tadox®
TERI Advanced Oxidation Technology

POLICY BRIEF

INTEGRATION OF TADOX® TECHNOLOGY TO ACHIEVE NET ZERO IN TEXTILE WASTEWATER TREATMENT: **POLICY RECOMMENDATIONS BASED ON PILOT STUDY IN A CETP**

Dr Nupur Bahadur

जल शक्ति मंत्रालय
MINISTRY OF JAL SHAKTI
सत्यमेव जयते
NAMAMI GANGE
THE ENERGY AND RESOURCES INSTITUTE
Creating Innovative Solutions for a Sustainable Future
NMCG-TERI Centre of Excellence on Water Reuse
नमामि गंगे

Authors

Dr Nupur Bahadur, Senior Fellow & Associate Director, TERI
Mr Nipun Bhargava, Senior Researcher, Ph.D. Program, TERI

Advisors
Mr G Asok Kumar, Director General, National Mission for Clean Ganga (NMCG), Ministry of Jal Shakti, Government of India
Dr Vibha Dhawan, Director General, TERI

Dr J V Sharma, Programme Director, TERI

Internal Reviewers
Dr S K Sarkar, Distinguished Fellow, TERI
Dr Suneel Pandey, Director, TERI

External Reviewers
Mr A K Srivastava, Executive Director (Technical), National Mission for Clean Ganga (NMCG), Ministry of Jal Shakti, Government of India
Dr Arindum Basu, Director General, North Indian Textile Research Association (NITRA), Ministry of Textiles, Government of India.
Prof. Arun Kansal, Vice Chancellor, TERI School of Advanced Studies

Internal Reviewers
Dr S K Sarkar, Distinguished Fellow, TERI
Dr Suneel Pandey, Director, TERI

PUBLISHED BY

The Energy and Resources Institute (TERI)

FOR MORE INFORMATION

Dr. (Mrs.) Nupur Bahadur
Associate Director, NMCG-TERI Center of Excellence on Water Reuse (NTCoE),
Environment and Waste Management Division
The Energy and Resources Institute (TERI), 6C, Darbari Seth Block,
India Habitat Centre, Lodhi Road, New Delhi–110003, India
Email: nupur.bahadur@teri.res.in | Web: https://nmcgtericoe-wr.in
Contact: +91-11-24682100, Ext: 2151

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EXECUTIVE SUMMARY

Textile & Coloration Industry faces the most challenging issue of removal of colour and dissolved organics due to the presence of complex dyes and pigments in the effluent, which are not being able to be removed by conventional and biological treatment technologies. Which in turn impacts the biological treatment making is shock prone and leading to inadequate treatment with discharge of coloured effluent through drains in the rivers. This also impacts downstream tertiary treatment and makes ZLD highly resource and energy intensive and hence unsustainable, unaffordable, unacceptable and non-compliant. Moreover, such a resource and energy intensive nature of wastewater treatment contributes to GHG emissions and Climate Change and ultimately impacts the Life Cycle of effluent treatment. Hence in order to address the major issue of colour and curb point source pollution, mitigate associated climate risks and quantify environmental footprint it is vital to integrate in current systems, certain novel approaches and promising technologies like Advanced Oxidation which could help in addressing these gaps and challenges.

It is in this pursuit, The Energy and Resources Institute (TERI), New Delhi, has developed a novel technology called TERI Advanced Oxidation Technology (TADOX®), which involves UV-TiO_2 Photocatalysis as an Advanced Oxidation Process (AOP), which removes colour and dissolved organics from the effluent, and when integrated and retrofitted at pre-biological treatment stage, safeguard it and makes it shock proof and reduces load on tertiary treatment, help achieve ZLD in much resource and energy efficient manner thereby expected to reduce GHG emissions and carbon footprint and overall operational expenditure.

Central to this study is the demonstration of TERI Advanced Oxidation Technology (TADOX®) Technology at the Textile Common Effluent Treatment Plant (CETP) in Rooma Industrial Area, Kanpur, a project executed under the Namami Gange National Mission, funded by the National Mission for Clean Ganga (NMCG) (http://nmcg.nic.in) Ministry of Jal Shakti (MoJS), Govt. of India. The end-to-end TADOX® plant, treating raw effluent from the equalization tank at a rate of 1000 Liters Per Hour (LPH) or 20 Kilo Liters per Day (KLD) has shown exceptional operational resilience and adaptability for over six months of continuous operation. Notably, the system has effectively reduced Chemical Oxygen Demand (COD) from 990 to 55 mg/L and Biochemical Oxygen Demand (BOD) from 312 to 11 mg/l, adhering to strict compliance norms with significant reductions in key pollutants such as TSS by 97.8%, Oil and Grease by 92.3%, COD by 94.5%, BOD by 96.5%, and color intensity by 98.2%. This has enabled biological treatment system shock proof with improved biodegradability. Hence TADOX® Technology is proposed to be implemented as a retrofittable solution at pre-biological treatment stage of the existing 1.55 MLD CETP, which is expected to reduce load on RO and tertiary treatment and make Zero Liquid Discharge (ZLD) compliance of CPCB, Govt. of India, archivable, sustainable, economically viable, acceptable and compliant. This is 1st of its kind demonstration in the World of UV-Photocatalysis based Advanced Oxidation Technology for treatment of Textile Effluent in a CETP at 20 KLD capacity.

In order to find out the benefits of TADOX® Technology integration to help achieve ZLD compliance in existing system as compared to ZLD implementation alone in the existing system, Life Cycle Assessment (LCA) was carried out. Thus, three scenarios are presented for study as follows:

1. Scenario 1: Existing CETP (Control)
2. Scenario 2: Existing CETP + ZLD
3. Scenario 3: Existing CETP + TADOX® integration at pre biological + ZLD

From Life Cycle Assessment (LCA) results, in line with ISO 14040 and ISO 14044 standards, for the Existing System (Scenario I), the Total CO_2 Equivalent is calculated to be 13.3 tCO_2e/m^3, which is expected to increase to

34.7 tCO_2e/m^3 if ZLD is implemented in the Existing CETP (Scenario II) where inadequate treatment is taking place and the CETP is non-compliant. However, if TADOX® Technology is integrated at pre biological stage followed by ZLD Plant at the tertiary stage (Scenario III) then the Total CO_2 Equivalent is calculated to be 23.6 tCO_2e/m^3, representing a 32.11% reduction from Scenario II. Hence this highlights TADOX®'s role in lowering the Global Warming Potential (GWP) of treated water, which is crucial for scaling up capacities to meet the textile industry's increasing demands while adhering to environmental regulations.

Operational expenses were determined to be approximately INR 100/m^3, resulting in a comprehensive ZLD cost of about INR 220/m^3. This is a significant reduction from the conventional ZLD systems' cost of INR 400/m^3. Furthermore, integrating renewable energy sources like solar power could amplify TADOX®'s sustainability and reduce operational expenses further by up to 40%, steering it towards a net-zero energy solution. Also it will address the concerns of various Textile Associations who want to implement ZLD but fear of its cost implications.

Hence the study recommends policy shifts to encourage AOP adoption like TADOX®, ZLD guideline revisions to include TADOX® use, and renewable energy integration within treatment systems. These actions, aimed at the major Regulatory Body like the CPCB and SPCBs in the Country, which are crucial steps toward fostering sustainable industrial frameworks. Also this initiative would strongly support the industry's shift towards sustainable wastewater management practices, offering a viable solution for meeting ZLD requirements in National Mission like Water Vision@2047 and 'Namami Gange', where the core objective of rejuvenation of rivers and in particular achieving the goal of 'Nirmal Dhara', the 'Unpolluted Flow' will be achieved.

Thus the Textile & Coloration Industry has a huge responsibility of balancing economic development with environmental stewardship for ensuring the long-term sustainability and growth of the sector.

1. Indian Textile Industry: Meeting Economic, Environmental and Sustainability Challenges

The Indian Textile Industry plays a very crucial role in Country's economic development and accounts for 2.3% of its GDP, 13% of its industrial production, 12% of its exports, 4% share of the global trade and provides direct employment to approximately 45 million people. At the same time, the textile and dyeing industry is exceptionally water-intensive, for processing textile materials. It is estimated that about 1.6 million Liters of water is used daily for processing 8,000 kilograms of textile materials. The water requirements for textile manufacturing vary depending on the specific processes and types of products.

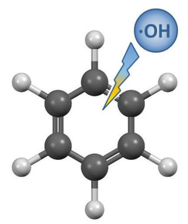
Also this industry is attributed to almost 20% of all freshwater pollution with release of harmful chemicals and dyes into the environment, posing a severe threat to aquatic life, environment and ecosystem. 'Bleeding Rivers' is what often quoted in the media with a distressing and alarming situation in many local rivers like the Hindon in Ghaziabad, UP, the Cooum river in Chennai and Noyyal river in Tirupur in Tamil Nadu, the "blue" Bandi river in Pali and Loni river in Balotra in Rajasthan etc. Ultimately this pollution through tributaries reaches the river basins of the Country like the Ganga, the Cauvery and others. Thus Textile Industry has a huge responsibility of balancing economic development with environmental stewardship for ensuring the long-term sustainability and growth of the sector.

2. Status of Textile Wastewater Treatment & Need for Integration of Advanced Oxidation Technology

Textile Wastewater Treatment faces many issues however the most challenging is the removal of colour and chemicals, which are organic in nature with complex dyes and pigments, which bring in toxicity and impacts the biological treatment making is shock prone and leading to inadequate treatment. Further when this inadequately treated coloured water goes as the feed for tertiary treatment, involving RO leads to chocking and biofouling of membranes and create associated problems of higher CAPEX and OPEX. RO reject further goes to a few cycles of Multi Effect Evaporators (MEE) and its reject goes for further drying and in many instances MEE Condensates still have colour. Thus the main problem of colour and organics does not seems to end, making ZLD and the overall wastewater treatment and management highly resource and energy intensive and hence unsustainable, unacceptable, unaffordable and non-compliant. The Large industrial houses could still afford tertiary treatment to achieve ZLD, whereas the MSME sector is left with limited choice of discharging the inadequately treated coloured water to drains and to natural water bodies ultimately reaching rivers. Moreover, such a resource and energy intensive nature of wastewater treatment in textile industry contributes to GHG emissions and Climate Change and ultimately impacts the Life Cycle of ETP and CETP.

Hence in order to address the major issue of colour and curb point source pollution, mitigate associated climate risks and quantify environmental footprint it is vital to integrate in current systems, certain novel approaches and advanced technologies which could help in addressing these gaps and challenges. It is in this pursuit, The Energy and Resources Institute (TERI), New Delhi, has developed a novel technology called TERI Advanced Oxidation Technology (TADOX®), which provides treatment of wastewater streams containing high colour, high Chemical Oxygen Demand (COD), Biochemical Oxygen Demand (BOD), Total Oxygen Demand (TOC), dissolved organics, non-biodegradable and Persistent Organic Pollutants (POPs) present in effluents of grossly polluting industries like textile and dyeing.

2.1 ABOUT TERI's TADOX® Technology



TERI Advanced Oxidation Technology (TADOX®) is under TERI's Patent (grant awaited) and also under various categories of Trademark with the Trademark Office, Govt. of India. TADOX® involves UV-TiO_2 Photocatalysis as an Advanced Oxidation Process (AOP), where nano-TiO_2 powdered material is mixed in primary treated effluent, given contact time, aeration and passed through a Photocatalytic Reactor (PCR) where effluent is exposed through suitable UV Light radiations leading to generation of hydroxyl radicals which oxidatively degrade and mineralize targeted organic pollutants and dye molecules present in the effluent stream and thereby remove colour, as illustrated in Figure 1a.

The used nanomaterial is separated at source and reused up to a few months with same efficiency. Thus, the overall process of TADOX® Technology involves novel approaches which make use of very less amount and less number of chemicals leading to much reduced quantum of sludge, preventing secondary pollution and provide highly resource and energy efficient treatment. Two stage process of TADOX Technology is represented with a Process Flow Diagram in Figure 1b.

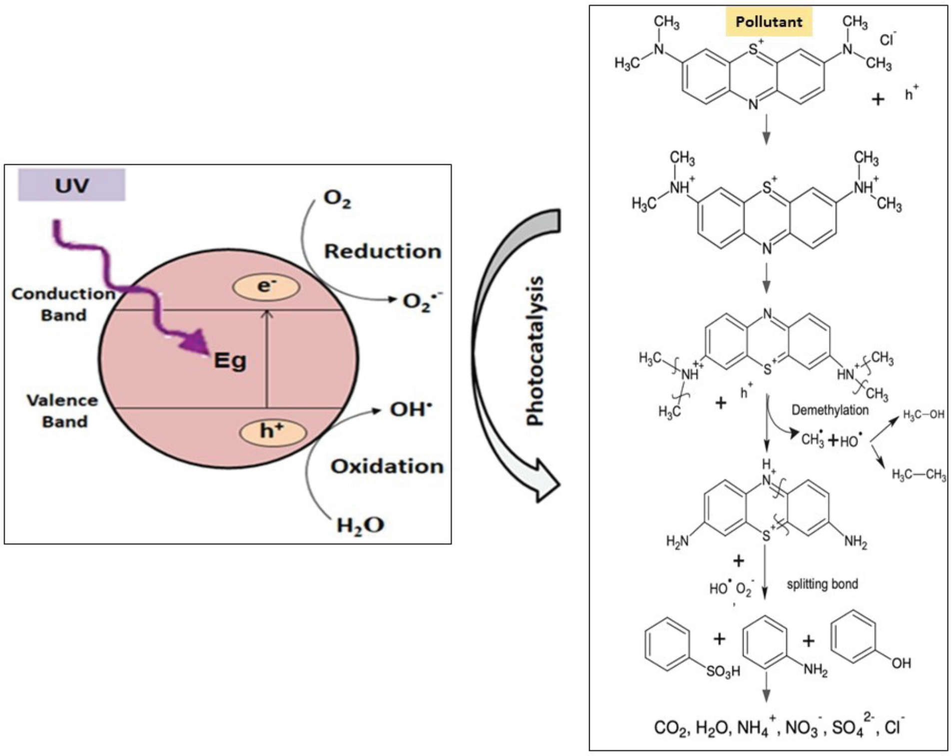


Figure 1a: TADOX® involves UV-TiO2 Photocatalysis as an Advanced Oxidation Process degrading dye and organic pollutants

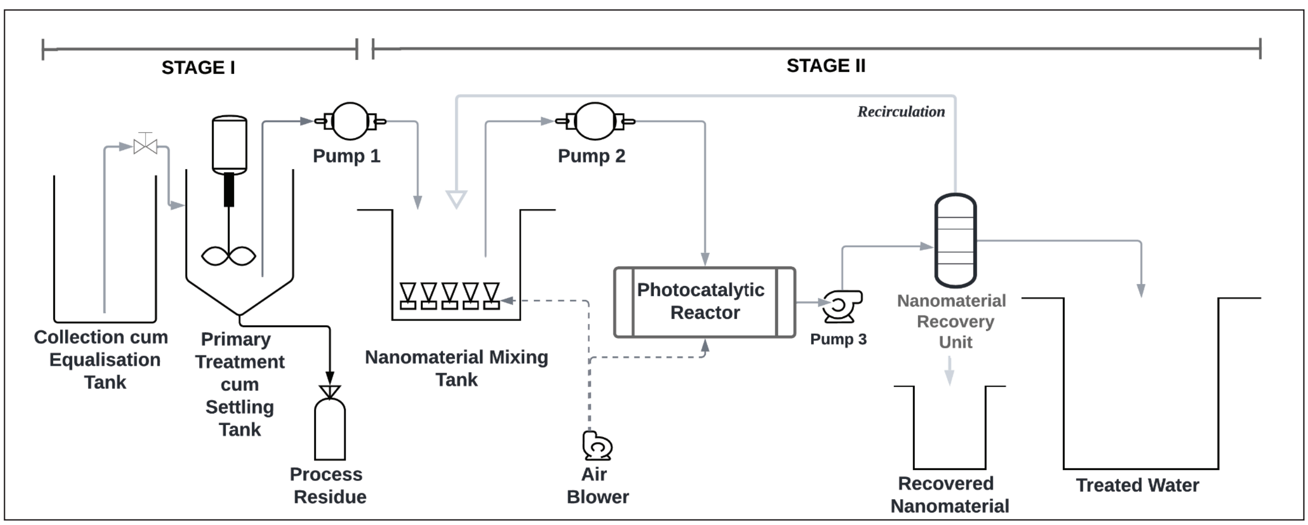


Figure 1b: Process Flow Diagram of TADOX® Technology (patented by TERI)

3. Field Implementation of 20 KLD TADOX® plant in Textile cluster CETP

3.1 Project Introduction

The Energy and Resources Institute (TERI) developed a novel technology for wastewater treatment called TADOX® the TERI Advanced Oxidation Technology, which was developed during 2017-2020 through funding support of DST-Water Mission, Water Technology Initiative (WTI) Program of the Ministry of Science and Technology, Government of India (GoI). In 2020, TADOX® Technology was selected by the National Mission for Clean Ganga (NMCG), Ministry of Jal Shakti, Government of India for the river Ganga rejuvenation under 'Namami Gange' National Mission. 1st funded project given to TERI was a Textile & Hosiery Park in a CETP in Rooma Industrial Area of Kanpur Dehat, UP under UPSIDC.

3.2 Project Site & Current inadequate Treatment

Google Earth image of the CETP site at Rooma, Kanpur, UP, India is provided in Figure 2.

This textile cluster is home to 11 large cotton and hosiery dyeing and finishing units, which generate around 0.55 MLD of wastewater. To reduce the pollution load, all 11 units have installed their own Primary Effluent Treatment Plants (PETPs), before wastewater enters the CETP. The sludge generated from the CETP is around 6-7 Tonnes per month. The CETP uses a conventional treatment process which includes a screen chamber and collection sump that leads to an equalization tank. This design allows for a regulated flow into primary treatment stages where lime, ferrous salts, and alum are introduced through flash mixer units, followed by poly aluminium chloride to facilitate coagulation. The effluent is then directed to a tube settler, separating the supernatant from primary sludge, which is subsequently stored for landfill disposal. The clarified supernatant undergoes further processing in a biological treatment facility employing extended aeration techniques, followed by multigrade and activated-carbon filtration. The filtered water is channelled into irrigation systems, while the remaining sludge is pressed and repurposed as manure. The CETP has a design capacity of 1.55 MLD, which can handle the current and future wastewater generation of the cluster. The average running load of the CETP is 0.75 MLD, indicating that the plant is being operated at around 50% capacity. This leaves enough room for handling any potential increase in wastewater generation in the future. The CETP is not meeting the discharge standards and through a Canal the inadequately treated effluent is being discharged into the holy river Ganga, as depicted in Figure 3 below.

Figure 2: Google Earth image of the CETP site at Rooma, Kanpur, UP, India

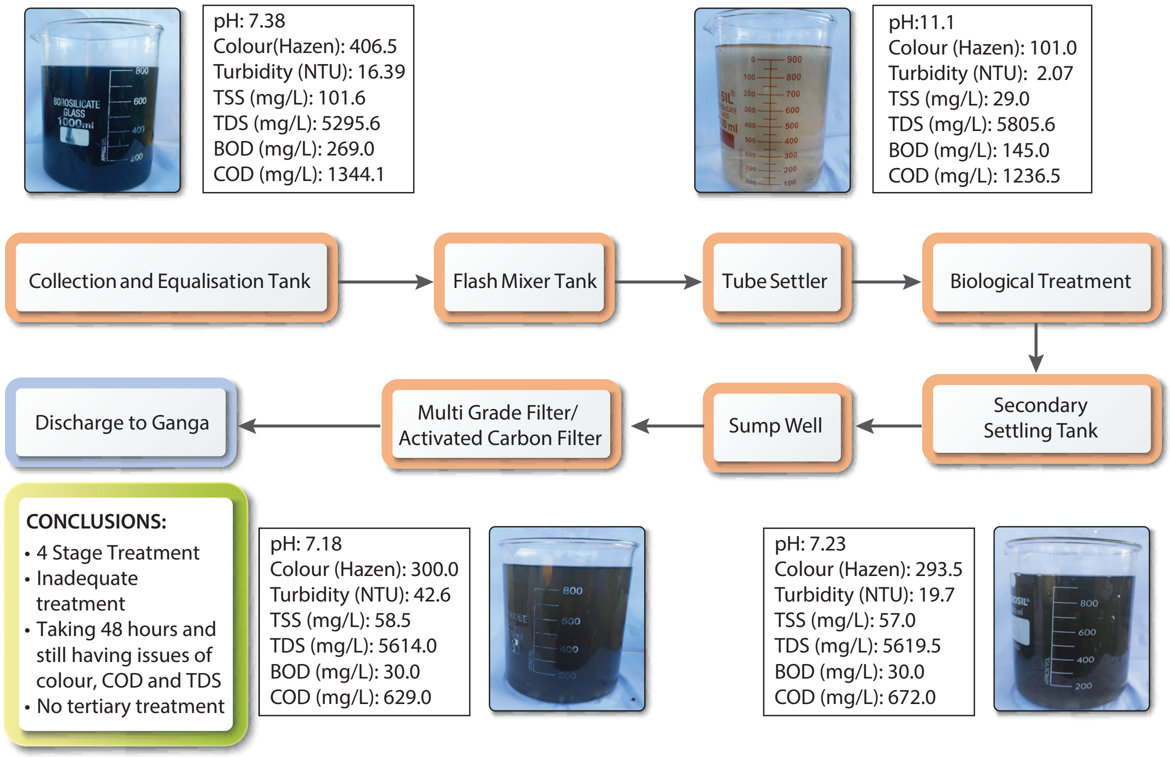


Figure 3. Current treatment which is inadequate and leading to pollution in river Ganga

3.3 Project Objectives

In order to demonstrate TADOX® technology for the 1st time in real field conditions of a textile CETP, a 20 KLD Pilot Plant was commissioned with the following objectives:

(I) To establish, optimize and demonstrate treatment of Textile Wastewater using end-to-end TADOX® technology with an onsite 20 KLD pilot plant;

(II) Treated water aimed to achieve color <50 Hazen, COD <250 mg/L with improved biodegradability using TADOX® alone.

3.4 Project Execution

TERI (The Energy and Resources Institute) being the patentee TERI Advanced Oxidation (TADOX®) Technology bagged the project from the Client and signed a Subcontract Agreement with M/s Perfact Advanced Water Solutions Pvt Ltd, Delhi (PAWS), Delhi, for Design, Supply, Installation, Testing and Commissioning (DSITC).

3.5 Plant inauguration and Commissioning stage

The 20 KLD pilot plant was commissioned on 6th Feb 2023 and formally inaugurated on 17th Feb 2023 by Shri G Asok Kumar, IAS Director General (DG), NMCG in presence of NMCG team, Rooma Pollution Control Association (RPCA) and its members, PAWS and TERI teams as depicted in Figure 4.

After successful commissioning of the plant, samples were drawn from the equalisation tank and final treated water tank and were analysed at an accredited laboratory as shown in Table 1 and Figure 5.

Figure 4: 20 KLD Plant (Left) inaugurated by Director General (DG), NMCG on 17th February 2023

Table 1: Water quality characteristics of the Raw water and TADOX® treated effluent as analysed on 17th February 2023

S. No.	Parameters (Units)	Raw Effluent from Equalization Tank	Tadox® Treated Water	% Change
1	pH	8.5	8.1	-
2	BOD (mg/L)	112	40.6	64
3	COD (mg/L)	1000	256	75
4	Colour (Hazen)	2243	44	98

Analysis done by Prakriti Environmental Solutions Pvt Ltd, Lucknow (NABL and MoEFCC recognised laboratory as per ISO/IEC 17025: 2017)

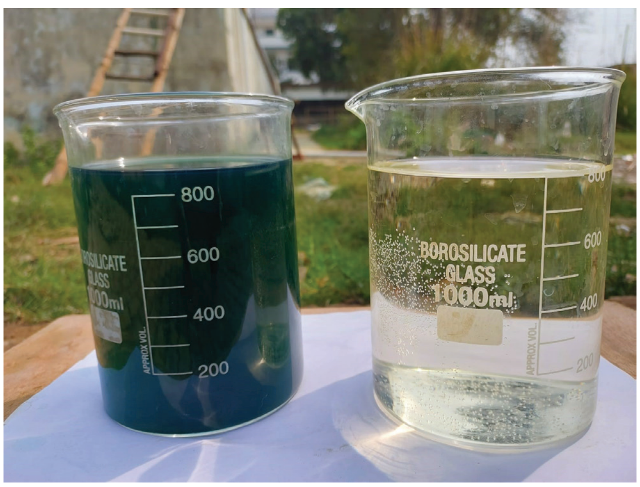


Figure 5: Samples of Raw water and TADOX® Treated on 17th Feb 2023

3.6 Performance Guarantee Test Run of the Plant

After continuous operation of the plant for more than 6 months, on 09th August 2023 NABL accredited Government lab of Council of Scientific and Industrial Research - Indian Institute of Toxicological Research (CSIR-IITR) Lucknow, UP analysed the untreated effluent and TADOX® treated samples as per ISO/IEC 17025: 2017. From the test report, the percentage removal was calculated and was found removal of TSS by 97%, Oil and Grease by 92.3%, COD by 94.5% and BOD by 96.5%. The Techno Economic feasibility data showed an average electrical energy consumption of 8.37 kWhr/m^3 and an average cost of treatment of INR 100 /m^3. Detailed characterization is shown in the Table 2 and samples depicted in Figure 6.

Table 2: Water quality characteristics of the Raw water and TADOX® treated effluent as analysed on 9th August 2023

S. No.	Parameters (Units)	Raw Effluent from Equalization Tank	Tadox® Treated Water	% Change
1	pH	8.6	7.8	-
2	TSS (mg/L)	270	6	97.8
3	Oil and Grease (mg/L)	31.2	2.4	92.3
4	COD (mg/L)	990	54.4	94.5
5	BOD (mg/L)	312.5	11	96.5
6	Colour (Hazens)	1249	22.33	98.2

Figure 6: Samples of Raw water and TADOX® Treated on 9th August 2023

3.7 Key Conclusions from the Field Pilot Implementation

1. **Performance Metrics, Operational Duration and Volume Treatment**:
   - The plant cumulatively treated around 2 MLD (2139 m^3) over a total operational period of almost 8 months.
   - Flow Rate and Efficiency: The plant maintained an average flow rate of 1070 litres per hour. The energy consumption was remarkably low at 8.37 kWh/m^3, with the total cost of treatment being INR 100/m^3.
   - Quality of Treated Water: The treated water consistently met the standards for downstream biological treatment. Specifically, the plant achieved a Chemical Oxygen Demand (COD) of less than 250 mg/L and a color intensity of less than 50 Hazens, aligning with the project's o bjectives for a 20 KLD onsite plant.
2. **Sludge Quantity & Quality Assessment:**
   - The average sludge generated from end-to-end TADOX® Process was around 0.20 Kg/m^3 as against 30-40 Kg/m^3.
   - Studies on the primary sludge generated from TADOX® were carried out as per Schedule I of the Hazardous and Other Waste Management Rules, 2016 (HoWM 2016) wherein 88 parameters were studied as per TCLP (Toxicity Characteristic Leachability Protocol) studies. The results showed that sludge is nontoxic as per the rules.
3. **Nanomaterial Use and Reuse:**
   - Scanning Electron microscopy (SEM), Energy-dispersive X-ray analysis EDAX studies were carried out for the characterization of spent nanomaterials. The results showed that the catalyst was stable for reuse for up to 3 months with continuous operation without reduction in performance efficiency. Thus it further reinstates the fact the overall TADOX® Process led to very less use of chemicals in the entire process.
4. **Techno-Economic Assessment and Process Optimization:**
   - Cost and Energy Efficiency: The technoeconomic assessment indicated that the plant operation was cost-effective with minimal energy requirements, and these metrics are expected to improve with scale of economy.
   - TADOX Optimization: The pilot plant successfully implemented TADOX® optimization for treating RPCA Textile effluent, achieving the desired reductions in COD, BOD, and color at the proposed stages.
5. **Plant Performance and Engineering:**
   - Consistency and Reliability: The plant's performance was consistent, reliable, and largely independent of manual intervention.
   - UV Lamp Efficacy: The use of UV lamps proved resilient in treating effluent.
   - Engineering and Execution: The design engineering and onsite execution were exemplary, requiring minimal modifications from the original design and operation by semi-skilled staff.
   - Plant Capacity: The pilot plant effectively ran to its full capacity of treating 20 KLD.

4. Zero Liquid Discharge (ZLD) Compliance

The Central Pollution Control Board (CPCB), Govt. of India in 2015 released guidelines for implementing Zero Liquid Discharge (ZLD) in 17 water polluting industries, including textile and dyeing with the objective to address concerns about the indiscriminate use of water, its insufficiency, and issues related to wastewater disposal and river pollution. ZLD involves the installation of facilities and systems that enable absolute recycling of permeate and the conversion of solute into solid residue through concentration and thermal evaporation. ZLD is mandated for textile units with daily effluent discharge of more than 25 m^3/day and for all units in clusters, regardless of their wastewater discharge. From these field pilot studies following are major conclusions:

- TADOX® Technology alone was capable to achieve desired parameters of colour <50 Hazen, COD <250 mg/L with improved biodegradability, enabling biological treatment system shock proof.
- TADOX® plus biological is expected to further improve BOD and COD and reduces load on RO and tertiary treatment.
- Also permeate may be expected to be completely reusable for high end applications in process.

TADOX® Technology could be implemented as a retrofittable solution having integrated approach at pre-biological treatment stage of the existing 1.55 MLD CETP. The proposed scheme is figuratively described as follows in Figure 7.

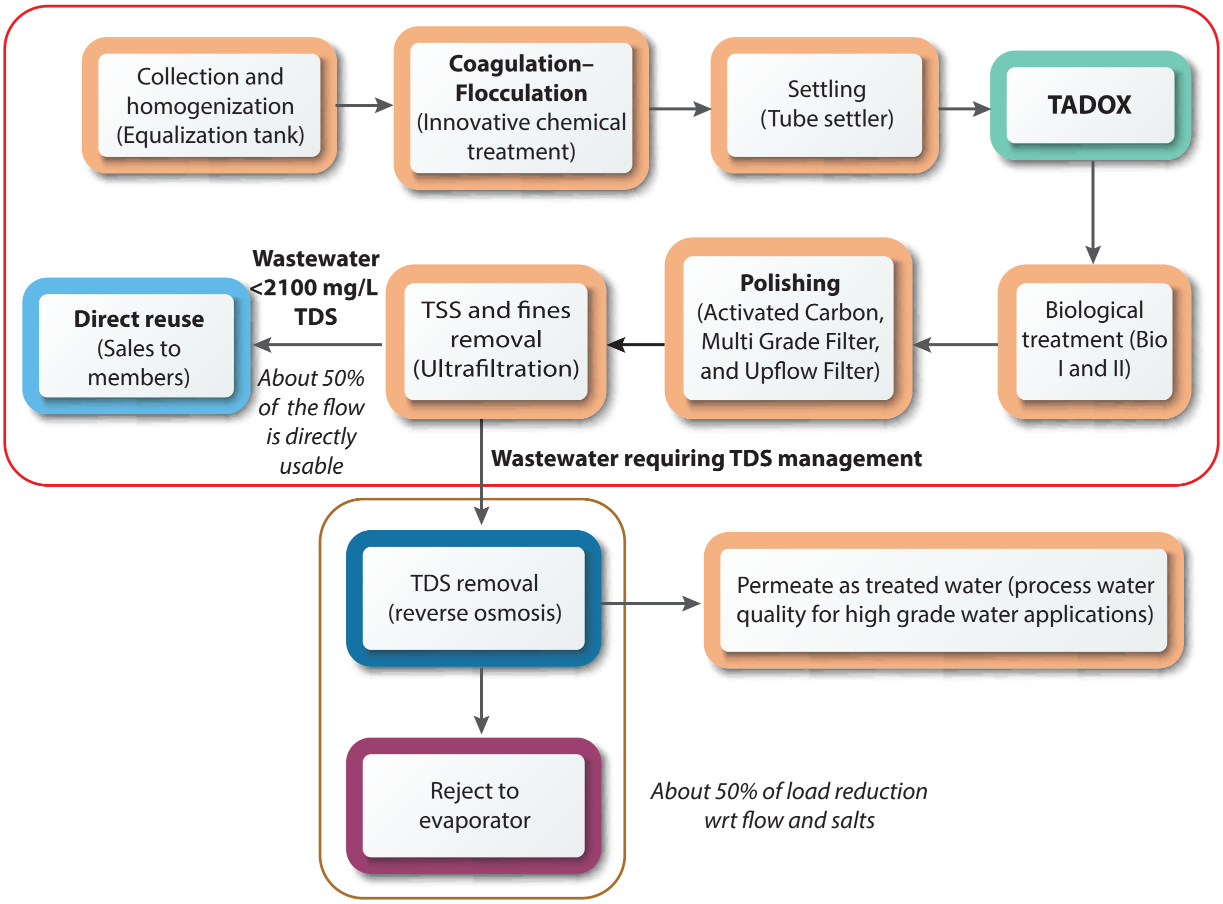


Figure 7: TADOX® Integration at Pre Biological Stage in CETP (as a concept)

Table 3 summarizes the set of challenges in ZLD implementation and how beneficial is AOP integration like TADOX® at pre-biological stage in meeting these challenges.

Table 3: Challenges in ZLD implementation and potential benefits integration of TADOX®

Challenge Category	Description of the challenge	Quantification of the challenge	Benefits of TADOX® Integration
Spatial and Commercial Viability	Textile factories often lack space for ZLD, and the land required for expansion is costly and scarce.	Typically, not exceeding 300 – 400 m^2 area is available with units but ZLD units require area up to 1200 m^2	TADOX® can reduce the footprint of ZLD systems by upto 30% by improving the efficiency of contaminant removal, possibly requiring less space.
Energy Demands and Environmental Trade-Offs	ZLD systems are energy-intensive, leading to increased fossil fuel use and potential air pollution.	3,000 to 15,000 kW daily electricity consumption	TADOX® may lower energy consumption by 30% by reducing the load on RO and evaporators, which are the most energy-intensive components.
Impact on Cost Competitiveness	High operational costs associated with ZLD impact the international competitiveness of products.	25-30% increase in operational expenses	By enhancing treatment efficiency, TADOX® could reduce operational costs by 40%, thereby improving cost competitiveness.
Waste Management Challenges	ZLD processes lead to accumulation of hazardous waste, complicating disposal and management.	Large quantities of mixed salts up to 30-40 kg/m^3	TADOX® can break down complex waste compounds, leading to easier and safer waste management and disposal.
High Carbon Footprint	ZLD facilities have high energy demands, leading to significant carbon emissions.	8 to 10 kW/m^3; up to 40 kW/m^3 for thermal evaporators	TADOX® could reduce the carbon footprint by 25 -35% minimizing the need for thermal processes and enhancing overall treatment efficiency.
Cost Structure of ZLD Plants	ZLD setup is expensive due to high capital and operational expenditures.	Rs. 8-9 crores per MLD capital costs	TADOX® integration may offer a cost-effective alternative to conventional ZLD processes, potentially reducing capital expenditures by 20%.
Operational Sensitivities	ZLD facilities are prone to operational issues, which can cause shutdowns and incur repair costs.	Extended downtime and substantial repair costs with typical OPEX in range of INR 225 INR/m^3	TADOX® being their robust in nature of operation and flexibility in implementation, could provide more stability to ZLD operations, reducing the likelihood of costly disruptions.

Based on the information presented in Table 1, it is evident that the implementation challenges with ZLD system in the textile industry may be alleviated through the integration of AOP technologies like TADOX®.

5. Life Cycle Assessment (LCA) and benefits of TADOX® integration in a Textile CETP

In accordance with ISO 14040, the LCA was carried out to understand the quantitate assessment of the sustainability of integration of TADOX® in a Textile CETP. This involved systematic data collection on the inputs and outputs of the WWTP. Primary data for operational processes were meticulously gathered, ensuring the accuracy of energy and chemical usage, as well as direct emissions. Secondary data, such as the background emissions for energy production, were obtained from the Ecoinvent database and the IPCC report, providing a robust foundation for the subsequent impact assessment.

5.1 Goal and Scope Definition

The study's goal is to provide a detailed environmental impact analysis in direct alignment with the objectives defined by ISO 14040 and ISO 14044, focusing on a 'gate to gate' approach for a functional unit of 1 m^3 of treated wastewater. The scope included all relevant operational stages, from initial wastewater receipt to final discharge or reuse, ensuring a comprehensive assessment of the treatment life cycle.

5.2 System Boundary

Consistent with ISO 14044, the system boundary was delineated to capture all significant processes within the WWTP's operational phase and it is demarcated in Figure 8 as under. This framework was instrumental in feeding data into the SimaPro and OpenLCA models, facilitating the assessment of textile wastewater treatment.

As given in Figure 8 , the flow chart in the system boundary delineates a generic material balance framework utilized to capture and analyse the flow of materials through various unit processes within Effluent Treatment Plant (ETP) scenario(s). It clearly shows the journey of wastewater through physicochemical processes, solid separation, AOPs like photocatalysis, downstream filtration, and finally, advanced treatments such as Reverse Osmosis

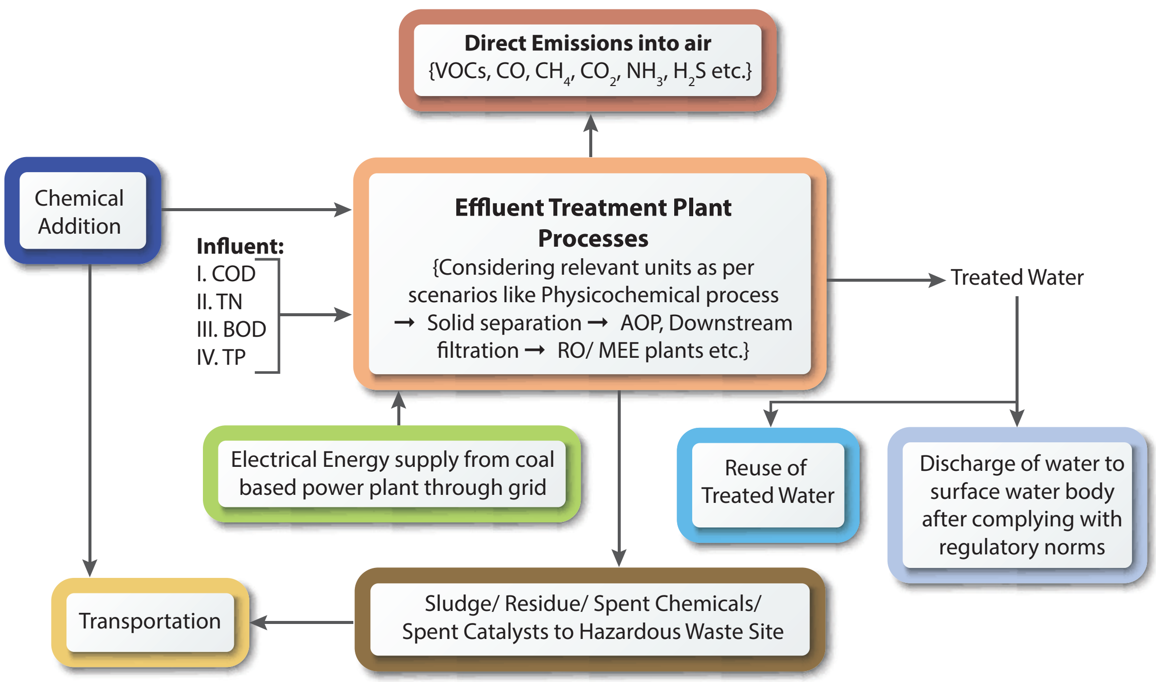


Figure 8: System boundary utilised for conducting the studies as per various scenario(s) using OpenLCA and SimaPro® 8.4

(RO) and Mechanical Vapor Compression Evaporation (MEE). This sequential representation is crucial for understanding the comprehensive treatment that wastewater undergoes before it is deemed suitable for reuse or discharge. Transportation is a parallel process that accounts for the movement of materials and chemicals necessary for the functioning of the ETP. It recognizes the significance of logistics in the overall environmental footprint and is an integral part of the material balance. The terminal processes of the system boundary are the Reuse of Treated Water and the Discharge of water to surface water bodies after complying with regulatory norms. The reuse path underscores the circular economy aspect of the treatment process, reflecting the potential of treated water in non-potable applications, which is a key element in achieving Zero Liquid Discharge (ZLD) norms. The discharge path, on the other hand, ensures that the environmental release of water meets all regulatory standards, mitigating the impact on natural ecosystems.

5.3 Setting up scenarios of the modelling

Model on SimaPro 8.4 was meticulously setup to examine the Life Cycle Assessment (LCA) for Climate Change Potential, specifically focusing on the 'Gate to Gate' segment for various cases of textile wastewater treatment with an objective to establish a framework for evaluating and comparing the environmental impact, particularly greenhouse gas emissions and Carbon Footprint, of different wastewater treatment scenarios:

Scenario 1: Existing CETP (Control)

Scenario 2: Existing CETP + ZLD

Scenario 3: Existing CETP + TADOX® integration at pre biological + ZLD

This approach aligns with the principles outlined in ISO 14044:2006, with the functional unit set as 1 cubic meter of treated water. These scenarios depicted together in Figure 9 provides a comprehensive picture of the potential environmental impacts across different stages of wastewater treatment, offering insights into the most sustainable practices for managing textile wastewater in Rooma CETP and also meeting compliance norms for safe discharge and reuse. To achieve ZLD it is required to have 3 stage RO and MEE for reject management. Also it is clear from Figure 9 that when TADOX® is integrated into the treatment chain, it acts as an additional stage of treatment, targeting colour and organic contaminants that are resistant to conventional treatment methods. TADOX® utilizes advanced oxidation principles to further reduce the chemical pollution load of water, making it suitable for further treatment by biological methods and thereafter reducing load on tertiary treatment, as required.

5.4 LCA Results

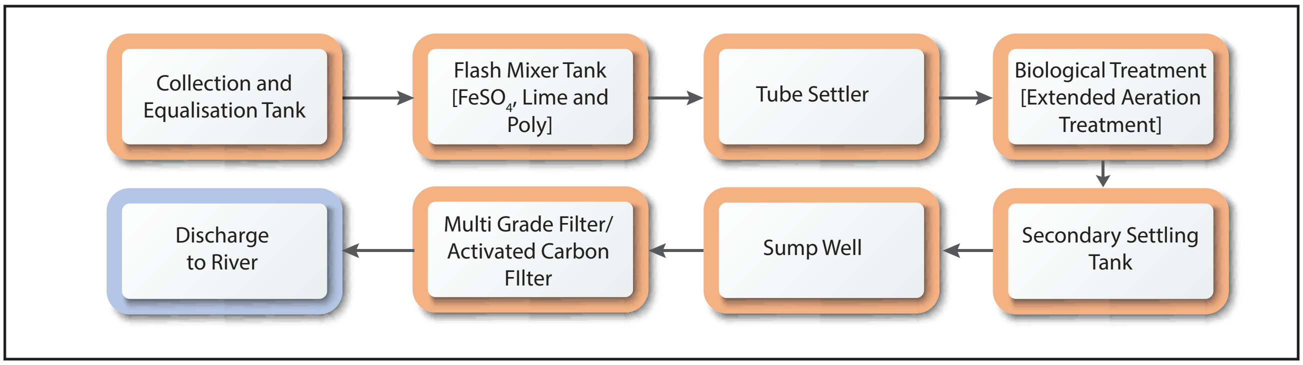
The flow diagrams in Figure 9 serves as a blueprint for the implementation of comprehensive wastewater treatment systems that not only clean the water but also facilitate its reuse, thereby supporting the circular economy in the industry. Now to quantify the same, LCA modelling was done and the same is represented in the bar chart with table inserted in Figure 10.

The bar chart delineates the overall carbon footprint in terms of kilograms of CO_2 equivalent per cubic meter of water treated (kg CO_2e/m^3) and isolates the contribution from five distinct factors: energy consumption, residual pollutants in the outlet, direct emissions, transportation, and chemical consumption.

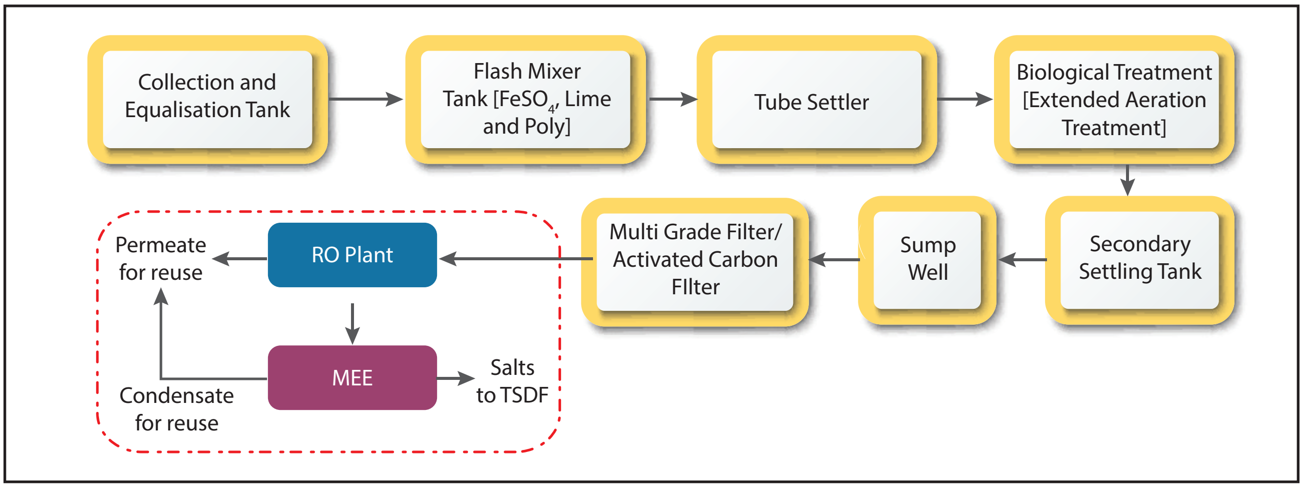
Key Outcomes from LCA Studies in three Scenarios:

- Tertiary Treatment Unit emissions were only applicable in Scenarios II and III, with a substantial reduction from 21.4 tCO_2e/m^3 to 10.7 tCO_2e/m^3 after TADOX® integration.
- Energy Consumption remained the same (2.6 tCO_{2e}/m^3) for Scenarios I and II but increased significantly to 5.6 tCO_2e/m^3 with TADOX® integration in Scenario III.
- Residual Pollutants in the Outlet decreased markedly from 1.1 tCO_2e/m^3 in Scenarios I and II to 0.3 tCO_2e/m^3 with TADOX® integration in Scenario III.
- Direct Emissions were reduced from 8.1 tCO_2e/m^3 in Scenarios I and II to 6.5 tCO_2e/m^3 with TADOX® integration in Scenario III.
- Transportation emissions saw a significant decrease with TADOX® integration, dropping from 1.1 tCO_2e/m^3 in Scenarios I and II to 0.1 tCO_2e/m^3 in Scenario III.
- Chemical Consumption was consistent across all scenarios at 0.5 tCO_2e/m^3.
- The Total CO_2 Equivalent was 13.3 tCO_2e/m^3 for the Existing System (Scenario I), increased to 34.7 tCO_2e/m^3 for the Conventional System to achieve ZLD

Scenario 1



Scenario 2



Scenario 3

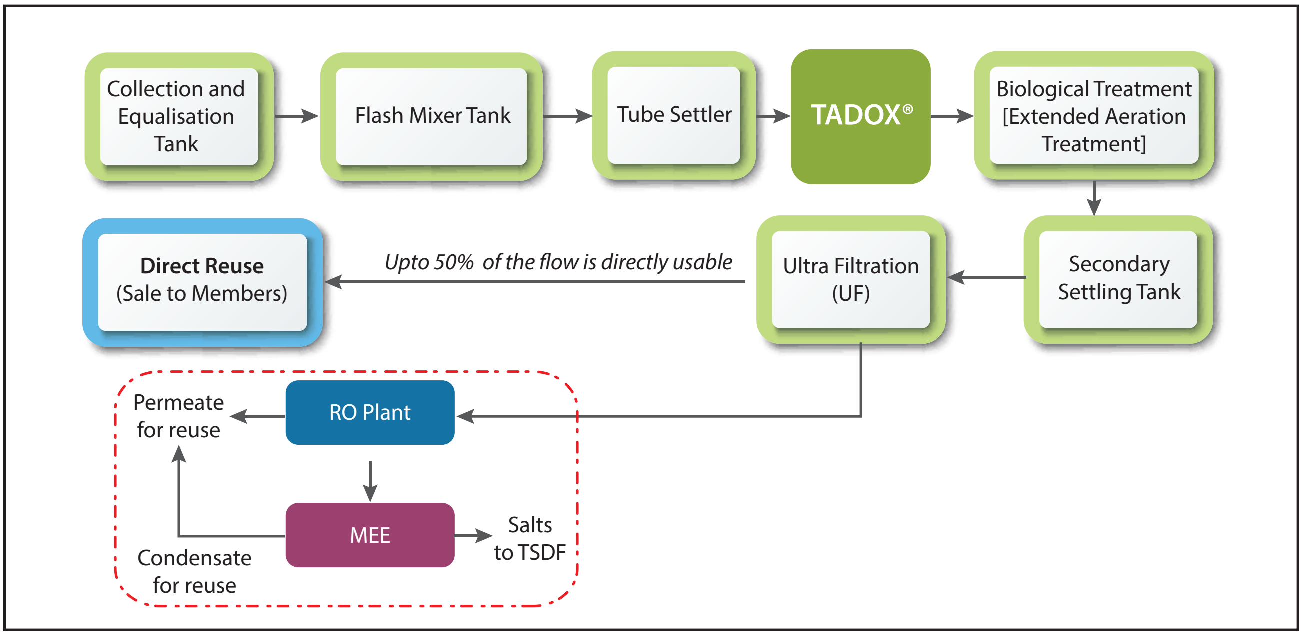
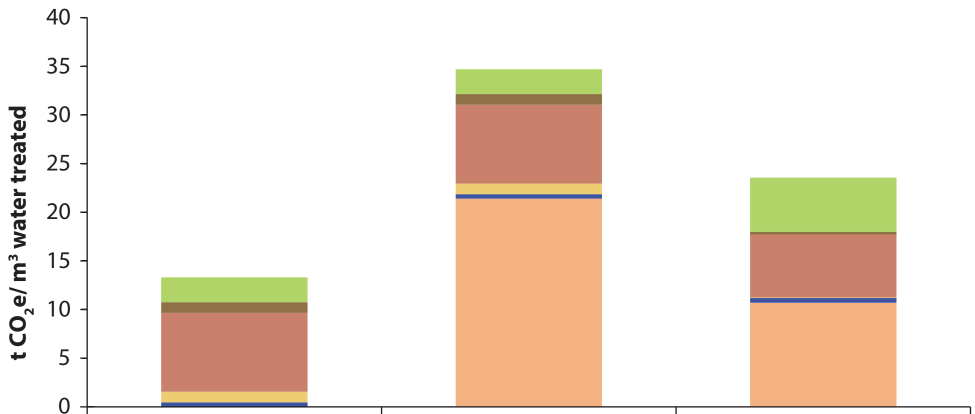


Figure 9: Process flow diagrams delineating of the three Scenarios of textile wastewater in CETP at Rooma, UP. Scenario 1: Existing CETP (Control); Scenario 2: Existing CETP + ZLD; Scenario 3: Existing CETP + TADOX® integration at pre biological stage + ZLD.



	Scenario I	Scenario II	Scenario III
	Existing Plant	Existing Plant with ZLD	Existing plant with TADOX® at Pre-biological stage with ZLD
A. Energy Consumption	2.6	2.6	5.6
B. Residual Pollutants in Outlet:	1.1	1.1	0.3
C. Direct Emissions:	8.1	8.1	6.5
D. Transportation	1.1	1.1	0.1
E. Chemical consumption	0.5	0.5	0.5
F. Tertiary Treatment Unit	0	21.4	10.7

Figure 10: Bar chart showing comparison of overall carbon footprint with contributing factors in tabular form (insert) for Scenario 1: Existing CETP (Control); Scenario 2: Existing CETP + ZLD; Scenario 3: Existing CETP + TADOX® integration at pre biological stage + ZLD.

(Scenario II), and decreased to 23.6 t CO_2e/m^3 with TADOX® integration to achieve ZLD (Scenario III), representing a 32.11% reduction from Scenario II to Scenario III.

5.5 Summary of the LCA studies & Potential for TADOX® as a Net Zero approach

As per section 5.4, it's evident that achieving ZLD in a standard treatment facility raises the carbon footprint from 13.31 kgCO_2e/m^3 to a striking 34.7 tCO_2e/m^3 due to the significant impact of tertiary treatment processes. In contrast, incorporating TADOX® within a ZLD framework leads to a substantial drop in total CO_2 emissions, bringing it down to 23.6 tCO_2e/m^3 from the higher emissions associated with conventional ZLD operations. This reduction is largely due to decreased energy needs, lowered direct emissions, and enhanced efficiency in downstream tertiary treatments enabled by the TADOX® system.

The outcomes highlight TADOX®'s role in propelling wastewater treatment processes towards greater sustainability. With an eye on integrating renewable energy sources, TADOX® could further drive the wastewater treatment sector towards a net-zero goal by significantly lowering or even fully offsetting the carbon footprint from its electrical energy consumption. The resilience and capability of the TADOX® system, especially when paired with renewable energy sources, offer a promising route to more environmentally responsible wastewater management practices. Policy support is crucial to broaden the uptake of TADOX® systems and to shift towards renewable energies, thereby bolstering the textile and dyeing industry's environmental stance. Adopting such policy directions promises not just a reduction in ecological impact but also strides towards global sustainability objectives.

Operational expenses were determined to be approximately INR 100/m^3, resulting in a comprehensive ZLD cost of about INR 220 per cubic meter. This is a significant reduction from the conventional ZLD systems' cost of INR 400/m^3. Introducing renewable energy sources to the TADOX® system offers the possibility of reducing operational expenses by up to 40%, pushing the technology towards achieving net-zero emissions. This deliberate shift towards renewable energy substantially decreases the carbon footprint, ensuring that wastewater treatment practices are in harmony with worldwide sustainability objectives.

6. Policy Recommendations for Implementation of TADOX® in the Indian Textile Sector

Given the compelling evidence from treatment efficacy data and Life Cycle Assessment (LCA) results, the following policy recommendations are proposed for the consideration of the Government of India and other relevant stakeholders:

1. **Incentivize Advanced Oxidation Process (AOP) Implementation:**
   - Provide financial incentives to textile industries for adopting TADOX® technologies, noting the 32% decrease in Global Warming Potential (GWP) per cubic meter of water treated for meeting ZLD norms and EPA 1986 discharge norms.
   - Offer tax rebates or subsidies for the capital required for retrofitting existing treatment systems with TADOX® technology.
2. **Mandate Renewable Energy Integration:**
   - Enforce policies that mandate the integration of renewable energy sources like solar energy with TADOX® systems to achieve net-zero emissions.
   - Encourage Public-Private Partnerships (PPPs) for the development of renewable energy infrastructure, specifically for textile wastewater treatment plants.
3. **Revise ZLD Guidelines**:
   - Update ZLD guidelines to include provisions for using TADOX® technology, highlighting the reduction in sludge generation, enhanced effluent biodegradability and adequate treatment.
   - Set progressive GWP reduction targets for the textile industry to promote greener wastewater treatment solutions.
4. **Develop Technical Standards**:
   - Collaborate with experts to create standard operating procedures and best practice guidelines for TADOX® technology implementation in textile effluent treatment.
   - Organize workshops and training for industry professionals to ensure technical standard compliance and efficient TADOX® operation.
5. **Fund R&D and Pilot Demonstrations**:
   - Allocate grants for R&D in optimizing TADOX® technology, focusing on maximizing treatment efficiency and minimizing costs.
   - Support pilot projects exploring TADOX® technology's innovative applications beyond the textile sector.
6. **Enhance Monitoring and Compliance**:
   - Implement stringent monitoring to ensure compliance with discharge norms when using TADOX® systems.
   - Establish a transparent reporting system to hold industries accountable for their environmental impact.
7. **Facilitate Knowledge Exchange**:
   - Create a platform for sharing TADOX® technology success stories and case studies in wastewater treatment.
   - Foster international collaboration for exchanging AOP best practices and technological advancements.
8. **Specific Recommendations for Ministry of Environment, Forests and Climate Change**:
   - **Amendment in Regulatory Norms**: Propose amendments to effluent treatment norms to incentivize TADOX® adoption and establish a certification program for water and wastewater treatment technologies.
   - **Business Incentives**: Leverage the export potential of textiles processed using eco-friendly TADOX® technologies and provide export incentives for sustainable practice commitments.
   - **Financial Incentives**: Adjust financial policies to reduce adoption barriers for SMEs and include environmental risk assessments in textile industry lending policies.

- **Support for Start-Ups**: Enhance Start-Up India Grants and Challenges, Invest India Fund, etc., for start-ups in wastewater treatment technology.

9. **Specific Recommendations for Ministry of Textiles:**
    - **Cluster Development Programme**: Use the MSE-CDP Scheme to address technology upgradation and cleaner technology options like TADOX® in wastewater treatment.
    - **Integrated Textile Parks Scheme**: Incentivize the adoption of cleaner technologies like TADOX® in new Textile Parks through the SITP.
    - **Technology Upgradation Fund Scheme (TUFS)**: Include cleaner technologies like TADOX® for subsidies and assistance in upgrading technologies for pollution control.
    - **Integrated Processing Development Scheme (IPDS)**: Incorporate TADOX® in the IPDS for bridging the gap between technology adopters and providers in textile wastewater treatment.

Conclusion

The Pilot demonstration of TADOX® technology in a CETP of Rooma Industrial Area of Kanpur, Uttar Pradesh has shown a possibility of revolutionizing wastewater treatment & management in India's textile sector. The proposal of integrating TADOX® Technology at the pre-biological stage while implementing ZLD system shows the possibility of overcoming majority of the traditional challenges of ZLD implementation like high costs, intense energy demands, and significant sludge generation. Particularly, TADOX® has removed colour and organics, improved health of biological treatment and enabled downstream tertiary treatment more resource and energy efficient. Integration has improved overall operational efficiency, processing capacity for larger wastewater volumes faster, which is vital for meeting the growing needs of the textile industry within environmental compliances. Its efficient operation, requiring fewer chemicals and less amount of chemicals, also minimizes sludge generation, easing both ecological and economic pressures.

TADOX®'s integration at pre-biological stage together with ZLD systems is expected to enhanced treatment efficacy and environmental sustainability, as evidenced by Life Cycle Assessment (LCA) studies, highlighted a substantial reduction by 32% in Global Warming Potential (GWP). The potential integration of renewable energy sources like solar power with TADOX® presents an avenue to further reduce operational costs by up to 40%, steering the technology towards a net-zero emission target. This strategic energy integration significantly lowers the carbon footprint, aligning wastewater treatment with global sustainability goals.

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References

Bahadur, N., 2015. 'Design and development of photocatalytic reactor for treatment of Industrial effluent as well as sludge using recently patented technology', in Proceedings of the India International Science Festival-Young Scientists' Meet Department of Science and Technology, Government of India, pp. 1–5.

Bahadur, N. and Bhargava, N., 2019. 'Novel pilot scale photocatalytic treatment of textile & dyeing industry wastewater to achieve process water quality and enabling zero liquid discharge', Journal of Water Process Engineering, 32, Available at: https://doi.org/10.1016/j.jwpe.2019.100934.

Bahadur, N., Das, P. and Bhargava, N., 2020. 'Improving energy efficiency and economic feasibility of photocatalytic treatment of synthetic and real textile wastewater using bagasse fly ash modified TiO2', Chemical Engineering Journal Advances, 2, Available at: https://doi.org/10.1016/j.ceja.2020.100012.

Bahadur, N., 2021. 'TERI Advanced Oxidation Technology (TADOX) to treat textile and dyeing wastewater, achieve zero liquid discharge, and enhance water reuse: R&D-based policy recommendations', The Energy and Resources Institute Policy Brief.

Bahadur, N. and Bhargava, N., 2022. 'TERI Advanced Oxidation Technology (TADOX®) to treat industrial wastewater with integration at pre-and post-biological stage: case studies from India', Water Practice & Technology, 17, Available at: https://doi.org/10.2166/wpt.2022.065.

Bahadur, N., Bhargava, N., Sarkar, S.K. and Dhawan, V., 2023a. 'Breakthrough in Treatment of Sewage Using TADOX®, By-Passing Biological Treatment with removal of Micropollutants to enable high end Water Reuse', Journal of The Institution of Engineers (India): Series A, Available at: https://doi.org/10.1007/s40030-023-00738-5.

Bahadur, N., Bhargava, N., Sarkar, S.K. and Dhawan, V., 2023b. 'TERI advanced oxidation technology (TADOX®) for treatment and rejuvenation of open drains and surface water bodies: making habitats sustainable', Water Practice & Technology, 18, pp. 1357–1365, Available at: https://doi.org/10.2166/wpt.2023.087.

Bahadur, N., Bhargava, N., Sarkar, S.K. and Dhawan, V., 2023c. 'Integration of TADOX® technology to improve water reuse efficiency of constructed wetland-treated water', Water Practice & Technology, 18(8), pp. 1891–1897, Available at: https://doi.org/10.2166/wpt.2023.114.

Bhargava, N., Bahadur, N. and Kansal, A., 2023. 'Techno-economic assessment of integrated photochemical AOPs for sustainable treatment of textile and dyeing wastewater', Journal of Water Process Engineering, 56, 104302, ISSN 2214-7144, Available at: https://doi.org/10.1016/j.jwpe.2023.104302.

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