



REVIEW ARTICLE

Balancing crop productivity, soil health and heavy metal dynamics in industrial effluent irrigation of okra (*Abelmoschus esculentus* (L.) Moench)

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Abstract

In water-scarce peri-urban agriculture systems of South and Southeast Asia, the use of industrial effluents for irrigation is gaining momentum. Okra (*Abelmoschus esculentus* (L.) Moench), being a popular vegetable crop, is grown under effluent-irrigated conditions due to its adaptability and economic importance. The review presented here compiles research articles published from 2000 to 2025 studying the effects of irrigation with distillery, textile, tannery, paper and pulp and sugar mill effluents on okra, focusing on plant growth, physiological response, soil health and heavy metal accumulation. Accumulated evidence demonstrates a concentration-dependent response of okra and soil systems to industrial effluent irrigation. Effluent suitability for agriculture is strongly industry-dependent: distillery and sugar mill effluents, at low dilution, supply useful nitrogen (N), potassium (K) and organic matter with comparatively lower heavy-metal risk, whereas tannery and textile dyeing effluents carry substantially higher chromium, cadmium and lead loads and require treatment before safe reuse. Nitrogen, phosphorus (P), K and organic matter are often supplemented for improved seed germination, vegetative development, chlorophyll production, yield and nutrient availability, particularly at low effluent dilutions (5–25 %). Osmotic stress, oxidative damage, growth inhibition and a reduction in photosynthetic activity occur at concentrations exceeding 50 %. Regardless of effluent type, continued irrigation increases soil salt content, alters microbial and enzyme activity and drives accumulation of heavy metals cadmium, chromium, lead and nickel, which translocate to edible pods and can exceed recommended food safety limits, posing a measurable health concern. Knowledge gaps remain regarding varietal differences in metal uptake, stress tolerance mechanisms, molecular responses and their long-term field-scale implications under tropical conditions. Mitigation strategies showing the most promise include biochar amendment, phytoremediation crop rotation, constructed wetland pre-treatment and precision dilution.

Keywords: *Abelmoschus esculentus*; biochar amendment; constructed wetland; crop stress physiology; food safety limits; heavy metal translocation; osmotic stress; phytoremediation; soil enzyme activity; wastewater reuse

Introduction

More than 72 % of global freshwater withdrawals are used to support agriculture and the demands on freshwater for agriculture are growing relative to freshwater demands for domestic, industrial and environmental uses (1). Water scarcity is one of the major constraints on food production, especially in low-income tropical and sub-tropical countries, where increased population, urbanisation and irregularity of rainfall result in a decrease in water availability per capita (1–3). In peri-urban areas, smallholder farmers are increasingly finding it difficult to access the canal and groundwater resources due to reduced availability resulting from the abstraction by municipalities and industries from upstream (4, 5). Consequently, the treated industrial effluents/municipal sewage is being used as a water source for irrigation on many farms (4). Historically, wastewater has

long been utilised in agriculture (6, 7). Industrial effluents from textile, tannery, distillery, paper mill and sugar industries differ substantially in their physicochemical composition, reflecting their production processes. When optimally diluted, these discharges supply balanced amounts of nitrogen (N), phosphorus (P), potassium (K) and micronutrients that support crop growth and enhance soil organic matter. However, if the concentrations are not reduced through dilution and serial application is not observed, heavy metal accumulation, alteration of the soil microflora and movement into edible plant tissues can cause ecological stress and human health concerns (8). Okra (*Abelmoschus esculentus* (L.) Moench), a member of the family Malvaceae, is among the most prevalent vegetables cultivated in effluent-irrigated peri-urban farms across tropical Asia. India is the major producer and the production is expected to be about 7.25 million metric tonnes in 2023–24 (9, 10). The crop is

tolerant of temperatures between 20–35 °C and can be harvested for the first time about 10 weeks after sowing, making it ideally suited to use in smallholder cropping operations, which may have to manage irregular water supplies (10). The pods are rich in vitamins A, B and C, calcium (~84 mg/100 g fresh weight), iodine, digestible protein and dietary fibre. Okra serves as an ideal model crop for evaluating pollution-associated risks due to its tendency to accumulate contaminants from irrigation water. Although previous reviews have evaluated the impacts of individual industrial effluents on soil quality, a comprehensive synthesis focused specifically on okra productivity, soil health and heavy metal dynamics remains lacking (11, 12). In this review, empirical literature concerning the effects of industrial effluent irrigation on okra is synthesised across three interconnected domains: Productivity, soil health and heavy metal dynamics. The concentration-dependent stimulatory and inhibitory effects on growth are assessed, the underlying physiology and biochemical mechanisms are discussed, the pathway of metal transfer from soil to edible pod is described and important gaps in knowledge and risk reduction strategies are identified.

Methodology

The search process for literature involved the identification of key search terms relevant to the study. These are related to industrial effluent, irrigation with wastewater, okra, *Abelmoschus esculentus*, soil quality, heavy metals, bioaccumulation, food safety and remediation. The databases used for this research were Web of Science, ScienceDirect, Scopus and Google Scholar. Only those publications that were published in the English language in the

period 2000 to 2025 were included. The overall methodology used for literature identification, screening, eligibility assessment and final study selection is illustrated in Fig. 1. The search strategies used and the number of articles retrieved from each database are summarised in Table 1.

The detailed criteria applied for including or excluding articles during the selection of appropriate review papers are presented in Table 2.

Major industrial effluents used in agricultural irrigation

The physicochemical characteristics of industrial effluents vary considerably depending on industrial processes, raw materials and treatment. Many wastewater sources, such as distillery, textile, tannery, paper and sugar factories, are discharged into peri-urban agricultural zones of South and Southeast Asia, where freshwater resources are limited and are frequently reused for crop cultivation (13). The major physicochemical characteristics, beneficial constituents, contaminants of concern and potential agricultural implications of the principal industrial effluents used for irrigation are summarised in Table 3. Such effluents can provide agronomically good nutrients like N, P, K, calcium, magnesium and organic carbon; however, they frequently exhibit high biochemical oxygen demand (BOD), chemical oxygen demand (COD), dissolved salts and potentially toxic heavy metals, which can impair soil quality, crop productivity and food safety (14, 13). The characteristics of distillery effluent are its high organic loading, acid pH levels and high K and N contents, as well as spent wash and post-methanated distillery

Table 1. Strategies for collecting appropriate review articles

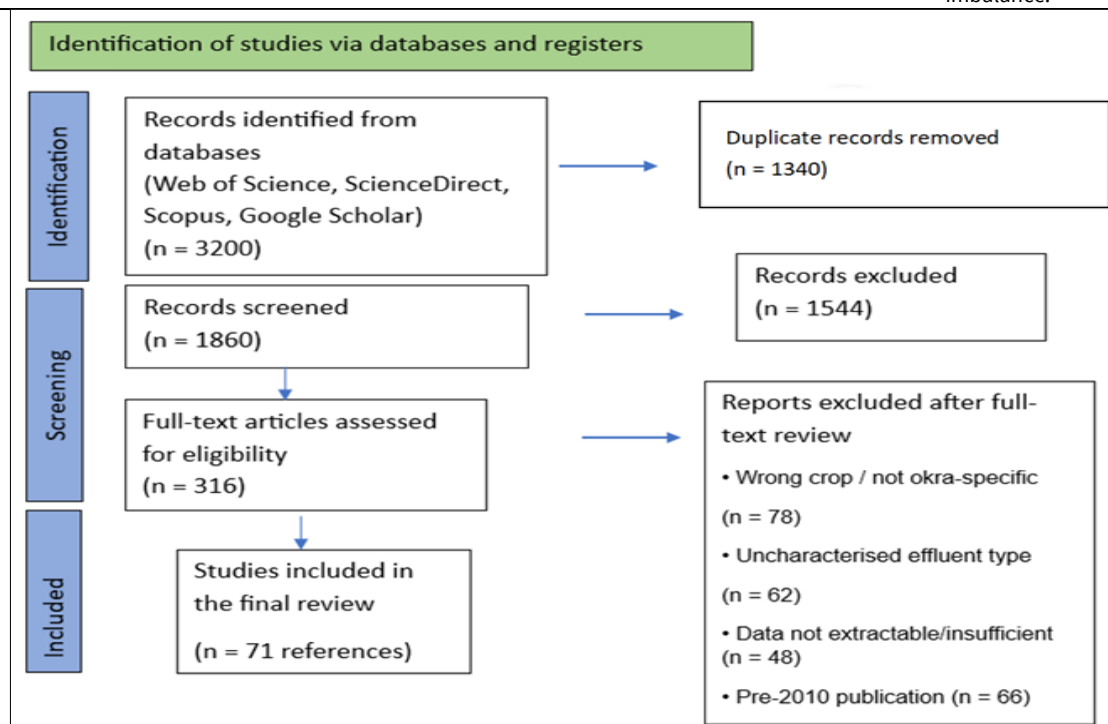
Search strategy	Web of Science	ScienceDirect
Industrial effluent irrigation and okra (<i>Abelmoschus esculentus</i>)	124	421
Industrial effluent, crop productivity and soil health	287	243
Heavy metal accumulation in vegetables	412	378
Wastewater irrigation and agricultural soils	498	98
Heavy metal uptake and translocation in okra	156	134
Soil microbial activity under effluent irrigation	234	198
Seed germination and effluent toxicity	178	152
Bioaccumulation and food safety risk assessment	315	276
Crop-to-human transfer / dietary exposure	198	167
Mitigation strategies (biochar, phytoremediation and constructed wetlands)	143	119

Table 2. Criteria for inclusion and exclusion strategy for selecting an adequate review paper

Criteria	Inclusion	Exclusion
Focus of study	Studies examining industrial effluent (distillery, textile, tannery, paper mill, or sugar mill) irrigation on okra (<i>Abelmoschus esculentus</i>) covering crop productivity, soil health, heavy metal dynamics, or phytotoxicity	Studies that do not involve okra or industrial/wastewater irrigation; purely theoretical or modelling papers with no experimental data
Publication year	2000–25	Publications before 2000
Study type	Original research articles, experimental field studies, controlled pot/greenhouse experiments and review articles synthesising empirical data on effluent-irrigated crops	Conference abstracts, editorials, opinion pieces, book chapters without original data, grey literature
Language	English-language publications only	Publications in languages other than English
Database access	Open-access and institutional-access articles available in full text	Articles available only as abstracts with no full-text access
Parameters reported	At least one of: germination/seedling growth, vegetative/yield parameters, physiological/biochemical responses, soil physicochemical or biological properties, heavy metal accumulation (BCF, TF, Health Risk Index, EDI)	Studies reporting exclusively on unrelated crops, non-industrial effluents with no characterisation, or non-agricultural outcomes
Effluent characterisation	Studies that characterise the effluent type (distillery spent wash, tannery effluent, textile dye wastewater, paper mill or sugar mill effluent) or reference known physicochemical parameters (pH, EC, BOD, COD, metal content)	Studies using completely uncharacterised 'mixed wastewater' with no effluent-type identification
Heavy metal/food safety data	Studies reporting metal concentrations in soil, plant tissue, or pods, or providing risk indices (BCF, TF, HRI, EDI) for consumer exposure assessment	Studies reporting metal data only for atmospheric, industrial, or non-agricultural contexts
Mitigation relevance	Studies evaluating remediation strategies applicable to effluent-irrigated soils: biochar amendment, phytoremediation, constructed wetlands, or precision dilution protocols	Studies on industrial wastewater treatment technology not related to agricultural reuse or crop/soil safety

Table 3. Major industrial effluents used for agricultural irrigation and their general characteristics

Type of industrial effluent	Source industry	General physicochemical characteristics	Beneficial constituents	Major contaminants of concern	Potential agricultural implications	References
Distillery effluent (spent wash/post-methanated distillery effluent)	Alcohol and ethanol industries	High organic load, high BOD and COD, acidic to neutral pH, rich in dissolved solids and dark coloured due to melanoidins	Organic matter, N, K, Ca and Mg	Melanoidins, high salt load and potentially toxic metals depending on source	At low dilutions, supplies nutrients and organic matter that improve crop growth; prolonged or undiluted application may cause salinity, oxygen depletion, phytotoxicity and heavy metal accumulation.	(12, 15, 17)
Textile dyeing effluent	Textile dyeing and finishing industries	Generally alkaline, high EC, TDS, BOD and COD, coloured due to synthetic dyes	Limited nutrient contribution	Synthetic dyes, detergents, salts, Cr, Cu, Zn, Ni, Cd and Pb	Diluted effluent may supplement irrigation water, whereas continuous use may increase soil salinity, reduce germination and growth and promote heavy metal accumulation.	(18, 19, 31)
Tannery effluent	Leather processing industries	High dissolved solids, chlorides and sulphides; variable pH depending on processing	Negligible agronomic nutrient value	Chromium (major contaminant), sulphides, Na and other trace metals	Requires adequate treatment before agricultural use because long-term irrigation may result in chromium accumulation, soil degradation and food safety concerns.	(20, 21)
Paper and pulp mill effluent	Pulp and paper industries	Generally alkaline with moderate to high COD, suspended solids and lignin-derived organic compounds	Organic carbon, Ca, Mg and small quantities of plant nutrients	Chlorinated organic compounds and trace metals such as Zn, Cu, Pb and Cr	Appropriate dilution may improve soil organic matter and nutrient availability; long-term use may lead to accumulation of recalcitrant organics, salts and trace metals.	(22, 23, 24)
Sugar mill effluent	Sugar manufacturing industries	Rich in biodegradable organic matter with moderate BOD and COD; near-neutral to slightly alkaline pH	Organic matter, N, P, K, Ca and Mg	Sulphates, chlorides and trace metals depending on processing	Properly diluted effluent can improve soil fertility and crop productivity, whereas repeated application may increase salinity and nutrient imbalance.	(12, 25, 33)

**Fig. 1.** Methodology and literature review.

effluent (PMDE). Dilute application has been reported to promote okra growth and yield, while higher levels are reported to be phytotoxic and can lead to the accumulation of cadmium, chromium and lead in agricultural systems (15–17). The effluents generated from textile mills are typically alkaline in nature and are loaded with various types of dyes, salts, detergents and heavy metals such as chromium, zinc, copper, cadmium, nickel and lead. Plant growth could be stimulated by diluted wastewater as nutrients; however, repeated use can lead to salt accumulation in the soil and soil plant tissues and toxic contaminant levels in the soil (13, 18, 19). The effluents generated by the tannery are among the most polluted effluents as they contain a higher concentration of chromium. These effluents are not only rich in chromium but also contain sulphides, ammonium compounds, chlorides, sodium and some heavy metals as well. Increased soil chromium levels, changes in microbial populations and transfer of chromium to crop tissues have also been reported due to long-term irrigation with tannery effluents (20, 21). The effluents from paper and pulp mills are more alkaline, have higher COD levels and contain high levels of recalcitrant organic compounds such as chlorinated organics and lignin derivatives. Although moderate levels of dilution could help increase the soil's supply of organic carbon and nutrients, extended use can lead to the buildup of heavy metals like zinc, copper, lead and chromium in agricultural soils (22–24). Sugar mill effluents generally contain high concentrations of organic matter, sulphates, chlorides and plant nutrients, while heavy metal concentrations are usually lower than those reported for textile and tannery effluents. Dilute applications are used to help promote growth and fertility of the crop and soil but will cause salinity problems and trace metal accumulation in the soil and plant over time (25, 26). Generally, the suitability of utilisation of industrial effluents in agriculture is highly influenced by the chemical composition of the effluents, the dilution of the effluents, the frequency of application and the buffering capacity of the soil receiving the effluents. Therefore, proper management is crucial to optimise nutrient value, while reducing risks from salinity, soil degradation and heavy metals (13, 14, 27, 28).

Effects on seed germination and early seedling growth

Seed germination and early seedling establishment represent the most vulnerable phase of the okra growth cycle. Unlike mature plants, which can deploy multiple adaptive mechanisms, embryos and young seedlings lack robust physiological buffers against chemical stress. Studies spanning all five effluent types report a consistent biphasic response: stimulation at low concentrations and progressive inhibition as concentration rises.

Germination response

Industrial effluent at 5–25 % dilution provides N, K, calcium and organic carbon for imbibition in early growth stages, enhances the activities of alpha amylase and protease required to mobilise nutrient reserves and allows for the normal emergence of the radicle. Research indicated that high germination percentages were obtained with low levels of paper mill effluent and lower germination percentages were obtained with undiluted effluent as compared to freshwater controls. Likewise, it has been reported that very low concentrations of distillery effluent (around 25 %) do not affect seed germination and higher concentrations can affect post-germination seedling growth and establishment, even if seed germination is successful. The results suggest that the adverse effects of industrial effluents on early development are concentration-dependent, as the less diluted effluents are more

harmful, compared with the more diluted ones (23). This separation between germination *sensu stricto* and the formation of viable seedlings is significant; radicle emergence may continue at toxic levels, but the formation of seedlings does not (15, 23).

In a comparative study on marigold (*Tagetes erecta* L.), a slight stimulation of germination was observed at very low brewery-distillery effluent concentrations, germination at 75 % produced non-viable seedlings and complete inhibition was recorded at 100 % concentration (29); analogous concentration-dependent suppression of germination and seedling viability has been documented for okra under distillery and paper mill effluent, confirming that the threshold response is not crop-specific but is governed by effluent toxicity load (15, 23, 30). Mixed industrial effluents decreased okra germination to about 66 % compared to the control and biomass and yield were seen to decrease gradually with an increase in pollutant level (31). These patterns suggest that the germination percentage is not a sensitive enough response parameter of an effluent's toxicity; the vigour of seedlings and the length of the radicle are more sensitive.

Early seedling growth

The growth of radicle elongation, plumule development, hypocotyl extension and seedling vigour index are similar in their biphasic pattern. These parameters are near or slightly above control at 10–25 % effluent, which reflects the nutritional value of the dilute effluent. All parameters decrease at 50 % or more and the radicle's growth rate is always lower than the plumule's for all effluent types, which is thought to be due to the direct contact of the plant root with the dissolved phytotoxicant present in the substrate (23, 31). Studies found a decrease in radicle length and fresh weight of seedlings and vigour index under high concentrations of distillery effluent, suggesting that both osmotic stress and metal ion interference with the extensibility of cell walls were responsible for this (29). The growth-promoting activity of diluted industrial effluents has been observed directly in okra: wastewater irrigation at appropriate concentrations increased growth parameters, photosynthetic characteristics, chlorophyll content, yield and nutrient homeostasis of okra var. Nidhi, while higher concentrations (> 50 %) resulted in chlorosis, growth inhibition and elevated phytotoxicity (15, 31). A comparable stimulatory-to-inhibitory pattern was reported in fenugreek (*Trigonella foenum-graecum* L.) irrigated with distillery effluent at similar dilutions (32), further demonstrating that the biphasic effluent response is consistent across different crop species under analogous conditions.

Mechanisms of phytotoxicity

Three possible mechanisms contribute to phytotoxic effects on okra germination and seedling growth. First, osmotic stress induced by elevated electrical conductivity (EC) and total dissolved solids (TDS) levels diminishes the water potential gradient between the seed and substrate, which will directly decrease imbibition and radicle emergence (13). Second, increased Na^+ , Cl^- , Cr^{6+} and Cd^{2+} concentrations disrupt ion homeostasis, inhibit important enzymes for germination like alpha-amylase and protease and generate reactive oxygen species (ROS), which damage embryonic cell membranes (15). Third, recalcitrant organics in distillery effluent, melanoidins in distillery effluent, azo dyes in textile effluent and chlorinated organics in paper mill effluent disrupt the hormonal signalling and the synthesis of photosynthetic pigments in the emerging seedling (13, 23). The effects of various industrial effluents on germination and early seedling growth of *A. esculentus* are summarised in Table 4 as a function of the concentration.

Table 4. Effects of industrial effluents on seed germination and early seedling growth of *Abelmoschus esculentus*

Effluent type	Stimulatory conc.	Inhibitory conc.	Germination effect	Seedling effect	References
Distillery	10–25 %	> 75 %	No inhibition at 25 %; seeds germinate at 100 % but do not survive	Increased radicle and plumule at 25 %; collapse at >75 %	(15, 23)
Textile/Dyeing (treated)	< 25 %	50 %	Germination reduced to 66.67 % at full mixed effluent vs 100 % in control	Progressive decrease in fresh/dry weight; increased phytotoxicity index	(31, 41)
Paper Mill	5–25 %	> 50 %	83–79 % germination at 100 % vs 97–94 % in control	Decreased vigour index; increased Cr, Cd in seedling tissues	(23, 56)
Distillery + Sugar Mill (combined)	<2 %	> 75 %	Complete inhibition at 100 %; seeds at 75 % fail to produce viable seedlings	Biomass increases only at very low dilutions	(31, 36)
Tannery	< 10 %	> 25 %	Severe inhibition; Cr ⁶⁺ directly inhibits germination enzymes	Root tip necrosis; chlorosis at low concentrations	(20, 56)

Impact on vegetative growth and crop development

The biphasic concentration-response established during germination continues through the vegetative phase of okra development, though the complexity of plant-effluent interactions grows as the plant matures. Shoot growth, root development, leaf expansion and reproductive output each respond to effluent in patterns shaped by the balance between nutrient inputs and toxic constituents at any given concentration.

Shoot and root growth

Shoot length, stem girth and root length, together with fresh and dry weights, respond positively to effluent at concentrations of 5–25 %. Studies have shown that 25 % distillery effluent produces the greatest improvement in agronomic parameters, including root length, shoot length, leaf number, fresh and dry weights and pod yield, during both kharif and zaid seasons, whereas these parameters decline progressively at higher effluent concentrations (50–100 %) (15, 23). A similar dose-dependent response has been reported for paper mill effluent, where 5–25 % concentrations enhanced growth and yield parameters compared with borewell water controls across both seasons, while concentrations of 50–100 % adversely affected plant performance. A similar stimulatory response to sugar mill effluent at 5–25 % has been documented in French bean (*Phaseolus vulgaris* L.), where agronomic performance improved at moderate dilutions but undiluted effluent elevated heavy metal concentrations and impaired root growth and water uptake (33); analogous concentration-dependent patterns are expected in okra cultivated under the same effluent type, given shared physiological sensitivities. At high effluent concentrations, Cd²⁺, Cr⁶⁺ and Pb²⁺ ions interfere with auxin-mediated elongation and disrupt meristematic function in root tips, producing chlorotic plants with shortened internodes (15, 31).

Leaf development and chlorophyll content

Leaf area index (LAI), leaf number per plant and total chlorophyll concentration are integrative measures of photosynthetic capacity. All three parameters peak at 25 % effluent, reflecting the stimulatory effects of supplemental N and micronutrients on chloroplast development and chlorophyll biosynthesis (15, 23). Above 50 %, total chlorophyll and LAI decline sharply. Cadmium displaces magnesium from the central position of the chlorophyll porphyrin ring, disrupting the tetracyclic structure and reducing the efficiency of both photosystem I and II (21, 34). Chromium impedes delta-aminolevulinic acid synthesis, a committed step in chlorophyll

biosynthesis, while high soil salinity exerts osmotic stress that suppresses CO₂ assimilation and net photosynthesis (21). In a study of textile dyeing effluent, progressive decreases in fresh weight, dry weight and plant vigour as effluent concentration increased, with the most concentrated treatment yielding only 24.64 g total pod yield per plant compared with 67.97 g in groundwater controls (31).

Pod formation and biochemical quality

Five reproductive parameters, flower initiation, pod set, pod length, pod number per plant and total yield, respond to the same concentration thresholds as vegetative parameters. At 25 % effluent, crude protein, crude fibre and total carbohydrates in pods reach peak values, attributable to adequate N and organic carbon from the effluent, enhancing both protein and carbohydrate synthesis (15, 23). Studies demonstrated that 25–40 % sugar mill effluent optimised agronomic and biochemical outcomes in French bean (*Phaseolus vulgaris* L.), with performance declining at higher concentrations; this concentration-dependent biochemical pattern in a related leguminous vegetable under sugar mill effluent serves as a useful comparative reference for interpreting okra responses under similar conditions (33). At high effluent concentrations, osmotic stress diverts metabolic resources from pod filling toward proline synthesis and antioxidant defence, reducing carbon supply to reproductive sinks and depressing pod set, length and weight (15, 35). The effects of industrial effluents on vegetative growth and yield parameters of *A. esculentus* across concentration ranges are summarised in Table 5.

Physiological and biochemical responses

The growth and yield changes described in the study are underpinned by physiological and biochemical alterations at the cellular and subcellular levels. Effluent irrigation modifies gas exchange, photosynthetic electron transport, enzyme kinetics, membrane integrity and secondary metabolite biosynthesis. Understanding these mechanisms clarifies where in the concentration-response curve a transition from beneficial stimulation to irreversible damage occurs.

Photosynthesis and gas exchange

At low effluent concentrations (10–25 %), net photosynthetic rates increase marginally or remain comparable to freshwater controls due to the input of supplemental N and K. When EC is greater than 50 % and when osmotic stress is equal to or greater than 50 %, the stomata will shut down, preventing CO₂ from entering and slowing carboxylation. At the same time, Cd and Cr cause non-stomatal

Table 5. Vegetative and yield parameters of *Abelmoschus esculentus* under industrial effluent irrigation

Physiological parameter	Low concentration (5–25 %)	High concentration (50–100 %)	Probable mechanism	Effluent types reported	References
Shoot length	Increased shoot elongation; maximum response generally at 25 %	Progressive reduction in shoot growth and shortened internodes	Nutrient supplementation at low concentration; heavy metal toxicity (Cd, Cr, Pb) interferes with auxin-mediated cell elongation and meristem activity at higher concentrations	Distillery and paper mill	(15, 23)
Root length	Improved root development and elongation	Reduced root length, impaired root tips and restricted water uptake	Direct exposure of roots to salts and heavy metals causes osmotic stress and inhibition of meristematic activity	Distillery and paper mill	(15, 23, 31)
Stem growth (stem girth/biomass)	Enhanced stem development and biomass accumulation	Reduced stem growth due to inhibition of cell division and expansion	Balanced nutrient availability promotes vegetative growth, whereas toxic ions suppress growth processes	Distillery and paper mill	(15, 23)
Number of leaves	Increased leaf production	Reduced leaf number accompanied by chlorosis and premature leaf senescence	Improved nutrient availability at low concentration; salinity and metal toxicity accelerate leaf damage	Distillery, paper mill and textile	(15, 23, 31, 41)
Leaf area index (LAI)	Increased LAI and canopy development	Sharp decline in LAI	Reduced photosynthetic surface caused by chlorosis, leaf injury and inhibited leaf expansion	Distillery and paper mill	(15, 23)
Total chlorophyll content	Increased chlorophyll synthesis and improved photosynthetic capacity	Significant reduction in chlorophyll concentration	Cd displaces Mg from chlorophyll molecule; Cr inhibits δ -aminolevulinic acid synthesis; salinity suppresses photosynthesis	Distillery and textile	(21, 34, 36)
Photosynthetic efficiency	Improved photosynthetic performance	Reduced CO ₂ assimilation and photosystem efficiency	Nutrient stimulation at low concentration; chlorophyll degradation and osmotic stress at high concentration	Distillery, paper mill and textile	(15, 21, 23, 34)
Fresh weight	Increased fresh biomass	Marked reduction in fresh biomass	Reduced water uptake, inhibited cell expansion and metabolic disturbances under high pollutant load	Textile and paper mill	(31, 41)
Dry weight	Increased dry matter accumulation	Progressive decline in dry biomass	Reduced carbon assimilation and diversion of assimilates towards stress responses	Distillery, textile and paper mill	(15, 23, 31, 41)
Flower initiation and pod set	Improved flowering and pod formation	Reduced flower retention and pod set	Osmotic stress and reproductive impairment under elevated contaminant concentrations	Distillery	(15, 35)
Pod number per plant	Maximum pod production around 25 % effluent	Progressive decline with increasing effluent concentration	Reduced assimilate partitioning and impaired reproductive development	Distillery	(15, 23)
Pod yield	Highest yield obtained at optimum dilution	Significant yield reduction under concentrated effluent	Lower photosynthesis, impaired nutrient balance and reduced sink strength	Distillery and textile	(15, 23, 31)
Crude protein	Increased protein accumulation	Decreased protein content	Adequate nitrogen supply enhances protein synthesis at low concentration; stress inhibits storage protein accumulation	Distillery	(15, 23)
Crude fibre	Improved fibre content	Declined at higher effluent concentrations	Reduced carbohydrate metabolism and altered cell wall synthesis	Distillery	(15, 23)
Total carbohydrates	Increased carbohydrate accumulation	Reduced carbohydrate content	Carbon diverted from growth to stress metabolism and antioxidant defence	Distillery	(15, 23, 35)

limitations by affecting the oxygen-evolving complex of PSII and QB protein, which results in decreased quantum yield and increased non-photochemical quenching (36). Irrigation of okra with wastewater was reported to reduce stomatal conductance, net photosynthetic rate and leaf water potential, reflecting disruption of plant water relations and carbon assimilation (31, 36). These physiological constraints can reduce photosynthetic carbon fixation without the development of obvious symptoms like chlorosis or growth stunting. A comparable pattern of wastewater-induced photosynthetic suppression and reduced stomatal conductance has been documented in wheat (*Triticum aestivum* L.) (37), reinforcing that impairment of gas exchange is a conserved stress response across crop species irrigated with industrial effluents. Biochemical and physiological changes, therefore, provide early signals of stress and can lead to changes in crop performance before visible symptoms appear.

Oxidative stress and antioxidant enzyme responses

High concentrations of production of ROS (superoxide [O₂⁻] and hydrogen peroxide [H₂O₂] and hydroxyl radicals [OH]) can be produced by industrial effluent with high content of heavy metals

and recalcitrant organic contaminants. The presence of polyunsaturated fatty acids (PUFA) in membrane lipids is well known to be oxidised, resulting in the accumulation of malondialdehyde (MDA). Similarly, proteins and nucleic acids can also be damaged and meristematic cells and photosynthetic cells are particularly susceptible to damage due to high metabolic activity (38). In turn, okra activates a multi-component antioxidant defence system under heavy metal and effluent-induced oxidative stress: catalase (CAT) and ascorbate peroxidase (APX) remove H₂O₂, superoxide dismutase (SOD) converts O₂⁻ to H₂O₂ and glutathione reductase (GR) maintains the ascorbate-glutathione cycle. Studies on okra exposed to cadmium stress have confirmed significant upregulation of SOD, CAT and APX activities alongside elevated MDA and proline accumulation, demonstrating that these enzyme systems are directly activated in *A. esculentus* in response to heavy metal loading (39). Glutathione peroxidase (GPX) also helps neutralise peroxides present in the vacuolar and apoplastic compartments (38). In roots, GPX stimulates peroxidase activity, promoting endodermal lignification and strengthening of the Casparian strip, thereby reducing the symplastic movement of

heavy metals. This structural defence will lead to simultaneous reduction in the radial water transport and nutrient transport of the plants, which further aggravates the negative effects of industrial effluent on the water relations of the plants (13). Similar antioxidant enzyme responses to distillery effluent irrigation have also been documented in wheat (*T. aestivum*) and mustard (*Brassica juncea* L.) as comparative evidence of the broader stress mechanism across species (40).

Osmoprotectant accumulation

Okra accumulates compatible solutes to maintain cell turgidity under effluent-induced water stress. In leaf and root tissues, proline accumulates under osmotic and ionic stress, which decreases the cellular water potential without disturbing normal metabolism. Its concentration increases with effluent concentration but acts as a stress severity marker rather than an effective adaptive response at high effluent levels (35). In addition, total soluble sugars (TSS) and glycine betaine accumulate, which help in cytoplasmic osmotic adjustment and stabilisation of protein quaternary structure during dehydration. The agronomic relevance is the high carbon and N cost of osmoprotectant synthesis, which diverts resources from pod filling and decreases crude protein and pod dry matter at high effluent concentrations (15, 23).

Secondary metabolites and phenolic compounds

Industrial effluent stress alters secondary metabolism in okra, especially the phenolic compounds, flavonoids and mucilage components. When the concentration of heavy metal is at a moderate level, total phenolic content is increased in response to induction of the phenylpropanoid pathway that can act as a ROS scavenger, as well as a lignin precursor for strengthening the cell wall against heavy metal stress (34). Vacuole-localised flavonoids chelate free metal ions, limiting their bioavailability for interactions with enzymes or membranes. This protective response is effective at low to moderate effluent concentrations but fails in high effluent concentrations because of the reduced ability to build up phenylol biosynthesis capacity. The mucilaginous polysaccharides in okra pods are also modified, such as pectin, hemicellulose and glycoproteins, which affect their galacturonic acid content and pectin esterification degree and change the texture and viscosity of the okra pods, thus reducing the organoleptic quality and nutritional value. The key physiological and biochemical responses of *A. esculentus* to industrial effluent irrigation at low and high concentrations are summarised.

Mechanism of response

Physiological and biochemical evidence presented in the study points to a unifying principle: the reaction of okra to the industrial effluent irrigation is threshold-driven and concentration-dependent and not linear. The nutrient contribution of effluent N, P and K is more important than the toxic load of salts and other trace metals at low to moderate levels of dilution (10–25 %). Gas exchange is facilitated or slightly increased, the antioxidant enzymes (SOD, CAT, APX, GR) are not induced in a sustained manner, while the biosynthesis of phenolics and flavonoids is increased just enough to chelate the free metal ions and strengthen the cell walls without consuming a large share of carbon for reproductive growth (34). At this stage, proline and other osmoprotectants build up as an authentic adaptive buffer without measurable metabolic cost (35).

Once the effluent concentration and the resulting electrical conductivity/osmotic stress are greater than about 50 %, this

equilibrium is lost. Photosynthetically induced stomatal closure (when carbon assimilation decreases in response to osmotic stress) is combined with stomatal closure due to non-stomatal, metal-mediated, damage to PSII oxygen-evolving complex, which becomes apparent physiologically prior to its appearance morphologically (36, 37). At the same time, ROS production increases at a higher rate than the buffering capacity of the antioxidant system and therefore CAT, APX, SOD and GR levels also increase, as a sign of the degree of stress, but not as a controlled defence against it, along with increased MDA, which reflects actual damage to the membranes (38, 39). The same trend is observed for the secondary metabolite pool, where phenolic and flavonoid induction becomes protective at moderate concentrations, stabilises and then becomes ineffective when the biosynthetic capacity is surpassed, allowing metal ions to interact with membranes and enzymes (34). The carbon and N use of supporting such defences is also increasingly diverted away from production of the pods and is also a cause of yield depression (15, 23).

The biphasic response obtained from wheat, mustard and fenugreek exposed to similar types of effluent suggests that this threshold response is not okra-specific but can be generalised as a property of plant tolerance to industrial effluent stress. In practice, this model suggests that the safe range of dilution for irrigation lies on one side between nutrient limitation and on the other side a narrow physiological limit around 50 % effluent strength beyond which damage increases in a non-linear fashion (13, 31, 36).

Influence on yield and yield attributes

The important composite parameters of the above vegetative and reproductive processes directly involve growers and are pod number per plant, individual pod weight, pod length, pod girth and marketable yield. The results of the available data show a consistent concentration-response relationship, in which yields are increased at lower effluent concentrations and decreased at higher concentrations, with the magnitude of the increase or decrease dependent upon the type of effluent and season.

Pod number per plant is the best correlated of these parameters with pollutant load because it reflects both the success of pollination and the ability of the plant to support the development of fruits to harvest maturity. In one investigation, the maximum pods/plant were found in the kharif season with 25 % distillery effluent (DE), followed by appreciable reduction in the higher concentrations and at 100 % DE, it was lowest in pods/plant in the kharif season. A similar trend was observed with other effluents, okra var. The IHR-31 treated with paper mill effluent had the maximum number of pods at 25 % efficiency level, while 100 % efficiency decreased the number of pods by 30–45 % when compared to borewell water control (15). Individual pod weight also followed the same trend; pods from plants grown at lower concentrations were heavier and more turgid, whereas those from plants grown at the higher concentrations were not as heavy or turgid, because assimilates could not be efficiently loaded in the phloem.

This reduction in pod number and weight translates into reduced pod size and marketable grade as okra is sold mostly by pod size in regional markets. Effluent concentration can have two interrelated effects on pod length and girth: a direct effect through inhibition of growth of the developing pericarp and an indirect effect via reduction in the photosynthates available at high concentrations, which is a result of leaf area and chlorophyll loss. This reduction can be significant; for example, with the most intensive textile dyeing

effluent treatment, the pod yield decreased by approximately 64 % (41 g) compared to the groundwater controls (67.97 g) (31). Similar concentration dependence was seen in the case of paper mill effluent; germination and seedling growth were satisfactory at low irrigation rates and they decreased significantly with increasing concentration (23). The addition of mixed industrial wastewater (MIW) added another layer of complexity, with overall yields being good, but pod length being inconsistent and pod skin integrity being affected at high metal loading, resulting in some of the harvest that was discoloured and not suitable for market.

A change in resource allocation is behind these yield and quality losses. High effluent concentrations lead to a decrease in harvest index because carbon and N are shuttled to stress-response pathways like proline synthesis, antioxidant enzyme upregulation and ion exclusion. The nutritional composition has the same inflexion point, with pod tissue being highest in crude protein, crude fibre and total carbohydrate content around 25 % effluent, with sufficient N and organic C, but decreasing at higher levels due to interference with protein biosynthesis and starch metabolism by the accumulation of metals (15, 23). Importantly, these biochemical modifications are not apparent to the consumer, nor can they be detected by a conventional market inspection and indicate the need to be analytically monitored throughout the production and distribution of produce that is irrigated with industrial effluent.

Impact on soil health

Industrial effluent irrigation alters soil health through three interconnected pathways: changes to physicochemical properties, degradation of biological activity and shifts in nutrient cycling capacity. These changes accumulate with each irrigation cycle and can be difficult to reverse once critical thresholds are crossed,

making soil deterioration a longer-lasting consequence of effluent irrigation than any single season's yield outcome. The concentration-dependent progression of soil health impacts is illustrated in Fig. 2, which depicts the transition from beneficial nutrient inputs at low dilutions (5–25 %) to degraded soil conditions under long-term continuous use. Soil physicochemical, biological and nutrient responses to industrial effluent irrigation vary markedly with effluent type and concentration (Table 6).

Physicochemical properties

The direction and magnitude of physicochemical change depend strongly on effluent type and dose. Distillery effluent applied at 5–25 % dilution increases soil organic carbon and available N, P and K, with only moderate change in electrical conductivity (EC) in a beneficial range under controlled irrigation. Beyond 50–100 % strength, however, distillery effluent drives EC and sodium adsorption ratio (SAR) sharply upward, promoting sodicity and progressive deterioration of soil structure (15, 28). Paper mill effluent shows a comparable pattern: at 5–25 % dilution it improves soil organic matter and nutrient status, but at > 50–100 % concentration it increases alkalinity and salt accumulation, degrading soil physical properties over time (23, 28, 41). Textile dyeing effluent produces only a slight, short-term improvement in soil nutrient status at 10–25 % dilution, while concentrations above 50–100 % cause salt accumulation and heavy metal build-up in the soil profile (31). Tannery effluent, whether applied at high concentration or over prolonged irrigation, drives chromium accumulation and soil acidification, producing the most severe deterioration in soil quality among the effluent types considered here (20, 21, 43).

Beyond these type-specific effects, continuous effluent use in general raises EC and SAR, favouring sodicity; the subsequent

Table 6. Effect of industrial effluent type and concentration on soil physicochemical, biological and nutrient properties

Type of effluent	Concentration/dose	Physicochemical changes	Soil biological response	Nutrient dynamics	Overall impact	References
Distillery effluent	5–25 % dilution	Increased soil organic carbon and available N, P and K with moderate changes in EC	Increased microbial biomass and enzyme activity	Improved nutrient availability and mineralisation	Beneficial under controlled application	(15, 28)
Distillery effluent	> 50–100 %	Increased EC, SAR and salinity; deterioration of soil structure	Reduced microbial biomass and enzyme activities due to heavy metal accumulation	Reduced nutrient mineralisation and nutrient-use efficiency	Adverse under prolonged irrigation	(15, 28, 42, 43)
Paper mill effluent	5–25 % dilution	Improved soil organic matter and nutrient status	Moderate stimulation of microbial activity	Increased nutrient availability	Beneficial under appropriate dilution	(23)
Paper mill effluent	> 50–100 %	Increased alkalinity, salt accumulation and deterioration of soil physical properties	Decline in microbial activity following prolonged irrigation	Phosphorus fixation and reduced nutrient availability	Adverse	(23, 28, 41)
Textile effluent	10–25 % dilution	Slight improvement in soil nutrient status after dilution	Minor stimulation of microbial activity	Limited improvement in nutrient availability	Limited short-term benefit	(31)
Textile effluent	> 50–100 %	Salt accumulation and heavy metal build-up	Inhibition of microbial biomass and soil enzyme activities	Reduced nutrient cycling efficiency	Adverse	(31, 42, 43)
Tannery effluent	High concentration or prolonged irrigation	Chromium accumulation, soil acidification and deterioration of soil quality	Strong inhibition of dehydrogenase, urease and alkaline phosphatase activities	Reduced nutrient mineralisation and functional fertility	Highly adverse	(20, 21, 43)
Industrial/municipal wastewater (long-term use)	Continuous irrigation (> 10 years)	Increased EC, SAR, organic matter and salt accumulation with deterioration of soil physical structure	Altered microbial community composition, reduced microbial activity and enrichment of antibiotic resistance genes	Declining nutrient-use efficiency despite higher total nutrient content	Progressive soil degradation	(28, 41, 44, 47)

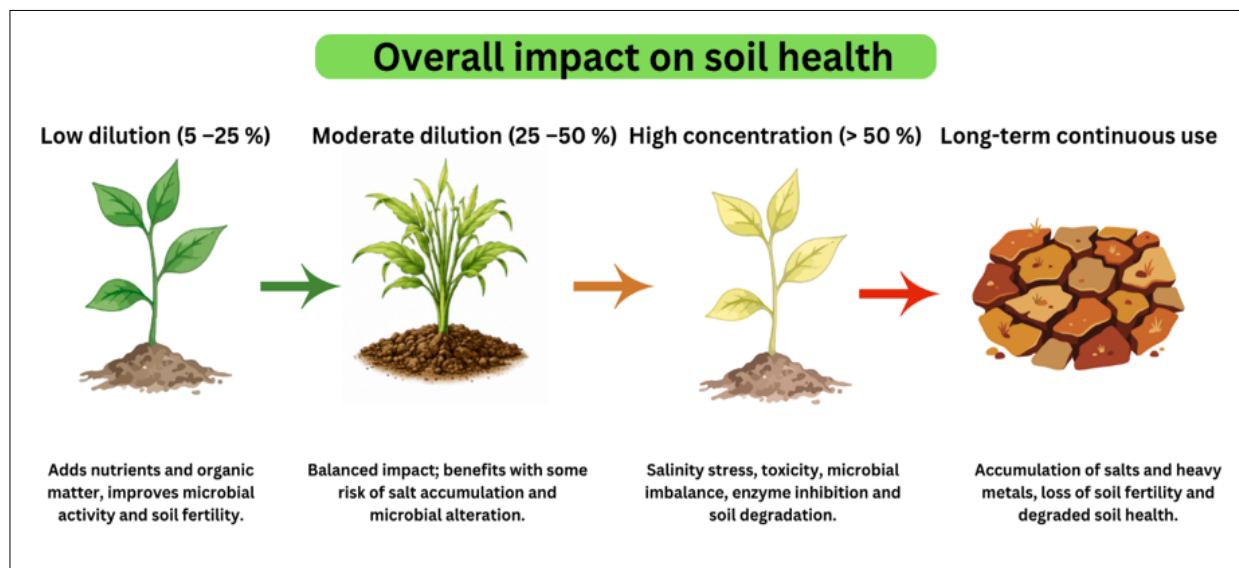


Fig. 2. Overall impact of industrial effluent irrigation within the varying intensity and duration of use. Low dilution (5–25 %) releases nutrients and enhances microbial activity, moderate dilution (25–50 %) has a balanced effect and has some risk of salinity, while high concentration (> 50 %) creates salinity stress, toxicity and soil degradation; and long-term continuous use causes salt and heavy metal accumulation and irreversible loss of soil fertility.

stage is dispersion of clay aggregates, leading to loss of macropore structure and reduced saturated hydraulic conductivity. Sewage effluent irrigation specifically has been shown to raise EC, organic carbon and the availability of N, P and K, with short-term agronomic benefits that are progressively offset by salt accumulation and degradation of soil structure, porosity and aeration under prolonged irrigation (28). Extended use of wastewater for irrigation has been shown to degrade soil structural integrity and crop quality (41). Soil pH direction depends on effluent source: distillery and tannery effluents are acidic and lower soil pH and exchangeable acidity, while paper and sugar mill effluents are alkaline. This pH shift alters nutrient form and availability. Acidification raises manganese and aluminium to phytotoxic levels and increases precipitated aluminium, while alkalisation precipitates P as calcium phosphates, reducing plant-available P even though total soil P remains high (14). Organic loading over time also raises organic matter content and temporarily increases water-holding capacity and bulk density, though compaction during intensive irrigation and aggregate destabilisation under sodic conditions gradually offset this gain.

Soil biological activity and microbial communities

Soil biological response to effluent irrigation is similarly dose- and type-dependent. At the low-dose end (5–25 % for distillery and paper mill effluent, 10–25 % for textile effluent), microbial biomass carbon (MBC), microbial biomass nitrogen (MBN) and enzyme activity are moderately stimulated, reflecting a short-term fertility benefit (15, 23, 31, 28). At high concentrations (> 50–100 %) or under chronic application, this benefit reverses across all effluent types: heavy metal accumulation shifts microbial community composition toward metal-tolerant species and inhibits microbial enzymatic activity, reducing overall microbial activity (42). Tannery effluent produces the most pronounced biological disruption, with strong inhibition of dehydrogenase, urease and alkaline phosphatase activity driven by chromium accumulation (20, 21, 43). More broadly, cadmium and chromium inhibit the electron transport chain (NAD^+/NADH) and significantly suppress dehydrogenase activity, an indicator of overall oxidative metabolism in soil microorganisms. Heavy metals also disrupt urease and alkaline phosphatase activity required for N and P mineralisation, respectively, through

competitive displacement of their cofactors, zinc and nickel (43). This decoupling of total nutrient pools from functional fertility has been quantified in chromium-contaminated Vertisols: As heavy metal loading increases with continued effluent input, total nutrient levels rise, but the capacity to mineralise those nutrients into plant-available forms declines (43). Long-term industrial and municipal wastewater irrigation compounds this effect, introducing antibiotic resistance genes and carbon-sequestration genes into the soil, indicative of simultaneous selection pressure on both (44). Across effluent types, an initial rise in salts, organic matter and nutrients gives way, after roughly 10 years of continuous irrigation, to declining biomass productivity despite elevated soil nutrient content, clear evidence of progressive soil degradation (28, 41). On this basis, soil biological monitoring is recommended alongside routine soil chemical testing.

Nutrient dynamics and long-term fertility trajectory

In the short to medium term, effluent irrigation increases soil available N, P, K, sulphur, calcium and magnesium at appropriate dilutions. In the longer term, however, nutrient use efficiencies decrease due to reduced enzyme activity and hence slower organic N mineralisation, pH changes and metal speciation changes that result in nutrient fixation and sodium displacing K from exchange sites that reduce the plant-available nutrient pools (14, 27, 45–48). The CO_2 evolution from chromium-contaminated soils indicates reduced carbon mineralisation compared to uncontaminated soils, suggesting a structural deficiency in the ability to mineralise nutrients from organic matter (43). This functional loss of fertility is limiting for okra, which needs nutrients in the rooting zone to be available as soon as possible.

Heavy metal dynamics in the soil-plant system

Before tracing how metals move through the soil-plant system, it is necessary to establish that the effluents themselves are a direct source of heavy metal loading, independent of any subsequent soil transformation. Of the five effluent types characterised in Table 7, tannery effluent carries the highest chromium burden, a consequence of the chrome-tanning process, along with measurable cadmium, lead and nickel (20, 21) textile dyeing effluent contributes chromium, copper and zinc from dye mordants and

Table 7. Key physiological and biochemical responses of *Abelmoschus esculentus* to industrial effluent irrigation

Parameter	Response at 10–25 % effluent	Response at >50 % effluent	Primary mechanism	References
Net photosynthetic rate	Increased or equivalent to control	Decreased stomatal and PSII inhibition	Non-stomatal limitation under osmotic stress	(31, 36)
Stomatal conductance	Maintained	Decreased; ABA-mediated closure	Elevated root-zone EC; reduced leaf water potential	(31, 36)
SOD, CAT, APX activity	Increased adaptive upregulation	Decreased enzyme denaturation at high metal load	ROS-induced gene expression, then metal-mediated inhibition	(38, 39)
MDA (lipid peroxidation)	Low / near-control	Increased, proportional to metal concentration	Membrane fatty acid oxidation by OH and O ₂	(38, 39)
Proline content	Moderate increase	High accumulation; indicator of stress severity	Osmotic adjustment; cytoplasmic protection	(35, 39)
Total soluble protein	Increased nitrogen-stimulated synthesis	Decreased; metal denaturation; ROS oxidation	Cd inhibits NR; ribosomal function is suppressed	(23, 39)
Total phenolics/flavonoids	Increased metal-chelation response	Declines at extreme concentrations	Phenylpropanoid pathway activation	(34)

ABA: abscisic acid; APX: ascorbate peroxidase; CAT: catalase; Cd: cadmium; EC: electrical conductivity; MDA: malondialdehyde; NR: nitrate reductase; O₂: molecular oxygen; OH: hydroxyl radical; PSII: photosystem II; ROS: reactive oxygen species; SOD: superoxide dismutase.

finishing auxiliaries (13, 18, 19) paper and pulp mill effluent adds zinc, copper, lead and chromium from pulping and bleaching chemicals (22–24) distillery effluent carries comparatively lower but non-negligible cadmium, chromium and lead (15–17) and sugar mill effluent is the least metal-loaded of the group (25, 26). This effluent-level characterisation is the baseline against which subsequent soil accumulation and plant uptake, discussed below, must be interpreted.

Detection and quantification of these metals across the reviewed literature is performed principally by atomic absorption spectrophotometry (AAS) and inductively coupled plasma optical emission or mass spectrometry (ICP-OES/ICP-MS), following acid digestion of the effluent, soil or plant tissue matrix. A sample is classified as exceeding safe limits when its metal concentration surpasses the applicable regulatory threshold national effluent discharge and irrigation-water standards for cadmium, lead and total chromium and FAO/WHO soil and food-safety guideline values for the same elements. It is this threshold-based detection criterion, rather than the raw concentration alone, that determines whether an effluent requires treatment before it can be safely used for

irrigation.

The pathway from industrial effluent through the soil system to root uptake and upward translocation to harvestable pods is depicted in Fig. 3.

Metal bioavailability and soil speciation

The total concentration of heavy metals in soil is a poor indicator of plant uptake, because only the bioavailable fraction (that in soil solution or loosely bound to exchange sites and thus available to the root surfaces) is available for uptake. The pH, organic matter content, redox potential and competing ion concentrations of the soil determine the metal speciation. In acidic soils (as are distillery and tannery effluent-irrigated soils), cadmium and zinc are mostly present as free ionic species (Cd²⁺ and Zn²⁺), which are most readily absorbed. Chromium behaviour is more complicated; Cr³⁺ is tightly bound to soil organic matter and Fe oxides and is not mobile, while Cr⁶⁺ exists as chromate (CrO₄²⁻) or dichromate and is very bioavailable (21). A temporary complexation of metals with elevated organic carbon in effluent loading may result in a temporary decrease in bioavailability, but subsequent release of metals from

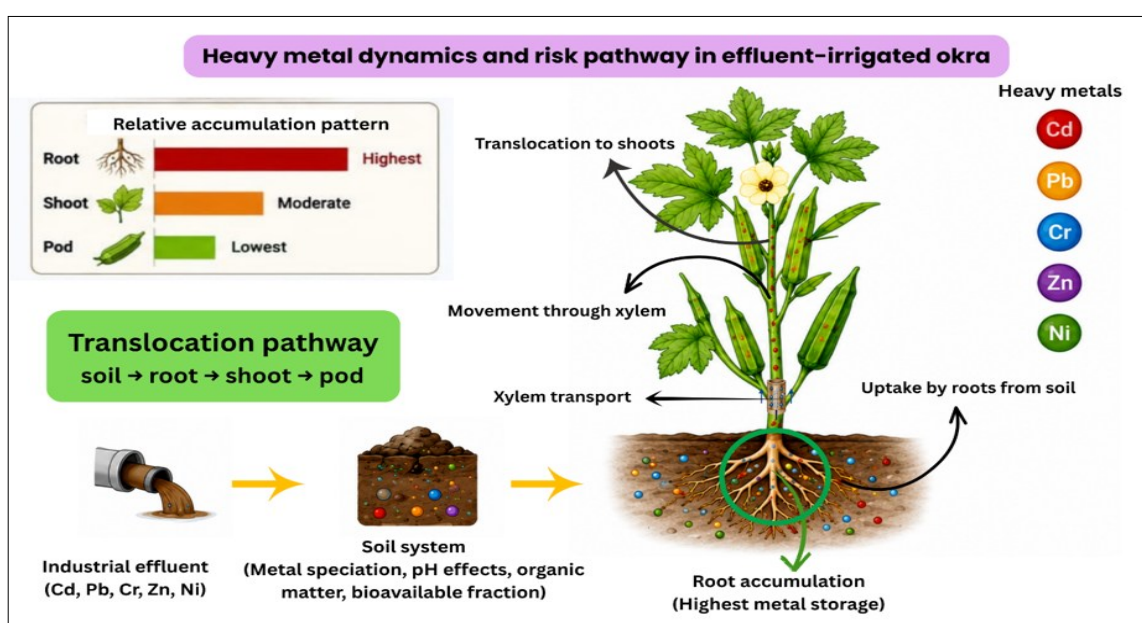


Fig. 3. Heavy metal dynamics and risk pathway in effluent-irrigated okra (*Abelmoschus esculentus*). Industrial effluent (Cd, Pb, Cr, Zn, Ni) enters the soil system, root uptake depends on the metal species, pH, organic matter and bioavailable fraction. The translocation pathway consists of the movement of metals from the soil, through the root, to the shoot and finally to the pod. In each case, the highest levels are recorded in the roots, moderate levels in the shoots and the lowest, although measurable, in the pods.

the complexation as organic carbon decomposes will create a delayed pulse of metals in the soil solution that will last for several seasons after the active effluent application. Effluent chemistry has been demonstrated to have a significant impact on soil fertility trajectories and heavy metal bioavailability across irrigated crops; for example, such dynamics have been quantified in rice (*Oryza sativa* L.) irrigated with mixed wastewater sources (26) and equivalent soil-plant metal transfer pathways are consistently reported in effluent-irrigated okra and other vegetable systems (49, 50).

Root uptake and internal translocation

There are two routes for the entry of metals into the roots of okra. Metals are passively transported along the apoplastic pathway to the endodermis, where the casparian strip prevents further movement. This barrier must be overcome by the metals, which will then have to pass into the symplast through membrane-bound transporters, which are frequently poorly selective, such as the zinc-regulated transporter, iron-regulated transporter-like protein (ZIP)-family transporters shared with zinc, or the calcium channels shared with lead because of the similarity in ionic radius (36, 51). In the symplast, metals are transported through plasmodesmata and into the xylem for long-distance transport to aerial organs. In previous studies, the distribution of metals in the tissues of okra grown with mixed industrial wastewater was reported and it was observed that the root is the main tissue for the accumulation of most of the metals, whereas the pods accumulate the lowest concentrations, indicating that roots serve as a partial barrier to upward metallic translocation. Despite this, measurable amounts of cadmium, lead, chromium, copper, zinc, nickel, iron and manganese were found in the harvested pods, increasing with the amount of metals in the soil. The same accumulation pattern has been reported with okra crops cultivated along a polluted river in Nigeria, which indicates that the transfer of metals to edible tissues is consistent irrespective of geographical and effluent conditions (52).

Bioconcentration and translocation factors

There are two dimensionless indices to measure the movement of metals in the soil-plant system. The bioconcentration factor (BCF = plant tissue concentration/soil concentration) reflects the efficiency of root uptake and values greater than 1.0 represent active uptake. The translocation factor (TF) is the ratio of the concentration of the metal in the shoots to the concentration of the metal in the roots. Cadmium and zinc BCF values are often greater than 1.0 in okra, indicating that the crop is susceptible to these elements, whereas the BCF values for chromium and lead are usually less than 1.0,

because they have a higher soil binding capacity and lower membrane permeability (36, 49). The accumulation patterns of heavy metals in the different vegetable species irrigated with wastewater are indicative of the fact that okra is not an isolated problem of food safety in wastewater-irrigated agriculture systems but is part of a larger problem (53–55). The TF values of most metals are below 1.0 (56) and pod concentrations in most cases do not exceed the maximum permissible limits set by FAO/WHO, even with sub-unity TF values for cadmium and lead, in the case of high soil metal loading. Elevated concentrations of chromium, cadmium, lead and nickel were detected in okra pods cultivated under effluent irrigation, exceeding permissible limits, with the highest accumulation observed in tannery-effluent-irrigated plots in Uttar Pradesh, India (50). These findings highlight the dietary importance and the fact that chronic dietary exposure to heavy metals via the consumption of effluent-irrigated vegetables is a measurable public health risk, especially for populations who consume local produce as a major dietary component (57–59). The bioconcentration factors, translocation factors and food safety risk levels for key heavy metals in *A. esculentus* under effluent irrigation are presented in Table 8.

Implications for effluent treatment

The above pod-tissue concentrations further support the idea that dilution alone, as discussed in earlier in the present study, is not a good means of ensuring that heavy metal loading does not exceed the detection limits reported above, especially for tannery effluent containing chromium and for textile effluent containing lead and/or cadmium, when irrigation is repeated over several seasons. The effluents that are not within these values must then be treated before use in fields instead of being treated as dilutions. Constructed wetland pre-treatment can lower concentrations of heavy metals in industrial effluent by 30–60 % through physical filtration, microbial transformation and phytoextraction (60–69); biochar amendment can provide an additional route for heavy metal immobilisation, after application to soil, via sorption, ion exchange and precipitation, which can also be adjusted to plant growth stage (60–62); and precision dilution protocols that involve real-time monitoring of conductivity, pH and metal concentration can ensure the dilution ratio is adjusted according to the plant growth stage instead of being applied at a fixed rate (70, 71). A detailed consideration of these options are given in this study.

Mitigation strategies and future directions

The weight of evidence reviewed here supports a precautionary approach to industrial effluent irrigation of okra. Several mitigation

Table 8. Heavy metal accumulation and transfer in *Abelmoschus esculentus* under effluent irrigation

Metal	Bioavailable form	Primary uptake pathway	BCF in okra	TF in okra	Pod risk level	Key reference
Cd	Cd ²⁺ (acidic soils)	ZIP transporters	> 1.0	< 1.0	High (HRI >1.0)	(36, 49)
Zn	Zn ²⁺ (acidic soils)	ZIP transporters	> 1.0	< 1.0	Moderate	(36, 49)
Cr	Cr ⁶⁺ as CrO ₄ ²⁻	Passive diffusion + active uptake	< 1.0	< 1.0	High (Cr ⁶⁺ carcinogenic)	(36, 56)
Pb	Pb ²⁺	Ca ²⁺ channels	< 1.0	< 1.0	High (HRI >1.0)	(36, 49)
Ni	Ni ²⁺	Non-specific cation channels	< 1.0	< 1.0	Moderate	(50, 56)
Fe	Fe ²⁺ /Fe ³⁺	IRT transporters	Variable	< 1.0	Low	(56)
Mn	Mn ²⁺	NRAMP transporters	Variable	< 1.0	Low	(56)

BCF: bioconcentration factor; Ca²⁺: calcium ion; Cd²⁺: cadmium ion; Cr⁶⁺: hexavalent chromium; CrO₄²⁻: chromate ion; Fe²⁺: ferrous ion; Fe³⁺: ferric ion; HRI: health risk index; IRT: iron-regulated transporter; Mn²⁺: manganese ion; NRAMP: natural resistance-associated macrophage protein; Ni²⁺: nickel ion; Pb²⁺: lead ion; TF: translocation factor; ZIP: zinc-regulated transporter, iron-regulated transporter-like protein; Zn²⁺: zinc ion.

strategies have sufficient preliminary support to warrant further investigation and field validation under tropical smallholder conditions.

Biochar amendment

The use of biochar is highly beneficial in the immobilisation of heavy metals and reduction in the translocation to plant tissues in contaminated soils. This is attributed to the presence of a large specific surface area, porous nature, abundance of oxygen-containing functional groups (carboxyl, phenol, lactone) and cation-exchange sites that contribute to biochar being an ideal soil conditioner and heavy metal immobiliser (60). Studies have demonstrated that biochar phosphate can decrease the mobility and translocation of cadmium to tomato fruits in a contaminated soil and similar results can be projected for okra plants (60). Metal retention takes place due to sorption, ion exchange and precipitation reactions, alongside positive changes brought about by improvement in soil structure, moisture retention capability and microbial activity (61, 62). When biochar is combined with the use of phytoremediating species, the efficiency of the remediation process is improved through soil improvement, growth promotion and increased metal accumulation in hyperaccumulating plants (63, 64). However, it is not yet determined whether the optimal feedstock, rates and efficacy under tropical field conditions with respect to the okra species. Furthermore, the long-term stability of metal-biochar complexes under alternating wetting-drying cycles, particularly in soils subject to effluent-induced acidification, requires comprehensive investigation.

Phytoremediation rotation

An alternative practical strategy for progressive cleaning of contaminated soils may be through phytoremediation rotation programs that incorporate cycles of metal-accumulating plants between okra production cycles. Plants reported to accumulate contaminants from contaminated effluents such as sunflower (*Helianthus annuus* L.), Indian mustard (*B. juncea*) and vetiver (*Vetiveria zizanioides* (L.) Nash) for the recovery of cadmium, lead and chromium from contaminated soils (65). Inoculation with plant growth-promoting rhizobacteria (PGPR) could improve the efficiency of phytoremediation by improving metal solubilisation in the rhizosphere and improving plant growth, thus increasing the amount of metal removed per cycle (66). Removal of productive land from vegetable production needs to be approached with care, as this could impact smallholder farmers whose livelihoods are dependent on such land for day-to-day income generation. The use of chelating agents like EDDS and citric acid during chelation-phytoextraction would be very helpful in metal removal from the rhizosphere (67).

Constructed wetland pre-treatment

The use of constructed wetlands represents an inexpensive and environmentally friendly method for reducing metal loadings before irrigation. In such systems, surface-flow and subsurface-flow wetlands containing species such as Typha, Phragmites or Eichhornia plants can reduce the presence of suspended solids in industrial effluents by 60–90 %, as well as BOD by 40–70 % and heavy metals by 30–60 %. This would entail removal of impurities by means of physical filtration, microbe-induced transformations, as well as phytoextraction (68). Such wetlands could ensure that metal loadings in industrial effluents fall within the 5–25 % range, wherein agricultural advantages exceed any toxicity issues, while at the same time providing a biomass that could serve as biochar or composting material. The limitations with wetlands include land area needs,

variations in performance depending on seasons and the necessity for harvesting metal-contaminated wetland sediments periodically. The performance characteristics of constructed wetlands depend on the hydraulic loading rates, along with plant selections (69).

Precision dilution protocols

The application of real-time measurement of the electrical conductivity, pH values and metal concentration, as well as automated mixing valves for drip irrigation, may enable the timely adjustment of the dilution ratio according to the phases of plant growth and environmental conditions. Dilution ratios would depend on the stage of plant growth, with higher dilutions being used during germination and early seedling development due to their high sensitivity and moderate concentrations at the phase of maximum vegetation due to nutrient demand. A combination of soil moisture sensors and weather forecasts may help achieve higher efficiency in water use while minimising metal accumulation. Technologically, the approach is proven for precision agriculture; however, applying the idea to smallholders' effluent irrigation systems requires cheaper technologies, readily available sensors and appropriate tech infrastructure (70). Use of cheap electrochemical sensors for real-time analysis of conductivity and pH is an encouraging option for technology adaptation (71).

Drawbacks and limitations of mitigation strategies

Each of the above strategies is promising in the early stages, but all four have limitations that limit their field-readiness. The optimal feedstock and application rate for tropical field conditions are not yet determined for biochar amendment in okra and the durability of metal-biochar bonds in the presence of repeated wetting-drying cycles and soil acidification by effluent use is uncertain (60–62). The rotation for phytoremediation involves the exclusion of productive land from vegetable production for one or more rotations, benefiting only the larger farmers with access to surplus land and adversely affecting the smallholder farmers who rely on the land for their livelihood (65–67). The land area required for constructed wetland pre-treatment is not always available in smallholder systems and may change seasonally in the ability of the system to remove metals; and the sediment produced by the constructed wetland contains metals in solution, which must be harvested and safely disposed of periodically (68, 69). Although such precision dilution protocols have been shown to work in commercial precision agriculture, they are not extensively tested in smallholder effluent-irrigated systems and are expensive to implement in real-time (70, 71). All projections have not yet been field validated under tropical smallholder conditions for okra; none of the four strategies has been tested. The major drawbacks of currently available mitigation strategies for industrial effluent irrigation are summarised in Fig. 4.

Conclusion

Industrial effluent irrigation provides measurable agronomic benefits in okra, such as improved establishment rate, vegetative growth and yield at sustainable irrigation rates (5 to 25 %), but beyond this level, the benefits are significantly reduced and replaced by osmotic stress, oxidative stress and yield loss. Of greater concern, the progressive accumulation of heavy metals (Cadmium, chromim, lead and nickel) in soil followed by their translocation to edible pods and reported concentrations in several studies that exceeded permissible food safety limits, has resulted in an increased human health risk index. Sustainability

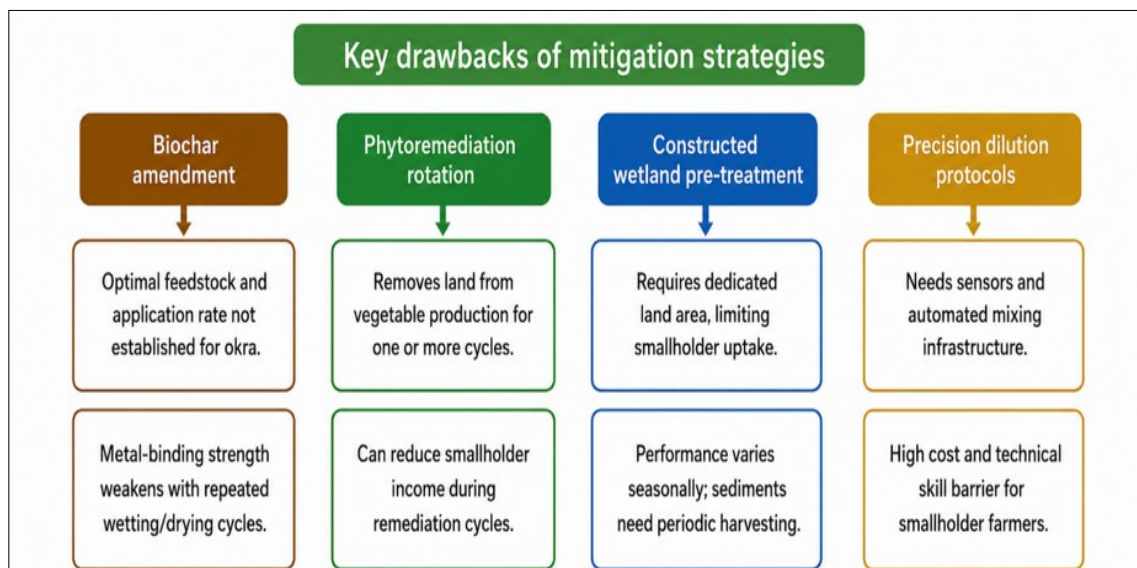


Fig. 4. Key drawbacks of biochar amendment, phytoremediation rotation, constructed wetland pre-treatment and precision dilution protocols as mitigation strategies for industrial effluent irrigation, highlighting their technical, economic and operational limitations that may restrict large-scale adoption in agricultural systems.

assessment can thus not be based on short-term yield data only but must take into account soil quality, ecosystem function and endpoints related to food safety, supported by multi-season field trials over the long term, as well as by integrated mitigation measures (such as biochar amendment, phytoremediation, constructed wetlands, precision dilution) validated under different agroecological conditions. The use of industrial effluent for agricultural irrigation should therefore be seen not as an alternative to fresh water but rather as a "technical resource" that needs to be monitored closely and the science base needs to be developed to create a reuse plan.

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Authors' contributions

GJ conceptualised the study, developed the methodology, conducted the investigation, curated the data, performed the formal analysis and drafted the original manuscript. VM, the corresponding author, conceptualised the study, supervised the research, administered the project, validated the results, provided resources and critically reviewed and edited the manuscript. MS contributed to methodology development, formal analysis, visualisation and manuscript review and editing. BM participated in the investigation, provided resources and assisted with data curation. RP performed the formal analysis, contributed to validation and assisted with manuscript review and editing. RS contributed to manuscript review and editing. All authors read and approved the final manuscript.

Compliance with ethical standards

Conflict of interest: Authors do not have any conflict of interest to declare.

Ethical issues: None

References

1. FAO. 2025 AQUASTAT Water Data Snapshot. Rome: Food and Agriculture Organization of the United Nations; 2025.
2. Biswas A, Sarkar S, Das S, Dutta S, Choudhury MR, Giri A, et al. Water scarcity: a global hindrance to sustainable development and agricultural production-a critical review. *Camb Prisms Water*. 2024. <https://doi.org/10.1017/wat.2024.16>
3. Dotaniya ML, Meena VD, Saha JK, Dotaniya CK, Mahmoud AE, Meena BL, et al. Reuse of poor-quality water for sustainable crop production in the changing scenario of climate. *Environ Dev Sustain*. 2023;25:7345–76. <https://doi.org/10.1007/s10668-022-02365-9>
4. Drechsel P, Scott CA, Raschid-Sally L, Redwood M, Bahri A, editors. Wastewater irrigation and health: assessing and mitigating risks in low-income countries. London: Earthscan/IDRC/IWMI; 2010.
5. Agrawal M, Singh B, Rajput M, Marshall F, Bell JNB. Effect of air pollution on peri-urban agriculture: a case study. *Environ Pollut*. 2003;126:323–9. [https://doi.org/10.1016/S0269-7491\(03\)00245-8](https://doi.org/10.1016/S0269-7491(03)00245-8)
6. Ungureanu N, Vlăduț V, Voicu G. Water scarcity and wastewater reuse in crop irrigation. *Sustainability*. 2020;12:9055. <https://doi.org/10.3390/su12219055>
7. Hussain I, Raschid L, Hanjra MA, Marikar F, van der Hoek W. Wastewater use in agriculture: review of impacts and methodological issues in valuing impacts. Working Paper 37. Colombo: International Water Management Institute; 2002.
8. Nriagu JO, Pacyna JM. Quantitative assessment of worldwide contamination of air, water and soils by trace metals. *Nature*. 1988;333:134–9. <https://doi.org/10.1038/333134a0>
9. FAOSTAT. Crops and livestock products: okra production statistics. Rome: Food and Agriculture Organization of the United Nations; 2024.
10. Benchasri S. Okra (*Abelmoschus esculentus* (L.) Moench) as a valuable vegetable of the world. *Ratar Povrt*. 2012;49:105–12. <https://doi.org/10.5937/ratpov49-1172>
11. Bharagava RN, Chandra R, Rai V. Phytoextraction of trace elements and physiological changes in Indian mustard plants (*Brassica nigra* L.) grown in post-methanated distillery effluent irrigated soil. *Bioresour Technol*. 2008;99:8316–24. <https://doi.org/10.1016/j.biortech.2008.03.002>
12. Fito J, Tefera N, Kloos H, Van Hulle SW. Physicochemical properties of the sugar industry and ethanol distillery wastewater and their impact on the environment. *Sugar Tech*. 2019;21:265–77. <https://doi.org/10.1007/s12355-018-0633-z>
13. Scott CA, Faruqi NI, Raschid-Sally L. Wastewater use in irrigated

- agriculture: management challenges in developing countries. In: Scott CA, Faruqui NI, Raschid-Sally L, editors. Wastewater use in irrigated agriculture: confronting the livelihood and environmental realities. Wallingford: CABI Publishing; 2004. p. 1–10. <https://doi.org/10.1079/9780851998237.0001>
14. Manegabe BJ, Msagati TA, Ojitalayo AA, Ntbugi MM, Dewar JB, De Bryun K. Assessment of heavy metals pollution in vegetables grown on irrigated soil and their potential threat to human health and global food security. *Hyg Environ Health Adv.* 2025;14:100129. <https://doi.org/10.1016/j.heha.2025.100129>
 15. Chopra AK, Srivastava S, Kumar V, Pathak C. Agro-potentiality of distillery effluent on soil and agronomical characteristics of *Abelmoschus esculentus* L. (okra). *Environ Monit Assess.* 2013;185:6635–44. <https://doi.org/10.1007/s10661-012-3052-8>
 16. Umair Hassan M, Aamer M, Umer Chattha M, Haiying T, Khan I, Seleiman MF, et al. Sugarcane distillery spent wash (DSW) as a bio-nutrient supplement: a win-win option for sustainable crop production. *Agronomy.* 2021;11:183. <https://doi.org/10.3390/agronomy11010183>
 17. Naveed S, Rehim A, Imran M, Anwar MF, Hussain S. Effect of distillery spentwash fertigation on crop growth, yield and accumulation of potentially toxic elements in rice. *Environ Sci Pollut Res.* 2018;25:31113–24. <https://doi.org/10.1007/s11356-018-3067-y>
 18. Imtiazuddin SM, Mumtaz M, Mallick KA. Pollutants of wastewater characteristics in textile industries. *J Basic Appl Sci.* 2012;8:554–6. <https://doi.org/10.6000/1927-5129.2012.08.02.47>
 19. Yaseen DA, Scholz M. Textile dye wastewater characteristics and constituents of synthetic effluents: a critical review. *Int J Environ Sci Technol.* 2019;16:1193–226. <https://doi.org/10.1007/s13762-018-2130-z>
 20. Nagajyoti PC, Lee KD, Sreekanth TVM. Heavy metals, occurrence and toxicity for plants: a review. *Environ Chem Lett.* 2010;8:199–216. <https://doi.org/10.1007/s10311-010-0297-8>
 21. Shanker AK, Cervantes C, Loza-Tavera H, Avudainayagam S. Chromium toxicity in plants. *Environ Int.* 2005;31:739–53. <https://doi.org/10.1016/j.envint.2005.02.003>
 22. Hubbe MA, Metts JR, Hermosilla D, Blanco M, Yerushalmi L, Haghighat F, et al. Wastewater treatment and reclamation: a review of pulp and paper industry practices and opportunities. *BioResources.* 2016;11(3). <https://doi.org/10.15376/biores.11.3.Hubbe>
 23. Kumar V, Chopra AK. Ferti-irrigational effect of paper mill effluent on agronomical characteristics of *Abelmoschus esculentus* L. (okra). *Pak J Biol Sci.* 2013;16:1426–37. <https://doi.org/10.3923/pjbs.2013.1426.1437>
 24. Zainith S, Chowdhary P, Bharagava RN. Recent advances in physico-chemical and biological techniques for the management of pulp and paper mill waste. In: Emerging and eco-friendly approaches for waste management. Singapore: Springer; 2018. p. 271–97. https://doi.org/10.1007/978-981-10-8669-4_13
 25. Nigam RK, Singh P, Singh JS. Assessment of sugar mill effluent discharge on soil physico-chemical attributes and its correlation with soil microbial biomass in paddy fields. *Discov Agric.* 2025;11:e15da3155. <https://doi.org/10.54905/diss.v11i24.e15da3155>
 26. Bedair R, Elliethy MZ, Mansour MM, Saeed E, El-Sherbeny ME. Effects of irrigation water sources on soil fertility, heavy metal accumulation in both soil and rice (*Oryza sativa* L.). *Plant Soil.* 2026;1–20. <https://doi.org/10.1007/s11104-026-08383-0>
 27. Yadav RK, Minhas PS, Lal K, Chaturvedi RK, Yadav G, Verma TP. Accumulation of metals in soils, groundwater and edible parts of crops grown under long-term irrigation with sewage mixed industrial effluents. *Bull Environ Contam Toxicol.* 2015;95:200–6. <https://doi.org/10.1007/s00128-015-1547-z>
 28. Rattan RK, Datta SP, Chhonkar PK, Suribabu K, Singh AK. Long-term impact of irrigation with sewage effluents on heavy metal content in soils, crops and groundwater-a case study. *Agric Ecosyst Environ.* 2005;109:310–22. <https://doi.org/10.1016/j.agee.2005.02.025>
 29. Sharma A, Malaviya P. Irrigational impact of untreated and treated brewery-distillery effluent on seed germination of marigold (*Tagetes erecta* L.). *J Environ Biol.* 2016;37:115–9.
 30. Tripathi S, Singh K, Singh A, Mishra A, Chandra R. Organo-metallic pollutants of distillery effluent and their toxicity on freshwater fish and germinating *Zea mays* seeds. *Int J Environ Sci Technol.* 2022;19:2025–38. <https://doi.org/10.1007/s13762-021-03233-1>
 31. Sadek MB, Hassan J, Saif HB, Biswas A, Sultana S. Toxic effect of textile dyeing effluents on germination, growth, yield and nutritional quality of okra (*Abelmoschus esculentus*). *Int J Ecotoxicol Ecobiol.* 2016;1:82–7.
 32. Kumar V, Chopra AK. Fertigation effect of distillery effluent on agronomical practices of *Trigonella foenum-graecum* L. (fenugreek). *Environ Monit Assess.* 2012;184:1207–19. <https://doi.org/10.1007/s10661-011-2033-7>
 33. Kumar V, Chopra AK. Ferti-irrigational impact of sugar mill effluent on agronomical characteristics of *Phaseolus vulgaris* (L.) in two seasons. *Environ Monit Assess.* 2014;186:2469–84. <https://doi.org/10.1007/s10661-014-3974-4>
 34. Goncharuk EA, Zagorskina NV. Heavy metals, their phytotoxicity and the role of phenolic antioxidants in plant stress responses with focus on cadmium: review. *Molecules.* 2023;28:3921. <https://doi.org/10.3390/molecules28093921>
 35. Hayat S, Hayat Q, Alyemeni MN, Wani AS, Pichtel J, Ahmad A. Role of proline under changing environments. *Plant Signal Behav.* 2012;7:1456–66. <https://doi.org/10.4161/psb.21949>
 36. Sharma P, Dubey RS. Lead toxicity in plants. *Braz J Plant Physiol.* 2005;17:35–52. <https://doi.org/10.1590/S1677-04202005000100004>
 37. Hajhashemi S, Mbarki S, Skalicky M, Noedoo F, Raeisi M, Brestic M. Effect of wastewater irrigation on photosynthesis, growth and anatomical features of two wheat cultivars (*Triticum aestivum* L.). *Water.* 2020;12:607. <https://doi.org/10.3390/w12020607>
 38. Hasanuzzaman M, Bhuyan MHMB, Zulfiqar F, Raza A, Mohsin SM, Mahmud JA, et al. Reactive oxygen species and antioxidant defense in plants under abiotic stress: revisiting the crucial role of a universal defense regulator. *Antioxidants.* 2020;9:681. <https://doi.org/10.3390/antiox9080681>
 39. Mousavi A, Pourakbar L, Moghaddam SS. Effects of malic acid and EDTA on oxidative stress and antioxidant enzymes of okra (*Abelmoschus esculentus* L.) exposed to cadmium stress. *Ecotoxicol Environ Saf.* 2022;248:114320. <https://doi.org/10.1016/j.ecoenv.2022.114320>
 40. Chowdhary P, Yadav A, Singh R, Chandra R, Singh PK, Arora J, et al. Stress response of *Triticum aestivum* and *Brassica juncea* in presence of distillery effluent. *Environ Toxicol Pharmacol.* 2018;57:48–58.
 41. Saleh M, Salehi M, Khanaki S, Ebrahimian H, Liaghat A, Mousavi SM, et al. Effects of treated wastewater irrigation on soil properties, nutrient uptakes and crop yields of agronomic crops under different crop rotations. *Agric Water Manag.* 2025;316:109585. <https://doi.org/10.1016/j.agwat.2025.109585>
 42. Gong WJ, Niu ZF, Wang XR, Zhao HP. How the soil microbial communities and activities respond to long-term heavy metal contamination in electroplating contaminated site. *Microorganisms.* 2021;9:362. <https://doi.org/10.3390/microorganisms9020362>
 43. Dotaniya ML, Rajendiran S, Meena VD, Saha JK, Coumar MV, Kundu S, et al. Influence of chromium contamination on carbon mineralization and enzymatic activities in Vertisol. *Agric Res.* 2017;6:91–96. <https://doi.org/10.1007/s40003-016-0242-6>
 44. Gatica J, Cytryn E. Impact of treated wastewater irrigation on antibiotic resistance in the soil microbiome. *Environ Sci Pollut Res.* 2013;20:3529–38. <https://doi.org/10.1007/s11356-013-1505-4>
 45. Chiroma TM, Ebewe RO, Hymore FK. Comparative assessment of heavy metal levels in soil, vegetables and urban grey wastewater used for irrigation in Yola and Kano. *Int Refereed J Eng Sci.* 2014;3:1–9.
 46. Khan S, Cao Q, Zheng YM, Huang YZ, Zhu YG. Health risks of heavy

- metals in contaminated soils and food crops irrigated with wastewater in Beijing, China. *Environ Pollut.* 2008;152:686–92. <https://doi.org/10.1016/j.envpol.2007.06.056>
47. Singh PK, Deshbhratar PB, Ramteke DS. Effects of sewage wastewater irrigation on soil properties, crop yield and environment. *Agric Water Manag.* 2012;103:100–4. <https://doi.org/10.1016/j.agwat.2011.10.022>
 48. Barker AV, Pilbeam DJ, editors. *Handbook of Plant Nutrition*. 2nd ed. Boca Raton: CRC Press; 2015. <https://doi.org/10.1201/b18458>
 49. Khaliq MA, Javed MT, Hussain S, Imran M, Mubeen M, Nasim W, et al. Assessment of heavy metal accumulation and health risks in okra (*Abelmoschus esculentus* L.) and spinach (*Spinacia oleracea* L.) fertigated with wastewater. *Int J Food Contam.* 2022;9:11. <https://doi.org/10.1186/s40550-022-00097-2>
 50. Khan ZI, Ugulu I, Sahira S, Ahmad K, Ashfaq A, Mehmood N, et al. Determination of toxic metals in fruits of *Abelmoschus esculentus* grown in contaminated soils with different irrigation sources by spectroscopic method. *Int J Environ Res.* 2018. <https://doi.org/10.1007/s41742-018-0110-2>
 51. Clemens S. Toxic metal accumulation, responses to exposure and mechanisms of tolerance in plants. *Biochimie.* 2006;88:1707–19. <https://doi.org/10.1016/j.biochi.2006.07.003>
 52. Gwana AM, Edet BE, Badawi HL, Bala HM, Marte MU, Mohammed A, et al. Appraisal of some heavy metals and elements in irrigated vegetables and fruit cultivated in College Farm, Maiduguri, Nigeria. *Int J Appl Agric Sci.* 2017;3:78–86. <https://doi.org/10.11648/j.ijaas.20170303.14>
 53. Aftab K, Iqbal S, Khan MR, Busquets R, Noreen R, Ahmad N, et al. Wastewater-irrigated vegetables are a significant source of heavy metal contaminants: toxicity and health risks. *Molecules.* 2023;28:1371. <https://doi.org/10.3390/molecules28031371>
 54. Muchuweti M, Birkett JW, Chinyanga E, Zvauya R, Scrimshaw MD, Lester JN. Heavy metal content of vegetables irrigated with mixtures of wastewater and sewage sludge in Zimbabwe: implications for human health. *Agric Ecosyst Environ.* 2006;112:41–48. <https://doi.org/10.1016/j.agee.2005.04.028>
 55. Singh A, Sharma RK, Agrawal M, Marshall FM. Health risk assessment of heavy metals via dietary intake of foodstuffs from the wastewater irrigated site of a dry tropical area of India. *Food Chem Toxicol.* 2010;48:611–19. <https://doi.org/10.1016/j.fct.2009.11.041>
 56. Khan MN, Aslam MA, Muhsinah AB, Uddin J. Heavy metals in vegetables: screening health risks of irrigation with wastewater in peri-urban areas of Bhakkar, Pakistan. *Toxics.* 2023;11:460. <https://doi.org/10.3390/toxics11050460>
 57. Balkhair KS, Ashraf MA. Field accumulation risks of heavy metals in soil and vegetable crop irrigated with sewage water in western region of Saudi Arabia. *Saudi J Biol Sci.* 2016;23:S32–44. <https://doi.org/10.1016/j.sjbs.2015.09.023>
 58. Mapanda F, Mangwayana EN, Nyamangara J, Giller KE. The effect of long-term irrigation using wastewater on heavy-metal contents of soils, crops and groundwater—a case study in Harare, Zimbabwe. *Agric Ecosyst Environ.* 2005;107:151–65. <https://doi.org/10.1016/j.agee.2004.11.005>
 59. Woldetsadik D, Drechsel P, Keraita B, Itanna F, Gebrekidan H. Heavy metal accumulation and health risk assessment in wastewater-irrigated urban vegetable farming sites of Addis Ababa, Ethiopia. *Int J Food Contam.* 2017;4:9. <https://doi.org/10.1186/s40550-017-0053-y>
 60. Naciri R, Chtouki M, El Maalam L, Hirt H, Belkachach D, Ouakroum A. Phosphate-modified biochar attenuates cadmium availability in contaminated soil and reduces its transfer to tomato fruits. *Environ Res.* 2025;279:121775. <https://doi.org/10.1016/j.envres.2025.121775>
 61. Beesley L, Marmiroli M. The immobilisation and retention of soluble arsenic, cadmium and zinc by biochar. *Environ Pollut.* 2011;159:474–80. <https://doi.org/10.1016/j.envpol.2010.10.016>
 62. Rajapaksha AU, Chen SS, Tsang DCW, Zhang M, Vithanage M, Mandal S, et al. Engineered/designer biochar for contaminant removal/immobilization from soil and water: potential and implication of biochar modification. *Chemosphere.* 2016;148:276–91. <https://doi.org/10.1016/j.chemosphere.2016.01.043>
 63. Li X, Li R, Zhan M, Hou Q, Zhang H, Wu G, et al. Combined magnetic biochar and ryegrass enhanced the remediation effect of soils contaminated with multiple heavy metals. *Environ Int.* 2024;185:108498. <https://doi.org/10.1016/j.envint.2024.108498>
 64. Ali H, Khan E, Sajad MA. Phytoremediation of heavy metals—concepts and applications. *Chemosphere.* 2013;91:869–81. <https://doi.org/10.1016/j.chemosphere.2013.01.075>
 65. Gurajala HK, Cao X, Lin T, Ramesh TM, Lu M, Yang X. Comparative assessment of Indian mustard (*Brassica juncea* L.) genotypes for phytoremediation of Cd and Pb contaminated soils. *Environ Pollut.* 2019;254:113085. <https://doi.org/10.1016/j.envpol.2019.113085>
 66. Dary M, Chamber-Pérez MA, Palomares AJ, Pajuelo E. In situ phytostabilisation of heavy metal polluted soils using *Lupinus luteus* inoculated with metal resistant plant-growth promoting rhizobacteria. *J Hazard Mater.* 2010;177:323–30. <https://doi.org/10.1016/j.jhazmat.2009.12.035>
 67. Chengatt AP, Sarath NG, Sebastian DP, Mohanan NS, Sindhu ES, George S, et al. Chelate assisted phytoextraction for effective rehabilitation of heavy metal(loid)s contaminated lands. *Int J Phytoremediation.* 2023;25:981–96. <https://doi.org/10.1080/15226514.2022.2124233>
 68. Vymazal J. Constructed wetlands for wastewater treatment: a review. *Ecol Eng.* 2021;170:106253. <https://doi.org/10.1016/j.ecoleng.2021.106318>
 69. Kadlec RH, Wallace S. *Treatment Wetlands*. 2nd ed. Boca Raton: CRC Press; 2009. <https://doi.org/10.1201/9781420012514>
 70. Basma L, Asma L, Abdelhamid B. Irrigation and fertigation for greenhouse cultivation. In: *Greenhouse Technology for Sustainable Agriculture*. 2025. p. 63–84. <https://doi.org/10.1201/9781003455967-3>
 71. Alam AU, Clyne D, Deen MJ. A low-cost multi-parameter water quality monitoring system. *Sensors.* 2021;21:3775. <https://doi.org/10.3390/s21113775>

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