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# TERI advanced oxidation technology (TADOX®) for treatment and rejuvenation of open drains and surface water bodies: making habitats sustainable

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## ABSTRACT

Open drains contain sewage waste and find route to surface water bodies mainly due to the absence of dedicated conveyance of wastewater to centralized wastewater treatment facilities. This poses severe environmental, public health and occupational health hazard and there is an urgent need for onsite treatment of open drains. TADOX® (TERI Advanced Oxidation Technology) from TERI (The Energy and Resources Institute, New Delhi) is an advanced approach treat drains using photocatalysis as an advanced oxidation process. This paper presents a case study of an open drain, which when treated with TADOX® Technology, improved water quality parameters meeting the regulatory norms. The untreated open drain did not meet Class E of the Water Quality Criteria laid down by the regulatory body, and attained Class A Water Quality Criteria after end-to-end treatment within 5 h. TADOX® treatment resulted in the removal of 63.5% chemical oxygen demand, 99% biochemical oxygen demand, 96% phosphate, 61% nitrogen, 3 log reduction in E. coli and 4 log reduction in total coliform values with a doubling in dissolved oxygen levels. Micropollutant load reduction of 93.5% in acetaminophen, 96% in sulfamethoxazole, 96% in ibuprofen and 89% in caffeine was also recorded in the study.

**Key words:** micropollutants, non-point source pollution, open drains, photocatalysis, SDGs, TADOX®

## HIGHLIGHTS

- TADOX treatment of open drain bypassed biological treatment and resultant treated water complied with Class A of Designated water reuse criteria defined by CPCB, India.
- The overall 5-hour end-to-end treatment resulted in significant removal of primary pollutants like 63.5% COD, 99% BOD, 96% phosphate and 61% TKN.
- 3 log reduction in *E. coli* and 4 log reduction in total coliform values.

## 1. INTRODUCTION

Larger towns and modern-day cities in developing countries have the requisite infrastructure to tackle sewage management and managing water resources; however, rural areas, villages and satellite towns lack resources for efficient wastewater treatment and management of water resources. Many of these villages are adjoining big cities and are developing very fast into peri-urban areas where economic activities are prevalent but there are also rural community areas where there are typical issues such as open defecation, animal husbandry and allied activities, agricultural activities, common bathing and washing areas that lead to multiple sources of pollution into nearby lakes, and surface water bodies.

Open drains also face continuous ecological and climatic effects and experience anthropogenic activities leading to a high risk of infection and transmission of communicable diseases. In this regard, microbiology parameters like *Escherichia coliform*, total coliform and total aerobic count are important to be investigated and treated suitably. Open drains from such peri-urban areas also contain high biochemical oxygen demand (BOD), chemical oxygen demand (COD), total suspended solids (TSS), sulfides, nitrates, ammonical nitrogen and phosphates, and micropollutants such as steroids, antihistamines, analgesics, antibiotics, pesticides and

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fertilizers (Giannakis *et al.* 2015; Bagheri *et al.* 2017; Fawzi Suleiman Khasawneh & Palaniandy 2019; Liang *et al.* 2019; Khasawneh & Palaniandy 2021; Krishnan *et al.* 2021; Yacouba *et al.* 2021; Yin & Shang 2020; Żyłła *et al.* 2019). Such open drains easily find their way based on natural topology and drainage patterns into natural ponds, lakes and rivers which are important water resources.

Moreover, several of these peri-urban areas have small-scale industries, cottage industries and small-scale workshops that are insignificant polluters on an individual basis however cumulatively account for a large pollution load into the water bodies, thus leading to a quality which is highly heterogeneous and difficult to treat. Therefore, it is of utmost importance to treat these drains before they join the natural water bodies; however, it is a difficult challenge as open drains are mostly untraceable and are easily created based on the topography of the area, climate of the area, etc. Furthermore, open drains could also be seasonal (only visible in monsoon season), could be prone to shock loads in terms of quality/quantity and could have the ability to alter water course with slight changes in drainage pattern of the area due to anthropogenic activities. Therefore, these open drains are difficult to be tapped into the centralized as well as decentralized wastewater treatment plants (STPs/DWWT) being run by the urban local bodies (ULBs). Severely contaminated open drains could percolate several micropollutants, dissolved organics or toxic compounds into the groundwater of the area causing immediate exposure/ingestion by the population. This situation is potentially hazardous for human health, occupational health and ecological health.

Conventional treatment technologies like chemical coagulation treatment followed by anaerobic–aerobic biological treatment systems cannot be directly integrated into such drains and streams with the intermittent flow and seasonal variations. These technologies require a homogenous flow and load influent on the treatment systems. For this reason, Shrivastava *et al.* (2020) supported the installation of either decentralized approaches or an *in situ* constructed wetland (CW) as an approach for enhancing the self-purification of surface water bodies; CW is also a promising approach given that there is limited operation and maintenance. Though this may be a potential abatement plan, CW may not efficiently remove low biodegradable organics, and micropollutants and cannot disinfect coliforms from sewage water. Several researchers have published reports on various technological interventions in mitigating these challenges, such as Wang *et al.* reported use of diffused aeration by placement of aerators into the Qing River, Beijing, China (Md Anawar & Chowdhury 2020); while another report evaluated the use of physicochemical treatment in Lake Rusalka, Poland through systematic addition of $FeSO_4$ to the lake (Md Anawar & Chowdhury 2020).

Advanced oxidation processes (AOPs) have shown to be promising in simultaneous removal of microbial toxicity and micropollutants wherein a significant removal was observed in 2 h, and the authors concluded that AOP could be a viable strategy to facilitate drain disposal of contaminated waters (Phillips *et al.* 2020). While not many advanced oxidation-based treatments have been used at a large scale for the abatement of polluted rivers, lakes and water bodies. A recent report by Tabla-Hernandez *et al.* (2020) discussed continuous diffused $O_2$ and $O_3$ purging directly through a floating reactor system into the Valsequillo reservoir in Puebla, Mexico for 5 months to reduce COD, BOD and increase DO levels. To the best of our knowledge, this has been the most recent and large-scale non-point-source pollution abatement strategy at this real scale. Whereas there are limited reports available on real-time treatment of a flowing open drain; none of the reports study the treatment of these small open drains/nallahs.

This report shows a case study where an open untreated drain passing through The Energy and Resources Institute (TERI) Gwal Pahari campus at Gurugram, Haryana, India has been treated using TERI Advanced Oxidation Technology (TADOX®); this drain is highly discoloured and has a strong and pungent odour throughout its flow in TERI campus. TADOX® utilizes an advanced coagulation–flocculation-based primary treatment, nanotechnology-enabled heterogeneous photocatalysis (UV/n-$TiO_2$) and nanomaterial recovery as tertiary treatment (Bahadur 2015, 2021; Bahadur & Bhargava 2019, 2022; Bahadur *et al.* 2020; Das *et al.* 2020). The treatment efficiency has been evaluated in terms of physicochemical characteristics; pathogens like *E. coli* and faecal coliforms; micropollutants like caffeine, acetaminophen, ibuprofen, naproxen, sulfamethoxazole, diclofenac, bisphenol-A (BPA) and pesticides.

## 2. MATERIALS AND METHODS

### 2.1. Sample selection and collection

Untreated drain with an average depth of 3 m with an average velocity of 1 m/s, originating about 100 m north direction from the Mandi village (shown in Figure 1). It passes daily in a continuous manner through the TERI

**Figure 1** | Satellite imagery showing the location of Mandi village nearby the TERI campus and the open drain entering the TERI campus.

campus comprising of raw sewage, domestic, agricultural and veterinary wastewater. It may be considered as naturally aerated and follows the natural contour and drainage of the area with a horizontal span of 4–6 m within the campus (as shown in Figure 2). From this open drain, a grab sample was collected around Noon on a weekday, the sample was collected from the middle of the flowing stream at about 1.5 m depth with a simple 20 L Polypropylene jar. Water from the polypropylene jar was decanted into two 10 L glass bottles and sealed with a metallic cap ensuring that there was no space for air. Pilot testing on the TADOX® plant on the same day and all samples were sent for testing and characterization to an accredited laboratory within 6 h in an ice box maintained at 4 °C.

As shown in Figure 2, the wastewater is slightly discoloured and there is intermittent flow at the point of collection of wastewater. About 5,000 L of sewage flows every day from the village and is only naturally

**Figure 2** | Photos of the drain flowing through the TERI campus containing untreated sewage from nearby villages.

aerated, ultimately the drain joins the city drain channelized to the common sewage treatment plant of Gurugram.

### 2.2. Operation of the plant

Technical information and detailed methodology of the TADOX® technology-based pilot scale plant treating 100 litres per day (LPD) and its operation has been published in another recent article. Details of plant operation, analysis of the wastewater quality parameters, computation of energy requirements and evaluation of the figures of merit have been already given in the earlier publication of this series of case studies (Kumar & Mathur 2004, 2006; Bahadur 2015, 2021; Bahadur & Bhargava 2019, 2022; Bahadur *et al.* 2020; Das *et al.* 2020). It involves UV/$TiO_2$ photocatalysis as the secondary treatment followed by nanomaterial recovery at the source. Such a photocatalytic treatment has been established to be useful in dye intermediates, basic organics, dye molecules, synthetic textile effluent, real textile and dyeing wastewater treatment systems and has been successful in eliminating the need of biological treatment at any stage (Kumar & Mathur 2004, 2006; Bahadur *et al.* 2010, 2020; Kumar *et al.* 2014; Bahadur 2015, 2021; George *et al.* 2016; Bahadur & Bhargava 2019, 2022; Das *et al.* 2020).

### 2.3. Analysis of wastewater quality characteristics

pH, electrical conductivity and total dissolved solids (TDS) were analysed by Pocket Pro Plus multi-tester by HACH, USA. UV–Vis spectra were recorded on UV–Vis spectrophotometer model DR6000 by HACH, USA. Analysis of other wastewater quality parameters was carried out at National Accreditation Board for Testing and Calibration Laboratories, India (NABL) Accredited laboratory as per ISO/IEC 17025:2017. Micropollutants and pathogens were analysed as per standard methods given in Standard Methods for the Examination of Water and Wastewater by American Public Health Association (APHA) 23 edition 2017 (Rice *et al.* 2017). The analysis took place in triplicates so that relative standard deviation (RSD) and other statistical inferences could be drawn.

The extent of degradation of COD and BOD are computed as per Equations (1) and (2) shown below:

$$\%\text{ COD Removal} = \frac{C_i - C_f}{C_i} \times 100 \tag{1}$$

$$\%\text{ BOD Removal} = \frac{B_i - B_f}{B_i} \times 100 \tag{2}$$

where $C_i$, $B_i$ refer to the concentration of COD and BOD for the untreated sample in mg per litre and $C_f$, $B_f$ refer to the COD and BOD of treated sample in mg per litre, respectively.

## 3. RESULTS AND DISCUSSION

Figure 3 represents the comparative UV–visible spectra of untreated and TADOX® treated open drain samples (a, b) along with the visual images of the same in the inset. The picture of the untreated drain clearly depicts the presence of enormous pollutants in the form of TSS and colour. While complete decolourization of the untreated drain is clearly visible in the pre- and post-treated pictures of the sample after TADOX® treatment, which was also supported by the trend obtained in UV spectra of the pre- and post-treated samples, where almost complete reduction of dissolved organic content in the untreated drain was seen, which is indicated by the reduction in absorbance around 280 nm.

The wastewater characteristics of the untreated and TADOX® treated open drain have been given in Table 1, which clearly indicates a significant reduction in various physicochemical parameters like COD, BOD, TDS, TKN - total Kjeldahl nitrogen and phosphates along with microbiological parameters and hazardous micropollutants like caffeine, acetaminophen, ibuprofen, naproxen, sulfamethoxazole, diclofenac, bisphenol-A and pesticides.

Tabulated data in Table 1 clearly shows that TADOX® was able to reduce all primary pollutants such as COD, BOD, TSS, etc. This quality of water also meets the regulatory requirements laid down by the Central Pollution Control Board (CPCB), Government of India and National Green Tribunal (NGT) which requires COD less than 50 mg/L and BOD less than 10 mg/L with TSS below 20 mg/L before the treated water can be discharged onto surface water bodies (Ministry of Environment & Forests 1986a, 1986b; Kumar & Goyal 2020).

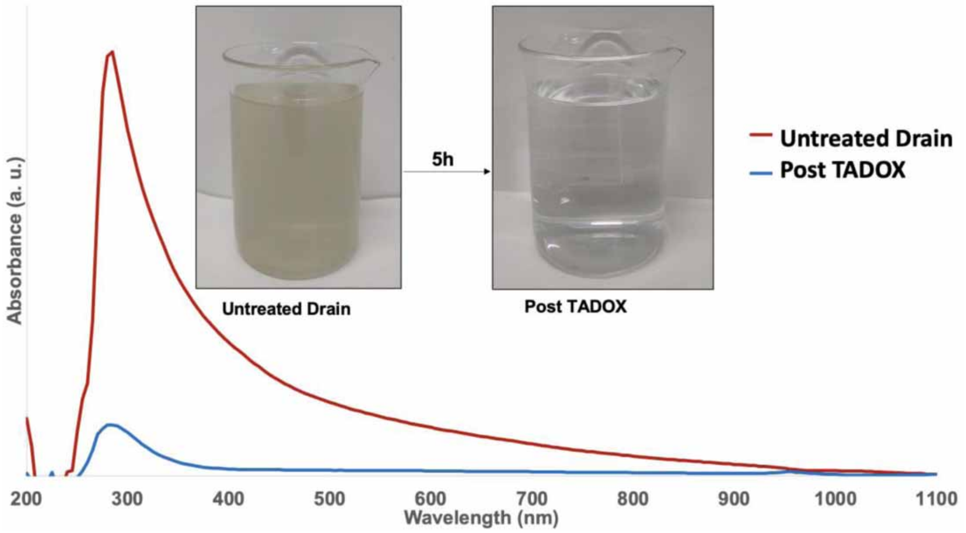

**Figure 3** | UV spectra of the untreated drain (a) and post-TADOX® (b).

**Table 1** | Water quality characteristics of the untreated drain and post-TADOX treated samples

| Parameter | Untreated drain (a) | Post-TADOX® (b) | % Change |
|---|---|---|---|
| *Physicochemical parameters* | | | |
| pH value | 7.3 | 8.4 | – |
| Conductivity (μmho/cm) | 1,276.0 | 271.3 | 79 |
| Total dissolved solids (mg/L) | 637.0 | 135.6 | 79 |
| COD (mg/L) | 96.0 | 35.0 | 63.5 |
| BOD (mg/L) | 27.0 | $< 1$ | 99.9 |
| DO (mg/L) | 3.2 | 6.3 | – |
| Nitrate nitrogen (mg/L) | 45.1 | 31.8 | 29 |
| Nitrite nitrogen (mg/L) | 1.4 | 5.2 | – |
| TKN (mg/L) | 9.3 | 3.6 | 61 |
| Phosphate (mg/L) | 2.6 | 0.1 | 96 |
| *Pathogens* | | | |
| *E. coli* (MPN/100 ml) | $30.1 \times 10^3$ | 16 | 99.9 |
| Total coliform bacteria (MPN/100 ml) | $28 \times 10^4$ | 30 | 99.9 |
| Total count (CFU $\times 10^3$/100 ml) | 10,600 | 0.4 | 99.9 |
| *Micropollutants* | | | |
| Caffeine (CFF) (μg/L) | 8.7 | 0.92 | 89 |
| Acetaminophen (ACT) (μg/L) | 142.4 | 9.2 | 93.5 |
| Ibuprofen (IBU) (μg/L) | 80.3 | 3.2 | 96 |
| Naproxen (NPX) (μg/L) | 10.1 | 7.2 | 28 |
| Sulfamethoxazole (SMZ) (μg/L) | 6.0 | 0.2 | 96.5 |
| Diclofenac (DCF) (μg/L) | 3.6 | 0.8 | 77 |
| Bisphenol-A (BPA) (μg/L) | 2.1 | 0.4 | 80.5 |

TADOX® also led to a substantial reduction in total nitrogen and phosphorus content of untreated drain water, which are the potential reasons for downstream eutrophication in water bodies, where total nitrogen reduction of 61% and phosphate reduction of 96% was observed within 5 h of treatment. In addition, a nitrate reduction of 24% was also found, while there was a marginal increase in the level of nitrite after the treatment. Reduction in nitrate level and increase in nitrite level might have occurred due to the photolysis of nitrates under UV light that causes the generation of hydroxyl ions and nitrite ions as a by-product (Vinge *et al.* 2020).

Moreover, TADOX® treatment resulted in a 3 log unit *E. coli* reduction and 4 log unit total coliform bacteria reduction and a 4 log unit reduction in the total count (CFU/ml). Significance of these reported values are shown in Table 2 which shows the designated best use of the surface water bodies as per the regulatory body, i.e. Central Pollution Control Board, India (CPCB) (Central Pollution Control Board n.d.; Ministry of Environment & Forests 1986a, 1986b). The extent of pathogen inactivation is an essential parameter to decide the end use of the untreated and treated stream. Due to the promising pathogen inactivation presented in this work, the treated water quality as shown in Table 1 has been compared to the Class A quality as per water quality criteria shown in Table 2.

**Table 2** | Designated best use water quality criteria as defined by Central Pollution Control Board (CPCB) (CPCB 1974)

| Designated best use | Class of water | Criteria | Value |
|---|---|---|---|
| Drinking water source without conventional treatment but after disinfection | A | Total coliform | 50 MPN/100 ml or less |
| | | pH | 6.5–8.5 |
| | | DO | 6 mg/L or more |
| | | BOD | 2 mg/L or less |
| Outdoor bathing (organized) | B | Total coliform | 500 MPN/100 ml or less |
| | | pH | 6.5–8.5 |
| | | DO | 5 mg/L or more |
| | | BOD | 3 mg/L or less |
| Drinking water source after conventional treatment and disinfection | C | Total coliform | 5,000 MPN/100 ml or less |
| | | pH | 6.0–9.0 |
| | | DO | 4 mg/L or more |
| | | BOD | 3 mg/L or less |
| Propagation of Wildlife and Fisheries | D | pH | 6.5–8.5 |
| | | DO | 4 mg/L or more |
| | | Free ammonia | 1.2 mg/L or less |
| Irrigation, industrial cooling, controlled waste disposal | E | pH | 6.0–8.5 |
| | | Electrical conductivity | 2,250 μmho/cm or less |
| | | Sodium absorption ratio | 26 or less |
| | | Boron | upto 2 mg/L |
| Below E | | Not meeting any of the above | |

TADOX® treatment may be directly compared with several other studies that report the rejuvenation of surface water bodies in different ways. One such study evaluated the use of direct placement of aerators into the Qing River in Beijing, China; this resulted in 60% removal of BOD while the DO concentration increased from negligible to 6 mg/L which led to improvement in aquatic life in the water body (Md Anawar & Chowdhury 2020). Another study has also evaluated the use of chemical coagulation and flocculation to reduce phosphorus and nitrogen concentration in water to avoid eutrophication in Lake Rusalka, Poland through the systematic addition of $FeSO_4$ to the lake (Tabla-Hernandez *et al.* 2020). Another interesting report from Swarzędzkie Lake, Poland shows a 38% reduction in phosphorus and improvement in aquatic life indicated by cyanobacteria through a chemical-cum-biological treatment (Md Anawar & Chowdhury 2020; Tabla-Hernandez *et al.* 2020).

A more recent laboratory-scale study on feasibility of sequential batch (SBR) operation under aerobic (SBRAe) and aerobic-anoxic (SBRAex) microenvironments was done in Siripuram village, Telangana, India showed 76.2% of organic fraction, 73.3% of phosphate and 81.6% of nitrate removal and concluded that the modified biological treatment systems could be utilized as a decentralized treatment system to implement community-level ZLD (Kopperi *et al.* 2023).

AOP has been utilized for similar compounds degradation on a laboratory scale study by Phillips *et al.* (2020) wherein three different AOPs UV/$H_2O_2$, $O_3/H_2O_2$ and electrochemical oxidation (boron-doped diamond (BDD) anode) have been compared to treat herbicides, pesticides, pharmaceuticals and flame retardant (Phillips *et al.* 2020). For most of the contaminants, AOPs were able to degrade about 100% parent compounds within 2 h of treatment which showed a viable strategy towards AOP as an approach to pretreat contaminated water prior to biological treatment. This study was only done for tap water and had the usual background matrix, which does not emulate the actual sample treatment (Phillips *et al.* 2020).

While not many advanced oxidation-based treatments have been used at a large scale for the abatement of polluted rivers, lakes and water bodies but a recent report from Valsequillo reservoir in Puebla, Mexico which is a highly polluted body of water shows the use of a combined $O_2 + O_3$ purging as a promising method (Tabla-Hernandez *et al.* 2020). The study shows the use of three large vessels, which injected 144 tons of $O_3$ and 300 tons of $O_2$ in 5 months at various locations in the reservoir. This led to oxidative degradation of various alkenes and phenols with successful degradation of 20–65% in heavy metal content and reduction of up to 20% in terms of COD and BOD. The study is very crucial as this is the only report of AOP-based non-point-source abatement of surface water (Tabla-Hernandez *et al.* 2020).

In comparison with the global trends in surface water pollution abatement, TADOX® can degrade primary pollutants such as COD, BOD and TSS in a much more efficient and easy manner while at the same time requiring less space, deployment time, residence time and treatment time. One of the major challenges that TADOX® was able to overcome is the mobility of the system and its speed of deployment. TADOX® is designed to be modular and can be manoeuvred within the surface water body as per requirements, while other technologies require a lot of plant and machinery, and it may be difficult for these plants to manoeuvre. For treatment of open drains, TADOX® plant could be installed adjacent to the drain and the upstream flow could be channelized to the TADOX® system and the downstream flow could be sent back to the surface body thereby tapping, cleaning and restoring the drain simultaneously. Therefore, the presented study opens tremendous scope for non-point water pollution abatement in an affordable, easy and sustainable manner. This could influence policymakers to come out with specific policies and action plans to restore/rejuvenate surface water bodies while laying special emphasis on the permissible levels of physicochemical, microbiological, specific contaminants and micropollutants in the surface water body.

## 4. CONCLUSION

This study shows that the flowing open drains containing raw sewage and other mixed wastewater pose a serious environmental and occupational health hazard. Most importantly, the TADOX treatment was end-to-end, bypassing the requirement of any biological treatment technology. The overall 5-h end-to-end treatment resulted in significant removal of primary pollutants such as 63.5% COD, 99% BOD, 96% phosphate and 61% TKN with a double increase in DO concentration. It simultaneously led to a 3 log reduction in *E. coli* and a 4 log reduction in total coliform values, which represent microbial contamination load in the open drain. This results in treated water complying to Class A of designated water reuse criteria defined by CPCB, India. Moreover, TADOX treatment led to a reduction in micropollutant (MP) pollution load by 93.5% in acetaminophen, 96% in sulfamethoxazole, 96% in ibuprofen and 89% in caffeine. This reduction has not been reported elsewhere during surface water rejuvenation using AOPs. The remarkable reduction in persistent organic pollutants (POPs), pathogens, hazardous micropollutants and contaminants of emerging concern (CECs) shows that modern-day wastewater challenges need advanced interventions. TADOX Technology based on heterogeneous photocatalysis utilizing $UV/TiO_2$ holds tremendous potential as highly efficient, clean, green and future ready technology for wastewater treatment. Such a study will also open avenues for bringing in regulatory compliance and policy norms for the discharge of MPs in open drains and surface water bodies.

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## STATEMENTS & DECLARATIONS

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## DATA AVAILABILITY STATEMENT

Data cannot be made publicly available; readers should contact the corresponding author for details.

## CONFLICT OF INTEREST

The authors declare there is no conflict.

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