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GENOTOXIC EFFECTS OF HEAVY METALS ON PLANTS

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ABSTRACT

Heavy metal contamination represents a persistent environmental challenge with significant implications for plant health, genomic stability in turn impact on agricultural productivity. This review studies the genotoxic effects of major heavy metals, particularly cadmium (Cd) and arsenic (As), along with mercury (Hg), nickel (Ni) and lead (Pb). These metals induce DNA damage through both direct interactions and indirect pathways mediated by reactive oxygen species (ROS), leading to oxidative stress. Key genotoxic effects include DNA strand breaks, chromosomal aberrations, altered DNA methylation and impaired DNA repair mechanisms. The cumulative effects constitute plant growth, reproduction and transgenerational genome integrity. Understanding these molecular mechanisms operated by heavy metals is essential for developing phytoremediation strategies and obtaining sustainable crop production even in contaminated areas.

KEYWORDS: Genotoxicity, Heavy metals, Oxidative stress, DNA damage, Chromosomal aberrations, Plant genome stability.

1. INTRODUCTION

Heavy metals are non-biodegradable environmental pollutants that pose serious threats to plant systems due to their persistence and bioaccumulation. Among these, cadmium (Cd) and arsenic (As) are particularly hazardous due to their widespread occurrence and high toxicity. These metals disrupt cellular homeostasis by inducing genotoxic effects that impair DNA integrity, cell division and metabolic processes (Shahid *et al.*, 2017).

Genotoxicity in plants involves damage to genetic material, including DNA strand breaks, base modifications, and chromosomal alterations. Heavy metals exert their toxicity primarily through oxidative stress caused by excessive production of reactive oxygen species (ROS), which interfere with cellular components and genetic machinery (Gill and Tuteja, 2010). Additionally, metals can directly bind to DNA and proteins involved in replication and repair, increasing mutation rates and genomic instability (Sharma and Dietz, 2009).

2. Mechanisms of Heavy Metal-Induced Genotoxicity

Heavy metals induce genotoxic effects through two principal mechanisms:

2.1 Oxidative Stress-Mediated Damage

The overproduction of ROS leads to oxidative damage, including DNA strand breaks, nucleotide modifications, and chromosomal aberrations (Zucca et al., 2013). ROS also degrade purine and pyrimidine bases, compromising genome stability.

2.2 Direct Interaction with Genetic Material

Heavy metals can bind directly to DNA and nuclear proteins, disrupting replication and repair processes. They inhibit essential DNA repair pathways such as base excision repair (BER) and nucleotide excision repair (NER), resulting in mutation accumulation (Balali-Mood et al., 2021).

3. Genotoxic Effects of Specific Heavy Metals

3.1 Cadmium (Cd)

Cadmium is a highly toxic, non-essential metal that induces severe genotoxic effects in plants. It causes DNA strand breaks, chromosomal aberrations, and micronucleus formation. Cd interferes with antioxidant defense systems, enhancing oxidative stress and impairing DNA repair enzymes (Gill and Tuteja, 2010).

Studies using *Allium cepa* have demonstrated mitotic abnormalities such as chromosome stickiness, laggards, and bridges, along with reduced mitotic index (Fiskesjö, 1985; Tran and Popova, 2013).

3.2 Arsenic (As)

Arsenic exists primarily in inorganic forms (arsenite and arsenate) and is a potent genotoxic agent. It induces oxidative DNA damage, chromosomal instability, and inhibition of DNA repair mechanisms (Finnegan and Chen, 2012).

In *Arabidopsis thaliana*, arsenic exposure leads to DNA fragmentation, micronucleus formation, and altered gene expression (Sharma and Dietz, 2009). It also disrupts phosphate metabolism, indirectly affecting nucleic acid synthesis.

3.3 Nickel (Ni)

Nickel is an essential micronutrient but becomes toxic at elevated concentrations. Excess Ni induces chromosomal aberrations, DNA damage, and mitotic disruptions. It interferes with spindle formation and increases ROS production, leading to oxidative stress (Gajewska and Skłodowska, 2007; Mishra and Srivastava, 2015).

3.4 Mercury (Hg)

Mercury exhibits strong genotoxic potential by inducing DNA strand breaks and chromosomal fragmentation. It disrupts microtubule formation, leading to abnormal chromosome segregation and inhibition of mitosis (Patra and Sharma, 2000). Additionally, Hg binds to sulfhydryl groups, impairing protein function and DNA repair.

3.5 Lead (Pb)

Lead affects genome stability by reducing the expression of DNA repair genes and inducing micronuclei formation. It disrupts chromosomal integrity and significantly lowers the mitotic index, thereby impairing plant growth and reproduction (Balali-Mood et al., 2021).

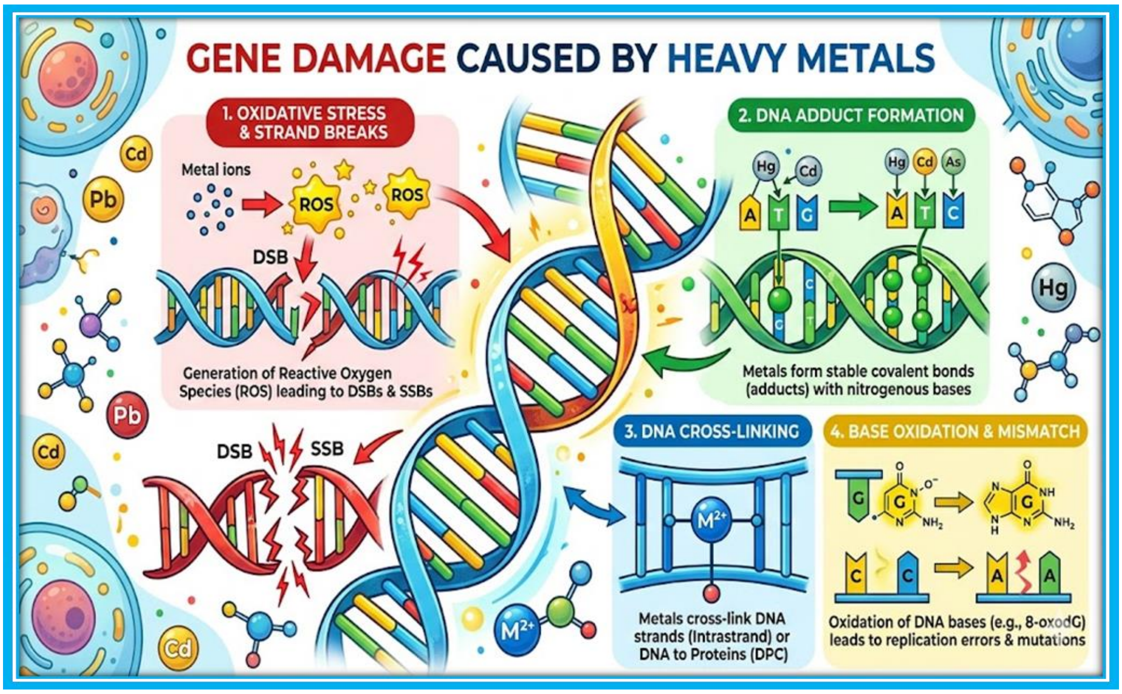

Figure 1.1 Showin gvarious types of gene damaga.

Genotoxic Effects of Heavy Metals on Plant Genomes

The following table summarizes common genotoxic changes occurring in plant genomes due to exposure to specific heavy metals.

Table 1.1 Genotoxic Effects of Heavy Metals on Plant Genomes

Heavy Metal	Primary Genotoxic Effects & Genomic Changes	Impact on Genome Stability	References
Mercury (Hg)	Induction of double-strand breaks (DSBs); binding to tubulin-SH groups impairing spindle formation; inhibition of Base Excision Repair (BER) and Nucleotide Excision Repair (NER).	Leads to chromosomal aberrations and aneuploidy; specifically targets mitochondrial and nuclear DNA.	(Hani et al., 2020; Laoye et al., 2025)
Arsenic (As)	Induction of oxidative DNA damage; inhibition of zinc-finger DNA repair proteins; alteration of histone modifications (H3K4me3 and H3K27me3).	Acts as a co-mutagen, enhancing the effects of other environmental stressors; causes DNA hypomethylation.	(Laoye et al., 2025; Balali-Mood et al., 2021).
Nickel (Ni)	Generation of ROS-mediated DNA damage; substitution of essential metal ions in DNA-binding proteins; induction of chromosomal gaps and breaks.	Interferes with DNA replication and transcription fidelity.	Rashid et al., 2023; El-Sappah et al., 2024).
Cadmium (Cd)	Significant increase in chromosomal aberrations; inhibition of DNA mismatch repair (MMR) and DNA methyltransferase (DNMT) activity; induction of DNA strand breaks.	Leads to high mutation rates; causes global DNA hypomethylation and altered chromatin structure.	(Hani et al., 2020; Laoye et al., 2025).
Lead (Pb)	Reduced expression of DNA repair genes (BER, NER, and DSB repair); induction of micronuclei formation and sister chromatid exchange.	Causes genomic instability and significant reduction in the Mitotic Index (MI).	(Laoye et al., 2025; Balali-Mood et al., 2021).

4. Molecular Techniques for Detecting Genotoxicity

The Random Amplified Polymorphic DNA (RAPD) technique is widely used to detect DNA damage induced by heavy metals. RAPD analysis reveals genomic alterations such as mutations, deletions, and polymorphisms (Williams et al., 1990).

Studies have successfully applied RAPD to assess genotoxic effects in species such as *Phaseolus vulgaris*, *Trifolium repens*, and *Urtica dioica*, demonstrating its effectiveness in detecting DNA damage caused by heavy metal exposure (Cenkci *et al*., 2009; Gjorgieva et al., 2013).

5. Implications for Plant Genome Stability

Heavy metal-induced genotoxicity leads to:

- Increased mutation rates.
- Chromosomal aberrations and aneuploidy.
- Altered DNA methylation and epigenetic modifications.
- Impaired DNA repair mechanisms.

These effects collectively compromise plant growth, productivity, and reproductive success, ultimately impacting ecosystem stability and food security (Rashid et al., 2023; Laoye et al., 2025).

6. CONCLUSION

Heavy metals such as cadmium and arsenic exert profound genotoxic effects on plants by disrupting DNA integrity and cellular processes. The resulting genomic instability not only affects individual plant health but also has long-term ecological and agricultural consequences. Advancing our understanding of these mechanisms is crucial for developing effective phytoremediation strategies and mitigating environmental risks associated with heavy metal contamination.

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