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Treatment and Use of Distillery Wastewater for Irrigation Purposes

Urwah Fiaz[1], Mohsin Nawaz[1,2*], Sarfraz Hashim[1], Abid Hussain[3], Mohsin Khan[1], Umair Sultan[1]

[1]Department of Agricultural Engineering, Muhammad Nawaz Shareef University of Agriculture, Multan, Pakistan.
[2]Faculty of Arts and Sciences, Aga Khan University, 74800 Karachi, Pakistan
[3]Department of Soil and Environmental Sciences, Muhammad Nawaz Shareef University of Agriculture, Multan, Pakistan

***Corresponding Author: Mohsin Nawaz**, mohsin.nawaz@mnsuam.edu.pk

Abstract

Distillery digester overflow (DOF) from sugar industries is a dark and high-strength wastewater containing recalcitrant melanoidins, which prevent light from passing through and spoil soil quality. This study investigated the exclusive removal of DOF colour through hydrogen peroxide (H2O2) oxidation, subsequently sutilising the clarified effluent for irrigating wheat and cotton under controlled pot conditions. Treatment of melanoidin with H2O2, used at concentrations up to 12–15% v/v, provided a high degree of colour decolourisation, which is in agreement with the results from other reports that sdecolourised 64-97% at neutral to alkaline pH. The H2O2-treated effluent was then applied at a fixed dilution to Triticum aestivum (wheat) and Gossypium hirsutum (cotton) plants. Key growth parameters (plant height, yield and tiller count) and soil properties, such as pH, electrical conductivity, K (potassium) and P (phosphorus), were sanalysed in detail. Compared to crops grown with untreated DOF irrigation, the plants of crops treated with H2O2-treated DOF showed significantly better growth characteristics: the height and grain yield of wheat plants were increased, and plant height and number of leaves of cotton plants were improved. Post-harvest soil analysis was conducted, which revealed improved soil fertility, especially for K and P requirements, in pots irrigated with the treated effluent. This approach has the dual advantage of conserving freshwater and increasing the nutrient content of soil. The One-Way Analysis of Variance (ANOVA) was used to statistically

analyse soil data gathered in the experiment, in order to determine whether the differences between the irrigation treatments were significant. The results of the crops irrigated with the distillery effluent treated with H2O2 were found to be statistically significant ($p<0.05$), which clearly proved that the removal of melanoidin using oxidation had a positive effect on the growth of the plants and on the fertility of the soil.

Keywords: *Wastewater irrigation, Melanoidin removal, H2O2 oxidation, Distillery effluent.*

1. Introduction

The global sugarcane industry, playing a role in the development of the Agro-economy in many tropical and subtropical countries, is a major user of freshwater resources and an important source of high-strength industrial wastewaters (Gbadeyan et al., 2024; Raza et al., 2021). A challenging byproduct is the spent wash from the distillation of ethanol, primarily used in biogas production, leaving wastewater in the form of digester overflow (DOF) (Fito et al., 2019; Sankaran et al., 2014). This effluent is marked by high levels of dissolved organic pollutants and consequently, the Biochemical Oxygen Demand (BOD) and Chemical Oxygen Demand (COD) are high and the effluent has a distinctive dark brown colour (Naresh Bharagava, 2018; Rani & Pal, 2013). This colour is primarily attributed to melanoidins, a heterogeneous group of recalcitrant, high-molecular-weight polymers (Hayase et al., 1984). Melanoidins are derived from the Maillard reaction, which is a non-enzymatic browning reaction with amino acids and reducing sugars under high temperature conditions encountered during sugar processing (Wang et al., 2011). Their complex polymeric structure confers high resistance to conventional biological degradation, enabling their persistence in the environment (Li et al., 2024). Discharge of melanoidin-containing wastewater into natural water bodies severely affects the penetration of sunlight in water bodies (Younis et al., 2025; Khan et al., 2024), thereby affecting the level of photosynthesis, depleting the amount of oxygen dissolved in water, which leads to anaerobic conditions and is detrimental to water bodies (Chandra et al., 2018; Badar et al., 2024). In terrestrial applications, melanoidins can alter soil chemistry, decrease soil alkalinity, and exhibit phytotoxic properties that may impede seed germination and microbial activity (Naresh Bharagava, 2018; Verma et al., 2020). Consequently, the development of effective treatment strategies for the removal of melanoidin is a crucial prerequisite for the safe disposal (Mustafa et al., 2024) or beneficial reuse of this wastewater (Rani & Pal, 2013). While biological

treatments are successful in the reduction of BOD, they are mostly inefficient in the removal of the recalcitrant colour imparted by the melanoidins (Agarwal et al., 2010; Ali et al., 2021). Therefore, physicochemical methodologies are often studied. Among these, Advanced Oxidation Processes (AOPs) have demonstrated significant promise (Abdel-Wahab & Batchelor, 2002). The oxidant agent hydrogen peroxide (H_2O_2), which is a powerful and environmentally benign oxidant, is a fundamental part of many AOPs (Hayase et al., 1984). It is able to degrade complex organic molecules, especially if scatalysed (e.g. Fenton reactions) or under alkaline conditions that will favour the formation of strongly oxidising hydroxyl radicals. Pioneering work by (Hayase et al., 1984) reported that H_2O_2 achieved 64% oxidation of melanoidin colour at neutral pH and up to 97% at pH 10, illustrating its capacity to break down high-molecular-weight fragments into smaller, colourless, and more biodegradable compounds. Practically, H_2O_2 treatment could bring distillery effluent of significantly less colour, less BOD, and less COD, which subsequently becomes much safer for land application (Ali Rajput et al., 2021). The reuse of treated industrial effluent for irrigation offers a great potential for the creation of a circular economy, particularly in arid and semi-arid areas (Kassem et al., 2025) where water availability is a major limitation to agricultural development (Gbadeyan et al., 2024). Treated wastewater can provide a stable water source (Rehman et al., 2023), as well as plant nutrients which are considered essential for local food production, and thus may help to reduce the dependence on freshwater abstraction and the use of synthetic sfertilisers (Benaafi et al., 2024). For example, the use of treated distillery wastewater has been shown to increase soil potassium (K), phosphorus (P) and other essential nutrients (Hassan et al., 2021). However, such practice requires good management to reduce the long-term risks of ssalinisation of soils and the accumulation of phytotoxic compounds (Naqvi et al., 2023). This work therefore examines H_2O_2 oxidation of distillery DOF as a single colour removal technology and critically offers an assessment of the H_2O_2 oxidation technology on the growth of two important crops: wheat and cotton (Verma et al., 2020). We shypothesise that H_2O_2-treated DOF, by reducing the phytotoxic effects of melanoidins while preserving beneficial nutrients, will aid the growth of plants comparably to what it is under fresh water, as opposed to raw DOF, which is known to be inhibitory.

2. Materials and Methods

2.1. Effluent Source and Treatment

Digester overflow (DOF) was obtained from the distillery unit of Tandlianwala Sugar Mills in Muzzaffargarh, Pakistan. The raw DOF had dark brown colouration, was basic (pH ~8.2), and had extremely high chemical oxygen demand (COD >50,000 mg/L) and melanoidin content. In the laboratory, samples of DOF were treated with different amounts of 30% commercial H_2O_2. Initial tests were done to determine the optimal amount of H_2O_2 required for full removal of the colours. For instance, the addition of approximately 3 mL of 30% H_2O_2 to 5 mL of raw DOF (resulting in a final concentration of ~12% H_2O_2) left the sample colourless. Guided by these preliminary trials, a practical treatment protocol was established: raw DOF was adjusted to approximately pH 7 using H_2SO_4, followed by treatment with H_2O_2 to achieve a concentration of ~10–12% (v/v) at ambient temperature. The mixture was stirred for 30 minutes and then left to settle. Following the reaction, there was residual H_2O_2 that was sneutralised and the treated effluent collected for irrigation experiments as shown in Fig. 1.

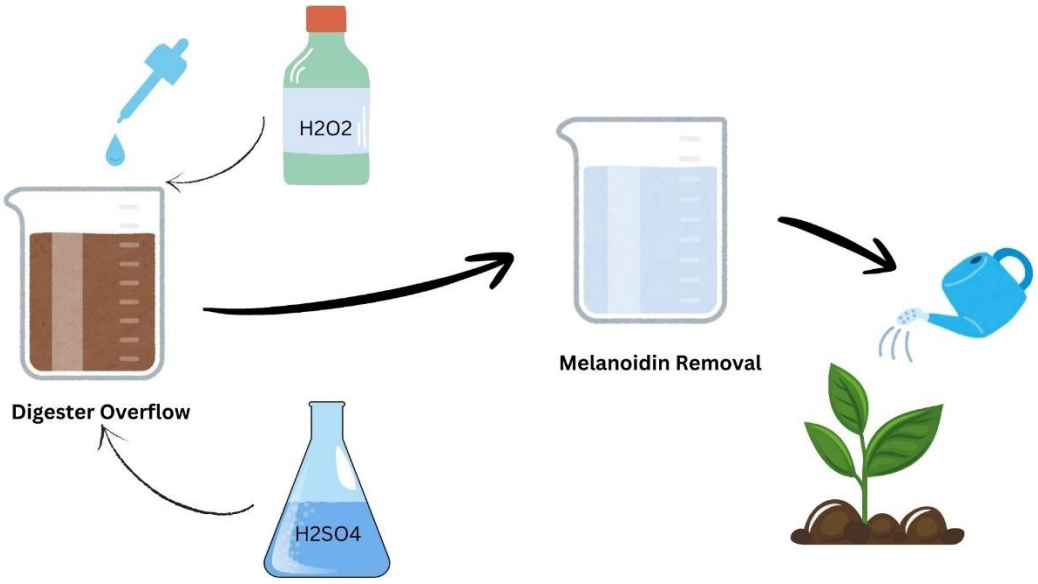

Figure 1: Schematic diagram of experimental procedure

2.2. Pot Experiments on Wheat and Cotton Crop

Pot experiments were conducted using pots filled with uniform loamy soil (pH ~7.8). Three different treatments were tested, each with three replications: (1) Control, irrigated with tap water; (2) Raw DOF, irrigated with a 20% (v/v) dilution of raw digester overflow; and (3) Treated DOF, irrigated with a 20% (v/v) dilution of the H_2O_2-treated effluent. After germination, wheat or cotton seedlings from the flats were thinned to one plant per pot. Plants had irrigation twice per week with 200 mL of the treatment for 10 weeks. No supplementary sfertilisers were used.

2.3. Plant Measurements

The height of plants was recorded on a weekly basis. Upon reaching maturity, wheat plants were harvested at 4.5 months to determine tiller count, spike count, biomass, and grain yield. Cotton plants were grown for 12 weeks and then harvested to measure plant height, number of leaves, shoot length and root length. Soil samples were taken before sowing and after harvest for full analysis of pH, electrical conductivity (EC) and available K and P as shown in Fig. 2.

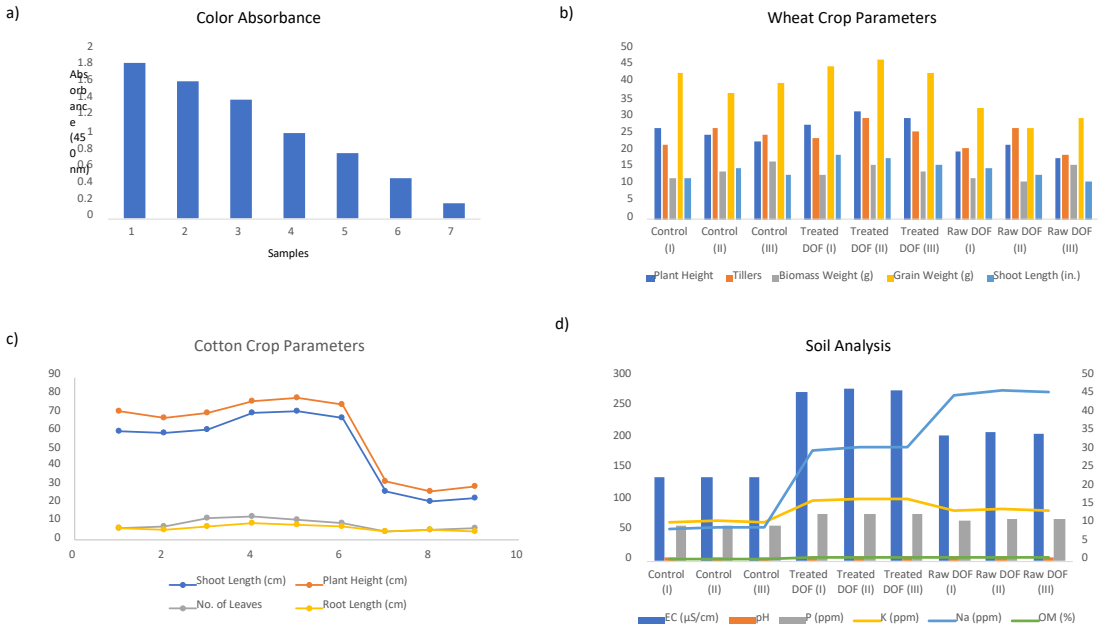

Figure 1: Analysis of a) Spectrophotometer b) Wheat Crop c) Cotton Crop d) Soil

3. Data Analysis

All collected data were subjected to statistical analysis using the statistical test of analysis of variance (ANOVA), complemented by post-hoc statistical tests, with significance being established at the level of $p<0.05$. The percentage of colour removal from the H_2O_2 treatment experiments was determined by measuring a reduction in UV-Vis absorbance at a wavelength of 450 nm, in comparison to the raw DOF.

4. Results and Discussion

4.1. Color Removal

Hydrogen peroxide oxidation was very effective in sdecolourising the DOF. At ambient pH, lower H_2O_2 concentrations (≤6%) gave only partial colour removal, about 40 to 50%. When the concentration was increased to about 10%, it resulted in about 85% decolourisation and at 12-15% H_2O_2, it resulted in almost complete decolourisation, i.e. 95-100%. These results are in agreement with other reports of (Hayase et al., 1984), who reported 97% sdecolourisation at

about 6.7% H_2O_2 in an alkaline environment. Increased concentrations of H_2O_2 aid in the oxidative degradation of high molecular weight melanoidin polymers to smaller, colourless, acidic compounds. Based on these observations, the concentration of 12% H_2O_2 at a roughly pH 7 was chosen for the treatment protocol as shown in Table 1.

Table 1: Colour Removal using H_2O_2

Sample No	H_2O_2 Added (mL of 30% stock)	H_2O_2 % (v/v)	Absorbance (450 nm)	Colour Removal (%)
1	0.25 mL	1%	1.85	~20%
2	0.50 mL	2%	1.62	~30%
3	0.75 mL	3%	1.40	~40%
4	1.50 mL	6%	1.02	~50%
5	2.00 mL	8%	0.78	~65%
6	2.50 mL	10%	0.47	~85%
7	3.00 mL	12%	0.18	~95%

4.2. Wheat Crop Growth

Wheat plants irrigated using H_2O_2-treated effluent showed good growth. The mean height of treated plants at harvest was 30 cm, while that of control plants (irrigated with water) was 25 cm and that of plants irrigated with raw DOF was significantly less (20 cm) at $p<0.05$. Correspondingly, grain weight per plant was found to be maximum in the treated group (45 g/plant), which exceeded the control group (40 g/plant) under the irrigation regime; the yield of the raw DOF application group was found to be only 30 g/plant. Tiller count and spike number also showed a similar positive trend. These observed improvements suggest that the sdecolourisation process effectively mitigated the phytotoxic effects associated with raw DOF. Furthermore, the inherent nutrient content of the treated effluent, particularly potassium and phosphorus, likely contributed to the enhanced plant growth as shown in Table 2.

Table 2: Wheat Crop Growth Parameters

Parameters	Plant Height	Spike length (cm)	No of spikes	Spikelets per spike	Tillers	Biomass Weight (g)	Grain Weight (g)	Shoot Length (in.)
Control (I)	27	6.6	24	21	22	12	43	12
Control (II)	25	4.6	29	17	27	14	37	15
Control (III)	23	8.3	23	23	25	17	40	13

Treated DOF (I)	28	13	25	41	24	13	45	19
Treated DOF (II)	32	4.6	26	16	30	16	47	18
Treated DOF (III)	30	9	29	25	26	14	43	16
Raw DOF (I)	20	7.3	18	24	21	12	33	15
Raw DOF (II)	22	4.3	32	14	27	11	27	13
Raw DOF (III)	18	7	21	22	19	16	30	11

4.3. Cotton Crop Growth

Cotton plants showed similar patterns of growth. Control cotton plants reached the average height of about 70 cm, while plants irrigated with raw DOF had a significantly shorter height (~30 cm) and showed chlorosis. On the other hand, H_2O_2-treated DOF plants had the greatest height, around 77cm. The number of leaves changed with a maximum of 13 leaves in the treated DOF and an average of 6 leaves in the untreated DOF, as shown in Table 3.

Table 3: Cotton Crop Growth Parameters

Parameters	**Shoot Length (cm)**	**Plant Height (cm)**	**No. of Leaves**	**Root Length (cm)**
Control (I)	60	71	7	7
Control (II)	59	68	8	6
Control (III)	61	70	12	8
Treated DOF (I)	70	77	13	10
Treated DOF (II)	71	79	11	9
Treated DOF (III)	68	75	10	8
Raw DOF (I)	27	33	5	5
Raw DOF (II)	22	27	6	6
Raw DOF (III)	23	30	7	5

4.4. Soil Nutrients

Post-harvest soil analysis indicated elevated nutrient levels, particularly potassium (K) and phosphorus (P), in pots that received treated effluent. Relative to the control, soils irrigated with treated DOF contained about 18% more K and 22% more P that were available. This observed

nutrient enrichment is probably caused by the presence of organic matter and minerals in the effluent. Soil pH was consistently near neutral in all treatment groups, ranging from 6.8 to 7.2, as shown in Table 4.

Table 4: Comparison of soil analysis of pre-application and post-application of effluent

Treatment	EC (µS/cm)	pH	P (ppm)	K (ppm)	Na (ppm)	OM (%)
Control (I)	137	7.05	59.0	10.7	9.0	0.82
Control (II)	136	7.02	59.6	10.9	9.3	0.83
Control (III)	138	7.04	59.1	10.8	9.1	0.84
Treated DOF (I)	275	7.08	77.0	16.5	30.0	1.25
Treated DOF (II)	280	7.10	77.9	16.8	31.2	1.28
Treated DOF (III)	278	7.07	78.2	17.0	30.8	1.29
Raw DOF (I)	205	7.00	67.5	13.8	45.0	1.05
Raw DOF (II)	210	6.98	68.2	14.1	46.5	1.07
Raw DOF (III)	208	7.01	67.9	13.9	45.8	1.06

* EC (Electrical conductivity < 4000 µS/cm is normal), P= Available Phosphorus > 14.0 is sufficient, OM= organic matter >0.86 is fine, K- extractable potassium < 80 is deficient, Na- extractable sodium <80 is safe, pH more than 8.5 refers to saline-sodic or sodic soil

5. Statistical Analysis Result

Single-factor analysis of variance (ANOVA) was used to test the significance of treatment effect in all components of the experiment. For the colour removal experiment, analysis of 7 spectrophotometric readings provided a p-value of 0.0045 confirmed that hydrogen peroxide concentrations caused statistically significant changes to the colour removal of melanoidin. In the wheat experiment, in which the measured plant's height, yield and parameters related to tilters were evaluated between treatment groups, the calculated p-value was $\mathbf{1.37 \times 10^{-14}}$, which is highly significant and the improvements are due to the application of the H_2O_2-treated effluent. Similarly, cotton growth parameters showed that the p-value is $\mathbf{2.99 \times 10^{-9}}$, which verified the positive and statistically significant impact of treated DOF irrigation. Pre- and post-harvest soil analyses also revealed highly significant variance across treatments with a p-value of $\mathbf{1.96 \times 10^{-22}}$, which confirmed that soil nutrient enrichment was highly affected by irrigation type. Overall, the low p-values across all analyses verify that the observed improvements were statistically meaningful and directly associated with the applied treatments.

6. Conclusion

Hydrogen peroxide oxidation showed significant activity in the sdecolourisation of high-strength sugar distillery effluent, with a reduction in melanoidin content of up to 95% or more under soptimised conditions. Treatment of wastewater with H_2O_2, after appropriate dilution, allowed for excellent growth of both wheat and cotton, with biomass yields comparable to and even

higher than freshwater irrigation. On the other hand, raw effluent had powerful inhibiting effects on plant development. Soil analyses also gave various supports for those essential nutrients that were potassium (K) and phosphorus (P) originating from treated effluent contributed positively to the soil fertility. Therefore, H_2O_2 treatment is a viable way to implement the use of distillery digester overflow as an important irrigation resource, while at the same time reducing environmental risks and providing valuable crop nutrients (fitting with the principles of sustainable agriculture).

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