Review on the Physicochemical Characteristics of Industrial Effluents and Their Effect on Crop Productivity

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Abstract: Industrialization and increasing water scarcity have intensified the need for safe wastewater management and reuse in agriculture. Sugarcane processing generates considerable quantities of wastewater containing organic matter, suspended solids, dissolved salts, nutrients, and, in some cases, heavy metals. The physicochemical characteristics of sugar mill effluent vary according to processing operations, raw materials, season and treatment practices. Important parameters include pH, temperature, turbidity, total dissolved solids (TDS), biological oxygen demand (BOD), chemical oxygen demand (COD), electrical conductivity, sulphates and mineral elements. Untreated effluent may adversely affect soil properties, microbial activity, seed germination, crop growth and ecosystem health. However, appropriately treated and diluted effluent can provide water and nutrients and may improve crop growth under suitable conditions. Studies reviewed in this article indicate that low concentrations of sugar mill effluent can sometimes stimulate germination and plant growth, whereas higher concentrations generally inhibit growth and cause physiological stress. Safe agricultural reuse therefore requires characterization, treatment, appropriate dilution, suitable irrigation methods, and regular monitoring of soil and water quality. The review highlights the potential of treated sugar mill effluent as a supplementary irrigation and nutrient resource while emphasizing the environmental and health risks associated with untreated or poorly managed effluent.

Keywords**:** Sugar mill effluent, industrial wastewater, physicochemical characteristics, crop growth, soil health, wastewater reuse, irrigation, phytotoxicity

1. INTRODUCTION

Water is an essential resource for agriculture, ecosystems and human development. Increasing population, industrialization, urbanization and climate variability have intensified pressure on freshwater resources. Consequently, the reuse of wastewater for agriculture has received increasing attention, particularly in regions where irrigation water is limited. Treated wastewater can provide water and nutrients, but its safe application depends on its physicochemical and biological quality (Angelakis & Snyder, 2015; Jaramillo & Restrepo, 2017; Al-Hazmi et al., 2023).

Sugarcane is an important commercial crop in India and supports a large agricultural and industrial sector. Sugar factories generate wastewater during several stages of processing, including cane washing, juice extraction, clarification, evaporation, crystallization, cooling and cleaning operations. The resulting effluent contains organic and inorganic constituents, and its pollution load can vary considerably according to the processing stage and management practices (Kushwaha, 2015; Poddar & Sahu, 2017; Moussa et al., 2023).

Sugar mill effluent commonly contains high concentrations of organic matter, suspended solids, dissolved solids and salts. Elevated BOD and COD indicate a substantial organic load and may reduce dissolved oxygen in receiving water bodies. Untreated discharge can therefore alter water quality, affect aquatic organisms and contribute to soil degradation when used directly for irrigation. Heavy metals such as Pb, Mn, Zn and Fe have also been reported in industrial effluents and may accumulate in soil and plant tissues (Poddar & Sahu, 2017; Yadav et al., 2021; Okereafor et al., 2020).

At the same time, wastewater contains nutrients and organic matter that may be beneficial when present at appropriate concentrations. Because of increasing freshwater scarcity, controlled reuse of treated industrial wastewater may provide an alternative irrigation resource. The central challenge is therefore to distinguish between potentially useful treated and diluted effluent and untreated effluent that may create environmental and agricultural risks.

The present review summarizes the major physicochemical characteristics of sugarcane industrial effluent, its effects on soil and crop productivity, the potential benefits and risks of agricultural reuse, and strategies for safe utilization.

2. NEED OF THE STUDY

The increasing scarcity of freshwater resources, coupled with the growing demand for irrigation water, has created an urgent need to explore alternative and sustainable sources of water for agriculture. Sugarcane processing industries generate considerable quantities of wastewater containing organic matter, suspended solids, dissolved salts, nutrients and potentially toxic elements. If such effluent is discharged untreated, it can adversely affect aquatic ecosystems, soil quality and agricultural productivity.

At the same time, sugar mill effluent contains organic matter and nutrients that may have potential value for agricultural production when appropriately treated and diluted. Previous studies have demonstrated that low or moderate concentrations of sugar industry effluent can sometimes enhance seed germination, plant growth, biomass, chlorophyll and other physiological parameters, whereas higher concentrations may cause osmotic stress, nutrient imbalance and toxicity. Importantly, the optimum concentration varies among crops and cultivars, indicating that a universal dilution level cannot be recommended.

There is therefore a need to systematically evaluate the **beneficial and detrimental effects of sugar mill effluent on soil and crop performance** and to identify suitable concentrations for agricultural use. Particular attention is required because repeated application of untreated or highly concentrated effluent may increase soil salinity and electrical conductivity, alter soil chemical properties, affect beneficial microorganisms and promote the accumulation of potentially toxic metals in soil and plant tissues.

Furthermore, existing studies indicate considerable variation in crop response to sugar mill effluent. Crop species and varieties differ in their tolerance, and biochemical responses such as changes in chlorophyll, proteins, soluble sugars, proline and antioxidant activity can provide valuable information about plant stress and tolerance mechanisms. Therefore, crop-specific experimentation is necessary to determine safe and effective effluent concentrations.

The present study is consequently needed to assess the potential of sugar mill effluent as an alternative irrigation and nutrient resource while simultaneously evaluating its environmental and agricultural risks. Such information can help establish appropriate treatment, dilution and application strategies, minimize adverse effects on soil and crops, and promote the conversion of industrial wastewater from an environmental liability into a **managed resource for sustainable agriculture**.

3. PHYSICOCHEMICAL CHARACTERISTICS OF SUGAR MILL EFFLUENT

Sugar industry wastewater is generated from multiple processing operations, including washing, extraction, heating, cooling and cleaning. The quantity and composition of wastewater differ according to factory design, processing technology, season and management practices. Washing operations may contribute substantially to the total wastewater volume, while extraction and crystallization processes increase the organic and chemical pollution load.

3.1 Colour and Odour

Colour and odour are important preliminary indicators of wastewater quality. Sugar industry effluent may vary from light brown to grey or black depending on its age and degree of decomposition. Brown coloration may result from phenolic compounds, melanoidins, caramelization products and other organic constituents. Anaerobic decomposition may produce dark-coloured wastewater and unpleasant gases such as hydrogen sulphide, ammonia, methane and carbon dioxide.

Strong odour is generally associated with decomposition of organic matter under anaerobic conditions. Hydrogen sulphide is particularly important because it has an unpleasant odour and can create environmental and health concerns at elevated concentrations.

3.2 Turbidity and Suspended Solids

Turbidity reflects the presence of suspended and colloidal materials in wastewater. High turbidity can interfere with light penetration and photosynthetic activity in receiving water bodies. Suspended solids may include organic residues, soil particles, fibres and other insoluble materials. Their accumulation can degrade water quality and disrupt aquatic ecosystem processes.

3.3 pH and Temperature

The pH of sugar mill effluent can vary depending on the processing stage and the chemicals used during sugar clarification and treatment. Changes in pH are environmentally important because aquatic organisms and soil microorganisms are sensitive to large deviations from normal conditions. The temperature of sugar industry wastewater may also vary considerably, with reported values ranging from approximately 20 to 60°C depending on the season and processing stage (Kushwaha, 2015; Poddar & Sahu, 2017).

3.4 BOD and COD

BOD and COD are among the most important indicators of organic pollution. BOD represents the oxygen required by microorganisms to biologically decompose organic matter, whereas COD indicates the oxygen requirement associated with chemical oxidation of organic substances. Sugar industry effluent is generally characterized by a relatively high organic load, although the magnitude varies with raw material handling, processing conditions and season (Kushwaha, 2015; Poddar & Sahu, 2017; Moussa et al., 2023).

High BOD and COD in untreated effluent can reduce dissolved oxygen in receiving water bodies and adversely affect aquatic organisms. Consequently, reduction of organic load is a major objective of effluent treatment.

3.5 Dissolved Solids, Nutrients and Mineral Elements

Sugar mill effluents may contain sodium, magnesium, sulphur, nitrogen, phosphorus and other dissolved constituents. Nitrogen and phosphorus are particularly important because excessive nutrient discharge can contribute to eutrophication. Sulphate may also be environmentally significant because its reduction under anaerobic conditions can contribute to hydrogen sulphide formation (Poddar & Sahu, 2017; Kushwaha, 2015).

The nutrient content of effluent may provide an agricultural advantage when concentrations are appropriate. However, excessive salts and mineral elements can increase soil electrical conductivity and alter soil chemical properties. Therefore, nutrient content should be considered alongside salinity, sodicity, and potentially toxic elements before agricultural application.

4. IMPACT OF INDUSTRIAL EFFLUENT ON SOIL HEALTH

Soil is a dynamic ecosystem consisting of mineral particles, organic matter, microorganisms, water and air. Continuous application of untreated industrial effluent can alter its physical, chemical and biological properties. Industrial wastewater may increase the concentration of soluble salts, organic carbon, nutrients and potentially toxic metals in agricultural soil (Yadav et al., 2021; Okereafor et al., 2020).

Sugar mill effluent has been reported to modify soil electrical conductivity, pH, sodium, potassium, calcium, magnesium, nitrogen, phosphate, sulphate and several micronutrients. Although some of these constituents can act as nutrients, excessive accumulation can disturb soil fertility and plant growth (Kumar, 2014; Yadav et al., 2021).

Long-term application of contaminated effluent may also influence soil microbial communities. Beneficial microorganisms responsible for nutrient cycling and soil fertility can be adversely affected by high pollutant concentrations. Heavy metals present in industrial wastewater may accumulate in agricultural soils and subsequently enter plants, animals and the human food chain (Okereafor et al., 2020; Yadav et al., 2021).

The impact of effluent is therefore concentration-dependent. Treated and appropriately diluted wastewater may improve soil organic matter and nutrient availability, whereas untreated or highly concentrated effluent may increase salinity, toxic-element accumulation and microbial stress.

5. EFFECT OF SUGAR MILL EFFLUENT ON SEED GERMINATION AND CROP GROWTH

The effect of sugar mill effluent on crops varies with crop species, effluent composition and concentration. Several studies reviewed in the present work indicate that low or moderate concentrations may stimulate germination and growth, whereas higher concentrations are generally inhibitory.

Kumar (2014) reported that sugar mill effluent influenced the chemical properties of soil and agronomic characteristics of maize. Application of different effluent concentrations increased several soil parameters, including EC, pH and mineral nutrient concentrations. A concentration of approximately 40% was identified as agronomically suitable under the study conditions.

Deepthi and Prabhakaran (2016) evaluated the use of paddy and green gram for treating sugar industry effluent. Increasing concentrations of untreated effluent reduced seed germination, whereas treated effluent produced considerably better responses. These observations emphasize the importance of treatment before agricultural reuse.

Similarly, Ijaz et al. (2018) investigated the use of diluted sugar mill effluent in maize, combined with plant growth-promoting rhizobacteria (PGPR). Effluent concentrations up to 75% improved several growth characteristics under the experimental conditions, while 100% effluent was harmful. PGPR application further improved plant performance.

Research on marigold demonstrated that 25% diluted sugar mill effluent could enhance plant height, leaf number and branching compared with the control. Biochemical parameters, including chlorophyll, soluble protein, soluble sugars and proline, were also evaluated.

Chickpea showed a similar concentration-dependent response. Suhail et al. (2020) reported that higher concentrations of crude sugarcane factory effluent inhibited seed germination and seedling growth, whereas approximately 10–25% effluent produced comparatively favourable responses in germination, seedling growth, biomass, chlorophyll and protein content.

Upadhyay and Rani (2022) also observed that a lower concentration of sugar industry wastewater had the greatest effect on seed germination and seedling growth, whereas higher concentrations progressively reduced plant performance.

Manikandan et al. (2023) reported a comparable pattern in sunflower. Low effluent concentration, particularly around 10%, promoted several germination and seedling growth parameters, whereas increasing concentrations reduced growth. The study evaluated parameters including root and shoot length, fresh and dry weight, phytotoxicity, tolerance index, and seed vigor index.

Recent research on canola also demonstrates that the optimum response is crop- and variety-dependent. Ullah et al. (2024) found improved germination and growth responses in some canola varieties at particular effluent concentrations, demonstrating that plant genotype can influence tolerance to industrial wastewater.

Overall, these studies demonstrate a general concentration-dependent pattern. Diluted effluent may supply nutrients and organic matter that stimulate plant growth, whereas excessive concentrations may cause osmotic stress, nutrient imbalance, toxicity and reduced germination. Consequently, there is no single universal dilution level suitable for all crops.

6. POTENTIAL BENEFITS AND RISKS OF AGRICULTURAL REUSE

Wastewater reuse has become increasingly important because of freshwater scarcity. Properly treated wastewater can supplement irrigation water and contribute nutrients and organic matter to agricultural soils. Reuse can reduce pressure on freshwater resources and provide an alternative method for managing industrial wastewater.

The potential agricultural benefits include improved nutrient availability, increased soil organic matter, enhanced microbial activity and, under suitable conditions, increased crop productivity. Some studies have reported improved crop yield following irrigation with treated wastewater compared with freshwater. Wastewater reuse may also reduce dependence on chemical fertilizers when its nutrient contribution is appropriately evaluated (Cirelli et al., 2012; Jaramillo & Restrepo, 2017; Wang et al., 2022).

However, these benefits must be balanced against potential environmental and health risks. Untreated industrial effluent may contain heavy metals, excessive salts, organic pollutants and microbial contaminants. Long-term irrigation can result in pollutant accumulation in soil and plants. Contaminants may subsequently enter groundwater or the food chain, creating potential risks to animals and humans (Mishra et al., 2023; Okereafor et al., 2020; Yadav et al., 2021).

The major risks associated with uncontrolled use include:

- deterioration of soil physicochemical properties;
- increased salinity and electrical conductivity;
- accumulation of potentially toxic metals;
- inhibition of beneficial soil microorganisms;
- reduced seed germination and crop growth;
- contamination of groundwater and surface water; and
- possible transfer of contaminants into edible plant tissues.

Thus, wastewater reuse should be considered a **managed resource-recovery strategy rather than direct disposal onto agricultural land**.

7. TREATMENT AND SAFE UTILIZATION STRATEGIES

Treatment is essential before industrial effluent is reused for irrigation. The major objectives are to reduce suspended solids, organic load, excessive salts, toxic metals, pathogens and other hazardous constituents. The selection of treatment technology depends on the composition and pollution load of the wastewater.

Physical, chemical and biological treatment approaches may be combined to improve treatment efficiency. Advanced techniques include membrane filtration, reverse osmosis, chemical precipitation, oxidation and adsorption. Emerging treatment approaches are increasingly being investigated for the removal of persistent organic pollutants and other contaminants (Kushwaha, 2015; Younas et al., 2021; Moussa et al., 2023).

Biological treatment is particularly important for reducing biodegradable organic matter and BOD. Microbial processes can convert organic pollutants into less harmful products and may form an important component of integrated treatment systems (Kushwaha, 2015; Moussa et al., 2023).

After treatment, effluent should be tested before agricultural application. Important parameters include pH, EC, TDS, BOD, COD, major nutrients, sodium, sulphate and potentially toxic metals. Periodic monitoring of irrigated soil and crop tissues is also necessary to identify long-term accumulation (Jaramillo & Restrepo, 2017; Mishra et al., 2023; Yadav et al., 2021).

Irrigation technology can further reduce risks. Drip irrigation can deliver water directly to the root zone and reduce contact between wastewater and plant leaves. This may decrease the potential for pathogen transmission and reduce unnecessary contamination of above-ground plant parts.

Dilution may also be appropriate where treated effluent still contains elevated concentrations of particular constituents. However, dilution should not be considered a substitute for adequate treatment. The appropriate concentration must be determined experimentally for each crop, soil type and effluent source (Deepthi & Prabhakaran, 2016; Ijaz et al., 2018; Suhail et al., 2020; Ullah et al., 2024).

8. FUTURE RESEARCH DIRECTIONS

Future studies should focus on developing integrated approaches for the safe utilization of sugar mill effluent. Detailed characterization of effluent should include physicochemical parameters, nutrients, heavy metals, organic pollutants and microbial communities. Such information will help identify both beneficial constituents and potential hazards.

Crop-specific research is particularly important because plant species and cultivars differ in their tolerance to industrial wastewater. Experiments should evaluate germination, root and shoot development, biomass, chlorophyll, photosynthetic performance and yield under different effluent concentrations.

Biochemical investigations can provide additional information about plant stress responses. Parameters such as soluble protein, sugars, proline, antioxidant enzymes and membrane-damage indicators can help explain the physiological mechanisms underlying effluent tolerance.

Microbial studies are another important research area. Identification of beneficial microorganisms capable of degrading organic pollutants or improving plant growth may support the development of biological treatment systems. The integration of effluent treatment with microbial inoculants and biofertilizers could provide an environmentally sustainable approach.

Long-term field experiments are also required because short-term pot experiments may not adequately reflect the consequences of repeated wastewater application. Future investigations should therefore integrate soil health, crop productivity, contaminant accumulation and food-safety assessment (Wang et al., 2022; Mishra et al., 2023; Okereafor et al., 2020).

9. CONCLUSION

Sugarcane processing generates substantial quantities of wastewater containing organic matter, suspended solids, dissolved salts, nutrients and potentially toxic substances. The physicochemical characteristics of the effluent determine its environmental impact and suitability for agricultural reuse. Untreated or highly concentrated effluent may adversely affect soil quality, microbial activity, seed germination, crop growth and aquatic ecosystems.

At the same time, treated and appropriately diluted effluent may provide irrigation water and nutrients and can contribute to resource recovery. The reviewed studies consistently indicate that crop response is concentration-dependent, with low or moderate concentrations sometimes improving growth, whereas excessive concentrations are inhibitory.

Therefore, agricultural reuse of sugar mill effluent should be based on **proper treatment, characterization, crop-specific dilution, appropriate irrigation methods and continuous monitoring**. Future research should emphasize long-term field evaluation, contaminant accumulation, plant biochemical responses, microbial interactions and food safety. Such an integrated approach can help convert industrial wastewater from an environmental liability into a controlled resource for sustainable agriculture.

REFERENCES

1. Al-Hazmi, H., Mohammadi, A., Hejna, A., Majtacz, J., Esmaeili, A., Habibzadeh, S., Saeb, M., Badawi, M., Lima, E., & Makinia, J. (2023). Wastewater reuse in agriculture: Prospects and challenges. *Environmental Research, 236*, 116711.
2. Angelakis, A. N., & Snyder, S. A. (2015). Wastewater treatment and reuse: Past, present, and future. *Water, 7*(9), 4887–4895.
3. Cirelli, G. L., Consoli, S., Licciardello, F., Aiello, R., Giuffrida, F., & Leonardi, C. (2012). Treated municipal wastewater reuse in vegetable production. *Agricultural Water Management, 104*, 163–170.
4. Deepthi, T., & Prabhakaran, J. (2016). Physico-chemical analysis of sugar mill effluents and its effect on seed germination of paddy (*Oryza sativa*) and green gram (*Vigna radiata*). *International Journal of Science Engineering and Advance Technology, 4*(1), 71–80.
5. Dotaniya, M. L., et al. (2022). Reuse of poor-quality water for sustainable crop production in the changing scenario of climate. *Environment, Development and Sustainability*.
6. Ijaz, M., Sarfraz, M., Nawaz, A., Yasir, T. A., Sher, A., Sattar, A., & Wasaya, A. (2018). Diluted sugar mill effluent application with PGPR improves the performance of maize (*Zea mays* L.) under an arid climate. *Agronomy, 8*, 67.
7. Jaramillo, M. F., & Restrepo, I. (2017). Wastewater reuse in agriculture: A review about its limitations and benefits. *Sustainability, 9*(10), 1734.

8. Kushwaha, J. P. (2015). A review on sugar industry wastewater: Sources, treatment technologies, and reuse. *Desalination and Water Treatment*, *53*(2), 309–318.
9. Kumar, V. (2014). Sugar mill effluent utilization in the cultivation of maize (*Zea mays* L.) in two seasons. *Journal of Waste Management*, 408509.
10. Manikandan, S., Sasikumar, S., & Thamizhiniyan, P. (2023). Study of sugar mill effluent and its impact on sunflower seed germination and growth (*Helianthus annuus* L.). *International Journal of Research in Engineering and Science*, *11*(3), 146–156.
11. Mishra, S., Kumar, R., & Kumar, M. (2023). Use of treated sewage or wastewater as an irrigation water for agricultural purposes: Environmental, health, and economic impacts. *Total Environment Research Themes*, *6*, 100051.
12. Moussa, A. W. N., Sawadogo, B., Konate, Y., Sidibe, S. D. S., & Heran, M. (2023). Critical state of the art of sugarcane industry wastewater treatment technologies and perspectives for sustainability. *Membranes*, *13*(8), 709.
13. Okereafor, U., Makhatha, M., Mekuto, L., Uche-Okereafor, N., Sebola, T., & Mavumengwana, V. (2020). Toxic metal implications on agricultural soils, plants, animals, aquatic life and human health. *International Journal of Environmental Research and Public Health*, *17*(7), 2204.
14. Poddar, P. K., & Sahu, O. (2017). Quality and management of wastewater in sugar industry. *Applied Water Science*, *7*, 461–468.
15. Saini, S. P., & Pant, S. (2014). Physico-chemical analysis of sugar mill effluent and their impact on changes of growth of wheat (*Triticum aestivum*) and maize (*Zea mays* L.). *IOSR Journal of Environmental Science, Toxicology and Food Technology*, *8*, 57–61.
16. Suhail, M., Singh, K. P., & Alia, I. (2020). Effects of crude sugarcane factory effluent on the morphological and biochemical parameters of chickpeas. *Indonesian Journal of Agricultural Science*, *21*(1), 30–38.
17. Ullah, H., Elahi, N. N., Imtiaz, M., et al. (2024). Impacts of sugarcane industrial effluent as an alternate source of irrigation on growth, chlorophyll contents and antioxidants of different canola varieties. *Scientific Reports*, *14*, 1912.
18. Upadhyay, V. K., & Rani, S. (2022). Analysis and characterization of sugar mill waste and its effect on growth and germination of seeds. *Journal of Applied Chemistry*, *15*(11).
19. Vaithiyanathan, T., & Sundaramoorthy, P. (2017). Analysis of sugar mill effluent and its influence on germination and growth of African marigold (*Tagetes erecta* L.). *Applied Water Science*, *7*, 4715–4723.
20. Wang, H.-J., Wang, J., & Yu, X. (2022). Wastewater irrigation and crop yield: A meta-analysis. *Journal of Integrative Agriculture*, *21*(4), 1215–1224.
21. Yadav, K. K., David, A. A., Swaroop, N., Thomas, T., Hasan, A., & Noman, M. (2021). Evaluation of Oudh sugar mill effluent impact on soil properties and heavy metal accumulation in the soil of Rosa, Shahjahanpur (U.P.). *The Pharma Innovation*, *10*(9), 1776–1782.
22. Younas, F., Mustafa, A., Farooqi, Z. U. R., Wang, X., Younas, S., Mohy-Ud-Din, W., et al. (2021). Current and emerging adsorbent technologies for wastewater treatment: Trends, limitations, and environmental implications. *Water*, *13*(2), 215.