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Effects of Physico-Chemical Characterization of Sugar Factory Effluent Pollution on the fresh River Water Fish Channa punctata (Bloch): A Case Study of the Chambal River Basin, Rajasthan

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ABSTRACT: Sugar factories rank among the largest contributors to agro-industrial pollution in freshwater river systems in India and their effluents also come under extremely high biochemical oxygen demand (BOD), chemical oxygen demand (COD), total dissolved solids (TDS), suspended solids and heavy metals. all these physicochemical parameters severely degrade the water body and its aquatic biodiversity. In this research, case study of the Chambal River Basin of Rajasthan is selected for study purpose as despite its ecological significance as a National Sanctuary, it is facing the challenge of industrial discharge, especially from sugar factories. Channa punctata (Bloch) is widely distributed teleost in the Chambal which is both economically important as a food fish and ecologically appreciated as a bioindicator species. However, increasing physicochemical characterization of sugar factory effluent is creating risk on their survival.

Hence, in this paper, secondary data-based case study analysis is conducted while utilizing single-case study design framework of Yin (2018). Findings from this research allows confirming that sugar factory effluent drastically reduces dissolved oxygen, upraises BOD and COD far beyond BIS (Bureau of Indian Standards) permitted limits. It also introduces heavy metals, specifically Cr and Ni into the aquatic environment. This study also offers recommendations for effluent treatment, river monitoring and policy enforcement to the Chambal Basin, Rajasthan so that negative impact of sugar factories on Channa Punctata can be decreased.

1. INTRODUCTION

Freshwater ecosystems across India are facing increasing pressure. Major reasons behind it are unregulated industrial discharge and agro-based industries. In regards to this, sugar factories are one of the most significant polluters of river systems (Solomon, & Swapna, 2022). Sugar is a part of our life and sugar factories generate large volumes of process wastewater which are rich in biodegradable organic matter, suspended solids, nitrogen, phosphate and also have heavy metals. All these aspects collectively create severe biochemical oxygen demand (BOD) as well as chemical oxygen demand (COD), which further creates burden on receiving water bodies (Prakash, & Capoor, 2018). Hence, it not only pollutes surroundings, but also pose effect water bodies and aquatic organisms. The subsequent reduction of dissolved oxygen (DO) and the involvement of toxic substances further create harmful conditions that are often poisonous to aquatic fauna, especially for fish. Water is an essential part of all living

organisms however, only 3% fresh water is available on the earth (Kumar, & Srikantaswamy, 2015). In this severely small amount of fresh water sources, entry of pollutants even makes the situation worse. In the current scenario, industrialization is increasing that consumes huge quantity of fresh water for the production process and also discharges waste in waterbodies which further adversely impacts aquatic life through creating systemic physiological stress, organ damage and metabolic depletion (Khair *et al.,* 2023).

The Chambal River is the 965 km long perennial tributary of the Yamuna River which originates in Madhya Pradesh (MP) and flows north-northeast through Rajasthan and Uttar Pradesh (Gautam *et al.,* 2025). This river is famous for its rich wildlife and remarkable ecological biodiversity. It includes critically endangered gharial, the Gangetic River dolphin, freshwater turtles and diverse fish accumulation, such as - Channa punctata (Bloch), Catla, Rohu, Golden Mahaseer, Calbasu, and many more (Gautam *et al.,* 2025).

It is identified that although, certain stretches of the Chambal have natural base flow and limited urban-industrial activity on its main stem, however, localized pollution, especially from industries creates severe challenge along its tributaries and it is an under-documented problem (Kumar *et al.,* 2015). From recent assessments, it is identified that with the growth of industrialization, Chambal Basin is facing the issue of critical water quality threshold, which is further decreasing DO and increasing pollutant loads posing negative impacts on all forms of aquatic life (Gupta *et al.,* 2022).

It is identified that among the fish species of the Chambal, Channa punctata is ecologically as well as economically significant. It is air-breathing teleost which is widely distributed in Indian freshwater systems and is consumed as a food fish, especially in rural communities near the Chambal Basin (Kuppu *et al.,* 2018). It has physiological resilience, which makes it widely used as sentinel species in aquatic toxicology research. Additionally, alterations in its behaviour, morphology, haematology and tissue chemistry also serve as early warning indicators of ecosystem degradation (Sharma *et al.,* 2023). This fish is highly valued as food, traditional medicine for wound healing and also used as biological model for toxicological research (Waghmare, & Baile, 2017).

Mostly existing studies that are focused on discussing impact of sugar factory waste on water animals, used survey-based designs, while giving concern to collect water samples from multiple factories and rivers. These researches are useful for broad comparisons however; it has created lack of contextual depth and created the demand of understanding the specific pollution dynamics of a specific river basin. Due to this reason, in this research paper, case study analysis is taken as it supported to conduct in-depth and context-grounded analysis of the problem, i.e. effects of physico-chemical characterization of sugar factory effluent pollution on the fresh river water fish (Channa Punctata) in regards to of the Chambal River Basin, Rajasthan. The reason behind selecting Chambal River Basin for study purpose is that it is a unique and ecologically sensitive system.

Research objectives of this paper are as follow:

- To assess the physico-chemical parameters of sugar factory effluent
- To identify the severe toxicity effects of sugar factory effluent on Channa punctata
- To recommend the strategies to decrease the negative impact of sugar factory effluent on Channa punctata

This paper examines three areas, they are: the physico-chemical properties of sugar factory effluent entering the Chambal River Basin; changes in river water quality parameters at due to these effluents; and observable biological and physiological effects on Channa Punctata populations inhabiting the impacted zone, especially in regards to haematological disruption, heavy metal tissue accumulation and behavioural stress responses. Case study findings about all three aspects have further supported to generate context-specific and evidence-based recommendations for sugar factory effluent management, environmental monitoring and to come up with regulatory enforcement to deal with the ecological sensitivities of the Chambal River Basin. This paper has supported to answer following research questions:

- What is the effect of physico-chemical characteristics of sugar factory effluent discharged into the Chambal River Basin on Channa punctata?
- What strategies can be used to deal with the negative impact of sugar factory effluents on the biological and physiological health of Channa punctata?

Natural Resources for Human Health
eISSN: 2583-1194

2. LITERATURE REVIEW

2.1 Physico-Chemical Parameters of Sugar Factory Effluent

From the research finding of Rahim, & Mostafa (2021), it is identified that effluents of sugar factory come under high-strength industrial wastewater and characterized as extreme organic pollution. The reason behind it is that it decreases pH (due to processing acids) and increases temperatures while enhancing excessive dissolved and suspended solids. Discharge of such untreated wastewater further leads to severe threats to aquatic ecosystems as well as agricultural land. At the same time, Rahim, & Mostafa (2021) pointed that effluents of sugar factories deteriorate water quality, due to their physical and chemical characteristics (Temperature, pH, Hardness, BOD, COD, DO, TSS, TDS, oil, grease, Zn, etc.) and make water unfit for consumption. Th severeness increases when most of the waste water parameters show higher than the Minimum Pollution Level (MPL) as it causes serious pollution problems for aquatic life, human and livestock. Kumar, & Chopra (2010) also explained that when sugar factory effluent discharges into the environment, it poses serious health risk to the rural as well as semi-urban populations, as they use river water for agriculture as well as domestic purposes. Additionally, it also adversely impacts fish mortality rate.

2.2 Severe Toxicity Effects of Sugar Factory Effluent on Channa Punctata

From the research finding of Lad *et al.* (2022), it is identified that wastewater from sugar factories is directly discharged into water source or in the open field which further create the issue of groundwater contamination and soil contamination. For this study purpose, twelve samples were collected (3 samples from the main industrial drain and 9 from open wells that are situated in the surrounding agriculture area of sugar factory). Sample outcome allowed evaluating physiochemical water quality parameters (Temperature, Total hardness, pH, EC, TDS, COD, BOD, etc.) (Lad *et al.,* 2022). Study outcome helped to observe that with the increase of sugar factory industrialization, concentration of the water quality parameters is decreased. Additionally, it is identified that due to waste disposal from sugar factories, concentration of potassium, oil, grease, chromium, COD and BOD is increasing which further making the water unsafe for domestic use as well as irrigation and creates the demand for remedial measures to cope up with such situation (Lad *et al.,* 2022).

In the views of Rahim, & Mostafa (2021), discharge of untreated sugar factory effluents degrades river water quality. Both surface water and groundwater get contaminated through these effluents and severely degrades the environment as well as aquatic life. At the same time, Kakade (2022) opined that adverse impact of sugar factory waste on aquatic animals and water quality can be decreased through enhancing focus on quality and management of wastewater by industries. In regards to this, quality and management of wastewater in sugar industry is discussed with the help of below flowchart.

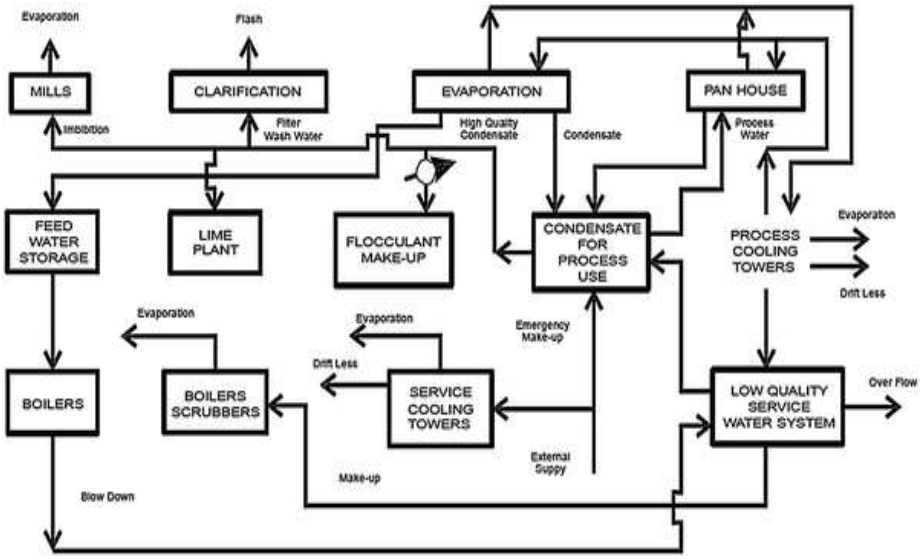

Figure 1: Quality and Management of Wastewater in Sugar Industry

(Source: Kakade, 2022)

Figure 1 showcases water management in a sugar industry while explaining various processing stages in which water moves in sugar factories. It includes mills, clarification, evaporation, boilers and cooling towers and explains recycling and reusing of different water quality streams (such as - condensate, process water and service water) so that waste can be minimized and efficiency across the production system can be optimized (Kakade, 2022).

Singh, & Prakash (2020) conducted research on Channa punctatus in different sublethal concentrations (2.5%, 5%, 7.5 % and 10 %) of the distillery effluent for 1 month and estimated different biochemical constituents of liver, such as - carbohydrate, fat, protein, nucleic acid and phosphatases enzyme. During investigation, sugar factory effluent was exposed to Channa punctatus. It is identified that this waste discharge decreased protein, glycogen, triglyceride, RNA and DNA significantly and increased the level of acid and alkaline phosphatases enzyme of liver at all sublethal concentrations (Singh, & Prakash, 2020).

2.3 Heavy Metal Accumulation and Haematological Effects on Channa punctata

Malik (2019) explained that sugar factory effluent not only creates the issue of physico-chemical deterioration of water, but it also creates the issue of heavy metals that directly accumulate in fish tissues and interrupt their physiological functioning. At the same time, research finding of Javed and Usmani (2013), it is identified that heavy metals (Fe, Mn, Ni, Cr, Cu) remain present in sugar factory effluent and make water bodies beyond safe limits (set by UNEP GEMS). When these metals enter in water bodies, their bioaccumulation takes place in tissues of Channa punctatus, especially in gills, liver, kidney and muscle. In support of this, (Mehjbeen Javed *et al.* (2016) pointed that exposure to industrial effluent led to haematological level disruption while further significant declines RBC count, haemoglobin and oxygen-carrying capacity of Channa Punctata blood, while increasing WBC count.

3. RESEARCH METHODOLOGY

To conduct this research paper, secondary data collection method is used and for this purpose, peer-reviewed journals, environmental monitoring reports and published case studies are used. Selection of this case study approach is methodologically appropriate for this paper as it allowed to understand how and why sugar factory effluent is affecting Chambal River and impacting fish, specifically Channa Punctata. Instead of drawing broad comparisons across multiple sites, this study has given concern to draw findings from Chambal River Rajasthan while focusing on comparative analysis of (village Satha). Single-case design framework proposed by Yin (2018) is used for study purpose. For collecting the secondary data, studies published between 2010 and 2024 are referenced for study purpose while including databases from Google Scholar, ResearchGate, PubMed and Springer. Additionally, data triangulation is applied across multiple independent sources which has supported to strengthen reliability and internal validity of findings (Yin, 2018).

To conduct case study analysis, geographically bounded location is selected for study purpose. For this purpose, defined stretch of the Chambal River affected by Sugar Factory waste discharge is selected for study purpose, while giving special focus on the active crushing season and the post-season period. Focus towards this temporal boundary supported to examine both peak pollution conditions (January–February) as well as recovery trends (April–May), which has supported to provide a complete picture of the seasonal pollution cycle. Additionally, upstream, downstream and industrial zone are also analyzed on different parameters (pH, DO, BOD, COD, TDS, Total Hardness, WQI, EC) to identify water quality in different locations and impact of industrialization on water quality. Additionally, physiological, biochemical and histopathological disruption of sugar factory effluent in Channa Punctata is discussed.

4. CASE STUDY ANALYSIS

4.1 Ecological Context of the Chambal River Basin

The Chambal River originates from the Vindhya Range near Mhow, MP and flows northward through Rajasthan before joining the Yamuna River in Uttar Pradesh (UP) *(See Fig.2)*. In regards to Rajasthan, it drains around 1,43,219 km² water and supplies it to Kota, Bundi, Sawai Madhopur and Karauli districts (Amit *et al.,* 2015).

Natural Resources for Human Health
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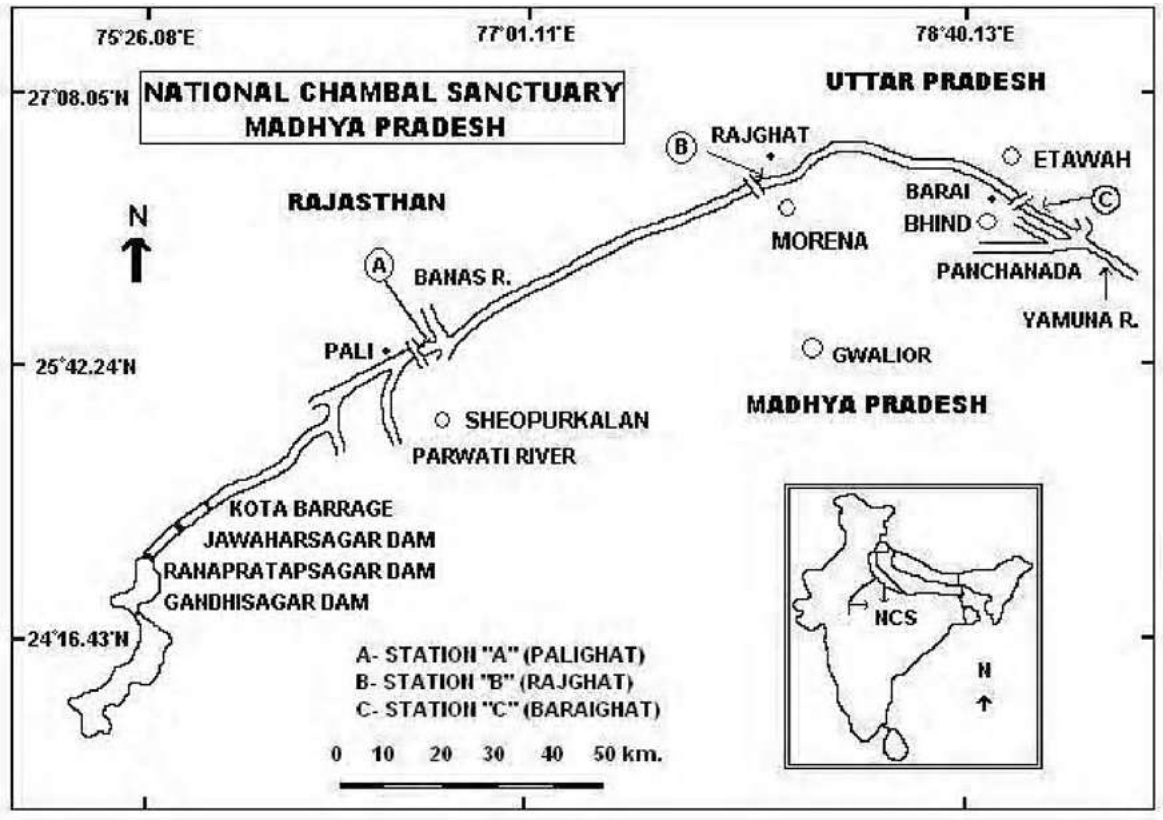

Figure 2: Chambal River Basin

(Source: Saksena *et al.,* 2008)

According to Saksena *et al.* (2008), this river historically maintains a perennial base flow from upland springs and catchment recharge, which further aids natural self-purification through dilution and reaeration. However, with the help of recent evaluations, it is confirmed that growth in industrialization (especially in Kota) is leading towards river pollution to a critical stage (Gupta et al., 2022). Upstream tributaries are receiving effluents from sugar factories that are majorly situated in smaller towns and creating the issue of specific and under-monitored pollution pathway into the main Chambal River. Channa punctata inhabits the Chambal River basin and it is a bottom-feeding carnivore, which majorly found in the quieter, shallow muddy shallows, vegetated stretches and interconnected wetlands of the river system (Akhand *et al.,* 2012).

4.2 Impact of the Sugar Industry on Channa Punctata

Channa punctata has pharmaceutical benefits for human being as it has the potential to prevent cardiac disorders, skin infections, diabetes, etc. The reason behind it is that it has fatty acid, glycine, lysine, arachidonic acid, DHA, etc. which are useful for biomedical and nutraceutical products (Shillewar, 2021). Channa Punctata is an air-breathing specie which has physiological resilience however, sugar factory effluent leads to severe haematological disruption, which further decreases RBC up to 75.42% and leads to immunological stress and elevate WBC counts. Accumulation of Channa Punctata that is contaminated with Cr can lead to severe gastrointestinal, renal and neurological toxicities in humans (Idrees *et al.,* 2020).

Natural Resources for Human Health
eISSN: 2583-1194

Figure 3: Channa Punctata

(Source: Shillewar, 2021)

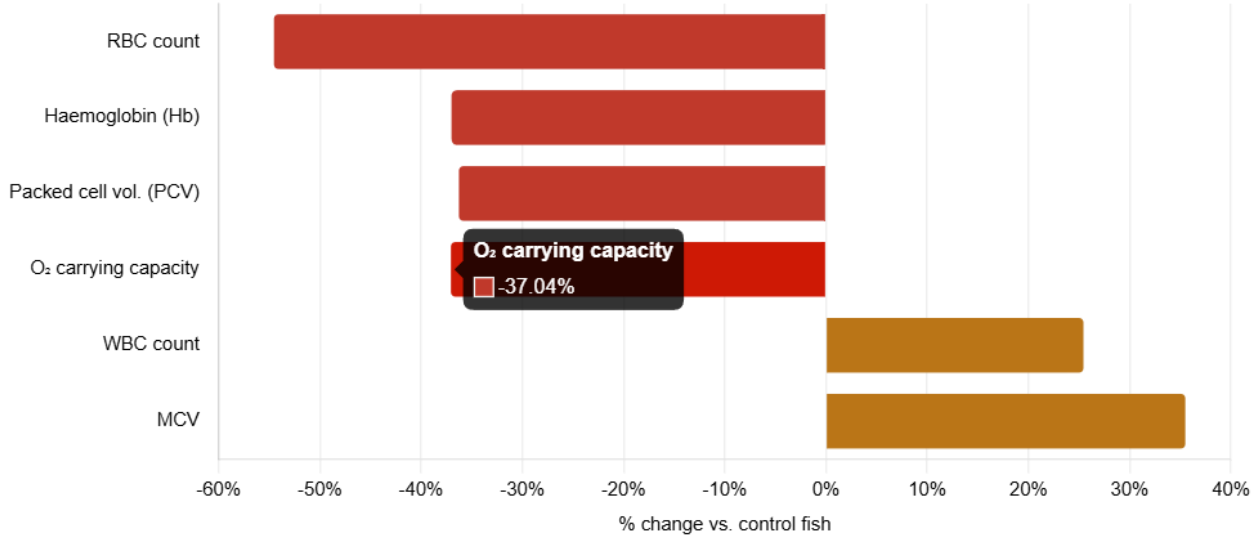

Figure 4: % Change in Haematological Parameters of Channa Punctata Under Sugar Factory Effluent Exposure

(Source: Mehjbeen Javed *et al.,* 2016)

Here: Red Colour - Decline (harmful decrease); Copper Colour - Elevation (stress indicator)

Fig. 5 showcases that when Channa Punctata is exposed to sugar factory effluent, then, change in haematological profile takes place due to which severe toxic stress, macrocytic hypochromic anemia and activated immune defence system take place (Mehjbeen Javed *et al.,* 2016). The reason behind it is that sugar factory effluents are highly rich in organic matter, hazardous chemical compounds and heavy metals, which further disturbs normal homeostatic mechanics of aquatic organisms (Mehjbeen Javed *et al.,* 2016). According to Javed, & Usmani (2013), sugar factory effluent increases the concentration of Chromium (Cr) in the edible muscle tissue which further exceeds USEPA from recommended maximum permissible limit for Channa Punctata. It is assessed as 'not safe to consume' criteria and direct public health relevance to Chambal Basin communities.

4.3 Effects of Physico-Chemical Disruption of Sugar Industry in Channa Punctata in the Chambal

Rajasthan supports sugarcane cultivation in belts of the Chambal and its tributaries due to fertile alluvial soil, especially in Kota, Baran and Bhilwara districts (Gautam, & Sharma, 2023). From the case study analysis, it is identified that a medium-scale cooperative sugar mill which is operating since the early 1990s processes approx. 2,500–3,500 tonnes of sugarcane daily during the crushing season and generates around 25 - 40 million litres of wastewater per season. According to the available documentary records from the RSPCB, it is indicated that this Factory's Effluent Treatment Plant (ETP) operates at sub-optimal capacity during peak season (Gautam, & Sharma, 2023). Moreover, due to improper infrastructure, discharge of partially treated or untreated waste is drained into the Chambal tributary. It is identified that Keshoraipatan Cooperative Sugar Mill (KCSM) is one

of the primary sugar factories that is impacting the water quality of Chambal River (Gautam, & Sharma, 2023). This factory is located right along the banks of the Chambal in Bundi district of Rajasthan.

From the research finding of Akhand *et al.* (2012), it is identified that accumulation of Zinc in the muscles of fishes observed which were collected from Chambal River. The metal concentration was estimated by the Atomic Absorption spectrophotometer (Perkin Elmer 3100). Increasing weight of fish also observed with the increasing concentration of Zinc in fish muscles from Chambal River.

At the same time, from the water quality modelling and simulation results of Gupta *et al.* (2022), it is identified that the water quality of the Chambal River flowing through Rajasthan has the potential to rejuvenate itself from alarming oxygen deficit within a short period. The reason behind it is that the concentration of dissolved oxygen in the Chambal River water highly sufficient to support the survival of the endangered species that inhabit the area (Gupta *et al.,* 2022). In the contrary, from the research finding of Dhakad *et al.* (2018), it is identified that increasing industrial pollution is adversely impacting benthic fauna in the Chambal River, subjected to industrial and sewage pollution, was studied with reference to the benthic fauna. With the analysis of different physicochemical parameters, it is found that increase in domestic and industrial effluent are changing the benthic community and decreasing species diversity. Values showed significant decrease in benthic fauna from the pre-pollution point to the post-effluent point (Dhakad *et al.,* 2018). To come up with effective research outcome, the coefficient of correlation was assessed between different physicochemical and different groups of benthic fauna and showcased the need of coming up with appropriate strategy to improve recovery.

From some published water quality monitoring data from the Chambal River, Rajasthan showcases that although upstream stretches retain moderate-to-good quality, however, increasing industrialization has impacted zones and showcased significant elevated pollutant loads.

Parameter	Dholpur Site - Upstream (Tiwari, & Singh, 2008)	Dholpur Site - Downstream (Tiwari, & Singh, 2008)	Kota stretch - annual avg. 2010–22 (Singh, & Saxena, 2025)	Nagda industrial zone WQI (Kushwah et al., 2025)	BIS/CPCB Limit (Bureau of Indian Standards, 2012)
pH	7.6	7.9	7.70 - 8.10	-	6.5 - 8.5
DO (mg/L)	8.4	5.1	-	-	≥4.0
BOD (mg/L)	1.08 - 3.66	12.1	-	-	≤30
COD (mg/L)	5.5 - 11.5	35.2	-	-	≤250
TDS (mg/L)	623	642	-	-	≤500 (drinking)
Total Hardness	341	341	-	-	≤300
WQI	34.58 (good)	-	52 - 156 (poor)	444 (severely polluted)	-
EC (µS/cm)	820 - 951	-	fluctuates	-	-

Table : Chambal River Water Quality Parameters from Published Monitoring Studies

(Source: Chem. Env. J., 2008, PubMed, 2025, Sharma *et al.,* 2025, BIS/CPCB)

From the above table, it can be discussed that the Chambal River upstream shows relatively clean conditions (WQI (Water Quality Index) - 34.58; DO - 8.4 mg/L; BOD - 1–3 mg/L). However, Kota stretch and Nagda show high level of WQI as these

locations come under industrial discharge zones with 156 (poor) - 444 (severely polluted) WQI which represent dramatical deterioration of water quality *(See fig. 3)*.

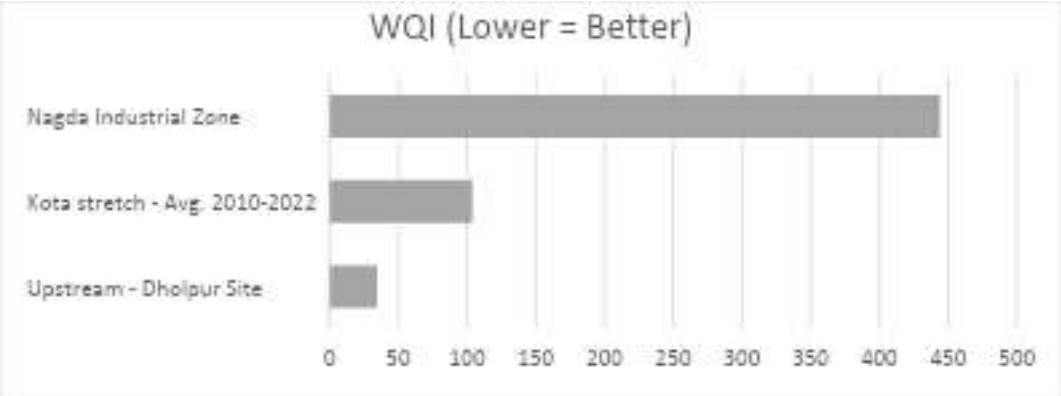

Figure 5: WQI Across Chambal River Zones

(Source: From Published Data)

This contrast water quality supports the case that localized industrial effluent (such as - sugar factories) has the potential to transform clean river water into critically polluted zone within a short distance.

In the views of Idrees *et al.* (2020), untreated sugar factory effluent induces physiological, biochemical and histopathological damage on Channa punctata. All these aspects collectively compromise the long-term survival of this specie. It also gives the evidence of the biological cost of industrial pollution on this ecologically as well as economically significant fish. Prakash and Capoor (2018) recorded that at the haematological level, statistically significant reduction found in RBC count, haemoglobin concentration and haematocrit values in Channa punctata which is exposed to sub subtoxic concentrations (5%, 10% and 20%) of sugar factory effluent for 30 days. Additionally, research finding of Prakash and Capoor (2018) helped to identify that haemoglobin level decreased 8.2 g/dL to 5.6 g/dL when effluent concentration was 20% (decline of approximately 31.7%) and indicated the commencement of macrocytic hypochromic anaemia. Alongside, total leucocyte counts also increased by around 200%. It further reflected systemic immune activation in response to circulating toxicants. These disruptions were found consistent with findings reported for the Chambal by Idrees *et al.* (2020), which states that Channa Punctata that are collected from effluent impacted zones showcased lower haemoglobin values (approx. 40% low) as compared to Channa Punctata from unpolluted reference sites.

While working on industrial effluent exposure in Channa punctata, Sharma et al. (2023), documented significant rise in micronucleated erythrocytes and nuclear abnormalities and chromosomal instability. It is found that micronucleus frequency increased from 0.8% to 6.4% (approx. 80fold rise) which signalled heightened risk of oncogenic transformation.

4.4 Comparative Analysis with Other Case in Rajasthan

Similar study is conducted at village Satha (located in the Mahwa Tehsil of Dausa district), which allowed identifying that wastes from sugar factories are drained into the canal. Due to this, presence of heavy metals, such as - {Fe (8.69 mgL-1)>Mn(2.13 mgL-1)> Zn (0.6 mgL-1)> Ni (0.24 mgL-1)> Cr (0.21 mgL-1)> Cu (0.12 mgL-1)> Co (0.08mgL-1)} are increasing and Fe, Mn, Ni (Nickel) and Cr (Chromium) were found beyond the limits set by UNEP GEMS (Global Environment Monitoring System) (Javed, & Usmani, 2013). Not only this, but also bioaccumulation of these heavy metals was detected in Channa Punctatus tissues, especially in liver, gills, kidney, muscle and integument). It has drastically declined the total RBC count (-75.42%) and increased WBC count (+546.17%) and decreased Oxygen carrying capacity of fish blood (-35.12%) which has created major issue of making the fish stressed and vulnerable to diseases (Javed, & Usmani, 2013).

Natural Resources for Human Health
eISSN: 2583-1194

Table- 1: Accumulation of heavy metals in the organs of *Channapunctatus*

Heavy metals	Gills	Liver	Kidney	Muscle	Integument
Cu	$^{a}40.83\pm0.827_{c}$	$^{ab}40.83\pm.0832_{b}$	$^{c}27.22\pm0.554_{c}$	$^{e}17.33\pm0.32_{d}$	$^{d}23.32\pm0.479_{c}$
Fe	$^{b}480.83\pm0.832_{a}$	$^{a}1760.83\pm0.83_{a}$	$^{c}393.87\pm0.56_{a}$	$^{de}182.33\pm0.34_{a}$	$^{d}183.31\pm0.47_{a}$
Mn	$^{b}18.3\pm0.86_{d}$	ND	ND	$^{a}21.2\pm0.329_{c}$	$^{c}13.32\pm0.473_{d}$
Cr	$^{a}12.5\pm0.00_{e}$	$^{e}0.033\pm0.002_{d}$	$^{b}6.66\pm0.00_{d}$	$^{cd}5.33\pm0.335_{e}$	$^{cbd}6.19\pm0.47_{e}$
Zn	$^{a}93.33\pm0.827_{b}$	$^{e}0.44\pm0.004_{c}$	$^{d}37.21\pm0.549_{b}$	$^{c}53.33\pm0.415_{b}$	$^{b}80.47\pm0.46_{b}$

Table 1: Accumulation of Heavy Metals in Channa Punctata

(Source: Javed, & Usmani, 2013)

Above table represents that accumulation of different heavy metals (Cu, Fe, Mn, Cr, Zn) were found in the organs of Channa Punctatus, they are: gills, liver, kidney, muscle and integument *(see table 2)* (Javed, & Usmani, 2013).

Table- 2: Bioaccumulation Factor of heavy metals in the different tissues of *Channapunctatus*

Heavy metals	Gills	Liver	Kidney	Muscle	Integument
Cu	340.25	340.25	226.83	144.41	194.33
Fe	55.33	202.62	45.32	20.98	21.09
Mn	8.59	ND	ND	9.95	1.53
Cr	60.67	0.160	32.33	258.88	30.04
Zn	155.55	0.733	62.01	88.88	134.11

Table 2: Bioaccumulation Factor of heavy metals in the Channa Punctata

(Source: Javed, & Usmani, 2013)

Above table shows that Cu is accumulated higher in gills (340.25), liver (340.25), kidney (226.83) and integument (194.33), whereas Mn found higher in muscle (258.88) *(see table 3)* (Javed, & Usmani, 2013).

Table- 3: Hematological parameters and oxygen carrying capacity of the fish *Channapunctatus*

Variable	Control *C. punctatus*	Exposed *C. punctatus*	% change over control
Total RBC (10^{6} mm^{-3})	7.00 ± 0.01*	1.72± 0.01*	-75.42%
Total WBC (10^{3} mm^{-3})	9.27 ± 0.11	59.9 ± 0.012	+546.17%
Hemoglobin (g/dL)	9.23± 0.10*	5.99 ± 0.13*	-35.10%
Oxygen carrying capacity (Vol %)	11.53 ± 0.11*	7.48 ± 0.13*	-35.12%

Values are given as Mean ± SD, (n = 8), *Significantly different at ($P < 0.01$)

Table 3: Hematological Parameters and Oxygen Carrying Capacity of Channa Punctata

(Source: Javed, & Usmani, 2013)

Above table reflects that exposure to effluent significantly reduces red blood cell counts (-75.42%), hemoglobin levels (-35.10%) and oxygen-carrying capacity (-35.12%) in Channa Punctata. At the same time, it also showcases substantial increase in white blood cell counts (+546.17%), which further indicates strong physiological and immune stress response to the exposure *(see table 4)* (Javed, & Usmani, 2013).

5. CONCLUSION & RECOMMENDATIONS

5.1 Conclusion

This research paper remains highly supportive to shed light on the impact of sugar factory effluent disbursal in the Chambal River system which carries BOD, COD, TDS and heavy metal loads and increases BIS and CPCB from permissible limits. Due to this reason, sugar factory waste creates a zone of chemical and physical degradation that further not only reduces the level of dissolved oxygen, but also introduces toxic metals, which collectively affect river stretch hostile to aquatic life. It leads to haematological disruption and declines RBC up to 75.42%, elevates WBC counts and creates the issue of immunological stress. Further, consumption of Channa Punctata that is contaminated with Cr increases the chances of severe health risks and accumulation by humans can lead to severe gastrointestinal, renal and neurological toxicities.

With the help of case study analysis, clear and well-evidenced findings gained regarding the impact of sugar factory effluent on the Chambal River Basin ecosystem and on Channa punctata. For this purpose, four themes are designed and analyzed, they are: ecological context of the Chambal river basin, effects of physico-chemical disruption of sugar industry in channa punctata in the Chambal and comparative analysis with other cases in Rajasthan. From the analysis, it can be concluded that sugar factory effluent decreases river water quality, fish biological response and gives serious ecological harm.

The Chambal River is a National Sanctuary which has ecological significance and a source of livelihood for different aquatic species, including Channa Punctata. Hence, it is essential to increasing focus towards decreasing the negative impact of industrialization on its fresh river water and to eliminate risk on Channa Punctata as controlling this pollution is necessary to protect aquatic biodiversity, maintain ecological balance and also to safeguard human health against bioaccumulation.

The case study approach adopted in this paper supported to lead contextually rich and ecologically meaningful interpretation with the help of available secondary sources related to the research topic. At the end, it can be concluded that at present, there is a need of immediate intervention to deal with sugar factory pollution in Chambal River water as it is degrading the ecological health as well as biodiversity of the Chambal River Basin. From both case studies, the Chambal River and Satha village, it is identified that both settings reveal the issue of same pollutants: heavy metal enrichment, tissue bioaccumulation in Channa punctata and acute haematological disruption (decline in RBC and oxygen-carrying capacity and increase in WBC). On the other hand, it can be concluded that the Chambal study showcases deterioration spatially, from clean upstream WQI of 34.58 to severely polluted downstream zones, whereas, Satha case allows quantifying the internal physiological damage. Hence, both of them, together confirm that sugar industry effluent is creating the issue of consistent toxic outcomes across distinct Rajasthan and helps to reinforce the study finding.

5.2 Recommendations

From the above case study analysis following can be recommended for the Chambal River Basin to decrease negative impact of sugar factory effluent on the fresh River Water Fish Channa Punctata:

- It is recommended for sugar factories to enhance concern towards adequate effluent treatment plant (ETP) upgradation to decrease chances of adverse impact of physico-chemical characterization on Chambal River Basin, Rajasthan and Channa Punctata. ETP upgradation should have the potential to handle full peak-season effluent volumes with functional secondary biological treatment. It is essential to ensure BOD ≤30 mg/L before discharging effluent in water body (as per BIS standards).
- It is recommended for smaller sugar factories in rural Rajasthan to use strategy of cost-effective bioremediation (such as - water hyacinth-based phytoremediation and microbial treatment ponds) to lead supplementary treatment measures.

- It is recommended for Rajasthan State Pollution Control Board (RSPCB) to come up with dedicated real-time water quality monitoring program during the crushing season (October to April). Regular compliance audits of ETP functioning with strict penalties is essential during peak crushing season to deal with the issue of discharging untreated effluent into the Chambal River.
- Additionally, formal advisories need to be circulated by Government to local communities regarding the risks of consuming Channa Punctata caught near industrial discharge zones, while showcasing them published evidence of Cr in edible muscle tissue exceeding USEPA limits.

5.3 Research Limitations

This research paper is highly useful as it offers evidence-based insights into the ecological damage that is caused by sugar factory effluent on the Chambal River Basin and on Channa Punctata. Hence, findings of this study serve as a valuable reference for environmental policymakers, aquatic toxicologists and conservation authorities that are working towards freshwater ecosystem protection and sustainable industrial regulation in Rajasthan. However, it is identified that this research is based on secondary data, so, if primary data is also used related to field measurements, direct water sampling, fish tissue analysis, etc. from the Chambal River Basin, then it could assist to increase the reliability and credibility of the research finding as they would provide more precise and site-validated conclusions through direct data from the Chambal Basin. Additionally, to conduct this research, single case study design is selected for study purpose, which has assisted to provide analytically rich study but also created limitation of external generalizability. Additionally, to conduct case study analysis, data is collected from the sources ranging from 2008 to 2025. Due to which, some inconsistency is found in the study related to comparability of values across different seasons, methods and geographic sub-regions.

Hence, there is opportunity for future researchers to utilize both primary as well as secondary data in future researches while focusing on large geographic locations and different cases while selecting only recent data sources. Focus towards these aspects can support to come up with better results for analysis of contemporary effects of physico-chemical characterization of sugar factory effluent pollution on Channa Punctata in India.

5.4 Future Implications

This research has future implications as it discusses the negative impact of sugar industry operations in the Chambal Basin and explains how growing sugarcane cultivation creates risk of effluent discharge in water bodies while providing evidence of physico-chemical pollution patterns and biological stress responses in Channa punctata while explaining the impact of water quality standards for ecologically sensitive river systems. Additionally, the framework used in this study can be replicable for future researches related to agro-industrial river systems across India. Moreover, this research also plays the role of groundwork for future researches while involving seasonal haematological, histopathological and genotoxicity assessments of Channa Punctata in the Chambal Basin and further strengthen the scientific and regulatory case for mandatory effluent treatment compliance.

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