INFLUENCE OF HEAVY METAL IONS ON METABOLIC PROCESSES IN PLANT CELLS AND ADAPTATION MECHANISMS

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Environmental pollution caused by anthropogenic factors is a global environmental problem. Heavy metal ions accumulate in the soil and aquatic environment as a result of industrial waste, transport emissions, and improper use of mineral fertilizers. Since they are not biodegradable, they persist in the environment for a long time and are bioaccumulated by plants [4]. In the plant body, these ions disrupt cellular metabolism and lead to disruption of physiological processes. Therefore, studying the mechanisms of heavy metal stress at the cellular level is important for environmental safety and agricultural sustainability.

When heavy metal ions enter plant cells, they primarily negatively affect energy metabolism. This process leads to disruption of cellular metabolism. As a result of the inhibition of chlorophyll biosynthesis and structural changes in chloroplast membranes, photosynthetic efficiency decreases[1]. This limits the ability of plants to accumulate biomass and reduces productivity.

At the metabolic level, heavy metal ions bind to the active centers of enzyme molecules, slowing down the rate of biochemical reactions and limiting the functional activity of some enzymes (Table 1). As a result, carbohydrate metabolism, amino acid biosynthesis, and respiration processes slow down [2,3]. In some cases, ions change the protein conformation and cause complete inactivation of the enzyme.

Table 1

Biochemical effects of heavy metals on plant cells

Heavy metal	Main effect	Effect on enzymes	Result
Pb^{2+}	Pigment breakdown	Catalase activity decreases	Growth slows down
Cd^{2+}	ROS production increases	Peroxidase activity increases	Stress increases
Cu^{2+}	Oxidative damage	SOD activity changes	The membrane is damaged.

Under stress conditions, the production of reactive oxygen species (ROS) in the cell increases. ROS accelerate lipid peroxidation, increase the permeability of cell membranes, and damage proteins and nucleic acids [5]. Oxidative damage also disrupts plant water metabolism and nutrient transport (Figure 1).

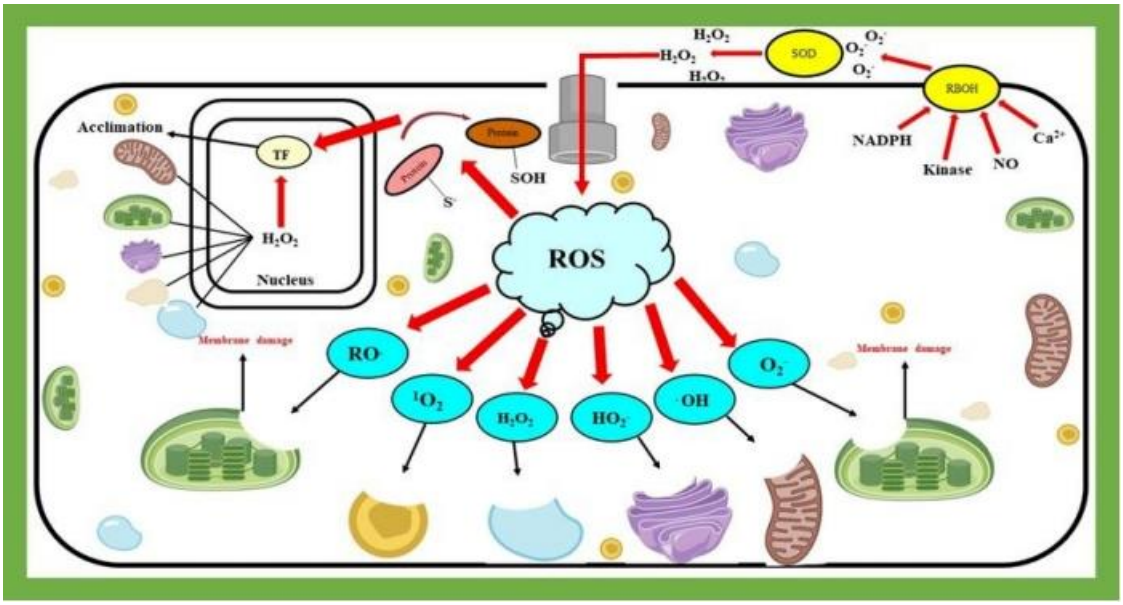

Figure 1. Mechanism of heavy metal ions inducing oxidative stress in plant cells.

In this study, the concept of "Metabolic Adaptation Index (MMI)" was proposed to assess metabolic and oxidative stress responses in plant cells under the influence of heavy metal ions (Pb^{2+}, Cd^{2+}, Hg^{2+}). This index is based on enzymatic biomarkers and ROS levels and allows for a quantitative assessment of the response of plants to metal stress. The study also revealed mechanisms of plant protection against toxic effects by complexing metal ions in vacuoles and cell walls, which provides a new approach for practical application in environmental monitoring and phytoremediation processes.

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