease Increase Increase Decrease Increase	Sharma et al. (2015)
Organochlorine	DDT	*G. max* L.	Soil	63.5 ng g^{-1}	60 d	Leaves Root	GST GST	Decrease Increase	Mitton et al. (2016)
		Medicago sativa L.	Soil	63.5 ng g^{-1}	60 d	Leaves Root	GST GST	Increase Increase	
Organophosphorus	Chlorpyrifos	*Vigna radiata* L.	Spray	15 mM	10 d	Leaves	APOX CAT GR SOD	Increase Decrease Increase Increase	Parween et al. (2012)
	Dimethoate	*V. radiata* L.	Culture soln.	30 ppm	4 d	Leaves	CAT DHAR GR SOD	Increase Increase Increase Increase	Singh et al. (2014)
				150 ppm	4 d	Leaves	CAT DHAR GR SOD	Decrease Decrease Decrease Increase	
	Glyphosate	*G. max* L. var. DM48	Spray	0.94 %	24 h	Leaves	APOX CAT POD	Increase Increase Increase	Moldes et al. (2008)
						Roots	APOX CAT POD	Increase Increase Decrease	
		G. max L. var. DM4800RG	Spray	0.94 %	24 h	Leaves	APOX CAT POD	Increase Decrease Increase	
						Root	APOX CAT POD	Increase Decrease Increase	
		G. max L. var. MSOY7501	Spray	0.94 %	24 h	Leaves	APOX CAT POD	Increase Decrease Increase	
						Root	APOX CAT POD	Increase Decrease Increase	
		G. max L. var. MSOY7575RR	Spray	0.94 %	24 h	Leaves	APOX CAT POD	Increase Increase Increase	
						Roots	APOX CAT POD	Increase Increase Increase	
		V. radiate L. var. PDM11	Seed	10 mM	12 d	Root	CAT GST POD	Increase Increase Increase	Basantani et al. (2011)
		V. radiate L. var. PDM54	Seed	10 mM	12 d	Root	CAT POD GST	Increase Increase Increase	
		Z. mays L. var. Kneza-640	Spray	10 mM	10 d	Leaves	CAT GST POD	Increase Increase Increase	Sergiev et al. (2006)
Phenoxy	Clodinafop-propargyl	*Secale cereale* L.	Spray	800 µg L^{-1}	7 d	Leaves	CAT APOX	Increase Increase	Lukatkin et al. 2013
		Triticum aestivum L.	Spray	800 µg L^{-1}	7 d	Leaves	CAT APOX	Increase Increase	
		Z. mays L.	Spray	800 µg L^{-1}	7 d	Leaves	CAT APOX	Increase Increase	
	Fenoxaprop-*p*-ethyl	*T. aestivum* L.	Spray	250 g ha^{-1}	15 d	Leaves	CAT POD	Increase Increase	Sing et al. (2013)
	Fusilade	*Arachis hypogaea* L.	Spray	60 ppm	14 d	Leaves	APOX CAT POD SOD	Increase Decrease Increase Decrease	Fayez et al. (2014)
	Haloxyfop-ethoxyethyl	*Triticum vulgare* L.	Drop on leaf	50 µM	12 h	Leaves	APOX CAT POD SOD	Increase Increase Increase Decrease	Janicka et al. (2008)
	Quizalofop-*p*-ethyl	*Helianthus annuus* L.	Spray	0.8 mM	15 d	Leaves	APOX POD	Increase Increase	Bayram et al. (2015)
	R-diclofop-methyl	*A. thaliana* L.	Culture medium	1 mg L^{-1}	28 d	Plantlets	CAT POD SOD	Decrease Increase Increase	Zhang et al. (2012)
	S-diclofop-methyl	*A. thaliana* L.	Culture medium	1 mg L^{-1}	28 d	Plantlets	CAT POD SOD	Increase Increase Decrease	

To be continued...

Table 2, cont...

Type of pesticide	Pesticide name	Plant name	Mode of application	Concentration of pesticide	Time after treatment	Plant part analyzed	Effect of pesticide on enzymatic antioxidants		Reference
							Parameter	Effect	
Pyrethroid	Deltamethrin	*G. max* L. Merr.	Spray	0.20 %	10 d	Leaves	APOX CAT GR SOD	Increase Decrease Increase Increase	Bashir et al. (2007)
Pyridine	Fluroxypyr	*O. sativa* L.	Culture soln.	0.8 mg L^{-1}	6 d	Leaves	APOX CAT POD SOD	No change Decrease Increase Increase	Wu et al. (2010)
Quaternary ammonium	Paraquat	*Papaver somniferum* L.	Spray	0.48 %	24 h	Leaves	CAT POD SOD	Increase Decrease Increase	Zhao et al. (2010)
Triazine	Atrazine	*Acorus calamus* L.	Culture soln.	8 mg L^{-1}	15 d	Leaves	POD	Increase	Wang et al. (2015)
Triazine	Atrazine	*Lythrum salicaria* L.	Culture soln.	8 mg L^{-1}	15 d	Leaves	POD	Decrease	Wang et al. (2015)
Triazine	Atrazine	*O. sativa* L.	Hoagland medium	0.4 mg L^{-1}	6 d	Leaves	APOX CAT GR GST POD SOD	Increase Increase Increase Increase Increase Increase	Zhang et al. (2014)
Triazine	Atrazine	*O. sativa* L.	Hoagland medium	0.4 mg L^{-1}	6 d	Root	APOX CAT GR GST POD SOD	Increase Increase Increase Decrease Increase Increase	Zhang et al. (2014)
Triazine	Atrazine	*Pennisetum americanum* L.	Soil	10 mg kg^{-1}	38 d	Shoot	APOX CAT POD SOD	Increase Increase Increase Increase	Jiang et al. (2016)
Triazine	Atrazine	*Pennisetum americanum* L.	Soil	10 mg kg^{-1}	38 d	Root	APOX CAT POD SOD	Increase Increase Increase Increase	Jiang et al. (2016)
Triazine	Atrazine	*Scirpus tabernaemontani* P.	Culture soln.	8 mg L^{-1}	15 d	Leaves	POD	Decrease	Wang et al. (2015)
Triazine	Atrazine	*V. faba* L.	Spray	1.79 kg a.i. ha^{-1}	12 d	Shoot	APOX CAT POD SOD	Decrease Decrease Decrease Decrease	Hassan and Alla (2005)
Triazine	Atrazine	*Z. mays* L.	Spray	1.79 kg a.i. ha^{-1}	12 d	Shoot	APOX CAT POD SOD	Decrease Decrease Decrease Increase	Hassan and Alla (2005)
Triazine	Atrazine	*Z. mays* L.	Spray	78 mM	5 d	Leaves	APOX POD	Increase Increase	Akbulut and Yigit (2010)
Triazine	Atrazine	*Z. mays* L.	Hoagland medium	10 mg L^{-1}	3 d	Shoot	CAT POD SOD	Increase Increase Increase	Li et al. (2012)
Triazine	Atrazine	*Z. mays* L.	Hoagland medium	10 mg L^{-1}	3 d	Root	CAT POD SOD	Increase Increase Increase	Li et al. (2012)
Triazine	Atrazine	*Z. mays* L. Hybrid 351	Soil	1.79 kg ha^{-1}	8 d	Shoot	APOX CAT POD GST SOD	Increase Decrease Decrease Increase Increase	Alla and Hassan (2006)
Triazine	Atrazine	*Z. mays* L. Giza 2	Soil	1.79 kg ha^{-1}	8 d	Shoot	APOX CAT POD GST SOD	Decrease Decrease Decrease Decrease Decrease	Alla and Hassan (2006)
Triazine	Prometryn	*T. aestivum* L.	Soil	12 mg kg^{-1}	10 d	Leaves	APOX CAT GST POD SOD	Increase Increase Increase Increase Increase	Jiang and Yang (2009)
Triazine	Prometryn	*T. aestivum* L.	Soil	12 mg kg^{-1}	10 d	Root	APOX CAT GST POD SOD	Increase Increase Increase Increase Increase	Jiang and Yang (2009)
Urea	Chlorotoluron	*T. aestivum* L.	Soil	25 mg kg^{-1}	10 d	Root	APOX CAT POD SOD	Increase Decrease Increase Increase	Song et al. (2007)
Urea	Chlorimuron-ethyl	*T. aestivum* L.	Soil	300 µg kg^{-1}	24 h	Leaves	POD	Increase	Wang and Zhou (2006)
Urea	Chlorimuron-ethyl	*T. aestivum* L.	Soil	300 µg kg^{-1}	24 h	Root	POD	Increase	Wang and Zhou (2006)
Urea	Fluometuron	*Z. mays* L.	Spray	2.98 kg a.i. ha^{-1}	12 d	Shoot	APOX CAT POD SOD	Decrease Decrease Decrease Decrease	Hassan and Alla (2005)

To be continued...

Table 2, cont...

Type of pesticide	Pesticide name	Plant name	Mode of application	Concentration of pesticide	Time after treatment	Plant part analyzed	Effect of pesticide on enzymatic antioxidants		Reference
Urea	Fluometuron	*V. faba* L.	Spray	2.98 kg a.i. ha^{-1}	12 d	Shoot	APOX CAT POD SOD	Decrease Decrease Decrease Decrease	Hassan and Alla (2005)
	Granstar	*S. cereale* L.	Leaf disk immersing	300 µg L^{-1}	3 h	Leaves	APOX CAT SOD	Increase Increase Increase	Gar'kova et al. (2011)
		T. aestivum L.	Leaf disk immersing	300 µg L^{-1}	3 h	Leaves	APOX CAT SOD	Increase Increase Increase	
		Z. mays L.	Leaf disk immersing	300 µg L^{-1}	3 h	Leaves	APOX CAT SOD	Increase Increase Increase	
	Isoproturon	*P. sativum* L.	Sand	10 mM	15 d	Leaves	APOX CAT GPOX SOD	Increase Increase Decrease Increase	Singh et al. (2016)
		T. aestivum L. .	Soil	2.5 L ha^{-1}	15 d	Shoot	APOX CAT SOD	Decrease Decrease Decrease	Alla and Hassan, (2014)
				4 mg kg^{-1}	10 d	Shoot	APOX CAT GR GST POD SOD	Increase Decrease Increase Increase Increase Increase	Liang et al. (2012)
				4 mg kg^{-1}	10 d	Root	APOX CAT GR GST POD SOD	Increase Decrease Increase Increase Increase Increase	
				10 mg kg^{-1}	10 d	Leaves	APOX CAT GST POD SOD	Increase Decrease Increase Increase Increase	Yin et al. (2008)
				10 mg kg^{-1}	10 d	Root	APOX CAT GST POD SOD	Increase Increase Increase Increase Increase	
			Spray	1 kg ha^{-1}	15 d	Leaves	CAT POD	Increase Increase	Sing et al. (2013)
	Rimsulfuron	*V. faba* L.	Spray	0.015 kg a.i. ha^{-1}	12 d	Shoot	APOX CAT POD SOD	Increase Increase Increase Increase	Hassan and Alla (2005)
		Z. mays L.	Spray	0.015 kg a.i. ha^{-1}	12 d	Shoot	APOX CAT POD SOD	Increase Increase Increase Increase	
	Sulfosulfuron	*T. aestivum* L.	Spray	800 g ha^{-1}	15 d	Leaves	CAT POD	Increase Increase	Sing et al. (2013)
Unclassified	Dichlorobenzene	*Z. mays* L.	Hoagland medium	80 mg L^{-1}	7 d	Root	GR POD	Increase Decrease	San Miguel et al. (2012)
						Leaves	GR POD	Decrease Decrease	
	Flurochloridone	*H. annuus* L.	Spray	11 mM	15 d	Leaves	APOX CAT GR GST SOD	Decrease Decrease Increase Increase Increase	Kaya and Yigit (2014)
		V. sativa L.	Spray	32 mM	15 d	Leaves	GR GST	Increase Increase	Kaya and Yigit (2012)
	Monochlorobenzene	*Z. mays* L.	Hoagland medium	80 mg L^{-1}	7 d	Roots	GR POD	Increase Increase	San Miguel et al. (2012)
						Leaves	GR POD	Decrease Increase	
	Trichlorobenzene	*Z. mays* L.	Hoagland medium	40 mg L^{-1}	7 d	Root	GR POD	Increase No change	
						Leaves	GR POD	Decrease No change	

Table 3 - Effect of pesticides on non-enzymatic antioxidants in plants

Type of pesticide	Pesticide name	Plant name	Mode of application	Concentration of pesticide	Time after treatment	Plant part analyzed	Effect of pesticide on non-enzymatic antioxidants		Reference
							Parameter	Effect	
Amide	Fomesafen	*Glycine max* L. Merr.	Spray	1000 g ha^{-1}	2 d	Leaves	HGSH	Increase	Andrews et al. (2005)
	Metosulam	*Vicia faba* L.	Seedling's root immersing	10^{-4} %	24 h	Leaves	Proline	Increase	Badr et al. (2013)
						Stems	Proline	Increase	
						Root	Proline	Increase	
Cyclohexene oxime	Clethodim	*Zea mays* L.	Soil	200 ppm	21 d	Leaves	Total phenolics	Increase	Radwan (2012)
Diamide	Chlorantraniliprole	*Z. mays* L.	Seed	0.5 ppm	7 d	Leaves	Proline	Increase	Kilic et al. (2015)
Dinitroaniline	Pendimethalin	*Foeniculum vulgare* L.	Soil	8.5 mg L^{-1}	84 d	Leaves	Total phenolics	Increase	El-Awadi and Hassan et al. 2011
Diphenyl ether	Oxyfluorfen	*G. max* L. Merr.	Spray	2500 g ha^{-1}	2 d	Leaves	HGSH	Increase	Andrews et al. (2005)
Imidazolinone	Imazapic	*Nicotiana tabacum* L.	Spray	0.12 mM	9 d	Leaves	GSH	Increase	Kaya and Doganlar (2016)
Neonicotinoid	Imidacloprid	*Brassica juncea* L.	Soil	300 mg kg^{-1}	60 d	Leaves	Ascorbate GSH Tocopherol Polyphenols Total phenolics	Increase Increase Increase Increase Increase	Sharma et al. (2016c)
					65 d	Leaves	GSH	Increase	Sharma et al. (2016b)
					80 d	Green pods	GSH	Increase	Sharma et al. (2017c)
		Oryza sativa L.	Sand	0.02%	12 d	Seedling	Proline	Increase	Sharma et al. (2013)
				0.015%	12 d	Seedling	Proline	Increase	Sharma et al. (2015)
Organophosphorus	Chlorpyrifos	*O. sativa* L.	Sand	0.06%	12 d	Seedling	Proline	Increase	Sharma et al. (2012)
				0.04%	12 d	Seedling	Proline	Increase	Sharma et al. (2015)
		Vigna radiata L.	Spray	15 mM	10 d	Leaves	Proline Ascorbate GSH	Increase Decrease Increase	Parween et al. (2012)
	Dimethoate	*V. radiata* L.	Culture soln.	30 ppm	4 d	Leaves	GSH Ascorbate	Increase Increase	Singh et al. (2014)
				150 ppm	4 d	Leaves	GSH Ascorbate	Decrease Decrease	
	Glyphosate	*Z. mays* L. var. Kneza-640	Spray	10 mM	10 d	Leaves	Proline GSH	Increase Increase	Sergiev et al. (2006)
Phenoxy	Fluzifop-*p*-butyl	*Arachis hypogaea* L. var. Giza 5	Spray	0.156 g L^{-1}	14 d	Leaves	Proline	Increase	Fayez et al. (2011)
	Quizalofop-*p*-ethyl	*Helianthus annuus* L.	Spray	0.8 mM	15 d	Leaves	Total phenolics	Increase	Bayram et al. (2015)
Pyrethroid	Deltamethrin	*G. max* L. Merr.	Spray	0.20 %	10 d	Leaves	Proline Ascorbate GSH	Increase Increase Increase	Bashir et al. (2007)
Pyridine	Fluroxypyr	*O. sativa* L.	Culture soln.	0.8 mg L^{-1}	6 d	Leaves	Proline	Increase	Wu et al. (2010)
Triazine	Atrazine	*Z. mays* L. Hybrid 351	Soil	1.79 kg ha^{-1}	8 d	Shoot	GSH Ascorbate	Increase Increase	Alla and Hassan (2006)
		Z. mays L. Giza 2	Soil	1.79 kg ha^{-1}	8 d	Shoot	GSH Ascorbate	Decrease Decrease	
Urea	Chlorotoluron	*Triticum aestivum* L.	Soil	25 mg kg^{-1}	10 d	Leaves	Proline	Increase	Song et al. (2007)
	Diuron	*G. max* L. var. Clark	Soil	2 ppm	7 d	Leaves	Proline	Increase	Fayez (2000)
		G. max L. var. Crawford	Soil	2 ppm	7 d	Leaves	Proline	Increase	
	Isoproturon	*T. aestivum*	Soil	2.5 L ha^{-1}	15 d	Shoot	GSH	Decrease	Alla and Hassan (2014)
Unclassified	Bentazon	*A. hypogaea* L. var. Giza 6	Spray	1.6 g L^{-1}	14 d	Leaves	Proline	Increase	Fayez et al. (2011)
	Flurochloridone	*Vicia sativa* L.	Spray	32 mM	15d	Leaves	GSH	Increase	Kaya and Yigit (2012)

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