MINIREVIEW OF ENVIRONMENTAL RISK OF PLASTIC MATERIALS MODULE (E02)
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EFFECTS OF BISPHENOL A ON THE PLANT GROWTH AND PHOTOSYNTHESIS

I. ABSTRACT

The high potential uptake of bisphenol A in vegetation underlines the necessity of studying its effect on morphological and biochemical changes in plants. BPA's uptake and distribution, and its effects on the growth of plant organs, reactive oxidative species (ROS), and photosynthesis are presented in this report based on published papers and reviews.

II. INTRODUCTION

Bisphenol A (2,2-(4,4-dihydroxyldiphenyl) propane) is a chemical compound that belongs to a group of phenols, which have two hydroxyl residues bound directly to the aromatic rings (Figure 1). BPA is a white and crystalline solid substance with a melting point of 156ºC and a boiling point of 220ºC. Manufactured by condensing two phenol molecules and acetone with catalyst support, over 95% of BPA production is for its use as a polymer material to enhance plastic rigidity in the production of polycarbonate plastic and epoxy resins, while other industrial products containing BPA include flame retardants, thermal paper, food containers, and electronic products. BPA is also used as a plastic antioxidant and stabilizer in vinyl chloride production. These wide ranges of BPA uses are owing to its good mechanical properties, low moisture adsorption and thermal stability (Michałowicz, 2014).

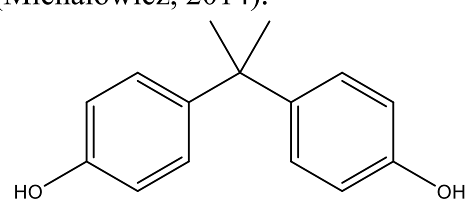

Figure 1. Chemical structure of BPA

Because of its massive use for the last 80 years, BPA has been ubiquitous in the environment. Extensive studies on the effects of BPA exposure in humans and experimental animals have been published, emphasizing the hazards of BPA as an endocrine disruptor and its effects on diseases related to the reproductive system (fertility) and cancer development (Flint et al., 2012). On the other side, BPA has been found in landfill leachate, sewage treatment plant effluent and sludge, surface water, and the air, indicating the potential exposure of BPA to plants through farmland irrigation and sludge. Recently, the trend is that many studies are working on the field of BPA effects on vegetation (Xiao et al., 2020). Therefore, this topic should be worthy of further investigation to create a comprehensive understanding of BPA ecological risk.

III. DISCUSSION

3.1. BPA Uptake and Distribution

There is a great uptake potential of BPA by the plants with moderate adsorption and bioaccumulation in soil sediments. Because BPA has a log K_{ow} of 3.40, it is expected to have poor weak plant migration, with a tendency for accumulating in plant roots that have high-fat contents (Wang et al., 2018). It was found that BPA was absorbed quite rapidly by cultivated plant cells. In the case of hydroponic tomatoes and lettuces, BPA accumulation was predominantly located in the roots, and it was poorly transported from the roots to the upper tissues (Dodgen et al., 2013; Ferrara et al., 2006). However, a study by Lu et al. (2015) indicates a dependency of the accumulation distribution of BPA still on the exposure pathways. BPA accumulation in tomatoes was found maximum in roots via subsurface root irrigation exposure (e.g. root>fruit>leaf >stem), while with overhead foliar spraying, BPA accumulation was highest in leaves and lowest in stems (e.g. leaf>fruit>root> stem).

Wang et al. (2018) found that a large amount of BPA was likely degraded or metabolized during wheat growth since the hydroxyl group of BPA can interact with compounds (e.g., sulfates) or binary ions in the soils. Such interaction will create conjugated estrogens which might change the BPA mobility in the soil-plant system. Following the uptake of BPA in plant tissues, BPA will be metabolized through three main pathways: glycosylation, selective hydroxylation, and redox reactions; producing highly polar polymers and non-extractable residues. Various enzymes, such as oxidases, polyphenol oxidase, and glycosylases, play an important role in the metabolizing xenobiotic like BPA through phytoremediation which is affected by pH and temperature (Nakajima et al., 2002). Plant defence systems such as glutathione transferase and UDP-glucosyltransferase, which were overexpressed following BPA exposure in *Arabidopsis thaliana*, also play a role in detoxification (Tian et al., 2014).

The distribution, metabolism, and detoxification of BPA in plant organs are affected by several parameters. Different plant species will lead to differences in adsorption capacity, metabolic pathways, and transport capacity of BPA, while other factors such as concentrations of BPA introduced, exposure time, and detection techniques could also be the reasons for the differences in many studies (Xiao et al., 2020). Mangrove *(B. gymnorihiza)*, for instance, could completely remove BPA (40 mg/dm^3) absorbed from the water after 51 days of treatment (Saiyood et al., 2012). Although BPA detoxification is a species-dependent process with different metabolic pathways, excessive amounts of BPA can still lead to bioaccumulation and induce toxic effects when the detoxification pathways reach saturation (Ferrara et al., 2006).

3.2. Effects on Growth of Plant Organs

The main organs that are directly exposed to BPA are plant roots. Several studies have found that BPA affected roots in a dose-dependent manner, as varying effects could occur (Pan et al., 2013; Tian et al., 2014). A low-dose BPA (1.5-3 mg/L) exposure was found to substantially promote the growth of the root, including its length, volume, and surface area, and raises the levels of growth hormone (e.g., zeatin and gibberellin) in roots, which stimulated the elongation and division of root cells (Wang et al., 2015). However, with higher doses (3-96 mg/L), BPA inhibited the growth of roots. The inhibition of root growth will be recognized from the decrease in root length, increasing sparsity in lateral roots, and the enhanced formation of gelatinous substances, alongside the necrosis and blackening of local roots and decrease of fresh/dry weight (Ferrara et al., 2006).

BPA also shows a concentration-dependent effect on the growth of the aboveground organs of the plants, such as plant height, stem, and leaf fresh/dry weight, as well as leaf area of plants (Xiao et al., 2020). Indicators usually used to evaluate BPA effects on plant organs are depicted in Figure 2.a. For example, leaf elongation impairment of seagrass was just observed when it was exposed to BPA in the highest concentrations of more than 0.3 µg/L (Adamakis et al., 2018). In another case of *Arabidopsis thaliana*, BPA concentrations of up to 10 µM were not lethally toxic to the plants, on the other hand, causing a significant decrease in flowering at both 10 nm and 10 µM concentrations, but not at intermediate concentrations. BPA inhibited flowering by a mechanism that might also involve signalling disruption of auxin hormone (Frejd et al., 2016).

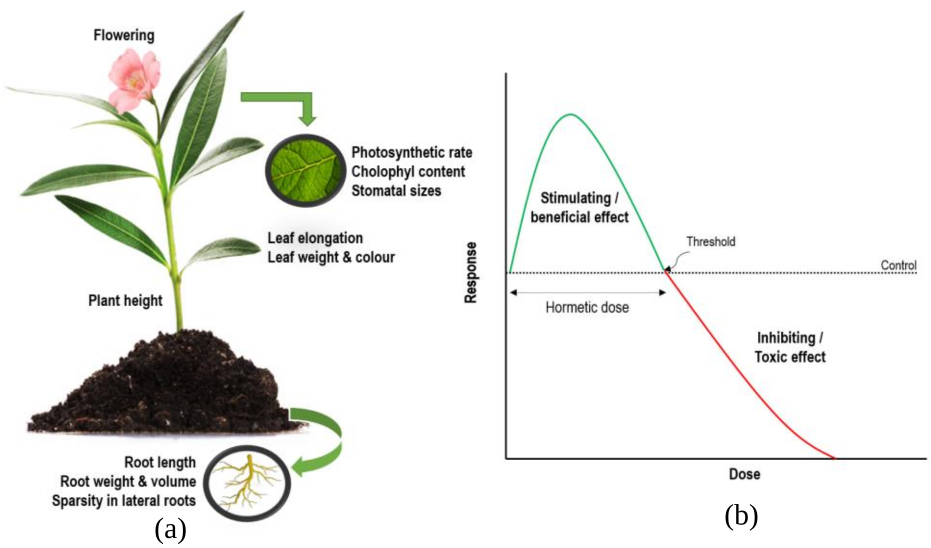

Figure 2. (a) Parameters in plant organs observed from BPA exposure and (b) hormesis effect curve of a substance

It was hypothesized that BPA has a hormesis effect on plant growth (Figure 2.b) (Xiao et al., 2020). In a low dose, BPA has cytokinin-like action, which may promote root growth by causing root cell elongation and proliferation. In addition, Nie et al. (2015) investigated that low BPA doses will allow high uptake of mineral elements from roots, and there is a positive correlation between mineral content and plant growth. From the endogenous hormones standpoint, dual effects of BPA might be associated with the interaction and regulating system of hormones. In lower BPA concentrations, ratios between growth and stress hormones in the plants are low. On the contrary, in higher BPA concentrations, the production of growth hormones is inhibited, leading to higher ratios between growth and stress hormones, and such condition causes the inhibition of soybean growth (Wang et al., 2015). Besides secretion of endogenous hormones, other biochemical and physiological processes like the production of reactive oxygen species (ROS) and photosynthesis also affect the mechanisms of BPA to inhibit plant growth (Xiao et al., 2020).

3.3. Effects on Reactive Oxygen Species (ROS)

The presence of BPA can also elevate the level of oxidative stress in plants. Normally, plants continuously produce reactive oxygen species (ROS) as a by-product of several metabolic pathways. Environmental stresses, such as the presence of BPA, can cause a balance disturbance and lead to the accumulation of ROS that exceeds the plant's antioxidant scavenging capacity, resulting in oxidative stress in chloroplasts, and plasma membranes, peroxisomes, and mitochondria. To deal with the external ROS stress, a protective antioxidant system (which includes an antioxidant enzyme and substances) was created. External stresses can be effectively resisted to a degree by the antioxidant system, but when the strength of the stress surpasses the resistance threshold, damage occurs (Ali et al., 2016; Xiao et al., 2020).

One of the methods to evaluate the presence of ROS is by measuring the endogenous level of TBARS (a product of lipid peroxidation), OH^-, and H_2O_2 as well as antioxidant enzyme activities. It was discovered that, with an increase in BPA concentration (200 µM), the amount of TBARS in both the roots and leaves of rice seedlings (*Oryza sativa)* increased considerably (86% and 78.2%, respectively), and this pattern corresponded to those of OH^- and H_2O_2. These findings confirmed that ROS production will increase lipid peroxidation. Other attenuating factors could have been present, as increased oxidative stress and lipid peroxidation may influence antioxidant enzyme activity as ROS “scavenging system”. The activity of important antioxidant enzymes (SOD, CAT, and ascorbate peroxidase) increased after exposure to low levels of BPA. However, the decreased activity of antioxidant enzymes in seedlings treated with the highest dose of BPA (200 µM) indicated that BPA exposure at this level may have overwhelmed the plant's self-defence system, causing cell structural and functional damage. Eventually, this condition will result in cell death (Ali et al., 2016).

3.4. Effects on Photosynthesis

If the photosynthetic system of a plant is altered or disrupted by exposure to contaminants from the environment, plant growth will be also damaged since the growth of the plant is strongly dependent on photosynthesis. Three parameters were usually used in studies, which are photosynthetic rate (P_n), chlorophyll (Chl) contents, and stomatal sizes. A study on soybean in different growth stages conducted by Jiao et al. (2017) investigated that BPA exposure at medium and high doses (17.2 and 50.0 mg/L) lowered the activity and conversion of key enzymes (e.g., PBG, Proto IX) and hence blocked Chl intermediates. Chl synthesis consists of five complex steps involving precursors and these enzymes. If any of these steps are blocked, the enzyme activity prior to the blockage is suppressed, resulting in a rise in the corresponding intermediate and a reduction in the intermediates that follow. Blocked Chl intermediates will eventually reduce the P_n.

A study on *Vigna radiata* by Kim et al. (2018) also found that a high dose of BPA (250 to 500 mg/L) decreased the stomatal opening size and increased the level of phytoestrogen genistein (genistein is considered a representative toxicity endpoint for endocrine-disrupting chemicals). Decreased sizes of stomata mean that BPA exposure blocked the intake pathway for elements like CO_2 and H_2O, affecting the synthesis of numerous nutrients essential for photosynthesis. Furthermore, in understanding the mechanisms by which BPA could affect photosynthesis in cucumbers, Li et al. (2018) found that photosynthetic inhibition was not the result of BPA-induced destruction of photosystem II (PS II). Instead, they suggested that photosynthesis inhibition is correlated with ROS accumulation by BPA since ROS accumulation could inhibit the repair of damaged PS II and corroborate PS II photoinhibition.

3.5. Prospective and Challenges

The findings of multiple BPA metabolic pathways in plants open new opportunities for environmental BPA detoxification and remediation through the ‘phytoremediation’ technique. Plants (e.g. macroalgae) might be employed as 'biofilters,' absorbing and detoxifying BPA from the environment (Xiao et al., 2020). For example, it was found by Phouthavong-Murphy et al. (2020) that hydroponic switchgrass (*Panicum virgatum*) demonstrated a significant BPA removal (40-46 %) over three months from wastewater, showing the plant's efficacy in BPA remediation. Kanwar et al. (2020) also obtained from their study that melatonin promoted the metabolism of BPA in tomatoes by enhancing GSH-dependent detoxification. This finding strengthens the phyto-remediating potential of melatonin and could be useful to eliminate BPA residue in plant-based food. The detoxification study of BPA on plants is also important because BPA is predominantly dispersed in plant roots, hence humans consuming rhizomatous vegetables like radishes, carrots, and onions may increase potential health concerns (Xiao et al., 2020).

However, according to Xiao et al. (2020), to create a comprehensive understanding of BPA effects on plants, there are some limitations in existing studies. Those concerns are: (1) most studies were performed in hydroponic conditions, not in the natural soil system in the environment; and (2) most studies in the past focused on morphological and biochemical processes of plants instead of cytological and molecular mechanisms. This is still a question as well as a challenge in the development of further research, regarding the effects of BPA on the cellular and molecular scale and whether the effects of BPA on hydroponic plants can be confirmed in the real soil case.

IV. CONCLUSION

Upon uptake, BPA tends to be accumulated in the roots of plants. The effects of BPA on plants depend on exposure route, plant species, as well as BPA concentrations, as BPA in lower concentrations does not induce toxicological effects to the plants, while in higher doses, inhibition actions are noticed in plant growth and photosynthesis. The BPA metabolism and detoxification processes in plants involve complex hormones, enzymes, and ROS processes.

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