

# Influence of Industrial Wastewater Irrigation on Agricultural Crops: A Comprehensive Review of Effects on Growth, Physiology, and Metabolism

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**Abstract**— Industrial wastewater, containing a complex mixture of organic and inorganic compounds, exerts a profound influence on crop physiology. When pollutant concentrations are managed through dilution or treatment, the agricultural reuse of this wastewater can promote sustainable practices by conserving scarce freshwater resources and providing valuable nutrients. However, irrigation with untreated or highly concentrated effluent leads to the accumulation of toxic heavy metals in plants, adversely affecting seed germination, plant growth, crop yield, and ultimately human health. This review synthesizes current research on the quality of wastewater from diverse industries and its differential effects on growth, yield, and key physiological and biochemical parameters in various crop plants. The analysis underscores that careful, context-specific management is imperative to harness benefits while mitigating significant ecological and agricultural risks.

**Keywords**— Industrial wastewater, plant growth, chlorophyll, heavy metals, oxidative stress, seed germination, genotoxicity.

## I. INTRODUCTION

Environmental pollution poses a multifaceted threat with local, regional, and global impacts, significantly endangering the health of humans, animals, and plants (1). Aquatic ecosystems are particularly vulnerable, with most water sources contaminated by substantial volumes of domestic sewage and industrial effluent. Wastewater from different industries varies greatly in composition, containing substances ranging from simple nutrients to highly toxic compounds and heavy metals, making treatment both complex and costly.

In arid and semi-arid regions, wastewater is increasingly considered a vital resource for irrigation and fertilization (2). Its use in agriculture can contribute to soil conservation and waste disposal, with many effluents and sludges containing nutrients that enhance soil fertility and crop production (3). Globally, wastewater irrigation is practiced for three primary purposes: (a) as a method of effluent disposal (4); (b) as a source of plant nutrients (4); and (c) as a strategy to alleviate water scarcity for agriculture (5). This practice presents a dualistic set of consequences. Positive implications include employment generation, improved food security, a reliable irrigation supply, and nutrient recycling. Conversely, long-term use can degrade soil health through salinization, heavy metal accumulation, and structural breakdown, ultimately restricting crop choice and reducing yields.

Given these competing merits and demerits, a critical evaluation of the toxic effects of effluents and their suitability for irrigation is essential. This review article comprehensively examines the impact of various industrial wastewaters on a wide range of crop plants and soil characteristics, analyzing effects from seed germination to cellular metabolism.

## II. PHYSICOCHEMICAL PROPERTIES OF INDUSTRIAL WASTEWATER

The principal constraint on expanding wastewater use for irrigation is its highly variable quality. Effluents from different industrial sources possess distinct chemical compositions, leading to disparate effects on plants. For instance, textile industry wastewater is reported to have variable pH, high electrical conductivity (EC), significant levels of cations ( $\text{Ca}^{2+}$ ,  $\text{Mg}^{2+}$ ,  $\text{Na}^+$ ,  $\text{K}^+$ ) and anions ( $\text{HCO}_3^-$ ,  $\text{CO}_3^{2-}$ ,  $\text{Cl}^-$ ), and often heavy metals like Zn, Cu, Cr, Pb, Mn, Ni, and Fe. Sugar mill effluents are

typically characterized by high biological and chemical oxygen demand (BOD and COD) (6,7), which can deplete aquatic oxygen and reduce biodiversity. Elevated EC, indicative of high dissolved ion concentrations, is a common feature of sewage and industrial wastewater (8). The carbon content and the balance of organic and inorganic constituents also vary with the source and treatment level. This variability means that while wastewater can be a valuable source of irrigation water and nutrients for farmers' fields, its specific composition must be the primary determinant of its use.

### III. EFFECTS ON SEED GERMINATION AND SEEDLING GROWTH

The presence of various chemicals in wastewater often detrimentally affects early plant development. Research demonstrates that the impact varies significantly both by effluent type and crop species. A linear decrease in germination percentage, speed, and germination value has been noted in vegetables like tomato, chilli, and onion when irrigated with effluent from petroleum refineries, paper mills, ordnance factories, and distilleries.

Gulfraz et al. (9) evaluated the suitability of different industrial effluents for wheat irrigation, finding seed germination was most severely affected by textile mill wastewater, followed by soap and detergent, oil refinery, hydrogenated oil, and rubber industry effluents. This study concluded that untreated wastewaters should not be discharged into agricultural systems and advocated for industrial treatment plants. Similarly, Karunyal et al. (10) reported a decline in germination, chlorophyll, and protein content in *Oryza sativa* with increasing concentrations of tannery effluent.

Conversely, studies also show the potential benefits of properly managed effluent. Kalaiselvi et al. (11) found that distillery spentwash at concentrations up to 10% improved seed germination and seedling growth in maize, suggesting its safe use as a fertilizer substitute after appropriate dilution. Singh et al. (12) observed that fertilizer factory effluent at 25% concentration could increase root/shoot length and chlorophyll content in gram (*Cicer arietinum*) after 21 days, though higher concentrations were toxic. These studies collectively affirm that the effects on germination and early growth are critically dependent on effluent source, concentration, and crop tolerance.

### IV. EFFECTS ON CROP GROWTH, BIOMASS, AND YIELD

Wastewater-induced plant damage typically results from a combination of osmotic stress and specific ion toxicity (13, 14). A major concern is the accumulation of trace elements (e.g., Pb, Cd, Ni) and microbial pathogens, which can degrade soil physical conditions and food safety (15). Despite these risks, many studies report growth and yield enhancements with wastewater application, primarily due to its nutrient content.

Garg and Kaushik (16) noted increased plant height and biomass in certain crops with diluted (6.25%) textile mill effluent. In sugarcane, spentwash application boosted yield and available nitrogen in soil (17). Research on rice indicates that distillery spentwash diluted 50 to 100 times can produce normal or even maximum grain yields (18, 19). However, inhibitory effects are clear with untreated effluents. Mohana et al. (20) reported that untreated coffee wastewater reduced plant height, tiller number, leaf area, dry matter, chlorophyll, and nutrient content in Palmarosa grass, while treated effluent performed better.

The nature of the effluent defines its impact. Giovacchino et al. (21) found that olive vegetable water (OVW) applied at over 10 L m<sup>-2</sup> increased total maize biomass by 30-40%. In contrast, crops produced with heavy metal-contaminated effluent often show poor growth and reduced shelf life (22). Sewage-irrigated crops may exhibit vigorous vegetative growth due to excess nitrogen but often have lower economic yield (23). Akhtar et al. (24) demonstrated that thermal power plant wastewater could enhance growth, photosynthesis, seed yield, and oil content in mustard and linseed when combined with balanced NPK fertilization, presenting it as a viable irrigation alternative. Shukry et al. (25) have reported increase in soluble nitrogen content in wheat grains when irrigated with industrial effluents.

### V. EFFECTS ON PHOTOSYNTHETIC PIGMENT CONTENT

Photosynthetic pigments are highly sensitive to pollution stress. Under effluent-induced stress, chlorophyll can undergo photochemical reactions like oxidation, reduction, and pheophytinization, altering plant physiology and biochemistry (26).

Studies consistently show pigment reduction under effluent stress. Akujobi et al. (27) reported decreased chlorophyll and protein in eggplants due to diesel oil pollution. Nath et al. (28) observed significant reductions in chlorophyll, pheophytin, and carotenoids in *Phaseolus mungo* with tannery effluent and Cr<sup>2+</sup>. Bamniya et al. (29) found similar decreases in chlorophylls and carotenoids in *Brassica oleracea* and *Spinacia oleracea* irrigated with mixed industrial-municipal wastewater.

Kakar et al. (30) provided a detailed physiological analysis, showing that municipal wastewater reduced stomatal conductance, transpiration rate, and photosynthetic rate by up to 69% in canola. Chlorophyll \*a\* and \*b\* were reduced by 68-86%, with the

higher-concentration effluent (100%) causing the most severe damage. This direct impairment of the photosynthetic apparatus is a primary mechanism behind the observed growth reductions.

## VI. EFFECTS ON METABOLISM, PROTEIN CONTENT, AND OXIDATIVE STRESS

Industrial effluents often induce metabolic stress, triggering the production of reactive oxygen species (ROS) such as superoxide radicals, hydrogen peroxide, and hydroxyl radicals (31, 32). These ROS can damage DNA, proteins, chlorophyll, and cellular membranes. Plants activate complex enzymatic and non-enzymatic antioxidant systems, including superoxide dismutase (SOD), catalase (CAT), peroxidase, and ascorbic acid, to mitigate this oxidative damage (33).

Elevated antioxidant activity is a common biomarker of effluent stress. Studies report increased catalase (34), peroxidase (28), and ascorbic acid (35) activities under heavy metal stress. Sangeetha et al. (36) documented a significant increase in SOD, CAT, and glutathione peroxidase (GPx) activity in maize seeds exposed to undiluted textile effluent, with a less drastic increase under diluted effluent treatment. This indicates that the plant's antioxidant defense system is engaged proportionally to the stress level, and its capacity can be overwhelmed by high concentrations of pollutants.

## VII. EFFECTS ON CELL DIVISION AND GENOTOXICITY

Wastewater irrigation can directly harm fundamental cellular processes. Effluents often reduce mitotic division rates in root meristems and induce chromosomal aberrations such as spindle defects, lagging chromosomes, fragments, and irregular chromosome distribution (37, 38).

Kara et al. (39) observed a decreased mitotic index in *Allium cepa* root tips exposed to industrial water samples from the Gediz River area. Srivastava and Jain (40) reported a 63% to 100% decline in mitotic efficiency in sugarcane root meristems treated with crude spentwash. The cytotoxic and genotoxic effects included spindle inhibition, chromosome stickiness, C-mitosis, multipolarity, and micronuclei formation. These effects are frequently attributed to heavy metals (e.g., Cr, Ni, Cd) in the effluent, which can cause oxidative DNA damage and disrupt spindle apparatus function (41). The inhibition of DNA synthesis or cellular energy (ATP) production are potential mechanisms behind this mitodepression (42, 43).

## VIII. NUTRIENT AND HEAVY METAL ACCUMULATION IN CROPS

The nutrient content of wastewater can improve soil fertility and crop yield, acting as a slow-release fertilizer rich in N, P, K, and micronutrients (44). Ouazzani et al. (45) found that wastewater-irrigated meadows received N and P at or above recommended fertilizer rates.

However, improper management leads to excessive nutrient and heavy metal accumulation in plants, reducing yield quality and introducing toxins into the food chain (46, 47). The bioavailability and translocation of metals vary significantly. For example, Cd can accumulate in edible parts at levels hazardous to consumers without harming the crop itself, whereas Pb and Cr are less plant-available (48, 49). Metal distribution within the plant also differs; Ni tends to accumulate in roots, while Fe, Mn, and Cu are more mobile and accumulate in shoots (50, 51). Antagonistic interactions between ions can also affect uptake; for instance, high  $Zn^{2+}$  and  $Mn^{2+}$  can depress  $Fe^{3+}$  absorption (52, 53, 54), and the translocation of  $Zn^{2+}$  and  $Ni^{2+}$  from roots to shoots is often limited (55).

## IX. CONCLUSION AND FUTURE PERSPECTIVES

This comprehensive review confirms that industrial wastewater reuse in agriculture presents a complex trade-off between significant benefits and serious risks. The body of research indicates that with proper dilution and pre-treatment, certain effluents can be a valuable source of water and nutrients, enhancing crop growth and yield. Conversely, untreated or concentrated wastewater leads to toxic effects including suppressed germination, reduced growth and photosynthetic efficiency, oxidative stress, genotoxicity, and the accumulation of heavy metals in edible tissues, posing a direct threat to ecosystem and human health.

Therefore, a universal endorsement of wastewater irrigation is not feasible. Its suitability is entirely context-specific, depending on the effluent's chemical profile, the degree of dilution or treatment, the crop species, and soil characteristics. A thorough economic and environmental impact analysis is prerequisite for any large-scale implementation. Future research should prioritize: 1) Long-term field studies on soil-pollutant-plant transfer dynamics; 2) The development of cost-effective, industry-specific tertiary treatment technologies; and 3) The breeding and selection of crop varieties with greater tolerance to common wastewater pollutants. Ultimately, rigorous, science-based guidelines and continuous monitoring are essential to harness the potential of this resource while safeguarding agricultural sustainability and public health.

## CONFLICT OF INTEREST

The authors declare no conflict of interest.

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