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ORIGINAL CONTRIBUTION

Breakthrough in Treatment of Sewage Using TADOX®, By-Passing Biological Treatment with removal of Micropollutants to enable high end Water Reuse

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Abstract When it comes to enhancing treated water reuse efficiency for non-potable, high-end reuse especially from municipal and sewage wastewater, the quality is not found suitable. Probably due to mixing of sewage with inadequately treated industrial effluents, use of conventional approaches and high reliability on biological treatment technologies, which being prone to shock loads, leads to inadequate treatment. In this regard, Advanced Oxidation Process (AOP)-based integration is a promising approach. Further any possibility of bypassing bioremediation will be nothing less than a breakthrough, which has been achieved using an in-house developed technology called, TERI (The Energy and Resources Institute) Advanced Oxidation Technology (TADOX®), which utilizes UV-TiO_2 Photocatalysis at secondary treatment stage. Present study aims at treating wastewater from Sewage Treatment Plant (STP) in two ways, (I) Outlet (STP-OUT), i.e. current biologically treated water is further polished with TADOX® and (II) Inlet (STP-IN), i.e. inlet is directly treated using TADOX®, bypassing any kind of bioremediation. %Change in colour, BOD, COD, NO3-N, PO3-P, Residual Total coliform bacteria and Residual E. Coli (in MPN/ 100 ml) in STP-OUT were 4.5, 70, 67, 22.5, 70, 406 and 206; whereas in STP-IN, were 88, 97, 94, 89, 80, 6 and 3, respectively. % Removal of Micro-pollutants like Diazinon, Caffeine, Acetaminophen, Ibuprofen, Diclofenac and Naproxen in STP-OUT were 55.5, 49, 20, 29, 83, 55; whereas in STP-IN, 87, 100, 93, 60, 100, 40, respectively. Also this study has explored the possibility of directly treating the STP-IN, enabling reduction in treatment times from average 24h to 5h, together reducing the footprint, making sewage treatment highly resource and energy efficient, enabling augmentation of treatment capacities within existing infrastructure and meeting SDG 6 in many aspects.

Keywords Sewage treatment · Bypassing biological treatment · Micropollutants · Treated water reuse · Municipal wastewater · TADOX®

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Introduction

The compelling need to enhance sources for high-quality treated wastewater for reuse makes the prevalent ways of treatment calls for an introspection, especially in case of sewage, when it is mixed with inadequately treated industrial effluents and treated using conventional and biological treatment technologies. So far, the centralized wastewater treatment system has been the standard wastewater management practice; however, it demands a vast sewerage network for collection, conveyance, treatment, and re-channelizing it for reuse, posing infrastructural and economic challenges, especially in densely populated areas and require complex operation and maintenance [1–3].

These constraints lead to more prevalence for decentralized wastewater treatment systems (DWWT) like anaerobic baffled wall reactor, anaerobic digesters (UASB) [4, 5], waste stabilization ponds, constructed wetlands, activated sludge process, membrane bioreactors (MBR), moving bed

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biofilm reactor (MBBR) [5–8]. Amongst these, MBBR is preferred choice, due to low cost and ease of operation; however, these also suffer from serious limitations of treatment efficiency, lack of shock bearing capacity, high maintenance together requiring large footprint raising capital expenditure [8–10]. Further, when it comes to treatment of modern-day sewage comprising of micropollutants, existing STPs, both centralized and decentralized, have proven to be highly inefficient ultimately releasing into the water bodies posing severe environment, health and occupational hazards [11–13].

Presently, developing nations require technologies for enhancing water reuse especially high-end reuse, and the high dependence on such biological treatment systems needs either an integration or complete bypass using Advanced Oxidation Processes (AOP)-based wastewater treatment. Amongst various AOPs, UV-TiO_2 Photocatalysis has emerged as a promising integrated wastewater treatment technology option, both in industrial wastewater [14–18] as well as sewage treatment [19–23]. Although, in case of sewage treatment, the use is limited to bench scale studies [24] with diluted sewage water and/or limited to treatment of STP outlet, i.e. used at a polishing stage [24–26]. Hence, UV-TiO_2 Photocatalysis is used as an end-to-end treatment of real sewage, bypass any kind of biological treatment, with use of in-house developed technology called TERI Advanced Oxidation Technology (TADOX®) (patent awaited, trademark accepted). Under this study, a detailed study is undertaken to improve physicochemical properties, microbial characteristics and removing micropollutants at the same time for enhancing treated water reuse efficiency for high-end reuse applications.

Methodology

Site Selection and its Rationale

TERI campus at Gwal Pahari, Haryana, India, is a 100 acres green campus having laboratories, hostel rooms, offices, guest house, retreat centre, etc., and the domestic sewage from the campus is centrally treated at the Combined Sewage Treatment Plant (CSTP) having a treatment capacity of 50 KLD based on Moving Bed Biofilm Reactor (MBBR) biological treatment process.

About the CSTP and Details of Sample Collection

Present study aims at treating wastewater from CSTP in two ways, (I) Outlet (STP-OUT), i.e. current biologically treated water is further polished with TADOX® and (II) Inlet (STP-IN), i.e. inlet is directly treated using TADOX®, bypassing any kind of bioremediation. Raw Effluent in CSTP comes from various in-house sources like R&D labs (Nanobiotechnology, Chemistry, Biotechnology and Soil Sciences), agricultural runoff, Nurseries, Recreational areas like golf course, cricket ground, etc., and student hostels, cafeterias, etc. Samples were collected from the equalization tank and treated water tank of the CSTP in Plastic/Polypropylene (PP) Jar bottle for immediate treatment at TADOX® Pilot plant along with part samples in pre-treated and sanitized glass bottles for testing, analysis and characterization of samples. The existing CSTP having 50 KLD treatment capacity is shown in Fig. 1.

All the incoming wastewater is collected in a reservoir from where the water is sent to aeration tanks and the biologically treated water is chlorinated using a sodium

Fig. 1 Operating common sewage treatment plant (CSTP) based on MBBR at TERI campus

hypochlorite solution dosing system. After chlorine contact, wastewater is polished using dual media filter (DMF), pressure sand filtration (PSF) and activated carbon filter (ACF) to remove suspended solids, colour and taste & odour compounds. Treated water is used for gardening, low end reuse and horticulture development within the institutional complex.

Methodology of Pilot Plant Operation

Technical information and detailed methodology of the pilot scale plant treating 100 L per day (LPD) and its detailed specifications have been published in an earlier article [16]. Figure 2 illustrates a process flow diagram of the said operation of the 100 LPD TADOX® wastewater treatment plant [16]. TADOX® treatment includes two stages, namely Stage I, i.e. primary treatment and Stage II, i.e. secondary treatment. Primary treatment is aimed to remove suspended solids using novel alkali earth metal oxide-based coagulant—flocculant formulation. Secondary treatment involves UV-TiO_2 as an Advanced Oxidation Process (AOP), where pollutant molecules are oxidatively degraded into smaller molecules and ultimately mineralizes as the result of photocatalytic action. Downstream treatment involves separation of the used nanomaterials from the photo catalytically treated water, using an in-house developed Nanomaterial Recovery Unit (NMRU) to enable a highly efficient recirculation, and recovery process for complete reuse of the nanotitania catalyst.

Analysis of Wastewater Quality Parameters

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 APHA 23 edition 2017 [27]. Analysis took place in triplicates so that relative standard deviation (RSD) and other statistical inference could be drawn.

Result and Discussion

Treatment of STP Outlet

Figure 3 describes TADOX® treatment of STP-OUT samples. High colour with suspended impurities and objectionable odour indicates poor efficiency of current treatment. The biologically treated sample was further treated or polished using TADOX® treatment for 3 h only and the post TADOX® treated sample was found to be transparent and free from malodor, indicating improved water quality. These observations are further supported by respective UV–Vis spectra, where complete decolourization and reduction in

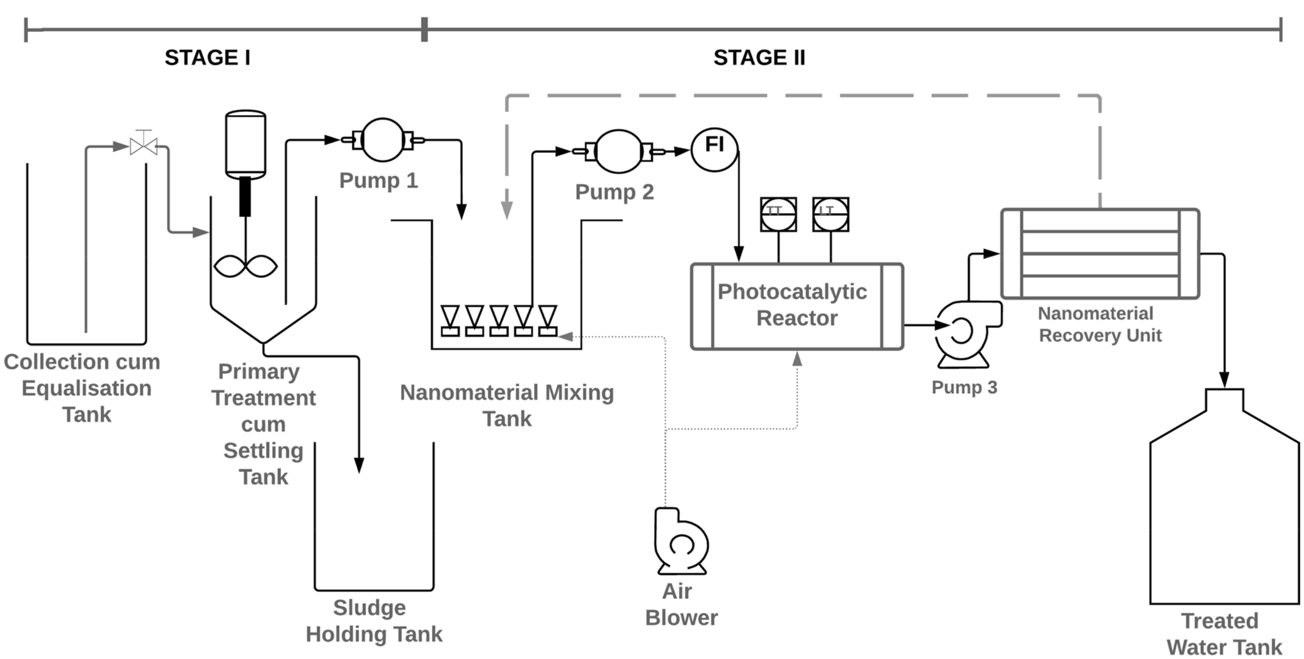

Fig. 2 Process flow diagram of TADOX® technology based on UV/ n-TiO_2 photocatalytic treatment as an advanced oxidation process for wastewater treatment [16]

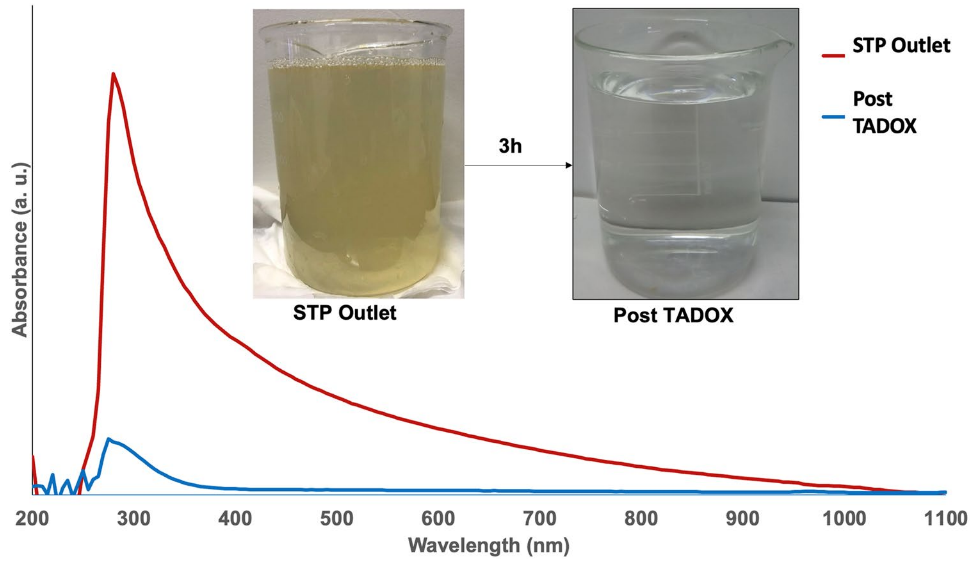

Fig. 3 UV spectra of STP outlet & Post TADOX® and Inset: Respective pictures of samples

absorbance around 280 nm which indicates reduction in COD, dissolved organics and micropollutants, which photocatalytic-oxidatively degraded.

In order to understand the extent of pollutant degradation by using TADOX® treatment at the polishing stage, analysis of the samples has been done for the significant parameters, which form the regulatory compliance and the values are tabulated in Table 1.

Effect on Physico-Chemical Parameters

Data from Table 1 clearly indicate that the COD and BOD values of the STP-OUT sample were well above the CPCB, Govt. of India surface discharge norms of 50 mg/L and 10 mg/L, respectively [28], and water is unfit for any reuse. Interestingly, post TADOX® treatment, a significant removal by 86.6% and 92.3% is achieved in each case and

Table 1 Comparative water quality data of STP-OUT and TADOX® treated water

Parameter, Unit	STP-OUT	Post TADOX®	% Change
pH Value	7.01	8.58	–
Conductivity, µmho/cm	1193	326	73
Total dissolved solids, mg/l	596.5	163.4	73
Total suspended solids, mg/l	294.5	9.3	97
COD, mg/l	60	8	87
BOD, mg/l	38	2.9	92
Nitrate nitrogen, mg/l	35.8	31.6	12
Nitrite nitrogen, mg/l	22.1	29.8	–
Total Kjeldahl nitrogen, mg/l	7.9	1.4	82
Phosphate, mg/L	10.4	0.25	98
Pathogens			
E. coli, MPN/100 ml	2.06×10^5	8	99.9
Total coliform bacteria, MPN/100 ml	4.06×10^7	1.10×10^2	99.9
Total count, CFU/100 ml	3.44×10^5	18	99.5
Micropollutants			
Caffeine (CFF), µg/L	3.21	0.08	97.5
Acetaminophen (ACT), µg/L	3.66	0.07	98
Ibuprofen (IBU), µg/L	0.29	0.11	61
Naproxen (NPX), µg/L	0.30	0.15	50
Sulfamethoxazole (SMZ), µg/L	ND	ND	ND
Diclofenac (DCF), µg/L	ND	ND	ND
Bisphenol-A (BPA), µg/L	ND	ND	ND

the discharged norms are met, making treated water safe for reuse for various non-potable operations.

Borges et al. [24] showed the potential of TiO_2-based photocatalysis for the tertiary treatment of biologically treated wastewater (ASP outlet), reported 60% of COD reduction after 4 h of photocatalysis. It is notable that the study was performed with a suspended TiO_2/UV system at lab/bench scale [24]. While with TADOX® we achieved 86.6% of COD reduction when TiO_2/UV photocatalysis is used at the secondary treatment stage at a pilot scale. To the best of our knowledge, none of the other study could be found in literature exhibiting improvement in physicochemical characteristics of sewage outlet streams with photocatalysis.

Effect on Microbiological Parameters

This current study also evaluated the disinfection potential of TADOX® technology towards biologically treated sewage water to enhance its reuse potential, where it can be clearly seen that there was negligible reduction in microbial load after biological treatment of the sewage water while TADOX® successfully disinfected the biologically treated sewage water with E. coli and coliform count reduction of 4 log and 5 log, respectively. The present observation is supported by the finding of Karaolina P et al., 2018, where complete bacterial disinfection was achieved in MBR treated urban wastewater by TiO_2-reduced graphene oxide (TiO_2-rGO) composite photocatalysts, after 120 min of solar irradiation [29].

UV photolysis (i.e. application of same amount of UV dose without n-TiO_2) resulted in a 2 log and 3 log removal in E. Coli and Total Coliform; this interesting result shows that hydroxyl radicals were able to destroy the microbial load to a greater extent as compared to the UV alone process. This is an expected outcome as in case of TADOX® treatment, and there is UV inactivation of microbes and oxidation of microorganisms in a simultaneous manner whereas UV alone cannot generate Reactive Oxidation Species (ROS). These ROS are responsible for degradation of organics, microbes in wastewater and are an essential component in reduction of microbial load present in the sample.

Effect on Micropollutants

It could be observed from Table 1 that current biological treatment contains micropollutants, with significantly high values indicating that these MPs are hydrophilic in nature and cannot be removed by biological process and could not removed with sludg either. Treated water showed significantly lower concentrations of the same micropollutants which suggests that the pollutants were photocatalytically degraded by insitu generated hydroxyl radicals. The reported data are similar to the earlier report by Teixeira et al. [30] and showed degradation of pharmaceutical drugs such as Carbamazepine, Gabapentin, Lamotrigine, Venlafaxine, Oxprenolol, Oxcarbazepine, and Bezafibrate, in sewage water from respective water treatment plant using TiO_2/UV photocatalysis [30, 31], where TiO_2 resulted in approximately 40% of reduction in all the drugs after 40 min of UV irradiation and it was expected to reach 95% after 4–5 h of irradiation [30].

It is noteworthy that the above-mentioned studies were performed at bench scale. On the other hand, the presented work reports much higher efficiency in removal of the micropollutants at larger scale. This also means that TADOX® integration in any existing treatment system will lead to greater efficiency in removal of these POPs in addition to the other advantages of TADOX®. Most importantly, it led to high-quality treated water that simultaneously meets the prescribed discharge standards and can be considered for both low and high-end reuse purposes. Thus, the superiority of TADOX® treatment at the polishing stage is highlighted leading to higher reuse efficiency. The obtained water quality parameters clearly indicate that TADOX® treated water could be very well utilized by nearby industries. It is also interesting to note that only a few studies are available in literature that have explored improvement in physicochemical parameters of biologically treated sewage water with integration of AOP systems. Also, it presents the performance of TADOX® in removing common emerging contaminants of concern from the current treatment. Thus, the polishing treatment took very little time to achieve this high quality and reusable water. The removal of these criteria pollutants and compliance to the norms laid down by Central Pollution Control Board (CPCB), Govt. of India shows that TADOX® will be able to improve the output from all existing MBBR installations and the like.

Treatment of STP Inlet

It is although important point to note that biological treatment processes have many limitations such as high maintenance because growth of microorganisms reduces in the presence of toxic pollutants and poses low biodegradability towards many pollutants, poor at decolourization, generates enormous amount of sludge, requires continuous aeration, highly complex, involves high land and maintenance cost and cannot bear fluctuation shocks [32].

Figure 4 describes TADOX® treatment of STP inlet samples, i.e. direct treatment of the inlet sample obtained from the equalization tank of the existing MBBR-based treatment plant. It can be clearly seen from the images in the figure that the water from the equalization tank had high amounts of colour, TSS and is aesthetically unpleasant, whereas the TADOX® treated water is clear, free of any visible suspended particulates and has pleasant overall

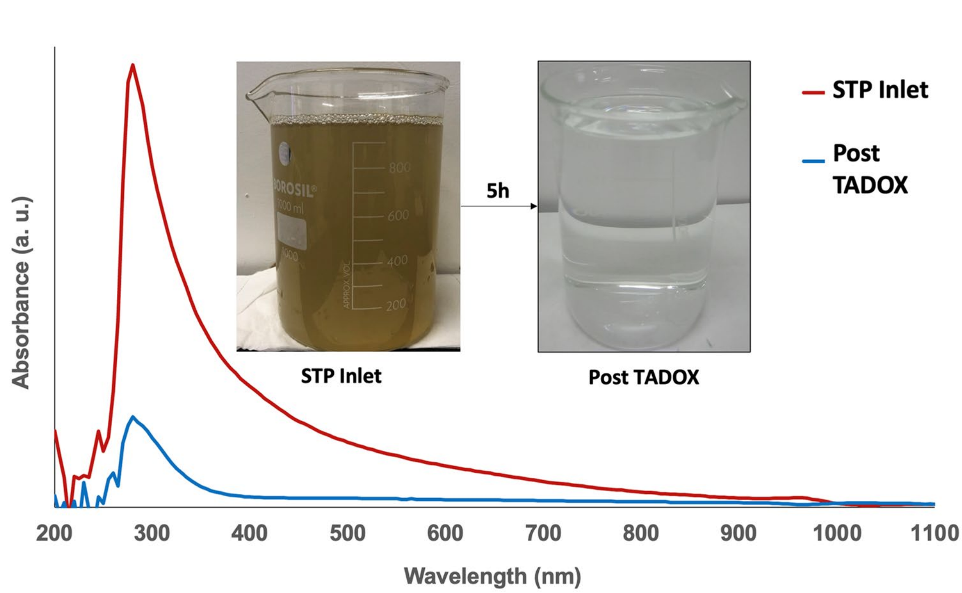

Fig. 4 UV spectra of STP inlet & Post TADOX® and Inset: Respective pictures of samples

aesthetics. These observations are further supported by respective UV–Vis spectra shown. One of the key observations, from data shown in Fig. 3, may be that the overall treatment took only 5 five hours as opposed to average 24-h treatment in the existing treatment plant.

Effect on Physico-Chemical Parameters

It can be seen from Table 2 that the entire treatment process leads to COD reduction of 94.3% in STP inlet, within 5 h of treatment. While in another study, photocatalysis of STP inlet water resulted in around 20% of COD reduction after

Table 2 UV–Vis Spectra showing photos of STP inlet sample and TADOX® treated comparison only

Parameter, Unit	STP Inlet	Post TADOX®	% Change
pH Value	7.33	8.14	–
Conductivity, µmho/cm	1243	413.5	66.7
Total dissolved solids, mg/l	622	206.1	66.8
Total suspended solids, mg/l	310.1	10.2	96.7
COD, mg/l	176	10	94.3
BOD, mg/l	110	3.4	96.9
Nitrate nitrogen, mg/l	16.85	5.04	70.1
Nitrite nitrogen, mg/l	24.6	29.3	–
Total Kjeldahl nitrogen, mg/l	8.11	2.81	65.35
Phosphate, mg/L	35.8	0.8	97.7
Pathogens			
E. coli, MPN/100 ml	149×10^4	23	99.9
Total coliform bacteria, MPN/100 ml	287×10^6	600	99.9
Total count, CFU $\times 10^5$ /100 ml	5.84	0.028	99.5
Micropollutants			
Caffeine (CFF), µg/L	6.3	ND	100
Acetaminophen (ACT), µg/L	4.57	0.3	93.4
Ibuprofen (IBU), µg/L	0.399	0.16	59.9
Naproxen (NPX), µg/L	0.384	0.23	40.1
Sulfamethoxazole (SMZ), µg/L	ND	ND	ND
Diclofenac (DCF), µg/L	0.641	0.11	82.8
Bisphenol-A (BPA), µg/L	ND	ND	ND

5 h of treatment and 90% of COD reduction was achievable in 1:4 times diluted sample, after 2 h of treatment [33]. In comparison, the COD reduction in the presented work is significantly high in case of raw STP inlet water. Data presented in Table 2 also show significant degradation of STP outlet samples after TADOX® treatment, where, with the present treatment scheme, only 86.6% of COD reduction was achieved. Finally, the treated water was able to meet prescribed discharge standards.

From the above results, it is also clear that TADOX® can result in significant treatment of raw sewage water by completely bypassing any kind of biological treatment process. Significant reduction in other inorganic pollutants of concern such as nitrate have also been recorded after treatment of STP inlet stream, where remarkable nitrate reduction of around 70% was observed, with final concentration reduced to 5.1 mg/L. It is noteworthy that the concentration of nitrate in drinking water is strictly regulated due to its serious health impacts and this reduction in wastewater during photocatalysis probably might have occurred due to photolysis phenomenon, where due to photosensitive nature of nitrogenous ionic species these are susceptible to photolytic transformations when irradiated with UV sources [34].

Reduction in Phosphate for STP inlet stream after TADOX® treatment was marginally low with reduction of around 11%. Although phosphates are known to adsorb on TiO_2 surface and enhance the photocatalytic activity, however at higher concentrations it may decrease the photodegradation efficiency by inhibiting the surface activity of TiO_2 or by scavenging holes and hydroxyl radicals [35, 36].

Effect on Microbiological Parameters

The current MBBR system alone is not expected to reduce microbial load, and it is evident from the data presented in Table 2 as no reduction in E. coli and total coliform count is observed. However, after TADOX® treatment of raw sewage, there is almost complete disinfection with 4 log reductions of reduction in E. coli and total coliform count, while total bacterial count was reduced 6 log reductions. After an extensive literature review, to the best of our knowledge, there is no other study reporting such promising results. Furthermore, UV photolysis alone was able to degrade 2 and 3 log of E.coli and Total coliform, respectively, which is in corollary to the data shown in Sect. "Effect on Micropollutants"; however, due to a higher initial load of microbial load, presence of higher amount of active colonies surviving on high organic load in the STP IN sample, there is a better microbial removal efficiency in this case.

Effect on Micropollutants

One of the most important highlights of the TADOX® treatment may be the high efficiency in removal of micropollutants from raw sewage water. From Table 2, it may be seen that there is significant removal of studied micropollutants from raw sewage without any bioremediation after only 5 h of treatment. Caffeine, Acetaminophen and Diclofenac have been removed with considerably high efficiency with overall removal of 100%, 93.4% and 82.8%, respectively. While in another report, Margot et al. [37] studied the removal of micropollutants from the STP wastewater with ozonation and PAC-UF (activated carbon/ultra-filtration) separately at pilot scale and reported that ozonation removed caffeine with around 92% of reduction, followed by PAC-UF with 65% reduction, while diclofenac was removed by 94% with ozonation and by 69% with PAC-UF treatment, with treatment duration of 20 min in case of ozonation and 40–170 min of HRT in case of PAC-UF, depending on flow rate. However, the report also found that ozonation was involved in the generation of toxic by-products such as bromates while PAC-UF technique was not cost effective [37].

TADOX® as an Advanced Decentralized Wastewater Treatment Technology (DWWT)

It is evident that with TADOX®, it is possible to treat the STP inlet stream directly and efficiently within 5 h, without any requirement of any kind of biological treatment process together having benefit of no stream segregation and simultaneously meeting discharge standards prescribed by the government and especially with no involvement of any. Additionally, along with the improvement in physicochemical features of the wastewater, it also leads to complete disinfection and remarkable removal of hazardous micropollutants which enhances the reusability potential of the treated water, whereas the conventional biological processes provide the treated water quality which is limited to horticulture purpose only, which is also not safe for irrigating crop land due to the presence of life-threatening pathogens and micropollutants.

Thus, the presented case studies depict a general scenario of inadequate treatment of MBBR-based STP systems. These systems were examined for their performance and the ineffectiveness in terms of treating non-biodegradable pollutants and have little or no effect on pathogens. This conventional approach is prone to failure in case when the influent contains high amounts of toxic compounds, possibly coming through some infiltration from industrial effluents or inefficiently segregated wastewater streams. These organic contaminants deactivate the biological system by hindering growth and metabolism of microorganisms in a bioreactor [38].

Furthermore, these conventional MBBR installations cannot effectively treat the contaminants of emerging concern (CECs), Persistent Organic Pollutants (POPs) and a class of Micropollutants (MPs), and therefore, these are required to be upgraded with more modern and advanced systems. To overcome the challenges associated with biological treatment plants and the growing concerns of regulators, judiciary, and environmentalists in rapidly developing countries like India, all industries and infrastructure projects need to adopt such advanced treatment interventions in the existing plants to bring in sustainably in the overall wastewater treatment.

Thus in all, we may have two approaches, either to treat the conventionally treated water, called polishing of STP-OUT and/ or directly treating the STP-IN. Both these approaches are depicted in Fig. 5.

It could be seen from the study that the proposed TADOX®-based treatment takes place in a few hours as opposed to average 24–36 h of treatment time required by MBBR-based STP. Further, direct treatment of STP-IN offers many fold advantages like (i) no stream segregation of grey and black water, (ii) complete bypass of any kind of biological and conventional treatment technology, (iii) makes overall treatment much more energy and resource efficient, (iv) drastic reduction in treatment times enable augmentation of capacities within existing infrastructure, and (v) smaller footprint with robust, flexible, and reliable system to handle varied characteristics of effluent further makes it the better technology [38]. The reusability potential of the treated water obtained after TADOX® is significantly high and the reuse of this water is not only limited to low end applications such as irrigation, landscaping and horticulture [14, 16, 17, 38]. It can be further hypothesized that the nearby Industries could potentially reuse this water for high-end applications like the boiler feedwater or cooling tower make up, etc., as the COD, BOD, TDS and pathogens of the treated water is meeting process water quality norms. In this manner, we propose the idea of complete reuse of treated sewage water as an alternative source of process water for the industries. This can greatly impact the environment because this would mean lesser abstraction of groundwater, higher freshwater availability for domestic needs and potable use in cities and towns; this is especially more relevant in water stressed countries like India. This hypothesized transaction of TADOX® treated sewage water to industries will also greatly offset costs of installation, operation, and maintenance of these advanced technologies in large-scale STPs.

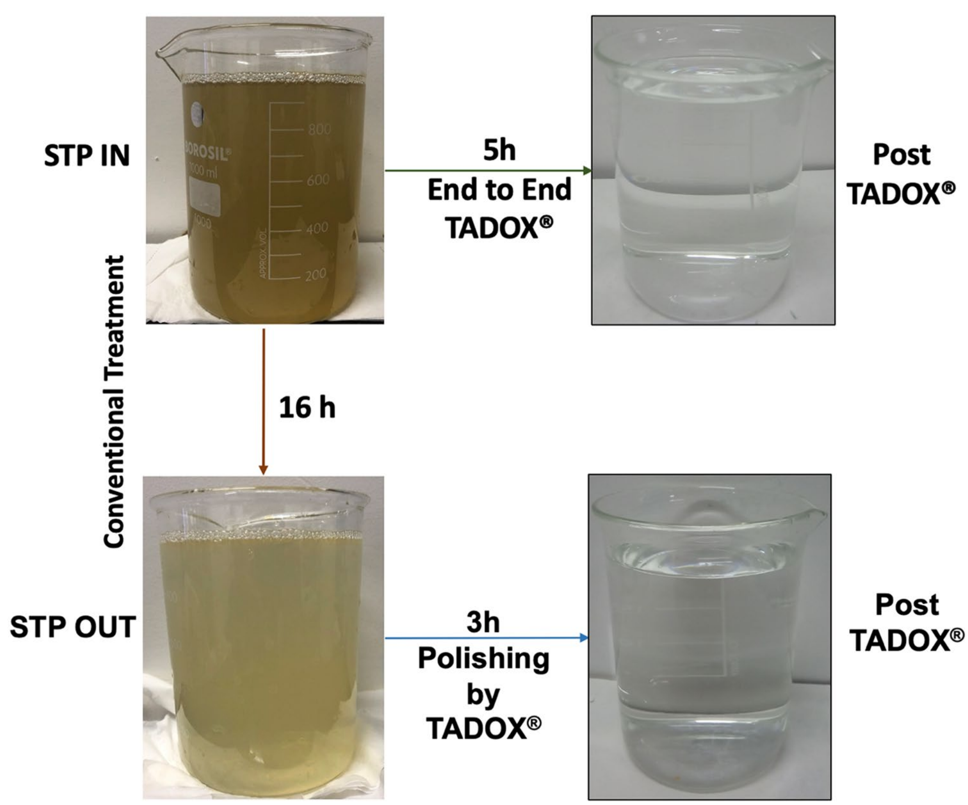

Fig. 5 Comparison of conventional biological treatment, i.e. current operating MBBR system, end-to-end implementation of TADOX®, i.e. STP-IN treatment and polishing of biotreated water TADOX®, i.e. STP-OUT treatment

Conclusions

Present study involves treatment of wastewater from a Sewage Treatment Plant (STP) in two ways, (I) Outlet (STP-OUT), i.e. current biologically treated water is further polished with TADOX® treatment and (II) Inlet (STP-IN), i.e. inlet is directly treated using TADOX® technology, bypassing any kind of bioremediation. % Change in colour, BOD, COD, NO_3-N and PO_3-N, in case of STP-OUT were 4.5, 70, 67, 22.5 and 70, whereas in case of STP-IN, were 88, 97, 94, 89 and 80, respectively. Microbiology parameters of Total coliform bacteria (in MPN/100 ml) and E. Coli (in MPN/100 ml) in case of STP-OUT were 406 and 206, while in STP-IN were 6 and 3, respectively. %Removal of some common Micropollutants like Diazinon, Caffeine, Acetaminophen, Ibuprofen, Diclofenac and Naproxen in case of STP-OUT were 55.5, 49, 20, 29, 83, 55; whereas in case of STP-IN, values are 87, 100, 93, 60, 100, 40, respectively. Thus, the high-quality treatment in case of directly treating the STP Inlet not only ensures adequate treatment but enhances treated water quality many folds for high-end Industrial and non-potable reuse. Bypassing biological treatment of any kind further enables smaller footprint, reduction in treatment time, improvement in shock load bearing capacity, augmentation of capacities within existing infrastructure and further expected to reduce life cycle costs of the STPs in the long run, hence achieving sustainability in all aspects.

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Data Availability The data that support the findings of this study are available from the corresponding author upon reasonable request.

Declarations

Conflict of interest The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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