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Seasonal variations in physico-chemical, ionic composition, biochemical, heavy metal and micronutrient status of industrial and municipal effluents in and around Guntur city: implications for water and soil quality

Y Tejaswi, T V Sridhar, B Asha Jyothi, K Srinivasulu and M Latha
Department of Soil Science and Agricultural Chemistry,
Acharya N G Ranga Agricultural University,
Agricultural College, Bapatla-522 101, Andhra Pradesh, India

ABSTRACT

This study examines the seasonal variation in physico-chemical, biochemical, heavy metal, and micronutrient characteristics of industrial and municipal effluents in and around Guntur City, and assesses their implications for water and soil quality. A total of ten effluent samples were collected during the monsoon season (August 2023) and the summer season (March 2024) and analyzed for key parameters, including pH, electrical conductivity, alkalinity, chlorides, carbonates, bicarbonates, calcium, magnesium, biological oxygen demand (BOD), chemical oxygen demand (COD), heavy metals (zinc, iron, cadmium, and lead), and selected micronutrients. The results revealed significant seasonal variations, with higher concentrations of pollutants observed during the summer season, attributable to reduced dilution and increased evaporation. These findings highlight the potential risks posed by untreated or inadequately treated effluent discharges to surrounding water bodies and agricultural soils. The study underscores the urgent need for effective wastewater treatment and management strategies, along with continuous monitoring, to prevent environmental degradation and protect public health in the region.

Keywords:*Heavy metals, Industrial effluents,Municipal effluents, Pollution, Soil quality and Water quality*

Industrial development has resulted in increased discharge of chemical effluents into natural ecosystems, leading to deterioration of environmental quality and biodiversity in many parts of India. Anthropogenic activities, coupled with the disposal of large volumes of municipal sewage, have contributed significantly to ecological imbalance. The rapid growth of industries such as textile, leather, sugar, pulp and paper, fertilizers, dyeing, chemical manufacturing, and petroleum refining has intensified the problem of improper effluent disposal, thereby causing serious environmental concerns (Islam & Mostafa, 2021b; Rahim and Mostafa, 2021; Shakil and Mostafa, 2021a; Monira *et al.,* 2022). Industrial effluents constitute a major source of urban pollution, adversely affecting both water and soil quality. Inadequate management of these effluents can result in severe environmental degradation, with direct implications for ecosystem health and agricultural productivity.

The discharge of industrial wastewater into local soils, surface waters, and stormwater drains poses substantial environmental risks (Islam and Mostafa, 2018, 2020; Saha *et al.,* 2021; Sayed and Mostafa, 2021). In this context, the present study aims to characterize the physico-chemical and biochemical properties, as well as the heavy metal and micronutrient status, of industrial and municipal effluents in and around Guntur City, with special emphasis on seasonal variations and their implications for environmental health. Understanding these seasonal fluctuations is crucial for developing effective wastewater management and mitigation strategies to protect water resources and agricultural soils. Given the importance of maintaining water quality for human consumption and ecological balance, this research underscores the need for a comprehensive assessment of factors influencing effluent composition and associated environmental risks.

MATERIAL AND METHODS

Effluent samples were collected from selected industrial and municipal discharge points during the monsoon season (August 2023) and the summer season (March 2024). Sampling locations were selected based on proximity to major industrial activities to ensure representative characterization of effluent quality. Samples were collected in one-litre polyethylene bottles that were pre-cleaned, rinsed with deionized water, and finally rinsed several times with the sample prior to collection. The collected samples were transported to the laboratory and preserved under appropriate conditions until analysis.

Physico-chemical parameters such as pH and electrical conductivity (dS m^{-1}), biochemical parameters including biochemical oxygen demand (BOD, mg L^{-1}) and chemical oxygen demand (COD, mg L^{-1}), heavy metals (cadmium and lead, mg L^{-1}), and micronutrients (zinc and iron, mg L^{-1}) were analyzed using standard analytical procedures. Statistical analysis was performed to evaluate the significance of differences between monsoon and summer seasons, enabling a comprehensive assessment of seasonal variability in effluent characteristics.

RESULTS AND DISCUSSION

pH

The values for physico-chemical parameters (pH and EC) of effluent samples during the study period Rainy (2023) and Summer (2024) seasons are presented in Table 1.

pH

The pH of effluent samples ranged from 7.12 to 7.51 during the monsoon season and from 6.83 to 7.39 during the summer season, with comparatively lower values observed in summer in samples collected from the Guntur–Budampadu region. The decline in pH during summer may be attributed to increased evaporation, enhanced decomposition of organic matter, and chemical reactions that generate acidic by-products. Since pH is a key indicator of environmental quality, even slight variations can influence the suitability of water for ecological and agricultural uses. Conversely, relatively higher pH values observed during certain periods may be associated with the discharge of alkaline detergents from residential areas and the presence of alkaline substances in industrial effluents. In addition, reduced rainfall during summer limits dilution, leading to the accumulation of acidic constituents in the effluent. Lower pH levels can adversely affect aquatic organisms and soil microbial activity, thereby disturbing ecological balance and potentially reducing biodiversity. These observations are in agreement with earlier reports by Bishoni and Roy (2010) on textile effluents from Sanganer, Rajasthan; Pia *et al.,* 2018 in Shitalakhya River waters; and Yonar *et al.,* 2018, who reported similar pH ranges in dairy effluents.

Electrical Conductivity (EC)

Effluent samples collected from the Guntur–Budampadu industrial region exhibited significantly higher electrical conductivity (EC) values during the

Table: 1. Physico-chemical properties of effluent samples collected during Rainy (2023) and Sum--mer (2024) seasons

EFFLUENT SAMPLE	pH		EC (dS m^{-1})	
	RAINY	SUMMER	RAINY	SUMMER
Effluent 1	7.44	7.39	1.53	1.93
Effluent 2	7.39	7.04	1.16	1.52
Effluent 3	7.33	7.21	1.21	1.67
Effluent 4	7.19	6.83	1.28	1.58
Effluent 5	7.18	7.08	1.3	1.65
Effluent 6	7.37	7.11	1.03	1.29
Effluent 7	7.12	6.92	1.33	2.23
Effluent 8	7.44	7.19	1.28	1.49
Effluent 9	7.51	7.12	1.32	1.91
Effluent 10	7.46	7.05	1.39	2.12
RANGE	7.12 -7.51	6.83 -7.39	1.03- 1.53	1.29-2.23
MEAN	7.34	7.09	1.28	1.73

summer season, primarily due to reduced rainfall resulting in lower dilution, coupled with increased evaporation and higher ionic concentrations. The elevated EC is further influenced by the continuous discharge of municipal and industrial wastes, which contribute substantial amounts of dissolved salts to the effluent, thereby enhancing salinity and posing risks of soil salinization and potential public health impacts when such water is used for irrigation or enters local water bodies. During the monsoon season, EC values ranged from 1.03 to 1.53 dS m^{-1}, whereas in summer they increased to between 1.29 and 2.23 dS m^{-1}. The higher salinity levels observed during summer may also be attributed to elevated temperatures that reduce freshwater inflow and limit natural land drainage. These findings are consistent with earlier studies by Saha *et al.,* 2015, Sahare *et al.,* 2014, and Hanumantarao and Dasog (2018), who reported increased soil and water EC due to irrigation with municipal and industrial wastewater. The data of the Ionic composition of effluent samples during the study period Rainy (2023) and Summer (2024) seasons are presented in Table 2.

Chlorine

Effluent samples from industrial locations between Guntur and Budampadu exhibited varying chlorine concentrations across ten samples. During the rainy season in August 2023, chlorine levels ranged from 4.64 meq L^{-1} to 7.41 meq $^{L-1}$, with an average of 6.37 meq L^{-1}. In the following summer, these levels increased, ranging from 5.84 meq L^{-1} to 8.15 meq L^{-1}, averaging 7.16 meq L^{-1}. These findings indicate consistently higher chlorine levels in summer, with all values exceeding the FAO's 1985 permitted limits. Similar trends were observed in studies by Venkatesan et al., 2016, Afzal *et al*., 2018, Pia *et al*., 2018, and Monira *et al*., 2024, where chlorine levels were higher before the rainy season. The elevated chlorine levels during summer in municipal and industrial areas are attributed to increased industrial activity, warmer temperatures accelerating compound breakdown, and reduced water flow, leading to the concentration of chlorinated substances. The consumption of untreated water from these sources poses a potential health risk, underscoring the need for pre-treatment before use.

Carbonates and Bicarbonates

Effluent samples from the industrial area between Guntur and Budampadu showed varying carbonate and bicarbonate levels, with concentrations higher in summer than in the rainy season. In August 2023 (rainy season), carbonate levels averaged 0.89 meq L^{-1} and bicarbonate 8.49 meq L^{-1}, while in March 2024 (summer), these averages increased to 1.24 meq L^{-1} and 9.19 meq L^{-1}, respectively. These levels exceeded FAO (1985) limits. The findings align with studies by Bincy *et al.,* 2015 and Monira *et al*., 2024, which also reported higher carbonate and bicarbonate levels in textile effluents, attributed to atmospheric CO, interacting with water and increased evaporation in summer. This elevated alkalinity poses

Table 2. Ionic Composition of effluent samples collected during Rainy (2023) and Summer (2024) season

EFFLUENT SAMPLE	Cl^{-1} (meq L^{-1})		CO_3^{-2} (meq L^{-1})		HCO_3^- (meq L^{-1})		Ca^{+2} (meq L^{-1})		Mg^{+2} (meq L^{-1})	
	RAINY	SUMMER	RAINY	SUMMER	RAINY	SUMMER	RAINY	SUMMER	RAINY	SUMMER
Effluent 1	5.41	6.61	0.84	1.92	9.87	10.9	4.66	5.26	4.47	4.71
Effluent 2	4.64	5.84	0.77	0.84	8.22	9.84	5.81	6.98	5.69	5.99
Effluent 3	6.25	7.78	0.82	1.15	10.2	10.7	7.23	7.67	8.39	8.78
Effluent 4	6.68	6.92	0.89	1.19	10.4	10.9	6.6	6.93	4.61	5.14
Effluent 5	7.41	7.79	1.21	1.42	8.63	8.81	8.48	8.33	5.82	6.02
Effluent 6	5.21	6.4	0.76	0.96	5.88	6.13	7.42	7.79	5.85	6.11
Effluent 7	6.8	7.33	0.87	1.18	8.21	8.35	7.87	8.92	4.29	4.96
Effluent 8	7.02	8.15	0.88	1.29	8.6	9.53	7.82	8.18	3.41	3.22
Effluent 9	6.24	6.87	0.71	0.91	7.27	7.81	8.01	8.8	4.23	4.58
Effluent 10	7.16	7.91	1.23	1.58	7.67	8.97	7.45	7.73	5.87	6.67
RANGE	4.64-7.41	5.84-8.15	0.71-1.23	0.84-1.92	5.88-10.4	6.13-10.9	4.66-8.48	5.26-8.92	3.41-8.39	3.22-8.78
MEAN	6.37	7.16	0.89	1.24	8.49	9.19	7.41	7.65	5.26	5.61

risks to aquatic life, potentially reducing biodiversity, especially in areas impacted by municipal sewage discharge.

Calcium and Magnesium

The analysis of calcium (Ca^{2+}) and magnesium (Mg^{2+}) concentrations in the studied area shows significant variability. In August 2023 (rainy season), average calcium levels were 7.41 meq L^{-1} (range: 4.66-8.48), and magnesium averaged 5.26 meq L^{-1} (range: 3.41-8.39). By March 2024 (summer), calcium levels increased to an average of 7.65 meq L^{-1} (range: 5.26-8.92), while magnesium averaged 5.61 meq L^{-1} (range: 3.22-8.78). These variations indicate the influence of natural mineral deposits and industrial activities. Elevated magnesium levels exceeded FAO (1985) permissible limits due to surface water contamination from industrial effluents. These findings align with studies by Varma and Jyothi (2011), Faridullah *et al*., 2017, and Monira *et al.,* 2024, which reported higher values in pre-rainy periods and effluent samples. The increased Ca and Mg levels in summer result from reduced dilution from lower rainfall and increased evaporation concentrating dissolved minerals.

BOD and COD

Effluent samples from the study area exhibited considerable variation in biochemical oxygen demand (BOD) and chemical oxygen demand (COD) across seasons. BOD values ranged from 160 to 360 mg L^{-1} during the monsoon season and increased to 184–414 mg L^{-1} in the summer season. Similarly, COD ranged from 324 to 680 mg L^{-1} in the monsoon and rose to 373–782 mg L^{-1} during summer. These elevated BOD and COD values indicate a high organic load and the presence of diverse chemically oxidizable substances in the effluents. In both seasons, the observed concentrations exceeded the permissible limits prescribed by FAO (1985), reflecting severe organic pollution. The higher levels recorded during summer can be attributed to reduced dilution, higher temperatures, and increased microbial decomposition of organic matter. Such elevated contamination poses serious risks to aquatic ecosystems, deteriorates water quality in receiving bodies, and may adversely affect public health if the water is reused for agricultural or domestic purposes. Hence, the findings emphasize the urgent need for effective wastewater treatment, strict regulatory control, and continuous monitoring of effluent discharges. Similar trends of elevated BOD and COD in industrial and agricultural effluents have been reported by Sharada *et al.,* 2014, Noorjhan and Sheeba (2017), and Pia *et al.,* 2018, supporting the present observations. Data pertaining to micronutrient and heavy Metal composition was depicted in Table 4

Micronutrient Composition

Effluent samples from the industrial zone between Guntur and Budampadu showed varying concentrations of iron (Fe) and zinc (Zn). In August

Table 3. Biochemical properties of effluent samples collected during Rainy (2023) and Summer (2024) seasons

EFFLUENT SAMPLE	BOD (mg L^{-1})		COD (mg L^{-1})	
	RAINY	SUMMER	RAINY	SUMMER
Effluent 1	228	253	578	664
Effluent 2	160	184	446	513
Effluent 3	284	322	552	635
Effluent 4	202	230	324	373
Effluent 5	240	276	340	391
Effluent 6	360	414	520	598
Effluent 7	182	207	668	768
Effluent 8	220	253	540	621
Effluent 9	184	207	592	681
Effluent 10	246	276	680	782
RANGE	160-360	184-414	324-680	373-782
MEAN	231	262	524	603

Table 4. Micronutrients and Heavy metals concentration of effluent samples collected during Rainy (2023) and Summer (2024) seasons

EFFLUENT SAMPLE	Fe (mg L^{-1})		Zn (mg L^{-1})		Pb (mg L^{-1})		Cd (mg L^{-1})	
	RAINY	SUMMER	RAINY	SUMMER	RAINY	SUMMER	RAINY	SUMMER
Effluent 1	4.54	4.68	1.43	3.05	0.45	0.68	0.144	0.205
Effluent 2	2.61	5.57	1.15	2.25	0.68	0.45	0.052	0.074
Effluent 3	3.9	8.32	1.3	2.77	0.49	0.69	0.018	0.025
Effluent 4	4.21	6.98	1.25	2.46	0.57	0.42	0.121	0.173
Effluent 5	3.86	5.23	1.11	2.36	0.61	0.63	0.135	0.193
Effluent 6	2.59	5.52	1.05	2.24	0.42	0.49	0.156	0.223
Effluent 7	4.36	5.3	1.13	2.41	0.67	0.67	0.26	0.371
Effluent 8	1.58	3.37	1.32	2.81	0.48	0.45	0.019	0.027
Effluent 9	2.53	5.39	1.37	2.9	0.53	0.58	0.154	0.22
Effluent 10	4.29	5.15	1.11	2.06	0.69	0.66	0.015	0.021
RANGE	1.58-4.54	3.37-8.32	1.05-1.43	2.06-3.05	0.42-0.69	0.42-0.69	0.015-0.260	0.021-0.371
MEAN	3.44	5.55	1.22	2.53	0.55	0.57	0.107	0.153

2023 (rainy season), iron levels averaged 3.44 mg L^{-1}, increasing to 5.55 mg L^{-1} in March 2024 (summer). Zinc concentrations averaged 1.22 mg L^{-1} in the rainy season and 2.53 mg L^{-1} in summer 2024. Iron levels exceeded BIS (2011) limits, while zinc remained acceptable. The high iron contamination in groundwater necessitates urgent mitigation measures, likely due to soil accumulation near textile effluents and corroded iron from sewage. The use of metal-based dyes in the textile industry contributes significantly to these levels. Studies by Rattan *et al*., 2005, Kharache *et al*., 2011, and Kumar *et al.,* 2016 indicate that sewage effluent often contains elevated zinc and iron levels, consistent with previous findings of increased concentrations during the pre-rainy season compared to the post-rainy season.

Heavy Metal Composition

Lead (Pb) concentrations in the sampled water ranged from 0.42 to 0.69 mg L-1, averaging about 0.55 mg L^{-1} in the rainy season and 0.57 mg L^{-1} in summer, while cadmium (Cd) levels varied from 0.015 to 0.260 mg L^{-1}, averaging 0.107 mg L^{-1} in the rainy season and 0.153 mg L^{-1} in summer. Pb is within acceptable limits, but Cd exceeds FAO (1985) critical limits. Surface water quality is compromised by unplanned industrial development, effluent discharge, and excessive agrochemical use. Although industrialization enhances employment and living standards, effective wastewater treatment is crucial. Heavy metals likely stem from metal-based dyes in the textile industry, posing toxicity risks and accumulating in the food chain. These findings are consistent with research by Khan *et al.,* 2022, Marofia *et al*., 2015, Kabir *et al.,* 2020, and Arti and Mehra (2023), which reported elevated levels of Cd, Cr, and Pb, particularly in the pre-rainy season, with increased summer concentrations linked to intensified industrial activities and higher temperatures.

CONCLUSION

Effluent samples collected from the industrial corridor between Guntur City and the Budampadu region present a concerning scenario with respect to water quality. The assessment of physico-chemical, biochemical, heavy metal, and micronutrient parameters clearly indicates that effluent quality deteriorates significantly during the summer season compared to the monsoon period. Elevated concentrations of electrical conductivity, alkalinity, chlorides, carbonates, bicarbonates, calcium, magnesium, biochemical oxygen demand (BOD), chemical oxygen demand (COD), zinc, iron, cadmium, and lead were consistently observed in summer samples. This seasonal pattern reflects the intensified impact of industrial and municipal discharges under conditions of reduced dilution and higher evaporation rates.

These findings highlight the substantial contribution of industrial activities to the degradation of surface water quality in the study area, posing potential risks to aquatic ecosystems, soil health, and human populations through irrigation reuse and environmental exposure. Therefore, the study emphasizes the urgent need for strict enforcement of effluent discharge standards, implementation of efficient wastewater treatment technologies, and establishment of regular monitoring programs. Such measures are essential to mitigate environmental contamination and to ensure the long-term protection and sustainable management of water resources in the region.

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