Plant Growth Regulation (2020) 91:327–347
https://doi.org/10.1007/s10725-020-00625-0

REVIEW PAPER

A review on morpho-physiological traits of plants under phthalates stress and insights into their uptake and translocation

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Received: 19 February 2020 / Accepted: 9 May 2020 / Published online: 18 May 2020

Abstract

Phthalates are synthetic chemical compounds that are primarily used as plasticizers in various plastics and polymers to improve their physical properties. They are reported as ubiquitous pollutants in different spheres of the environment due to the presence of physical bonding with the polymeric matrix. In animals, including humans, they are known to cause various toxic effects. Nevertheless, less attention has been paid to phthalate induced stress in plants, since plants are equally vulnerable to their exposure as they are immobile and being an important component of the environment cannot be ignored. Moreover, due to their frequent detection in higher amounts in agricultural soils globally, significant concern has been raised about phthalate induced stress in plants over the past decade. The main sources of phthalate in agricultural soils are the use of plastic mulching, irrigation with wastewater, pesticide spraying, use of biosolids for improving soil properties, etc. From the soils, phthalates could enter into plants mainly via roots and undergo biomagnification at different trophic levels in an ecosystem. Phthalates were declared as endocrine disruptors thereby, their accumulation in edible plants raises food security concerns. Moreover, the accumulation of phthalates in plants is observed to affect germination, growth and development as well as reported to interfere with normal plant metabolism which led to modulations in the content of pigments, osmolytes, stress biomarkers and activities of antioxidative enzymes, thus reducing the yield and quality of edible plants.

Keywords Emerging pollutants · Germination · Growth and development · Biochemical responses · Oxidative stress · Accumulation

Introduction

Phthalates are dialkyl or alkyl aryl esters of 1,2-benzenedicarboxylic acid. They are used as plasticizers to enhance their flexibility, durability, and elasticity of plastics or polymers (Mackintosh et al. 2004). In polymeric and non-polymeric matrices, phthalates are physically incorporated which leads to their easy escape into the environment because of slight alterations in the environmental factors viz., pH, temperature, pressure, and irradiation (Meng et al. 2014; Benjamin et al. 2015; Benjamin et al. 2017). The worldwide production of phthalates is increasing globally and from 2007 to 2017, it was predicted to increase from 2.7 to 6.0 million tons per year (Bauer and Herrmann 1997; Xie et al. 2007). Among all plasticizers, phthalates contribute approximately 84% of total plasticizers in the global market (ECHA 2013). The most abundant phthalates in the environment are diethyl phthalate, di-*n*-butyl phthalate, benzyl butyl phthalate, di(2-ethylhexyl) phthalate, di-*n*-octyl phthalate (Gavala et al. 2003). Phthalates have been extensively studied for their toxicities using animal systems. Humans are also prone to the frequent exposure of phthalates due to the extensive use of plastic products on regular basis. The human exposure to phthalates is confirmed by the detection of their metabolites in the body fluids and tissues (Hines et al. 2009; Jensen et al. 2015; Pan et al. 2015). Furthermore, the detected concentrations of phthalates and their metabolites in humans have been reported to be associated with high blood pressure, pregnancy loss, preterm birth, diabetes,

Electronic supplementary material The online version of this article (https://doi.org/10.1007/s10725-020-00625-0) contains supplementary material, which is available to authorized users.

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enhanced insulin resistance, anti-androgenic effects, cardiovascular disease, hypertension, etc. (Hoppin et al. 2013; Shiue 2014; Sun et al. 2014; Trasande et al. 2014; Whyatt et al. 2014; Bai et al. 2017). As phthalates are reported as potential toxicants to living organisms including humans but little attention has been given to studies on the plant systems. On the other hand, due to immobile nature of plants, they are at high risk to the exposure of phthalates. Thus, a concern regarding the potential toxic effects of phthalates on plants is being investigated by number of researchers. The studies have also demonstrated the negative effects of phthalates on edible plants by adversely affecting the normal metabolic processes. Phthalates are reported to affect seed germination in various edible plants (Ma et al. 2013, 2014; Zhang et al. 2016). Phthalates also declined the growth and development of different plants (Chen et al. 2011; Gao and Wen 2016; Gu et al. 2017). The exposure of phthalates to seedlings as well as plants directly affect the content of pigments, osmolytes, level of oxidative stress biomarkers and also altered the activities of antioxidative enzymes (Huang et al. 2006; Liao et al. 2006; Xu et al. 2010; Cheng and Cheng 2012; Ma et al. 2014; Gu et al. 2017; Duan et al. 2018; Gao et al. 2019; Kumari and Kaur 2019; Sharma et al. 2019; Kumari and Kaur 2020; Singh et al. 2020). The considerable accumulation and translocation of phthalates were observed in vegetables and crop plants (Sun et al. 2015, 2018). The main contributing factor for phthalates accumulation in plants is their lipophilic nature. After their uptake, they are transported to different plant parts and observed to accelerate the generation of reactive oxygen species (ROS) which imparts devastating effects on cellular levels as well as causes membrane disruption *via* lipid peroxidation (Li et al. 2006; Xu et al. 2010; Cheng 2012; Zhang et al. 2015a; Gao et al. 2019). Plants regulate these processes by switching the enzymatic and non-enzymatic antioxidative defense system. Thus, the elevation in the amounts of phthalates in different environmental media can influence the normal processes of plants which leads to severe damages at cellular components and ultimately reduce their overall productivity. Therefore, this review highlights the adverse effects of phthalates stress in plants, roles of antioxidative defense system, their accumulation and metabolites formation after being accumulated in plants.

Physico-chemical properties of phthalates

The uptake and accumulation of phthalates directly rely on their physico-chemical characteristics. Moreover, behavior and fate of phthalates in the environment and biological systems are also dependent on these properties. Phthalates vary in their physical properties which are responsible for their different chemodynamics in the environment (Staples et al. 1997). They are colorless and odorless liquid at ambient temperature. They are the product of esterification of phthalic acid and aliphatic alcohol.

The alcohol ranged from methanol (C_4) to texanol (C_{27}) (Sibali et al. 2013). Phthalates which are commonly used as plasticizers fall in the range of methanol (C_4) to tridecanol (C_{13}). The water solubility (W_S), vapor pressure (Vp), Henry's constant (H), air-water partitioning coefficient (K_{AW}) and octanol-water partitioning (K_{OW}) coefficient are the main indices to address the physico-chemical properties of phthalates (Table 1).

Water solubility (W_S)

It controls the distribution of phthalates between water, soil or sediment and atmosphere. In case of phthalates, water solubility is low and observed to be decreased with an increase in carbon chain length. Thus, being hydrophobic compounds, they get adsorbed onto suspended solids and colloids in surface water reservoirs. They also get firmly associated with soluble humic materials which change their solubilities (Ogner and Schnitzer 1970).

Vapour pressure (V_p)

Phthalates are semi-volatile in nature irrespective of their low vapour pressure. They are reported to be present in the vapour phase at environmentally relevant temperatures (Tienpont 2004). The vapour pressure of phthalates decreases with increase in alkyl chain length.

Henry's constant (H)

It indicates the tendency of the pollutants to escape from water into the air and can be calculated from the values of water solubility and vapour pressure. In the case of phthalates, Henry's constant values approximately equal to 1.01×10^{-2} indicate negligible volatility. The higher values of Henry's constant for phthalates with higher alkyl chains (4 to 13) indicates that they can transfer from aqueous phase to gaseous phase (Net et al. 2015).

Air-water partitioning coefficient (K_{AW})

It reflects the affinity of organic compounds for lipid molecules in living beings. It has been commonly employed to know the potential of contaminants to accumulate or concentrate in aquatic organisms (Lyman et al. 1990). In phthalates, the value of K_{AW} increases with an

Table 1 Physico-chemical properties of common phthalates with their chemical formula and structure

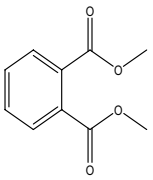
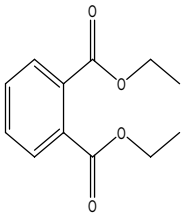
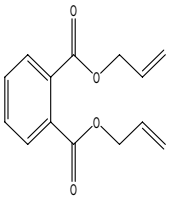
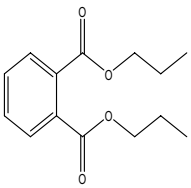
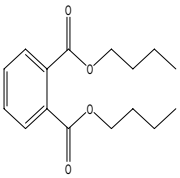
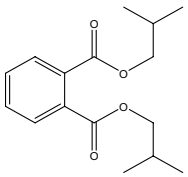
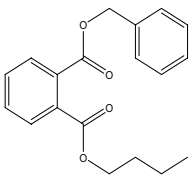
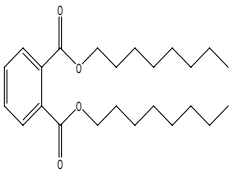
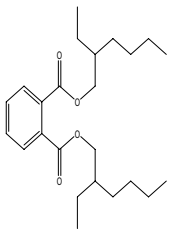
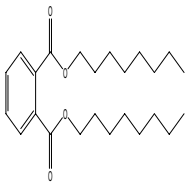
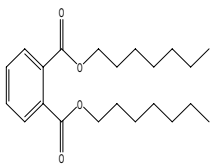
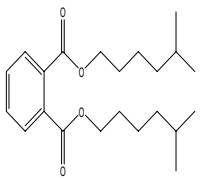
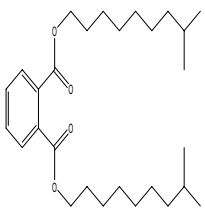
Phthalates	Chemical formula	MW (g/mol)	W_S (mg/L)	V_p (Pa)	log K_{OW}	log K_{AW}	H	Chemical structure
DMP	$C_{10}H_{10}O_4$	194.2	5220	0.263	1.61	− 5.40	9.78×10^{-3}	
DEP	$C_{12}H_{14}O_4$	222.2	591	6.48×10^{-2}	2.54	− 5.01	2.44×10^{-2}	
DAP	$C_{14}H_{14}O_4$	246.2	165	2.71×10^{-2}	3.11	− 4.76	4.28×10^{-2}	
DPP	$C_{14}H_{18}O_4$	250.3	77	1.74×10^{-2}	3.40	− 4.64	5.69×10^{-2}	
DBP	$C_{16}H_{22}O_4$	278.4	9.9	4.73×10^{-3}	4.27	8.54	0.133	
DiBP	$C_{16}H_{22}O_4$	278.4	9.9	4.73×10^{-3}	4.27	8.54	0.133	
BBP	$C_{19}H_{20}O_4$	312.4	3.8	2.49×10^{-3}	4.70	− 4.08	0.205	
DOP	$C_{24}H_{38}O_4$	390.6	2.49×10^{-3}	2.54×10^{-5}	7.73	− 2.80	3.95	

Table 1 (continued)

Phthalates	Chemical formula	MW (g/mol)	W_S (mg/L)	V_p (Pa)	log K_{OW}	log K_{AW}	H	Chemical structure
DEHP	$C_{24}H_{38}O_4$	390.56	2.49×10^{-3}	2.54×10^{-5}	7.73	− 2.80	3.95	
DiOP	$C_{24}H_{38}O_4$	309.6	2.49×10^{-3}	2.54×10^{-5}	7.73	− 2.80	3.95	
DNP	$C_{26}H_{42}O_4$	418.6	3.08×10^{-4}	6.81×10^{-6}	8.60	− 2.43	9.26	
DiNP	$C_{26}H_{42}O_4$	418.6	3.08×10^{-4}	6.81×10^{-6}	8.60	− 2.43	9.26	
DiDP	$C_{28}H_{46}O_4$	446.7	3.81×10^{-4}	1.84×10^{-6}	9.46	− 2.06	21.6	

DMP di-methyl phthalate, *DEP* diethyl phthalate, *DAP* diallyl phthalate, *DPP* dipropyl phthalate, *DBP* di-*n*-butyl phthalate, *DiBP* diisobutyl phthalate, *BBP* benzyl butyl phthalate, *DOP* dioctyl phthalate, *DEHP* di(2-ethylhexyl phthalate), *DiOP* diisooctyl phthalate, *DNP* dinonyl phthalate, *DiNP* diisononyl phthalate, *DiDP* diisodecyl phthalate, *MW* molecular weight, W_S water solubility, V_P vapour pressure, K_{OW} octanol–water partitioning coefficient, K_{AW} air–water partitioning coefficient, *H* Henry's constant

increase in alkyl chain and is directly proportional to bioconcentration/bioaccumulation.

Octanol–water partitioning coefficient (K_{OW})

It is the measure of the distribution of a substance between air and water. The low molecular weight phthalates are quite volatile and due to their low log K_{OW} values they can readily volatilize from their pure state but very slowly from aqueous media (Net et al. 2015).

Types of phthalates and their applications

On the basis of carbon chain length, phthalates are categorized into two categories i.e. high molecular weight phthalates (HMWP) and low molecular weight phthalates (LMWP) (Ventrice et al. 2013).

High molecular weight phthalates (HMWP)

These phthalates have 7 to 13 carbon atoms in their carbon chain. The most common high molecular weight phthalates are diisodecyl phthalate (DiDP), diisononyl phthalate (DiNP), di(2-propylheptyl) phthalate (DPHP), diisoundecyl phthalate (DiUP) and ditridecyl phthalate (DTDP). High molecular weight phthalates are primarily used as plasticizers in polyvinyl chloride (PVC). The other plasticized products with high molecular weight phthalates include wires and cables, flooring, truck tarpaulins, wall coverings, self-adhesive films or labels, synthetic leather, coated fabrics, roofing membranes and automotive applications (Wilkes et al. 2005; Cao 2010; ECPI 2014).

Low molecular weight phthalates (LMWP)

These include phthalates with 3 to 6 carbon atoms in their carbon chain backbone. Low molecular weight phthalates are di-*n*-butyl phthalate (DBP), diisobutyl phthalate (DiBP), benzyl butyl phthalate (BBP) and di(2-ethylhexyl phthalate) (DEHP) (Liao et al. 2018). They are used in various PVC products as well as in medical devices, adhesives, paints, inks and enteric-coated tablets (Wittassek et al. 2011; Czernych et al. 2017). The remaining phthalates such as dimethyl phthalate (DMP), diethyl phthalate (DEP) and diallyl phthalate (DAP) have one, two and three carbon-atoms respectively in their hydrocarbon chain. These are not classified as HMWP or LMWP because they are not used as plasticizers. These are mainly used as solvents and fixatives in fragrances, additives in cosmetics, medical devices, household and personal care products (Schettler 2006; Schlumpf et al. 2010; Philippat et al. 2012; Carlstedt et al. 2013; Frederiksen et al. 2013; ECPI 2014).

Phthalates in soils and sediments

In terrestrial ecosystems, soil acts as a natural sink for different pollutants. From soil, phthalates get a route to enter the plants including edible plants (Cai et al. 2008a). Phthalates are mainly released to the soils owing to their extensive use as agricultural plastic films (He et al. 2015). This can lead to potential human health risks *via* food chain. The major factors that contribute to phthalate pollution in agricultural soils are shown in Fig. 1.

Similarly, in an aquatic ecosystem, sediments act as a sink and source of phthalates deposition especially, which have low water solubility, melting point and volatility (Mitsunobu and Takahashi 2006). The analysis of five phthalates from the sediments of Gomti river was done using HPLC. The reported mean concentration values of phthalates viz., DEHP, DMP, DBP, DOP, DEP was 31.61, 10.54, 10.41, 5.16, 4.57 µg/kg respectively (Srivastava et al. 2010). A study conducted by Arukwe et al. (2012) reported a higher amount of phthalates from the leachates and sediment. The amount of phthalates sediment samples was 1000 times higher than run-off water samples.

Effects of phthalates on plants

In the last decades, the pollution load of phthalates has become a serious environmental issue and cannot be ignored because of their direct or indirect interference with normal physiological processes of living beings. Although, the

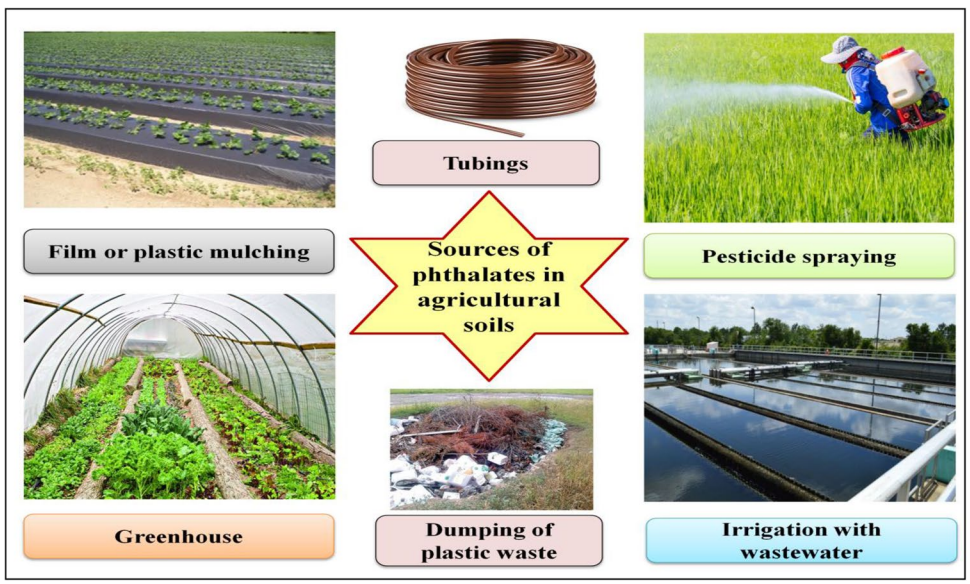


Fig. 1 The potential sources of phthalates in agricultural soils

adverse effects of phthalates are extensively documented on animals but in case of plants, the scenario is quite different. There are few studies which have examined phthalates induced stress in plants. The stress is a collective term used for both external abiotic or biotic constraints that limit plant growth and development *via* affecting photosynthesis and reducing carbon assimilation ability of plants (Grime 1977). Presently, people dealing with the production of food are facing number of challenges as the productivity of crops is not enough to meet the food demands (FAO 2009). Abiotic stresses are one of the major factors responsible for low productivity. To deal with such constraints number of strategies are adopted throughout the world. The introduction of mulching into the traditional agricultural practices is one of them. Undoubtedly, it has overcome number of issues but also generated concerns due the presence of high amount of additives. Among additives, main emphasis is laid on phthalates because these are highly preferred plasticizers. Phthalates are also reported to cause phytotoxic consequences among plants. However, under the exposure of pollutants they respond differentially and some of the plant species can withstand the adversities, while some of them are sensitive to the pollutants. Plants provide countless services to mankind as well as also play various important ecological functions (Beare et al. 1995; Kuzyakov and Blagodatskaya 2015). The survey of literature revealed that plants under phthalates stress showed adverse effects on germination, growth & development, biochemical and physiological processes.

Germination, growth and development

Germination is a process that starts with the uptake of water in order to set the metabolic events required to accomplish seed germination (Nonogaki 2008). It is considered as a crucial stage of higher plants as subsequent vegetative and reproductive growth of plant also depends upon it (Ma et al. 2013). The exposure of pollutants is more detrimental during early growth stages like germination and seedling growth in a plant life cycle (Macoustra et al. 2015). The process of germination was adversely affected by the exposure of phthalates in *Vigna radiata* (mung bean), *Cucumis sativus* (cucumber), *Brassica chinensis* (rape) (Ma et al. 2013, 2014; Zhang et al. 2016). The authors revealed little effects on germination of rape and mung bean and it may be related to developmental behavior of seeds. Rape and mung bean are dicotyledonous seeds and during seed germination they mainly rely on their own nutritive material *via* hypertrophic cotyledons rather than uptake of nutrients from soil (Shu et al. 1999). Whereas, cucumber seeds showed inhibition in germination under DMP stress. Thus, the effect on seed germination may be plant-specific or depends upon type of phthalate exposure. Phthalates may have disturbed the physiological and metabolic processes especially mobilization of food reserves of barley seeds during germination as shown in Supplementary Fig. 2. Moreover, phthalates may have imbalanced the level of plant growth regulators and enzymes which might have led to the reduction in seed germination and also affected the other associated parameters.

Phthalates are also reported to reduce the growth of plants at higher concentrations but at lower concentrations, they show plant hormone like properties (Ma et al. 2013, 2014). The exposure of phthalates was observed to decline the growth of algae, duckweeds, various monocotyledonous and dicotyledonous plants (Melin and Egneus 1983; Dueck et al. 2003; Liao et al. 2009; Gao and Wen 2016; Duan et al. 2018). The stress-induced by phthalates also declined the length of shoots and roots as well as biomass of the plants. The biomass of different plants like *Phaseolus vulgaris, Brassica campestris* var. *chinensis, Picea abies, Trifolium repens, Plantago major* and *Holcus lanatus* was declined under the expsoure of DBP (Dueck et al. 2003). The fresh weight was declined in *Raphanus sativus* treated with DEP and DEHP and in DBP treated *Brassica rapa* subsp. *chinensis* (Saarma et al. 2003; Liao et al. 2006). Thus, due to adverse effects of phthalates on germination, the growth and development of barley seedlings and plants was also affected. Because seed germination determines the subsequent growth quality of the plant.

Phthalates stress induced consequences on germination and growth according to previous studies are listed in Table 2.

Physiological responses

The primary source of phthalates in the agricultural soils is the application of plastic agricultural films (He et al. 2015). From soil, phthalates are reported to accumulate in plants which disturb the normal functioning of plants. The plants under phthalate stress show morphological and physiological responses. They also employ various strategies to maintain homeostasis under stressful environments. These strategies include alterations in morphological and developmental patterns (i.e. growth plasticity) as well as biochemical and physiological processes (Tuteja 2007; Saud et al. 2014). Phthalates are reported to affect the biochemical and physiological processes by affecting the contents of pigments, osmoloytes and stress metabolites.

Pigments

The alteration in the levels of chlorophyll pigment is a well avowed index in plants under stressed environment. The pigments posses an important role among the plants as they regulate photosynthesis rate (Zai et al. 2012).

Table 2 Effects of phthalates on seed germination and growth of different plants

S. no.	Phthalate(s)	Plant(s)	Concentration	Exposure duration	Studied parameters	Effects	References
Germination							
1.	DBP and DEHP	*Brassica chinensis* L.	0, 1, 5, 20, 100, 500 mg/kg	72 h	Seed germination	Little effects were observed on seed germination under DBP and DEHP stress	Ma et al. (2013)
2.	DBP and DEHP	*Vigna radiata*	0, 5, 20, 100, 500 mg/kg	72 h	Seed germination	Affected at higher concentrations	Ma et al. (2014)
3.	DMP	*Cucumis sativus* L.	0, 30, 50, 100, 200 mg/L	7 days	Seed germination	DMP affected seed germination at concentrations > 50 mg/L; inhibited germination index at higher concentrations; seed vigor index of seeds was inhibited	Zhang et al. (2016)
4.	DBP	*Hordeum vulgare* L.	0, 25, 50, 100, 200, 400, 800, 1600 mg/L	7 days	Seed germination and associated indices	Inhibited germination (%) percentage, speed of germination, peak value, etc.; values of seed mortality (SM) and phytotoxicity index (PI) were increased with increase in DBP concentrations	Kumari and Kaur (2017)
5.	BBP	*Hordeum vulgare* L.	0, 25, 50, 100, 200, 400, 800, 1600 mg/L	7 days	-do-	BBP declined germination (%), speed of germination, peak value, mean daily germination, germination value, mean germination time, seed vigour index, germination rate index; enhanced the SM and PI	Kumari and Kaur (2018)
Growth and development							
1.	DBP	*Chlorella emersonii* and *Selenastrum capricornutum*	10^{-3} to 10^{-7} M	7 days	Growth	Inhibited the growth of algae	Melin and Egneus (1983)
2.	DBP	*Phaseolus vulgaris, Brassica campestris* var. *chinensis, Picea abies, Trifolium repens, Plantago major* and *Holcus lanatus*	0, 0.8, 1.5, 3.5, 10 µg/m^3	different for all crops according to their life cycles	Biomass	Declined the biomass of roots and shoots; root biomass was more sensitive to DBP stress in some plants than shoots.	Dueck et al. (2003)

Table 2 (continued)

S. no.	Phthalate(s)	Plant(s)	Concentration	Exposure duration	Studied parameters	Effects	References
3.	DEP and DEHP	*Raphanus sativus*	0 to 10^{-4} M	24 h	Fresh weight (FW)	Decreased the fresh weight	Saarma et al. (2003)
4.	DBP	*Brassica rapa* subsp. *chinensis*	0, 10, 30, 50, 100 mg/L	35 and 42 days	Biomass	Declined the biomass	Liao et al. (2006)
5.	DBP	Cultivars (V1, V2, V3, V4, V5) of *Ipomoea aquatica.*	4.5, 10.3, 22.5 mg/kg	39 days	Biomass	Biomass of three cultivars (V1, V2, V5) declined with increase in concentration	Cai et al. (2008b)
6.	DBP	*Brassica rapa* var. *chinensis*	0, 30, 50, 100 mg/L	35 days	Biomass	Biomass declined in a dose-dependent manner	Liao et al. (2009)
7.	BBP	*Ipomoea aquatica* Forsk.	0, 1, 10, 30, 50, 100 mg/L	28 days	Growth	Declined at all concentrations except at 1 mg/L	Chen et al. (2011)
8.	DEP	*Spirodela polyrhiza*	0, 0.25, 0.5, 1.0, 2.0 mM	7 days	FW/DW ratio, relative growth rate	Growth declined at 0.5 to 2 mM; declined FW/DW ratio (except at 0.25 mM)	Cheng and Cheng (2012)
9.	DBP and DEHP	*Brassica chinensis* L.	0, 1, 5, 20, 100, 500 mg/kg	72 h	Growth	Inhibited elongation of root and shoot; declined biomass of seedlings; IC_{50} for DBP was less than 500 mg/kg; for DEHP IC_{50} was less than 1500 mg/kg	Ma et al. (2013)
10.	DBP and DEHP	*Vigna radiata*	0, 5, 20, 100, 500 mg/kg	72 h	Length and biomass	Declined length of shoots and roots; decreased the biomass of seedlings	Ma et al. (2014)
11.	DBP and DEHP	Wheat	0, 5, 10, 20 µg/mL	7 and 14 days	FW, DW	FW and DW of shoots and roots declined in both exposure durations but higher after 14 days of treatment	Gao and Wen (2016)
12.	DMP	*Cucumis sativus* L.	0, 30, 50, 100, 200 mg/L	7 days	Seedlings length	DMP at 30 mg/L stimulated the lateral root number and length significantly; inhibited these indices with increase in concentration	Zhang et al.(2016)
13.	DBP	*Scenedesmus obliquus* and *Chlorella pyrenoidosa*	0, 4, 8, 12, 16, 20 mg/L	0, 24, 48, 72, 96 h	Growth	Retarded the growth of both algae	Gu et al. (2017)
14.	BBP and DBP	*Spirodela polyrhiza*	0, 5, 10, 20 mM	7 and 15 days	Growth	Declined the fresh weight of	Kaur et al. (2017)

Table 2 (continued)

S. no.	Phthalate(s)	Plant(s)	Concentration	Exposure duration	Studied parameters	Effects	References
15.	DBP	*Hordeum vulgare* L.	0, 25, 50, 100, 200, 400, 800, 1600 mg/L	7 days	Growth	Inhibited the shoots and roots length, fresh and dry weight; declined net primary productivity (NPP)	Kumari and Kaur (2017)
16.	BBP	*Hordeum vulgare* L.	0, 25, 50, 100, 200, 400, 800, 1600 mg/L	7 days	Growth	Decreased the length, fresh weight, dry weight and NPP of barley seedlings	Kumari and Kaur (2018)
17.	DBP	*Chlorella vulgaris*	0, 5, 20, 50, 100 mg/L	2, 4, 6, 8, 10 days	Growth	Algae under lower doses of DBP showed faster growth than at high doses (50–100 mg/L) of DBP	Duan et al. (2018)
18.	DAP	*Spirodela polyrhiza*	0, 10, 20, 40, 80, 100, 200, 400 mg/L	7 days	Growth	Reduction in growth with increase in doses of DAP	Sharma and Kaur (2019)

Abiotic stresses are reported to affect the photosynthesis. For crops, reduction in photosynthetic capacity is directly related to their yield. For carbon assimilation, plants have to perform a series of complex reactions to form carbohydrates which are direct or indirect sources of energy for heterotrophs including human beings. The photosynthetic apparatus consists of pigments (Chl a, Chl b, pheophytins, and carotenoids), photosystems (PS), light reactions (for the generation of NADPH and ATP) and dark reactions (for CO_2 assimilation) (Singh and Thakur 2018).

Osmolytes

The carbohydrates are the final products of photosynthesis. In carbohydrates, disaccharides viz. sucrose, trehalose, raffinose, and fructans are the main forms of sugar that are observed to be involved in adaptation strategies during stress (Keunen et al. 2013; Song et al. 2019). They are soluble sugars and participate in osmotic adjustment (Kumari et al. 2018). Thus, they provide osmoprotection to stabilize the membrane structures as well as maintain turgidity of the cells (Gil et al. 2011). Proteins are also observed to be accumulated during stress in plants especially heat shock proteins (HSPs). They are commonly referred as 'molecular chaperones' and play roles in protein folding and assembly. They are categorized based on molecular weight e.g. Hsp70 family, chaperonins (GroEL and Hsp60), Hsp90 family, Hsp100 family and small Hsp family (Wang et al. 2004). A study showed the induction of the various genes and HSPs which acted together in different cascades to combat the heat stress consequences in rice (Chandel et al. 2013). There are other proteins which participate during stress regulation such as late embryogenesis abundant (LEA) proteins. These proteins are observed to accumulate in plants in response to water stress and are reported to act synergistically with trehalose to prevent protein aggregation during stress especially under water stress (Goyal et al. 2005). The exposure of DEP also observed to enhance the expression of HSP in *Spirodela polyrhiza* and *Raphanus sativus*. The accumulation of proline is commonly observed in plants under stressed conditions. It is also reported to act as a signaling molecule to modulate mitochondrial function (Szabados and Savouré 2010). It participates in number of functions like act as an osmolyte, ROS scavenger, and redox buffer. It also acts as a molecular chaperone and stabilizes the proteins and membranes (Krasensky and Jonak 2012; Hossain and Dietz 2016).

Oxidative stress markers

The environmental and biotic stresses trigger a common stress response *i.e*. oxidative stress in which the generation of reactive oxygen species (ROS) gets enhanced that causes damages to cell components (Demidchik 2015). ROS are the inevitable entities of plant's life and are produced in cells *via* different pathways and homeostasis is maintained by the antioxidant defense system. The high level of ROS leads to reversible or irreversible variations in biomolecules like proteins, carbohydrates, polynucleic acids and lipids (Møller et al. 2007; Farmer and Mueller 2013). Among these, oxidation of lipids is considered more damaging because it generates free radicals *via* chain reactions. Lipid peroxidation is referred as a 'hallmark' of oxidative stress in plants (Farmer and Mueller 2013). Malondialdehyde (MDA) and hydrogen peroxide (H_2O_2) are considered as indicators of oxidative stress among the plants. MDA is considered as a marker of lipid peroxidation of membrane (Hu et al. 2020). Stress mediates the generation of ROS which leads to decrease in membrane integrity due to lipid peroxidation. Moreover, under stress, H_2O_2 is generated along other with ROS. The generation of H_2O_2 gets accelerated *via* glycollate oxidase reaction that occurs in peroxisomes (Anjum et al. 2012). Phthalates are observed to enhance the level of ROS.

Antioxidative defense system

The generation of reactive oxygen species (ROS) is an inevitable response of plants under stressed environments. They are produced in plants *via* partial reduction of oxygen and referred as a collective term for oxygen species and non-radical oxygen species (Ahmad 2018). The presence of unpaired electrons is responsible for their high reactivity which can even mediate the oxidation of cell structures, biomolecules as well as disturb the cell integrity (Kanojia and Dijkwel 2018). The ROS formation also takes place under normal conditions because of various metabolic processes but their level observed to be accelerated during abiotic or biotic stresses. The cellular organelles like chloroplast, mitochondria, and peroxisome, with high metabolic activity act as main sites for ROS formation. Thus, to combat with the enhanced levels of ROS, plants have a defense grid that relies on endogenous enzymatic and non-enzymatic antioxidants (Yu et al. 2019). The enzymatic antioxidative defense system is intricate, efficient and includes enzymes like superoxide dismutase (SOD), guaiacol peroxidase (POD), catalase (CAT), ascorbate peroxidase (APX), glutathione reductase (GR), etc. (Supplementary Fig. 3).

The non-enzymatic antioxidants include glutathione, ascorbate, carotenoids, tocopherols, and polyphenolic compounds, etc. The effects of phthalates on pigments, osmolytes and oxidative stress markers and activities of antioxidative enzymes in different plants are given in Table 3.

Accumulation of phthalates

The advent of industrialization and other anthropogenic activities are responsible for the release of pollutants into the environment on a regular basis. The irregular or unorganized disposal of wastes on soils leads to potential risks to the biotic components particularly microorganisms, nematodes and plants (Bender and Heijden 2015). Moreover, the use of the untreated or partially reclaimed water for irrigation in some arid or semi-arid areas of the world contributed to soil pollution (Li et al. 2018). Sometimes, biosolids are also employed to improve the properties of the soil. The wastewater and biosolids contain variety of harmful inorganic and organic contaminants. The soil acts as a primary sink for different types of wastes such as chemical, domestic, industrial and agricultural wastes (Teng et al. 2014; Qing et al. 2015). These can also cause alterations in the physical and chemical characteristics of the soils. Plants being primary producers of terrestrial food chains are more prone to the exposure of these contaminants. Plants also have potential to uptake and accumulate such pollutants from soil and participate in their mitigation and transformation (Scheringer et al. 2004). Phthalates are one of such contaminants which are listed as priority pollutants by USEPA and due to their ubiquity throughout the world, they are also referred as world's second PCBs (polychlorinated biphenyls) (Zhou 1989). In plants, phthalates are reported to induce different morphological and physiological consequences. Furthermore, plants are reported to uptake phthalates mainly *via* roots from soil or aqueous media (Liao et al. 2006, 2009; Cai et al. 2008a, 2008b). In soil, phthalates are reported to decline the diversity of microbial communities and also affect the quality of crop plants (Kapanen et al. 2007).

Mechanism of uptake and metabolism

Several studies have been carried to explore the mechanisms of organic pollutant's uptake and translocation. There is number of reports which have revealed that the uptake of these pollutants takes place by the roots. During the process of uptake, firstly the organic pollutant gets enriched at root surface and then enters into the plant *via* roots along with water (Zhang et al. 2017). The contaminants including phthalates are reported to enter through the cuticle free

Table 3 Effects of phthalates on pigments, osmolytes, oxidative stress markers and antioxidative enzymes activities of different plants

S. no.	Phthalate(s)	Plant(s)	Concentration	Exposure duration	Studied parameters	Effects	References
Pigments							
1.	DBP	*Browallia speciosa* L. and *Raphanus satvius* L.	0, 1 to 4 µg/L	14 days	Carotenoids	Disturbed the carotenoids synthesis	Virgin et al. (1981)
2.	DBP	*Raphanus sativus*	0, 120 ng/dm^3	13 days	Photosynthesis	Declined the fluorescence enhancement ratio which reflected the inhibition in photosynthesis	Millar and Hannay (1986)
3.	DBP	*Spirodela polyrhiza* and *Lemna minor*	0 to 7.5 mg/L	7 days	Pigments content	Decreased content of pigments and induced chlorosis at higher concentrations which led to senescence	Huang et al. (2006)
4.	DBP	*Brassica rapa* subsp. *chinensis*	0, 10, 30, 50, 100 mg/L	35 and 42 days	Chlorophyll content	Declined the chlorophyll content	Liao et al. (2006)
5.	DBP	*Ceratophyllum demersum, Vallisneria spiralis* and *Potamogeton maackianus*	0, 0.03, 0.05, 0.07, 0.12, 0.15 mg/L	25 days	Chlorophyll content	Chlorophyll content increased in *Vallisneria spiralis*, *Potamogeton maackianus* with respect to control	Li et al. (2006)
6.	DBP	*Brassica rapa* var. *chinensis*	0, 30, 50, 100 mg/L	35 days	Chlorophyll content	Declined the Chl content with increase in DBP concentrations	Liao et al. (2009)
7.	DEHP	*Spirodela polyrhiza* and *Lemna minor*	0, 0.005, 0.010, 0.050, 0.100, 0.200, 0.400 mg/L	7 days	Chlorophyll content	Chlorophyll content decreased	Xu et al. (2010)
8.	BBP	*Ipomoea aquatica* Forsk.	0, 1, 10, 30, 50, 100 mg/L	28 days	Pigments content	Declined the contents of pigments	Chen et al. (2011)
9.	DEP	*Spirodela polyrhiza*	0, 0.25, 0.5, 1.0, 2.0 mM	7 days	Pigments, Chl a, Chl b, total chl carotenoids; chl a/chl b ratio; T chl/carotenoids ratio	Caused nacrosis after 4 to 5 days of exposure; pigments increased; Chl a/Chl b decreased; total Chl/carotenoids increased	Cheng and Cheng (2012)
10.	DBP	*Cucumis sativus*	0, 30, 50, 100, 200 mg/L	1, 3, 5, 7 days	Chlorophyll content	The content of chlorophyll decreased with increase in concentration and time	Zhang et al. (2015a)
11.	DMP	*Cucumis sativus* L.	0, 30, 50, 100, 200 mg/L	1, 3, 5, 7 days	Pigments content	Increased in 1-day treatment and at some concentrations after 7 days of exposure; declined at other exposure durations	Zhang et al. (2016)

Table 3 (continued)

S. no.	Phthalate(s)	Plant(s)	Concentration	Exposure duration	Studied parameters	Effects	References
12.	DBP	*Scenedesmus obliquus* and *Chlorella pyrenoidosa*	0, 4, 8, 12, 16, 20 mg/L	0, 24, 48, 72 and 96 h	Pigments content	No effect on photosynthetic pigments during early exposure durations; declined after 96 h of stress to *Scenedesmus obliquus;* in *Chlorella pyrenoidosa*, it declined for all exposure periods	Gu et al. (2017)
13.	DEHP	Wheat	0, 10, 20, 40 mg/kg	14, 24, 40 days	Photosynthetic and fluorescence indices	All indices declined except intercellular CO_2 concentration	Gao et al. (2018)
14.	DBP and DEHP	Wheat	0, 10, 20, 40 mg/kg	14, 24, 40 days	Chlorophyll content	Increased in all exposure durations	Gao et al. (2019)
Osmolytes							
1.	DEP and DEHP	*Raphanus sativus*	0 to 10^{-4} M	3 h	Protein content	Certain HSP proteins acted as indicator of DEP stress but their synthesis was not affected; numerous proteins were only found in DEP-treated samples over control; DEHP showed no effect	Saarma et al. (2003)
2.	DBP	*Spirodela polyrhiza* and *Lemna minor*	0 to 7.5 mg/L	7 days	soluble proteins content	Soluble proteins content decreased	Huang et al. (2006)
3.	DBP	Macrophytes (*Ceratophyllum demersum, Vallisneria spiralis* and *Potamogeton maackianus*)	0, 0.03, 0.05, 0.07, 0.12, 0.15 mg/L	25 days	Protein and carbohydrate content	Protein declined and carbohydrate increased in most of macrophytes	Li et al. (2006)
4.	DBP	*Brassica rapa* var. *chinensis*	0, 30, 50, 100 mg/L	35 days	Protein content	Expression of some proteins was found to increase in treated samples according to proteome analysis; expression of certain proteins were declined over control	Liao et al. (2009)
5.	DEHP	*Spirodela polyrhiza* and *Lemna minor*	0, 0.005, 0.010, 0.050, 0.100, 0.200, 0.400 mg/L	7 days	Protein content	Declined in both but higher in *Lemna minor* than *Spirodela polyrhiza*	Xu et al. (2010)
6.	BBP	*Ipomoea aquatica* Forsk.	0, 1, 10, 30, 50, 100 mg/L	28 days	Protein and proline content	Increased proline content and affected the expression of five proteins	Chen et al. (2011)

Table 3 (continued)

S. no.	Phthalate(s)	Plant(s)	Concentration	Exposure duration	Studied parameters	Effects	References
7.	DEP	*Spirodela polyrhiza*	0, 0.25, 0.5, 1.0, 2.0 mM	1, 2, 4, 7 days	Protein	1 mM DEP declined the proteins content; expression of HSP70 was observed after 7 days of exposure	Cheng (2012)
8.	DBP and DEHP	*Brassica chinensis* L.	0, 1, 5, 20, 100, 500 mg/kg	72 h and 14 days	Proline, free amino acids (FAA) and total soluble sugar (TSS) content	Proline accumulated in the shoots; in roots, proline accumulated but declined at higher doses of DBP; contents of FAA and TSS were increased; proline accumulated even after 14 days of stress	Ma et al. (2013)
9.	DBP and DEHP	*Vigna radiata*	0, 5, 20, 100, 500 mg/kg	72 h	Proline, FAA and TSS content	Accumulated in both shoots and roots under phthalates stress	Ma et al. (2014)
10.	DBP	*Cucumis sativus*	0, 30, 50, 100, 200 mg/L	1, 3, 5, 7 days	Root protein content	Root protein content declined gradually with increase in concentrations and time	Zhang et al. (2015c)
11.	DBP	*Hordeum vulgare* L.	0, 25, 50, 100, 200, 400, 800, 1600 mg/L	7 days	Protein, sugars, and proline	Proteins, sugars, and proline content increased in both shoots and roots of seedlings	Kumari et al. (2019)
12.	BBP	*Hordeum vulgare* L.	0, 25, 50, 100, 200, 400, 800, 1600 mg/L	7 days	Protein, sugars, and proline	Enhancement in protein, sugars, and proline content of shoots and roots (except in shoots protein content).	Kumari and Kaur (2019)
13.	DAP	*Spirodela polyrhiza*	0, 10, 20, 40, 80, 100, 200, 400 mg/L	7 days	Proline	Increased proline content with increase in doses of DAP except at 20 mg/L	Sharma and Kaur (2019)
Oxidative stress markers							
14.	DBP	*Spirodela polyrhiza* and *Lemna minor*	0 to 7.5 mg/L	7 days	MDA content	Increased the content of MDA duckweed	Huang et al. (2006)
15.	DBP	Macrophytes *Ceratophyllum demersum, Vallisneria spiralis* and *Potamogeton maackianus*	0, 0.03, 0.05, 0.07, 0.12, 0.15 mg/L	25 days	MDA content	Declined MDA content in *V. spiralis, P. maackianus* and it was increased in *C. demersum*	Li et al. (2006)
16.	DEHP	*Spirodela polyrhiza* and *Lemna minor*	0, 0.005, 0.010, 0.050, 0.100, 0.200, 0.400 mg/L	7 days	MDA content	Increased the content of MDA in both *Spirodela polyrhiza* and *Lemna minor*	Xu et al. (2010)
17.	DEP	*Spirodela polyrhiza*	0, 0.25, 0.5, 1.0, 2.0 mM	1, 2, 4, 7 days	MDA and H_2O_2	MDA increased significantly only in 7 days exposure; H_2O_2 accumulation was observed in leaves using 3,3′-diaminobenzidine (DAB) staining	Cheng (2012)

Table 3 (continued)

S. no.	Phthalate(s)	Plant(s)	Concentration	Exposure duration	Studied parameters	Effects	References
18.	DEP	*Spirodela polyrhiza*	0, 0.25, 0.5, 1.0, 2.0 mM	7 days	MDA and H_2O_2	MDA content enhanced; H_2O_2 content declined in J-shaped manner as concentrations increased	Cheng and Cheng (2012)
19.	DBP and DEHP	*Brassica chinensis* L.	0, 1, 5, 20, 100, 500 mg/kg	72 h and 14 days	MDA	MDA content increased	Ma et al. (2013)
20.	DBP and DEHP	*Vigna radiata*	0, 5, 20, 100, 500 mg/kg	72 h	MDA	MDA content in shoots and roots increased under DBP stress; DEHP exposure declined MDA content	Ma et al. (2014)
21.	DBP	*Karenia brevis*	0, 0.5, 1.0, 5.0 mg/L	0, 24, 48, 72 h	MDA	Increased significantly after 24, 48, 72 h treatment compared to control	Li et al. (2015)
22.	DBP	*Cucumis sativus*	0, 30, 50, 100, 200 mg/L	1, 3, 5, 7 days	MDA and H_2O_2 content	Both increased with increase in dose and duration	Zhang et al.(2015a)
23.	DMP	*Cucumis sativus* L.	0, 30, 50, 100, 200 mg/L	7 days	H_2O_2 content	Increased with increase in concentration	Zhang et al. (2016)
24.	DBP	*Chlorella vulgaris*	0, 5, 20, 50, 100 mg/L	2, 4, 6, 8, 10 days	Neutral lipids content	Increased with increase in concentration and time	Duan et al. (2018)
25.	DBP and DEHP	Wheat	0, 10, 20, 40 mg/kg	14, 24, 40 days	H_2O_2 content	Increased in both leaves and roots	Gao et al. (2019)
26.	BBP	*Hordeum vulgare* L.	0, 25, 50, 100, 200, 400, 800, 1600 mg/L	7 days	H_2O_2 and MDA content	Increased the protein content of shoots and roots in comparison to the control	Kumari and Kaur (2019)
Antioxidative enzymes activities							
1.	DBP	*Spirodela polyrhiza* and *Lemna minor*	0 to 7.5 mg/L	7 days	SOD and CAT	Increased SOD and POD activities in duckweed	Huang et al. (2006)
2.	DBP	*Brassica rapa* subsp. *chinensis*	0, 10, 30, 50, 100 mg/L	35, 42 days	SOD and POD	Expressed the scavenging activities of SOD and POD	Liao et al. (2006)
3.	DEHP	*Spirodela polyrhiza* and *Lemna minor*	0, 0.005, 0.010, 0.050, 0.100, 0.200, 0.400 mg/L	7 days	SOD and CAT	Increased to the mid of the concentration and declined at higher doses of DEHP in both plants	Xu et al. (2010)
4.	DEP	*Spirodela polyrhiza*	0, 0.25, 0.5, 1.0, 2.0 mM	7 days	SOD, POD, CAT, APX, and GR	Declined the activity of SOD, POD; increased CAT, APX, GR activity	Cheng and Cheng (2012)
5.	DBP and DEHP	*Brassica chinensis* L.	0, 1, 5, 20, 100, 500 mg/kg	72 h	SOD and CAT	SOD activity increased in roots and declined in shoots under DEHP stress; APX activity increased in both roots and shoots under DBP stress	Ma et al. (2013)

Table 3 (continued)

S. no.	Phthalate(s)	Plant(s)	Concentration	Exposure duration	Studied parameters	Effects	References
6.	DBP and DEHP	*Vigna radiata*	0, 5, 20, 100, 500 mg/kg	72 h	SOD, POD, and APX	Activities of all enzymes increased under both phthalates stress	Ma et al. (2014)
7.	DBP	*Karenia brevis*	0, 0.5, 1.0, 5.0 mg/L	0, 24, 48, 72 h	SOD and CAT	Activities of SOD and CAT increased over control	Li et al. (2015)
8.	DBP	*Cucumis sativus*	0, 30, 50, 100, 200 mg/L	1, 3, 5, 7 days	SOD, CAT, APX, and POD	SOD activity increased with doses and time; CAT, APX, POD activities declined; APX activity declined (except for 3 days treatment)	Zhang et al. (2015a)
9.	DMP	*Cucumis sativus* L.	0, 30, 50, 100, 200 mg/L	7 days	POD and CAT	POD and CAT activities increased by DMP stress	Zhang et al. (2016)
10.	DBP	*Scenedesmus obliquus* and *Chlorella pyrenoidosa*	0, 4, 8, 12, 16, 20 mg/L	0, 24, 48, 72, 96 h	SOD and CAT	Activities of SOD and CAT altered significantly	Gu et al. (2017)
11.	DEHP	Wheat	0, 10, 20, 40 mg/kg	14, 24, 40 days	SOD, CAT and APX	Activities of SOD, CAT, APX increased in shoot, stem, roots of plants in all the exposure durations	Gao et al. (2018)
12.	DBP and DEHP	Wheat	0, 10, 20, 40 mg/kg	14, 24, 40 days	SOD, APX, CAT, and GPX	Increased the activities of all enzymes in almost all exposure durations	Gao et al. (2019)
13.	BBP	*Hordeum vulgare* L.	0, 25, 50, 100, 200, 400, 800, 1600 mg/L	7 days	SOD, POD, CAT, APX, and GR	BBP altered the activities of all antioxidative enzymes with respect to the control	Kumari and Kaur (2019)
14.	DAP	*Spirodela polyrhiza*	0, 10, 20, 40, 80, 100, 200, 400 mg/L	7 days	SOD, CAT, POD, APX, and GR	Increase the activities of all antioxidative enzymes over the control	Sharma and Kaur (2019)

unsuberized cell wall (Müller and Kördel 1993; Kvesitadze et al. 2006). Furthermore, the cell wall between the cells of root cortex is porous, thereby contaminants can move freely before they reach the endodermis (Trapp and McFarlane 1994). Organic pollutants are reported to be translocated to different plant parts after their uptake (Lin et al. 2007). The two types of organic pollutant transport pathways are reported in higher plants i.e. intracellular and intercellular transport and first method is meant for short-distance transport, whereas the second relies on conducting tissue and meant for long-distance transport (Taiz and Zeiger 2002). The long-distance movement can occur either via apoplastic or symplastic way (Miller et al. 2016). It is general mechanism of contaminant uptake but there are also other factors that regulate the phenomenon of uptake like solubility, molecular mass of contaminant, pH, temperature and phase of plant growth, etc. (Korte et al. 2000; Kvesitadze et al. 2006). In case, if the solubility of contaminants is low, even then they can also be absorbed by the roots *via* passive or active uptake (Inui et al. 2008). Most studies reported that the uptake of organic contaminants by roots is passive as well as diffusive in nature except in some case like phenoxy acid herbicides, where active uptake is reported rather than passive (Ryan et al. 1988; Bromilow and Chamberlain 1995; Collins et al. 2006). During active uptake, lipid content and plant metabolism play important roles (Paterson et al. 1990; Collins 2008).

After uptake, in plants, phthalates may undergo enzymatic transformation to enhance the hydrophilicity to lower their toxicity. This process of contaminant's transformation in plants is referred as Sandermann's Green Liver Concept (Sandermann 1994) (Fig. 2).

The oxidation, reduction, hydrolysis, etc. are the main enzymatic reactions which mediate the conversion of hydrophobic contaminants into hydrophilic ones. This step leads to increases in the affinity of formed intermediate towards the enzymes and further transformations occur (Kvesitadze et al. 2009). After functionalization, the phthalates undergo conjugation. The process of conjugation enables them to react with intracellular endogenous components. There is another process that also operates besides conjugation i.e. deep oxidation but the amount of contaminant degraded through this process is very less (0.1 to 5%) and also depends upon the contaminant's structure (Kvesitadze et al. 2009). The conjugation proceeds towards the compartmentalization. It is the final step and in this, the soluble conjugate of phthalates may be accumulated in cellular compartments especially in vacuole. In plant cell, the soluble conjugates of various contaminants are reported to couple with peptides, amino acids, sugars, etc. On the other hand, the insoluble ones in plant cells get coupled with starch, lignin, xylan, pectin, etc. are carried out of the cell and accumulate mainly in the cell wall (Sandermann 1994). Thus, these insights into phthalates uptake and bioaccumulation can act as a significant cue for their transformation and mitigation in the environment. But the less attention was paid on the possible mechanism of phthalates metabolites in plants. In last few years, researchers explained possible mechanisms of frequently detected phthalates in the environment mainly in monocots. The existing literature have shown that a large proportion of hydrophobic xenobiotics taken up by plants can be transformed and formed transformation intermediates exert different biological activities than their parent form (Sun et al. 2015). Carboxylesterases (CXEs, EC 3.1.1.1) are specific esterases are reported to be involved in the metabolism of phthalates in plants that display hydrolyzing activity against carboxylic esters (i.e. de-esterification)

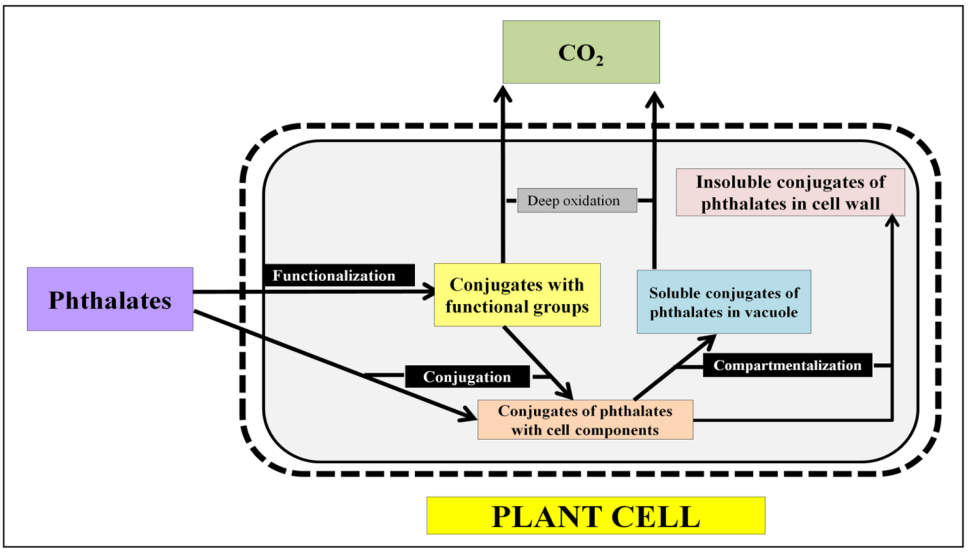


Fig. 2 Proposed mechanism of phthalates transformation in plants. Source: modified from Kvesitadze et al. (2009)

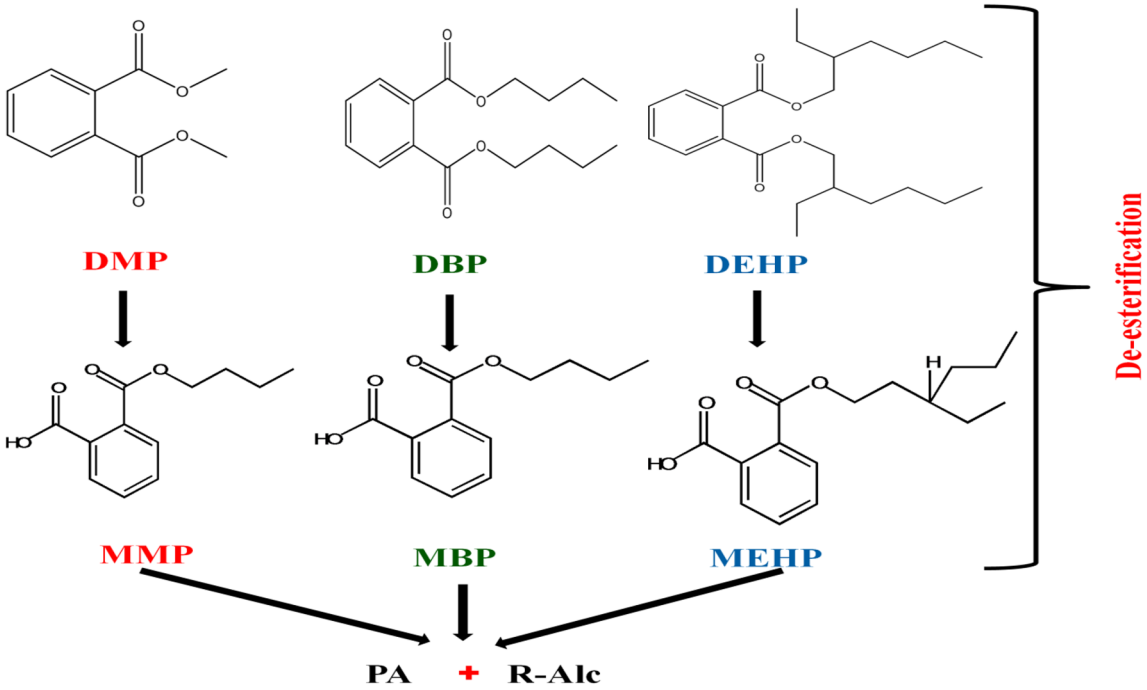


Fig. 3 Proposed mechanism of phthalates metabolites formation in plants (Sun et al. 2015; Lin et al. 2017). *DMP* dimethyl phthalate, *MMP* mono-methyl phthalate, *DBP* di-n-butyl phthalate, *MBP* mono-n-butyl phthalate, *DEHP* di(2-ethylhexyl) phthalate, *MEHP* mono-ethylhexyl phthalate, *p.a.* phthalic acid, *R-Alc* respective alcohol

as well as that are also documented to be involved in many functional roles in plants, including xenobiotics detoxification (Haslam et al. 2001; Gershater and Edwards 2007; Sun et al. 2015). Moreover, phthalates are derived from the esterification of phthalic acid and two alcohol molecules, belong to the carboxylic esters. Thus, the chemical structure of phthalates and literature reveals that CXEs play a significant role in the metabolism of phthalates in plants, especially in phase I hydrolysis (Lin et al. 2017). After hydrolysis, these metabolites conjugates rapidly in different components of plants and can be accurately determined via radioactive labeling. However, information about the importance of plant CXEs to phthalates metabolism is still limited. Furthermore, there is less knowledge regarding the activity of CXE in the subcellular fractions of phthalates exposed plants, which might reflect the localization and mechanisms of the enzymes involved in phthalates detoxification. The proposed mechanism for phthalates metabolism in plants is given in Fig. 3.

Conclusions

The present review is the outcome of extensive literature survey which highlighted the consequences of phthalates in plants in detail. This also provided insights into phthalates uptake, accumulation, and mechanism of metabolites formation. Plants have evolved tiered mechanisms for the metabolization and detoxification of pollutants. However, in case of phthalates, the exact mechanism of these processes is still unclear and there are number of lacunae. Therefore, further research is required especially to determine the occurrence of phthalate monoesters with parent contaminant during normal agronomic practices in vegetables and other edible crops under field conditions to know potential health risks. Thus, for better understanding of mechanism of phthalates action in plants, many detailed studies are required and the outcomes of this work will helpful for the generation phthalate tolerant varieties as well as to sustain the agricultural yield.

Acknowledgements The authors are highly thankful to University Grants Commission, New Delhi (India) for financial assistance provided under National Fellowship for Higher Education (NFHE) scheme (vide letter no. F1-17.1/2015-16/NFST-2015-17-ST-HIM-1038/(SA-111/Website)).

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