

Physicochemical Assessment of Industrial Wastewater Discharges in Hayatabad Industrial Estate, Peshawar, Pakistan: An Emerging Pollution Predicament

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ABSTRACT

Industrial wastewater is a major contributor to environmental degradation, posing significant risks to water resources, aquatic ecosystems, and public health. This study conducted a comprehensive physico-chemical analysis of effluent discharges from the Hayatabad Industrial Estate (HIE) in Peshawar, Pakistan, to assess compliance with Pakistan's National Environmental Quality Standards (NEQS). Ten wastewater samples were collected from key industrial discharge points and analyzed for critical parameters, including pH, Electrical Conductivity (EC), Total Dissolved Solids (TDS), Total Suspended Solids (TSS), total hardness, alkalinity, calcium, magnesium, chloride, and Biological Oxygen Demand (BOD). The results revealed severe contamination, with the majority of parameters exceeding NEQS permissible limits. Notably, mean concentrations of key pollutants were significantly elevated: chloride (1673 mg/L vs. 1000 mg/L NEQS), BOD (181 mg/L vs. 80 mg/L

NEQS), and TSS (246 mg/L vs. 150 mg/L NEQS). The findings conclusively demonstrate that the untreated and partially treated effluents from HIE constitute a serious pollution threat, endangering the ecological health of the Kabul River and the productivity of adjacent agricultural lands. This study underscores the urgent necessity for the installation and operation of centralized effluent treatment plants, coupled with stringent regulatory oversight and enforcement, to curb ongoing environmental damage.

Keywords: Industrial Effluent, Water Pollution, Physico-Chemical Parameters, NEQS, Hayatabad, Wastewater Treatment.

Introduction

Water is an indispensable natural resource, critical for ecological balance and human survival. However, rapid industrialization and urbanization have led to the contamination of freshwater resources, primarily through the discharge of untreated industrial and municipal wastewater (Tariq and Mushtaq, 2023). Globally, industrial wastewater has been recognized as a major source of environmental contamination due to its complex composition of hazardous chemicals, dyes, oils, and toxic heavy metals. Untreated effluents not only alter the physical and chemical properties of receiving water bodies but also cause eutrophication, biodiversity loss, and bioaccumulation of toxic elements in the food chain. The lack of efficient wastewater treatment infrastructure in most industrial zones of South Asia makes the issue more pronounced, as pollutants are directly released into natural ecosystems without prior treatment.

In developing countries like Pakistan, where water scarcity is escalating, the pollution of existing water bodies exacerbates the crisis, leading to severe public health and agricultural challenges (Batool and Shahzad, 2025). The Hayatabad Industrial Estate (HIE), established in 1963, is a major industrial hub in Peshawar, Khyber Pakhtunkhwa. It hosts over 240 functional industries across sectors including pharmaceuticals, textiles, ghee, steel, and plastics. A significant environmental concern is the direct discharge of untreated effluents from these industries into the Budni Nullah, which ultimately converges with the Kabul River (Tariq et al., 2006; Rehman et al., 2016, Ullah.,2019). This practice introduces a high load of pollutants, including heavy metals, organic matter, and suspended solids,

degrading water quality and threatening aquatic life and human health.

Previous studies on HIE have highlighted pollution issues but often with limited scope or outdated data (Khan et al., 2002; Tariq et al., 2006). This study aimed to provide a current and comprehensive assessment of the physico-chemical quality of HIE's wastewater, evaluate its compliance with national environmental standards, and discuss the potential ecological and health implications of its uncontrolled discharge.

In Pakistan, the environmental monitoring of industrial estates remains inadequate, and enforcement of effluent treatment regulations is weak. The National Environmental Quality Standards (NEQS) provide permissible limits for key wastewater parameters, but many industries continue to violate these standards due to poor regulatory oversight and the absence of functional effluent treatment plants (ETPs) (Pak-EPA, 2000; WWF, 2017). Assessing the current status of wastewater discharge from HIE is therefore crucial for understanding its contribution to regional water pollution, providing scientific evidence for policymakers, and proposing mitigation strategies to safeguard both ecological integrity and public health.

Materials and Methods

Study Area Description

The Hayatabad Industrial Estate (HIE) (geographical coordinates approximately 34.0109° N, 71.5060° E) is a premier industrial zone situated northwest of Peshawar, the capital of Khyber Pakhtunkhwa, Pakistan. Established in 1963, the estate spans an area of approximately 868 acres and hosts a diverse range of industries, including pharmaceuticals, textiles, ghee and cooking oil, steel fabrication, plastics, chemicals, and marble processing (Khan, 2019). A critical environmental concern is the estate's drainage system. Industries discharge untreated or partially treated effluents into a network of open drains that converge into a primary channel, the Budni Nullah. This nullah ultimately discharges into the Kabul River, a major transboundary river system, thereby posing a significant pollution risk to downstream aquatic ecosystems, agricultural lands, and communities reliant on the river for irrigation and other purposes (Tariq et al., 2006).

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Sampling Strategy and Protocol

A systematic wastewater sampling campaign was conducted in March 2023 during peak operational hours (10:00–14:00) to capture a representative pollutant profile from the Hayatabad Industrial Estate (HIE). Ten strategic sampling points were selected, comprising seven industrial point sources pharmaceutical (S1), textile (S2), ghee (S3), steel (S4), plastic (S5), and two chemical plants (S6, S7) and three mixed-source locations along the main drain, including intermediate (S8, S9) and final discharge points (S10). Sampling followed APHA (2017) standards using pre-cleaned 1-L HDPE bottles, rinsed with sample water before collection. Samples for BOD and microbial analysis were immediately preserved at 4°C in dark coolers, while metals samples were acidified to pH < 2 with HNO₃. All samples were transported to the laboratory within 4 hours for analysis.

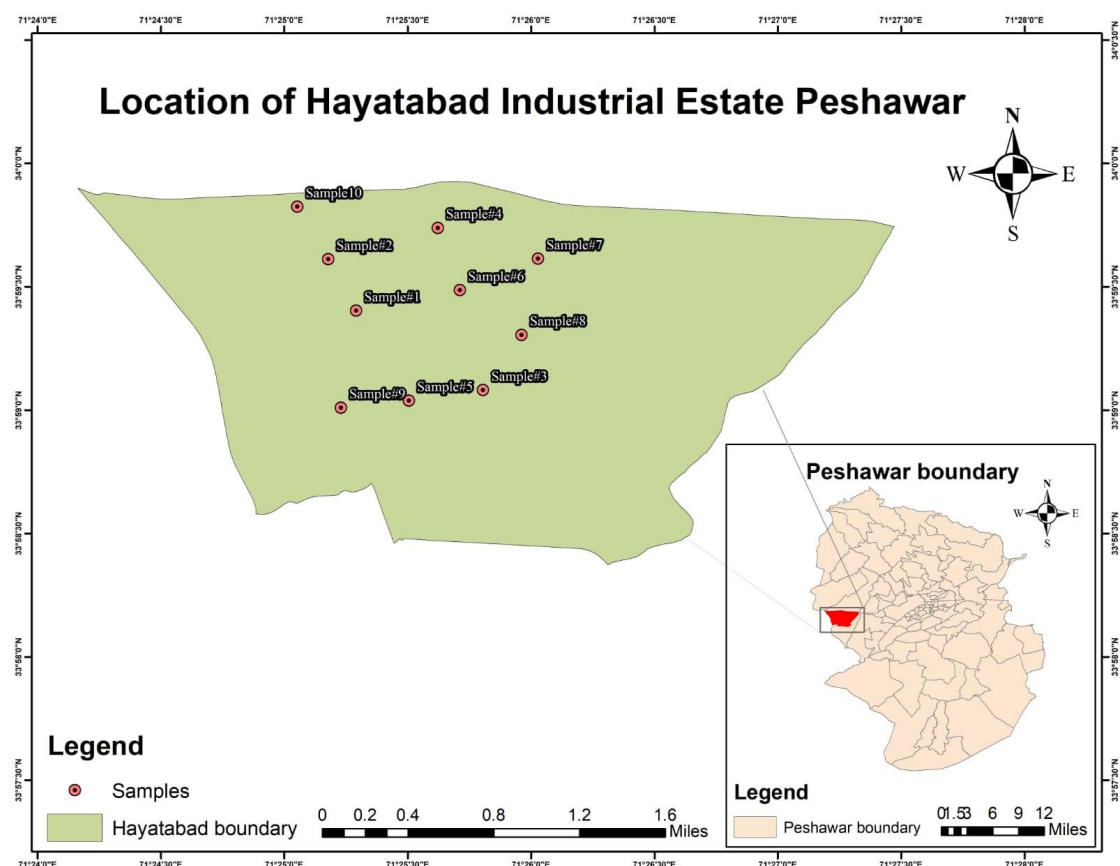


Figure 1: A map of the Study Area; the locations of the ten (10) wastewater sampling points.

Physical and Chemical Analysis

pH

The pH of water samples was measured potentiometrically using a calibrated portable pH meter following Standard Method 4500-H⁺ B. Regular calibration was carried out with standard buffer solutions (pH 4.0, 7.0, and 10.0) to ensure accuracy.

Electrical Conductivity (EC)

Electrical conductivity was determined using a conductivity meter equipped with a temperature compensation probe in accordance with Method 2510 B. The instrument was standardized with potassium chloride (KCl) solutions of known conductivity prior to measurement.

Total Dissolved Solids (TDS)

TDS was estimated from EC values using an appropriate conversion factor or measured directly by gravimetric analysis. For gravimetric determination, filtered samples were evaporated at 103–105 °C and the residue was weighed, following Method 2540 C.

Total Suspended Solids (TSS)

TSS was analyzed gravimetrically by filtering a known volume of water through a pre-washed and pre-weighed glass fiber filter (0.45 µm pore size). The retained residue was dried to a constant weight at 103–105 °C, following Method 2540 D.

Chemical Parameters

Total hardness was measured to determine the concentration of calcium and magnesium ions in the water samples. It was determined by titration with EDTA, using Eriochrome Black T as an indicator, which changed from wine-red to blue at the endpoint. This value was crucial as hardness affects soap efficiency and can cause scale formation. Results were standardized and expressed as mg/L of calcium carbonate (CaCO₃). The analysis followed the standard procedure outlined in APHA Method 2340 C.

Total Alkalinity

Total alkalinity was quantified to assess the water's capacity to neutralize acids. It was measured by titration with standard sulfuric acid to a fixed pH endpoint of 4.5. A mixed bromocresol green-methyl red indicator provided a clear color change from

green to pink at the endpoint. This parameter was vital for assessing buffering capacity. Results were reported as mg/L of CaCO_3 according to APHA Method 2320 B.

Calcium (Ca^{2+})

Calcium concentration was specifically measured by titration with EDTA using murexide as an indicator. This indicator formed a pink complex with calcium ions that turned purple at the titration endpoint. Determining calcium levels was important for understanding water scale potential. The result was calculated and expressed as mg/L of calcium carbonate (CaCO_3) for uniformity. The approved method for this test was APHA 3500-Ca B.

Magnesium (Mg^{2+})

Magnesium concentration was not measured directly but was derived mathematically. It was calculated as the difference between the total hardness and the calcium hardness. This value represented the portion of total hardness specifically attributable to magnesium ions. Its concentration was expressed as mg/L of calcium carbonate (CaCO_3). This calculation was performed as described in APHA Method 3500-Mg B.

Chloride (Cl^-)

Chloride was analyzed by argentometric titration with a standard silver nitrate solution. Potassium chromate was used as an indicator, forming a red silver chromate precipitate after all chloride ions had reacted. The result was directly reported in mg/L of chloride ion (Cl^-). The procedure was rigorously defined by APHA Method 4500-Cl B.

Biological Oxygen Demand (BOD)

BOD was measured to determine the amount of oxygen consumed by microorganisms to decompose organic matter. It was determined by comparing the dissolved oxygen concentration before and after a five-day incubation period at 20°C . This key parameter indicated the level of biodegradable organic pollution. The result was reported as the oxygen consumed in mg/L. The standard test method used was the BOD_5 test, APHA 5220 B.

Results and Discussion

The physico-chemical parameters of wastewater collected from the Industrial Estate Peshawar were analyzed to assess their compliance with the permissible limits set by the Pakistan National Environmental Quality Standards (Pak-NEQS). Samples were collected from different sites within the estate and subjected to laboratory analysis. The results were compared with the regulatory thresholds to evaluate potential environmental and public health implications.

Physical Parameters

pH

In the present study, the pH of industrial effluents ranged between 6.02 and 7.19, with minor variations among sampling sites. According to Pak-NEQS, the permissible range for pH is 6.5–8.5. The findings reveal that most samples fall within the acceptable range, although values recorded at the lower end (6.02) indicate slightly acidic conditions, which may be attributed to the discharge of untreated effluents containing acidic compounds from certain industries (Figure 2). Maintaining pH within the permissible range is crucial, as it acts as a master variable controlling chemical and biological process in wastewater. Acidic conditions, commonly resulting from untreated industrial discharges such as those from metal plating or textile processing, increase the solubility and bioavailability of toxic heavy metals (Nguyen et al., 2023). This elevates ecological risks and threatens public health. Additionally, low pH can inhibit microbial activity, impairing biological treatment efficiency (Nishan et al., 2024), and complicating safe wastewater reuse (Liu et al., 2024). Although most samples complied with standards, localized acidity underscores the need for targeted pretreatment and continuous monitoring. Mandatory on-site neutralization is essential to mitigate adverse impacts and protect water bodies, particularly in developing urban areas like Peshawar (Sharif et al., 2025).

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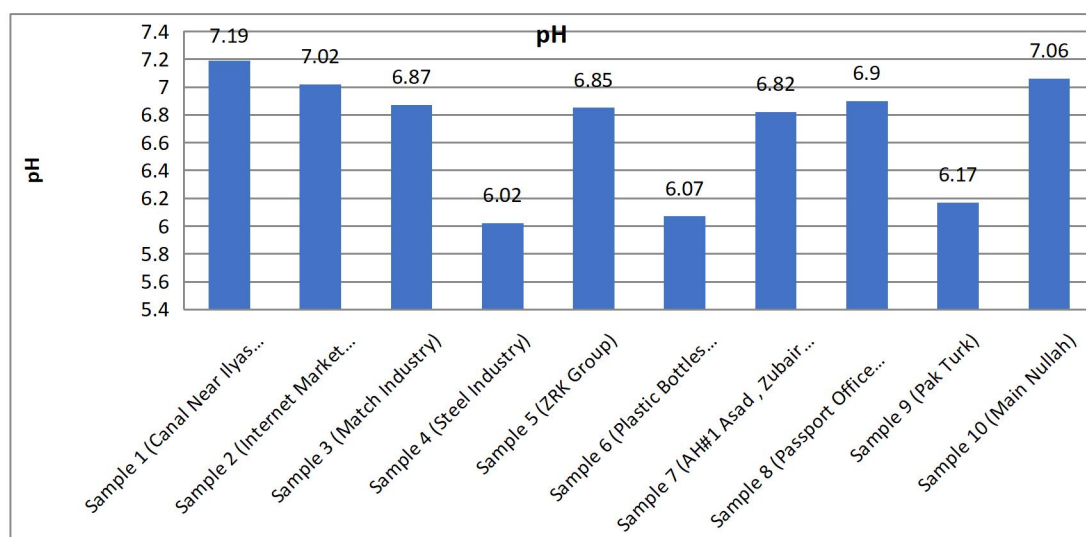
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Figure 2. pH levels of industrial effluent samples collected from different industries and discharge points in Hayatabad Industrial Estate (HIE), Peshawar.

Electrical Conductivity (EC)

In the present study, EC values of industrial effluents ranged from 642 to 1900 $\mu\text{S}/\text{cm}$. The lowest conductivity was recorded in effluents from ZRK (642 $\mu\text{S}/\text{cm}$), whereas the highest value was observed in the Match industry (1900 $\mu\text{S}/\text{cm}$). According to Pak-NEQS, the permissible limit for EC is 1500 $\mu\text{S}/\text{cm}$. Five samples fell within the acceptable range, while the remaining exceeded the standard, indicating localized high salinity levels (Figure. 3).

The elevated EC values, particularly in the Match industry effluent, may be attributed to the discharge of concentrated salts and inorganic chemicals used during manufacturing processes. High conductivity in wastewater can adversely affect aquatic life by increasing osmotic stress and can also limit the reuse of such effluents for irrigation due to risks of soil salinization and reduced crop productivity (Lemessa et al., 2023). Conversely, the lower EC values observed in ZRK effluents suggest relatively lower salt loads, possibly due to better wastewater management or less use of ionizing agents.

The electrical conductivity (EC) of the effluents, ranging from 642 to 1900 $\mu\text{S}/\text{cm}$, indicates significant variation in ionic pollution. While five samples complied with the Pak-NEQS limit of 1500 $\mu\text{S}/\text{cm}$, the exceedance by others, particularly the

high value from the Match industry (1900 $\mu\text{S}/\text{cm}$), points to the direct discharge of inorganic salts and ionic compounds from manufacturing processes (Monira et al., 2023). Such elevated salinity imposes osmotic stress on aquatic ecosystems and poses a serious risk for agricultural reuse due to the potential for soil salinization (Langeveld et al., 2023). The lower EC value from ZRK (642 $\mu\text{S}/\text{cm}$) suggests effective waste management or a less chemical-intensive operation. These findings underscore the necessity for targeted treatment strategies, such as desalination or ion exchange, in high-load industries to mitigate environmental impacts and enable safe water reuse.

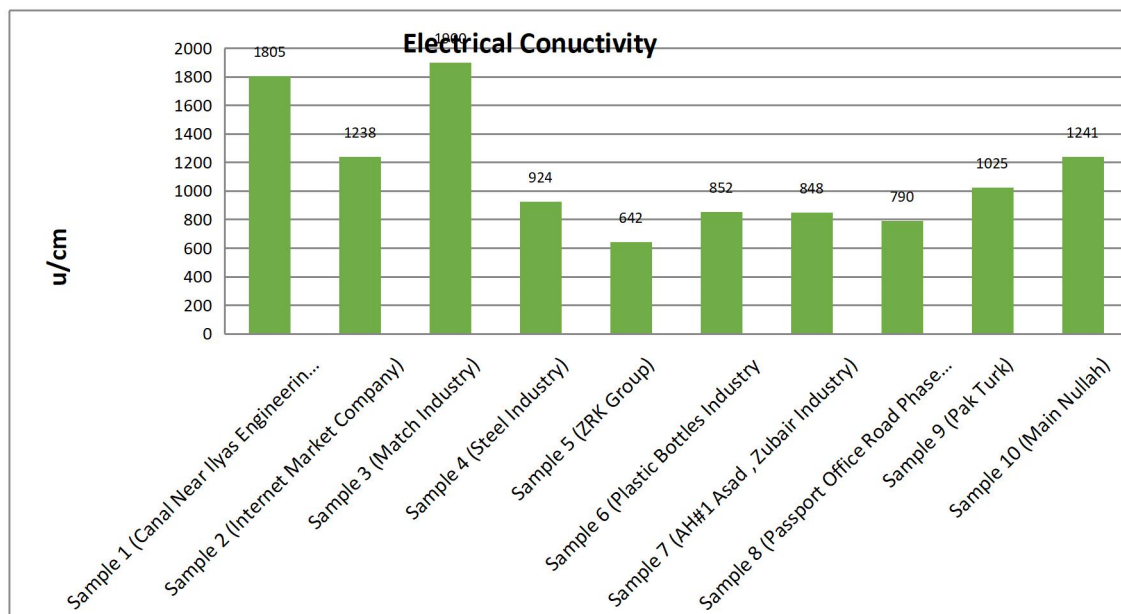


Figure 3. Electrical conductivity of industrial effluent samples collected from different industries and discharge points in Hayatabad Industrial Estate (HIE), Peshawar.

Total Dissolved Solids (TDS)

In the present study, TDS concentrations in industrial effluents ranged from 321 to 950 mg/L. The highest concentration (950 mg/L) was recorded in effluents from Ilyas Industry, whereas the lowest concentration (321 mg/L) was observed in ZRK effluents. According to water quality classification standards, TDS levels less than 300 mg/L are considered excellent, 300–600 mg/L good, 600–900 mg/L fair, 900–1200 mg/L poor, and values exceeding 1200 mg/L unacceptable. Based on this classification, some samples in the current study fell within the “good” category,

while others were classified as “fair” or “poor” (Fig 4). The concentration of total dissolved solids (TDS) is a critical parameter for assessing wastewater quality, as it reflects the load of dissolved inorganic salts and organic matter. These constituents significantly influence the water's chemical properties and its potential for reuse (APHA, 2017). In this study, TDS values in industrial effluents from the Peshawar Industrial Estate ranged from 321 mg/L to 950 mg/L. The highest concentration was recorded in effluent from Ilyas Industry, while the lowest was found in samples from ZRK. According to standard water quality classifications (WHO, 2017), this range spans from "good" to "poor," indicating considerable variability in the pollution load among different industries.

The elevated TDS level in Ilyas Industry's effluent (950 mg/L) suggests a significant discharge of soluble salts, likely originating from detergents, dyes, and other chemical residues common in manufacturing processes. Although this value remains below the critical Pak-NEQS threshold of 1200 mg/L, it may still adversely affect aquatic ecosystems by altering osmotic balance, increasing hardness, and reducing dissolved oxygen (Daud et al., 2017). Furthermore, such high TDS levels pose a salinity hazard to agricultural soils, potentially reducing permeability, causing nutrient imbalances, and diminishing crop productivity (Pushpalatha et al. 2022; Mohanavelu et al., 2021).

In contrast, the lower TDS value in the ZRK effluent (321 mg/L) indicates minimal salt loading. This may result from less chemically intensive industrial processes or more effective wastewater management practices. This finding aligns with previous studies by Hussain et al. (2012), who reported variable TDS concentrations in the region's effluents, noting that untreated discharges often exceeded acceptable limits while partially treated effluents were comparatively lower. Ahmed et al. (2022) also documented elevated TDS levels in the Kabul River, linking them to unregulated industrial and urban discharges.

From a public health perspective, while no samples exceeded the maximum permissible limit of 1200 mg/L, the "fair" to "poor" quality of several effluents necessitates caution. The long-term discharge of such wastewater into surface or groundwater can degrade drinking water sources, impart an undesirable taste, and pose health risks to dependent populations (Akhtar et al., 2021).

Although the TDS levels in the Peshawar Industrial Estate effluents comply with the regulatory threshold, the upper-range values indicate a concerning cumulative pollution burden. This burden carries potential long-term environmental and agricultural consequences. Therefore, the implementation of effective wastewater treatment technologies, coupled with stringent periodic monitoring, is essential to mitigate salinity-related risks and ensure sustained compliance with environmental standards (Shoda and Murphy, 2022).

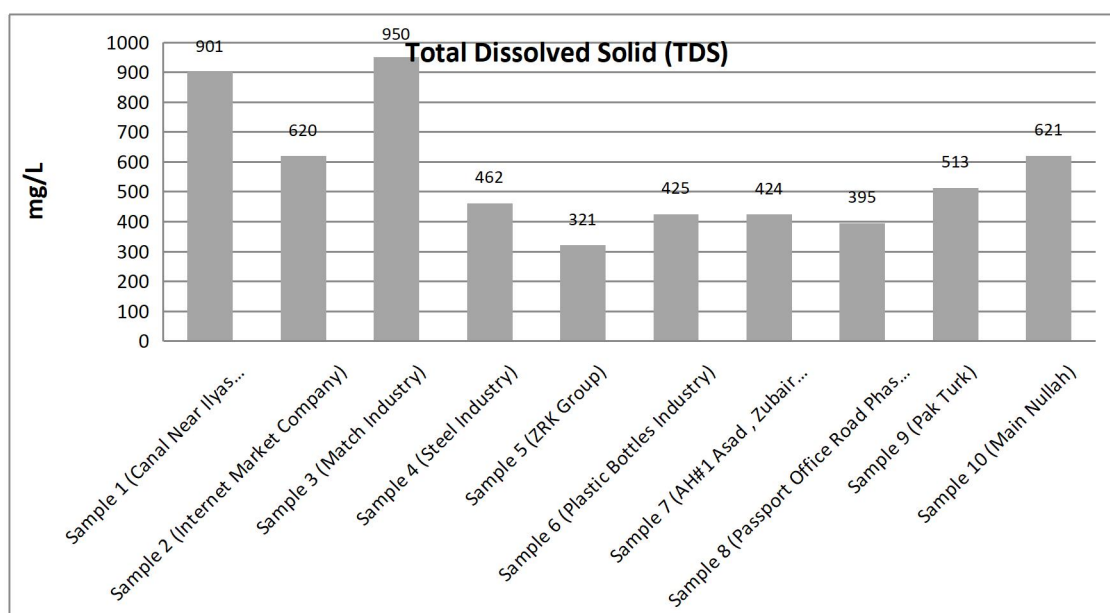


Figure 4. Total Dissolved Solids (TDS) in industrial effluent samples from Hayatabad Industrial Estate (HIE), Peshawar

Total Suspended Solids (TSS)

The concentration of total suspended solids (TSS) in the analyzed industrial wastewater samples ranged from 160 mg/L to 380 mg/L (Figure 4.1.4). The highest TSS value was observed in the effluent from the Steel Industry, while the lowest was recorded in the sample from the Internet Market Company. Critically, all measured TSS values exceeded the permissible limit of 150 mg/L established by the National Environmental Quality Standards (NEQS) (Figure 5). The elevated levels of total suspended solids (TSS) found across all industrial effluent samples represent a significant cause for environmental concern. The consistent exceedance of the NEQS limit of 150 mg/L indicates a widespread issue regarding solid waste management and wastewater treatment within the sampled industries.

The markedly high TSS load (380 mg/L) in the effluent from the Steel Industry is likely attributable to processes such as metal cutting, grinding, and washing, which generate fine metallic particles, rust, and other insoluble inorganic debris (Marangi et al., 2025). Without adequate filtration or sedimentation units, these solids are easily carried into wastewater streams. Conversely, the relatively lower (though still non-compliant) TSS level from the Internet Market Company (160 mg/L) suggests a different pollution profile, potentially stemming from organic matter, dust, or packaging materials, but still underscores a lack of proper pretreatment.

High concentrations of suspended solids have severe detrimental effects on aquatic ecosystems. Firstly, they increase water turbidity, which reduces the penetration of sunlight. This impedes photosynthesis, thereby disrupting the growth of aquatic plants and phytoplankton, which form the base of the food web (Lakshmikandan et al., 2024). Secondly, as these solids settle, they can smother the river or lake bed, destroying benthic habitats and spawning grounds for fish and invertebrates. The decomposition of organic suspended matter consumes dissolved oxygen, potentially creating hypoxic (low-oxygen) conditions that are lethal to most aquatic life.

From a public health and infrastructure perspective, discharging TSS-laden effluent is problematic. It can clog irrigation channels, reduce the efficacy of disinfection processes in water treatment plants (as pathogens can attach to particles), and impair the aesthetic quality of water bodies (WHO, 2017). For downstream communities, it increases the cost of potable water treatment (Siswanto, 25).

The universal exceedance of the regulatory limit highlighted in this study necessitates urgent intervention. It strongly indicates either the absence of or inadequacies in primary treatment systems, such as clarifiers, sedimentation tanks, or filters, across these industries. This finding aligns with other studies on industrial pollution, which frequently identify non-compliance with TSS standards as a primary pollutant due to the neglect of basic treatment steps (Hussain et al., 2012).

The pervasive violation of TSS standards poses a direct threat to aquatic life and water quality. There is an imperative need for regulatory bodies to enforce the implementation of effective primary wastewater treatment technologies across all

industries. Mandating the use of settling tanks, dissolved air flotation (DAF) units, or sand filters would significantly reduce the TSS load, representing a critical first step towards compliance and environmental protection (PAK, EPA, 2000).

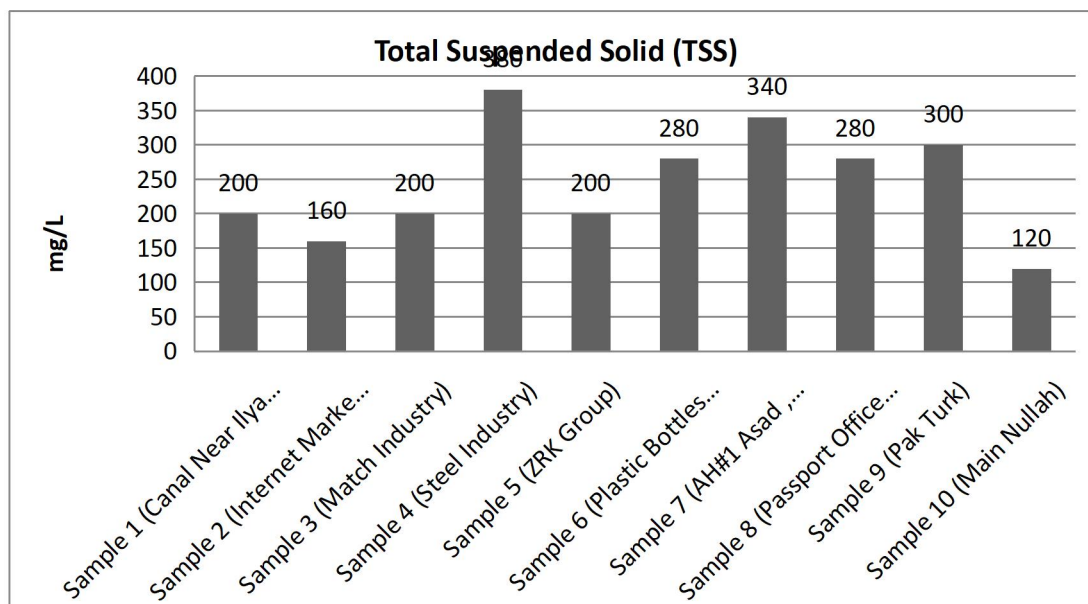


Figure 5. Total Dissolved Solids (TDS) in industrial effluent samples from Hayatabad Industrial Estate (HIE), Peshawar

Chemical Parameters

Total Hardness

Total hardness of water is primarily caused by the presence of dissolved calcium (Ca^{2+}) and magnesium (Mg^{2+}) ions. According to water quality classification, water with less than 50 mg/L hardness is considered soft, 50–150 mg/L moderately hard, 150–300 mg/L hard, and values above 300 mg/L very hard. In the present study, the total hardness of industrial effluents ranged from 120 to 380 mg/L. The highest value (380 mg/L) was recorded in the effluent from the Steel Industry, placing it in the very hard category.

The lowest hardness value (120 mg/L) was observed in the Main Nullah sample, which falls under the moderately hard category (Figure 6). These variations indicate significant differences in calcium and magnesium content among the effluents of different industries, with some exceeding the recommended safe limits for discharge. Elevated hardness in wastewater can contribute to scaling problems in pipelines and treatment plants, while also reducing the efficiency of detergents and

increasing operational costs. The total hardness of the industrial effluents, ranging from 120 mg/L to 380 mg/L, indicates variable mineral pollution across sampling sites. The Steel Industry effluent was classified as very hard (380 mg/L), a characteristic feature of metal processing operations where activities such as acid pickling, descaling, and cooling systems promote leaching of calcium and magnesium ions (Ullah 2009; Ingin et al., 2024).

In contrast, the Main Nullah sample showed moderate hardness (120 mg/L), likely resulting from dilution by other water sources, though still indicative of cumulative industrial discharge. Elevated hardness poses multiple environmental risks, including causing osmotic stress to aquatic organisms adapted to specific ionic conditions and reducing the efficacy of soaps and detergents. Furthermore, high concentrations of calcium and magnesium can influence the solubility and bioavailability of co-occurring contaminants such as heavy metals, potentially modifying their ecological toxicity (Mohammed et al., 2024).

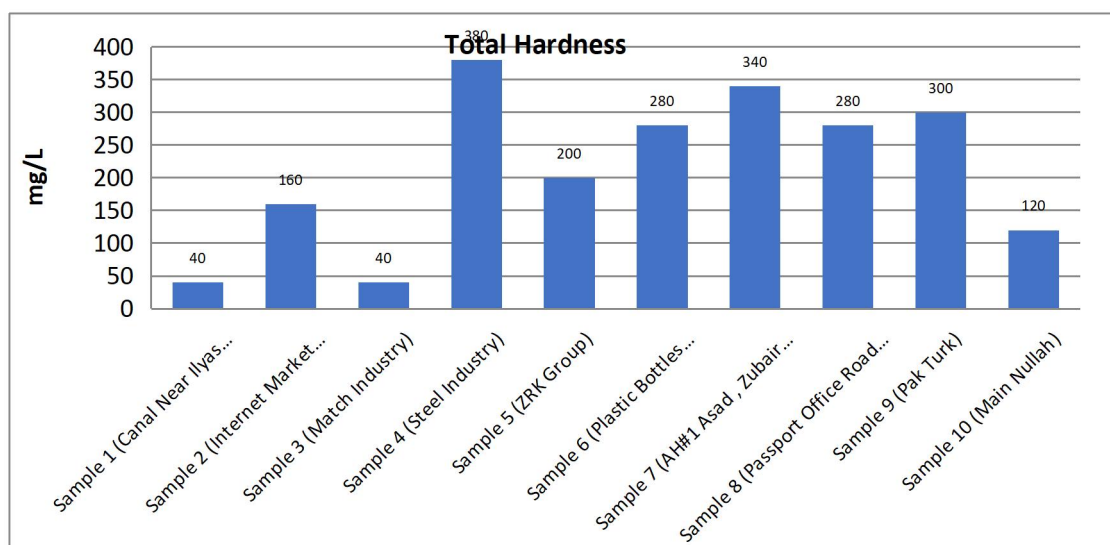


Figure 6. Total Dissolved Solids (TDS) in industrial effluent samples from Hayatabad Industrial Estate (HIE), Peshawar.

Total Alkalinity

In the present study, total alkalinity values of industrial effluents showed considerable variation among different industries. The highest value (700 mg/L) was recorded in the effluent from the Internet Market Company, which exceeds the permissible limit set by Pak-NEQS (500 mg/L). The lowest alkalinity value (310

mg/L) was observed in effluents from the Asad Zubair Industry, which falls within the acceptable limit (Figure 7).

These results indicate that while some industrial effluents comply with the regulatory standards, others exhibit excessive alkalinity, potentially due to the discharge of alkaline chemicals such as detergents, cleaning agents, or process by-products. Elevated alkalinity can increase buffering capacity, influence solubility of heavy metals, and impact the efficiency of biological wastewater treatment processes. Total alkalinity, which measures water's capacity to neutralize acids and is largely due to carbonates, bicarbonates, and hydroxides, varied significantly across industrial effluents.

The Internet Market Company effluent showed the highest value (700 mg/L), exceeding the Pak-NEQS limit of 500 mg/L, while the lowest alkalinity (310 mg/L) was recorded at Asad Zubair Industry, remaining within acceptable standards. High alkalinity likely stems from alkaline substances such as detergents, cleaning agents, or industrial by-products (Abdel and Alseroury, 219). Such elevated levels can enhance buffering capacity, alter heavy metal solubility, and interfere with biological treatment processes (Tibebe et al., 2022).

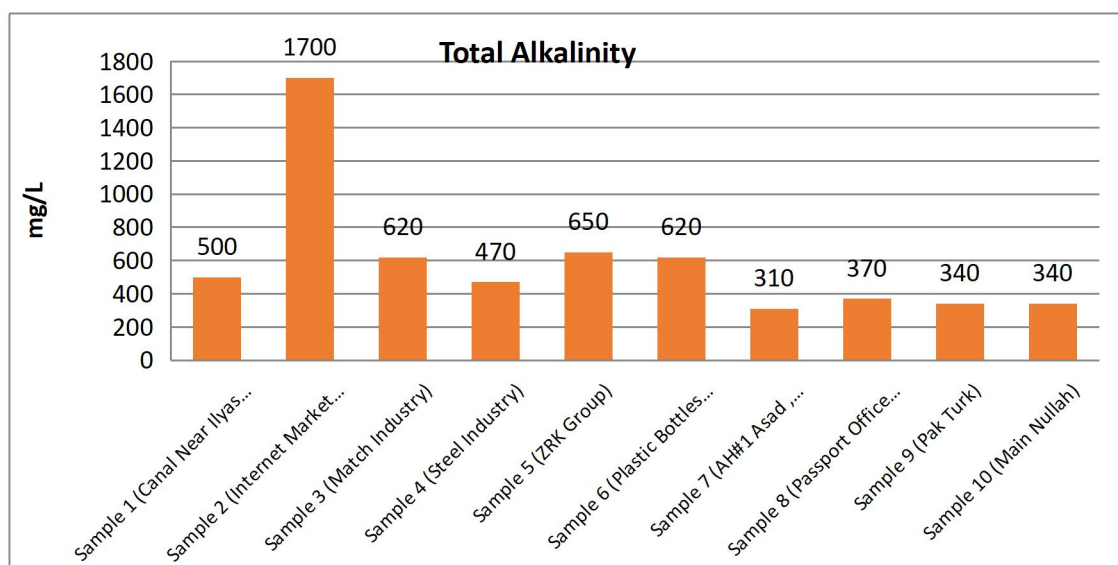


Figure 7. Total Alkalinity) in Industrial Effluent Samples from Hayatabad Industrial Estate (HIE), Peshawar

Calcium Concentration

The calcium concentration in the industrial effluent samples ranged from 272 mg/L

to 1128 mg/L (Figure 4.2.3). All measured values significantly exceeded the permissible limit of 200 mg/L established by the National Environmental Quality Standards (NEQS) (Figure 8). The highest concentration (1128 mg/L) was detected in the effluent from the Match Industry, while the lowest recorded value was 272 mg/L. Other measured values included 328 mg/L, 330 mg/L, 408 mg/L (two instances), 440 mg/L, 592 mg/L, 648 mg/L, and 936 mg/L. The universal exceedance of calcium concentrations beyond the NEQS limit of 200 mg/L indicates severe and widespread contamination across all industrial sectors. The exceptionally high level (1128 mg/L) in the Match Industry effluent likely originates from calcium-rich compounds used in match production, such as calcium carbonate filler or phosphates (Ou et al., 2023). Other industries also showed markedly elevated levels, suggesting common sources like process chemicals, cleaning agents, or water softening regenerants.

Such elevated calcium levels can lead to significant environmental consequences, including increased water hardness, scaling in pipes and infrastructure, and potential disruption of aquatic ecosystems by altering osmotic balance (Wen et al., 2023). The consistent non-compliance underscores a critical failure in wastewater management and emphasizes the urgent need for implementing calcium reduction strategies, such as ion exchange or chemical precipitation, to meet regulatory standards and mitigate environmental harm (World Health Organization, 2017).

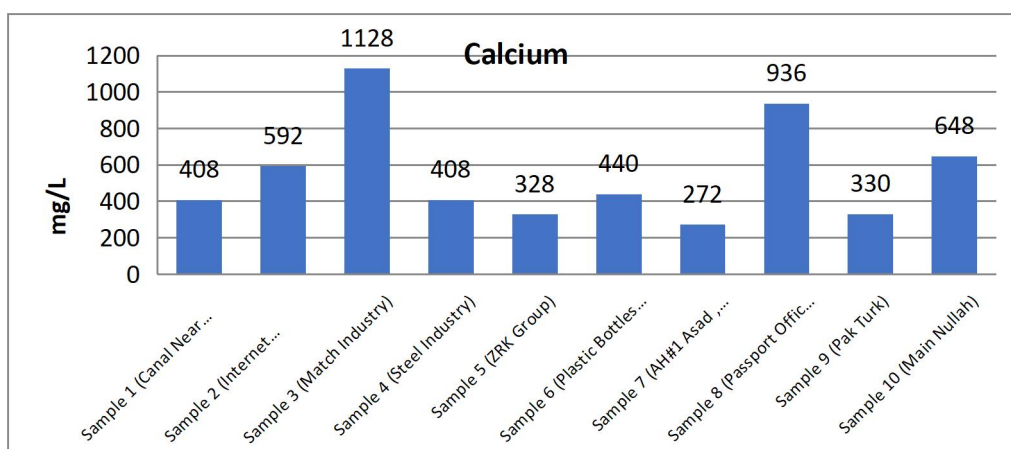


Figure 8. Calcium in Industrial Effluent Samples from Hayatabad Industrial Estate (HIE), Peshawar.

Magnesium Concentration

The magnesium concentration in the industrial effluent samples ranged from 18 mg/L to 262 mg/L (Figure 4.2.4). The National Environmental Quality Standards (NEQS) permissible limit for magnesium is 100 mg/L. Among the analyzed samples, four effluents exceeded this limit: Ilyas Industry (262 mg/L), Match Industry, Asad Zubair Industry, and Main Nullah. The remaining samples Internet Market Company, Steel Industry, ZRK Group, Plastic Bottles Industry, Passport Office Road, and Pak Turk showed concentrations within the permissible limit, with ZRK Group exhibiting the lowest concentration (18 mg/L) (Figure 9).

The variability in magnesium levels reflects differences in industrial processes and wastewater management practices. High concentrations likely originate from chemical manufacturing, detergent use, or metal processing activities, while lower values may indicate effective treatment or less magnesium-intensive operations. The variability in magnesium concentrations reflects significant differences in industrial processes and wastewater management practices. The elevated levels in Ilyas Industry (262 mg/L), Match Industry, Asad Zubair, and Main Nullah likely originate from magnesium-rich waste streams, including chemical manufacturing residues, detergent discharges, and metal processing effluents (Ou et al, 2023). In contrast, the lower concentrations observed in other industries suggest either less magnesium-intensive operations or more effective wastewater treatment (Tariq, A., & Mushtaq, 2023).

Exceedance of the NEQS limit poses environmental concerns, as elevated magnesium can contribute to water hardness, scale formation in infrastructure, and potential disruptions to aquatic ecosystems through altered ionic balances (WHO, 2017). The partial compliance among samples indicates inconsistent adherence to environmental regulations, highlighting the need for industry-specific mitigation strategies such as improved effluent treatment and regular monitoring to reduce magnesium discharge (Khan et al., 2012).

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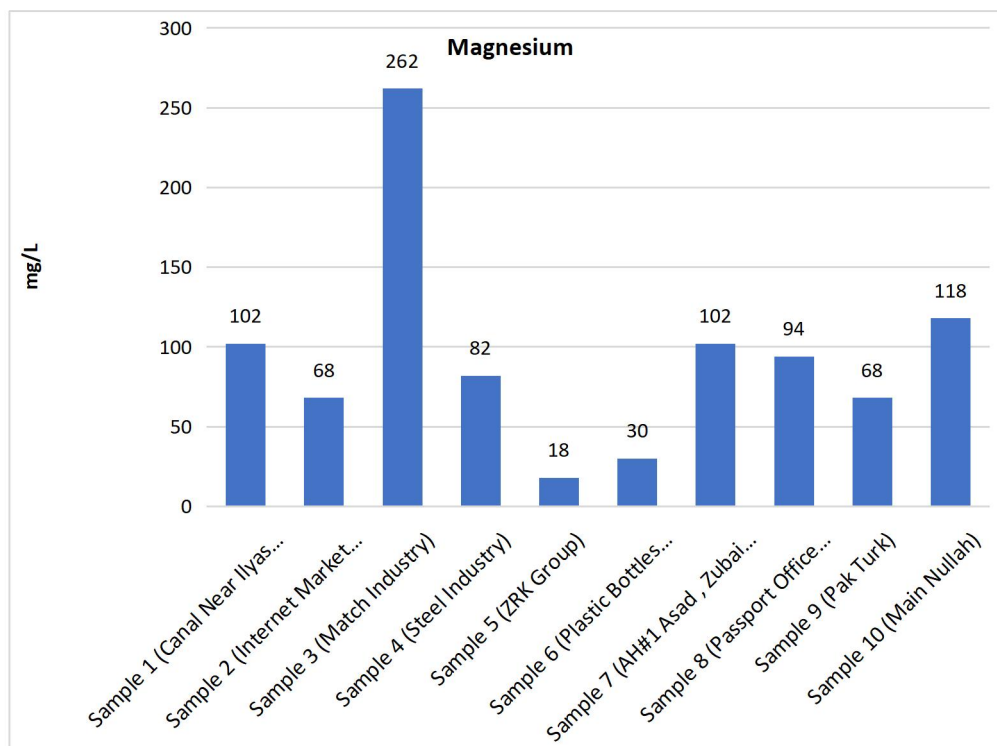
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Figure 9. Magnesium in Industrial Effluent Samples from Hayatabad Industrial Estate (HIE), Peshawar

Chloride Concentration

The chloride concentration in industrial effluent samples ranged from 440 mg/L to 3,263 mg/L (Figure 4.2.5). The National Environmental Quality Standard (NEQS) permissible limit for chloride in industrial effluent is 1,000 mg/L, as established by the Pakistan Environmental Protection Agency. Only one sample (Internet Market Company, 440 mg/L) complied with this standard. All other samples exceeded the limit, with the Steel Industry effluent showing the highest concentration (3,263 mg/L) (Figure 10). The widespread exceedances of chloride limits indicates significant industrial pollution, particularly from the Steel Industry, where processes such as pickling, acid cleaning, and cooling systems likely contribute high chloride loads (Alam & Ahmad, 2020). Elevated chloride levels can increase water salinity, corrode infrastructure, and harm aquatic ecosystems by disrupting osmotic balance in freshwater organisms (Khan et al., 2021).

The consistent non-compliance underscores urgent needs for chloride mitigation strategies, such as reverse osmosis or ion exchange, and stricter enforcement of

effluent treatment regulations (WHO, 2011). The findings of this study reveal a concerning trend of chloride contamination in industrial effluents, with concentrations ranging from 440 mg/L to 3,263 mg/L, far exceeding the NEQS limit of 1,000 mg/L in most cases. Except for the Internet Market Company sample, all other industries failed to comply with the regulatory threshold, highlighting the prevalence of untreated or inadequately treated discharges into the environment. The highest chloride concentration recorded in effluents from the Steel Industry suggests a direct link to industrial processes such as pickling, acid cleaning, and cooling system operations, which are well-documented sources of chloride pollution (Amin et al., 2010).

Excessive chloride levels in industrial discharges pose multiple environmental and infrastructural challenges. Elevated chloride concentrations not only increase the salinity of receiving water bodies but also accelerate corrosion in pipelines, concrete structures, and water distribution systems, leading to higher maintenance costs and reduced service life (WHO, 2017). From an ecological perspective, chloride contamination is particularly damaging to freshwater ecosystems. Elevated levels disrupt the osmotic balance of aquatic organisms, impair reproductive capacity, and reduce biodiversity by making habitats unsuitable for sensitive species (Khan et al., 2002). Thus, persistent chloride loading has both ecological and socio-economic implications.

The widespread non-compliance with NEQS standards observed in this study underlines the urgent need for stricter enforcement of industrial effluent management policies. Advanced treatment technologies, including reverse osmosis, ion exchange, and electro-dialysis, offer effective options for chloride removal but require significant financial investment and operational expertise. Moreover, industries should be encouraged to adopt process modifications and cleaner production technologies that minimize chloride use and discharge at the source. Alongside technical solutions, effective monitoring, regular inspections, and penalties for non-compliance are essential to ensure environmental sustainability.

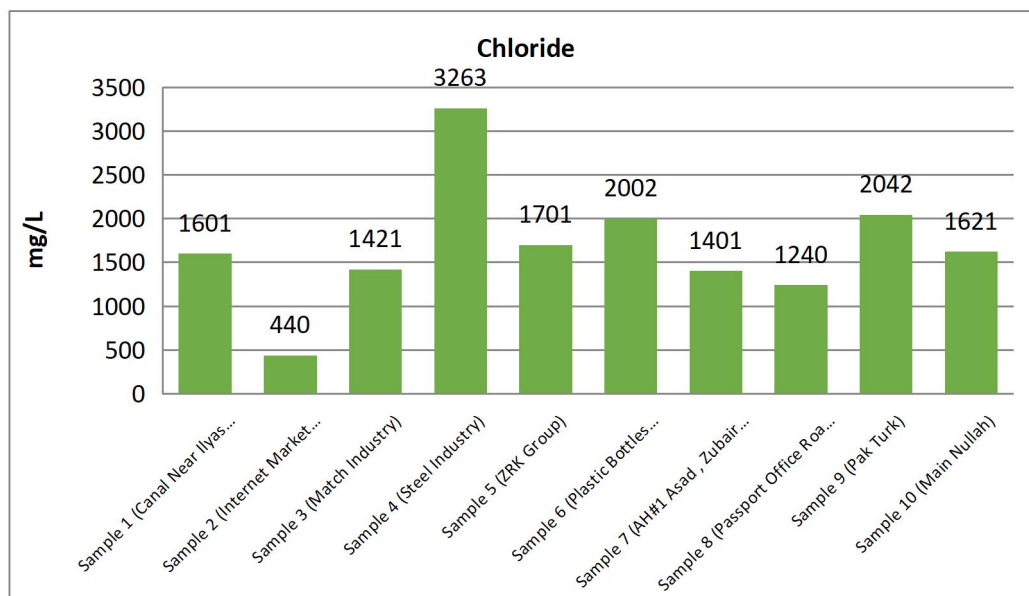


Figure 10. Chloride Concentration in Industrial Effluent Samples from Hayatabad Industrial Estate (HIE), Peshawar

Biological Oxygen Demand (BOD)

The Biological Oxygen Demand (BOD) of the industrial effluents ranged from 86 mg/L to 335 mg/L (Figure 11). All samples exceeded the National Environmental Quality Standards (NEQS) permissible limit of 80 mg/L for industrial effluents. The highest BOD levels were recorded in effluents from the Steel Industry, Passport Office Road, and Pak-Turk, indicating severe organic pollution. The universal exceedance of BOD limits signifies substantial organic pollution across all industries, with particularly high levels in the Steel Industry, Passport Office Road, and Pak-Turk effluents. Elevated BOD suggests the presence of biodegradable organic compounds from sources such as oils, greases, and organic solvents (Bader et al., 2020). High BOD depletes dissolved oxygen in water bodies, threatening aquatic life and disrupting ecosystem balance (Harefa et al., 2021). The consistent non-compliance highlights inadequate effluent treatment and underscores the urgent need for advanced biological treatment systems, such as activated sludge or anaerobic digesters, to reduce organic load before discharge (WHO, 2017). The results demonstrate alarmingly high Biological Oxygen Demand (BOD) values in all industrial effluent samples, ranging from 86 mg/L to 335 mg/L, with every sample exceeding the NEQS permissible limit of 80 mg/L. This universal non-compliance

reflects the severity of organic pollution across the studied industries. The highest BOD levels observed in effluents from the Steel Industry, Passport Office Road, and Pak-Turk indicate significant discharges of biodegradable organic matter, most likely derived from oils, greases, detergents, and organic solvents used in industrial operations (Nahiun et al., 2020).

High BOD levels are of particular concern due to their direct impact on aquatic ecosystems. Elevated BOD signifies that effluents have a high organic load, which, upon entering natural water bodies, increases microbial activity and rapidly depletes dissolved oxygen (DO). This oxygen depletion threatens the survival of fish and other aerobic aquatic organisms, disrupts food web dynamics, and leads to biodiversity loss (Bader et al., 2020). Furthermore, low oxygen conditions can promote the growth of anaerobic microorganisms, causing foul odors, production of toxic gases such as hydrogen sulfide, and deterioration of overall water quality. The consistent exceedance of BOD limits points to insufficient or absent wastewater treatment practices in the industries studied. Conventional treatment systems, if present, appear ineffective in reducing organic loads to permissible levels.

To mitigate this issue, the adoption of advanced biological treatment technologies such as activated sludge processes, trickling filters, or anaerobic digesters is essential. These methods can significantly reduce organic content by enhancing microbial degradation before effluents are discharged (WHO, 2017). In addition, industries should integrate pre-treatment steps, including oil–water separators and equalization tanks, to further reduce the pollutant load and improve the efficiency of biological treatment systems. Generally, the elevated BOD levels observed highpoints a critical pollution challenge, with serious ecological and public health implications. Addressing this requires not only the implementation of effective treatment technologies but also stricter monitoring and enforcement of effluent discharge regulations to ensure compliance and protection of freshwater resources.

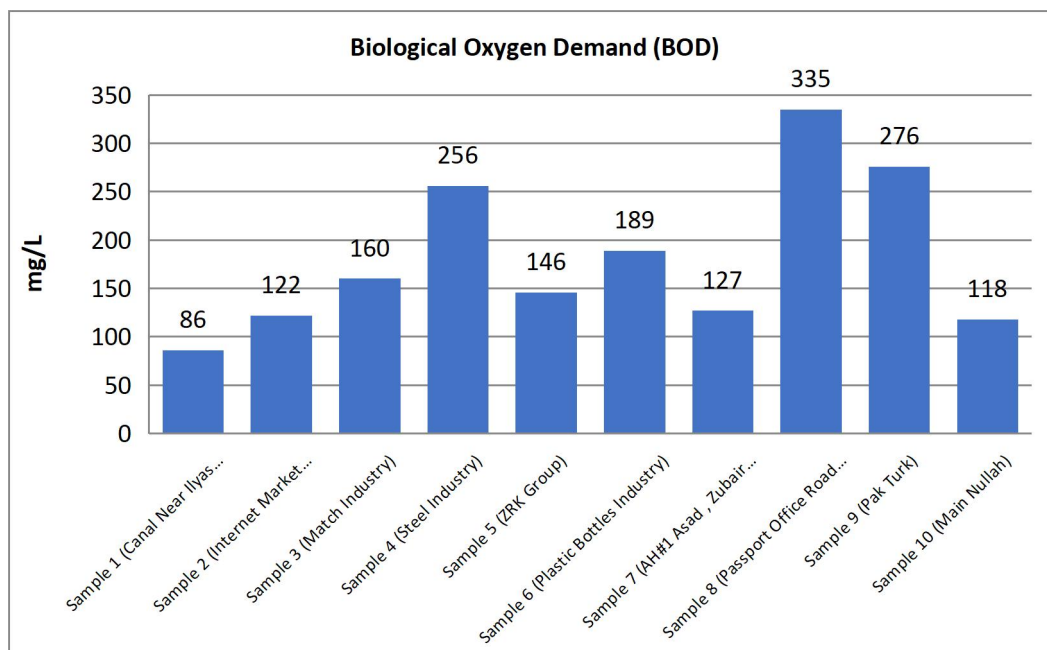


Figure 11. Biological Oxygen Demand (BOD) in industrial effluent samples from Hayatabad Industrial Estate (HIE), Peshawar

Conclusion

Industrial wastewater is a major driver of environmental degradation, posing serious risks to water resources, aquatic ecosystems, and public health. The present study's comprehensive physico-chemical analysis of effluent discharges from the Hayatabad Industrial Estate (HIE) in Peshawar, Pakistan, reveals a severe and widespread state of pollution, pointing to critical shortcomings in environmental management and regulatory enforcement.

The assessment of ten wastewater samples for key parameters demonstrated universal non-compliance with several National Environmental Quality Standards (NEQS). The results clearly indicate that untreated and partially treated effluents from HIE represent a significant pollution threat. Mean concentrations of major pollutants were considerably higher than permissible limits, with chloride levels reaching 1,673 mg/L against the 1,000 mg/L standard, indicating severe salinity contamination largely originating from metal processing activities. Biological Oxygen Demand (BOD) averaged 181 mg/L, more than twice the permissible 80 mg/L, signifying heavy organic pollution from oils, greases, and solvents. Similarly, Total Suspended Solids (TSS) averaged 246 mg/L compared to the 150 mg/L limit,

reflecting the absence of effective primary filtration across all industrial sectors. Further analysis showed that all samples exceeded permissible limits for both BOD and TSS, while calcium levels also demonstrated universal and severe violations. Other parameters, including Electrical Conductivity (EC) and magnesium, exhibited partial compliance but nevertheless contributed to a high cumulative pollution load. The continuous discharge of such contaminants into the Budni Nullah and ultimately into the Kabul River exacerbates oxygen depletion, elevates salinity and hardness, degrades habitats through sedimentation, and facilitates the potential bioaccumulation of toxic substances within aquatic food webs.

The root cause of this environmental crisis lies in the absence of functional effluent treatment plants (ETPs) and the systemic failure of regulatory enforcement. This study therefore highlights the urgent need for decisive interventions to halt ongoing environmental damage and to protect both the ecological health of the Kabul River and the productivity of adjacent agricultural lands. Recommended measures include the immediate installation and proper operation of centralized as well as industry-specific ETPs employing advanced treatment technologies such as biological processes, desalination, and chemical precipitation. In addition, stringent regulatory oversight, consistent enforcement of NEQS, and the establishment of continuous monitoring programs are essential to ensure long-term compliance and safeguard regional water quality.

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