Discussions and Discourses: Conversations on Water Remediation

Background and Motivation

India has a water problem that is as much about quality as about quantity. NITI Aayog's Composite Water Management Index (2018) estimated that about 600 million Indians face high to extreme water stress, that nearly 70% of the country's water is contaminated, and that about 200,000 people die every year because they lack access to safe water. On water quality, India ranked 120th out of 122 countries.Part of the reason is that most wastewater is never treated. The Central Pollution Control Board's 2021 report found that Indian cities generate 72,368 million litres of sewage a day, but only 20,235 million litres are actually treated. The rest, along with effluent from industries like textiles, tanneries and chemicals, reaches rivers, fields and groundwater.

My interest in water also comes from closer to home. My family runs Bateli Tea Estate in Assam, where I carried out a research project to develop a native Trichoderma biofungicide as an alternative to chemical fungicides. Working on the estate showed me how closely farming and water are linked. Water is used to spray the fields and process the tea, and the chemicals applied to the soil can wash into nearby streams and groundwater, posing health risks for the 5008-population made up of workers and their families who use the water for their daily needs.

This motivated me to understand how wastewater is actually treated and which technologies could treat it better.

Dr. Nipun Bhargava and Perfact Group

While looking for people in India working on wastewater treatment, I came across Perfact Group, a New Delhi environmental solutions company founded in 2004. Perfact works on environmental impact assessments, laboratory testing, waste management and regulatory compliance. It helped develop India's first leather tannery cluster at Ramaipur, Kanpur, including a 20 MLD common effluent treatment plant under the National Mission for Clean Ganga.

Dr. Nipun Bhargava is Perfact's Chief Operating Officer. He is also a researcher who has worked with The Energy and Resources Institute (TERI) and the TERI School of Advanced Studies on TADOX® (TERI Advanced Oxidation Technology). TADOX uses UV light and titanium dioxide (TiO_2) nanoparticles to produce hydroxyl radicals, which break down dyes, oils, pharmaceuticals and other pollutants that conventional treatment struggles with.

I contacted him to learn more about his work, and he shared seven of his research papers with me.

Overview of the Research Papers

Together, the papers trace TADOX from a pilot plant for textile effluent to a tool for sewage, open drains and several industries. In order of publication:

- **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*, 2019). A 100 L/day pilot plant treated real cotton-dyeing effluent in 5 hours without any biological step. It removed 91% of COD and 95% of BOD and produced 0.4 kg of sludge per m^3, about 100 times less than a conventional plant.
- **Improving energy efficiency and economic feasibility of photocatalytic treatment of synthetic and real textile wastewater using bagasse fly ash modified TiO_2** (*Chemical Engineering Journal Advances*, 2020). Adding sugarcane bagasse fly ash during TiO_2 synthesis reduced particle size from 14 to 7 nm and raised surface area from 65 to 74 m^2/g. On synthetic dye bath, COD removal rose from 56% to 75% and energy per order of removal fell by 41%.
- **TERI Advanced Oxidation Technology (TADOX®) to treat industrial wastewater with integration at pre- and post-biological stage: case studies from India** (*Water Practice & Technology*, 2022). Six case studies on pesticide, chemical, oil and gas, pharmaceutical, tannery and slaughterhouse effluent. Before biological treatment, TADOX raised biodegradability; after it, TADOX removed residual COD, colour and odour.

- **TERI advanced oxidation technology (TADOX®) for treatment and rejuvenation of open drains and surface water bodies: making habitats sustainable** (*Water Practice & Technology*, 2023). An open sewage drain near TERI's Gurugram campus went from below Class E to Class A water quality in 5 hours, with 99% BOD removal and 89–96% removal of caffeine, ibuprofen, acetaminophen and sulfamethoxazole.
- **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*, 2023). Raw sewage treated directly with TADOX reached 94% COD removal and a 4-log reduction in E. coli in 5 hours, compared with about 24 hours in the existing biological plant.
- **Integration of TADOX® technology to improve water reuse efficiency of constructed wetland-treated water** (*Water Practice & Technology*, 2023). TADOX polished the output of a root-zone wetland, removing 94% of the remaining BOD and 79–100% of several micropollutants that the wetland had barely reduced.
- **Techno-economic assessment of integrated photochemical AOPs for sustainable treatment of textile and dyeing wastewater** (*Journal of Water Process Engineering*, 2023). With Dr. Bhargava as first author, this compared UV photolysis, UV/H_2O_2, photo-Fenton and UV/TiO_2 on effluent from a 1 MLD textile treatment plant in Uttar Pradesh. UV/TiO_2 gave the lowest colour and the highest biodegradability, at about US$0.77 per m^3.

Literature Review and Analysis

I treated the seven papers as a small literature review. I first skimmed all of them to understand the overall TADOX process, then chose the three most relevant to my interest in materials and treatment chemistry for close reading: the 2019 pilot plant, the 2020 bagasse fly ash catalyst and the 2023 techno-economic comparison.

I had no prior background in this process, so I worked through the methods, tables and characterisation data in each paper. The main things I learned were:

- **The TADOX process.** Treatment runs in stages: coagulation and flocculation with an alkaline earth metal oxide and a polyelectrolyte, which removes suspended solids and raises the pH to about 9.5; UV/TiO_2 photocatalysis for 120 minutes in recirculation; recovery of the TiO_2 through a membrane unit; and, where needed, reverse osmosis.
- **How photocatalysis works.** UV light excites anatase TiO_2, and the resulting holes react with surface hydroxyl groups and water to form hydroxyl radicals. With dissolved oxygen present, these radicals oxidise dye molecules into smaller compounds and finally into CO_2, water and mineral ions. The nitrogen in azo dyes, for example, ends up as nitrate.
- **How water quality is measured.** COD measures total oxidisable pollution and BOD the part bacteria can break down, so the BOD:COD ratio indicates biodegradability. Colour is measured in Pt-Co units, and UV-Vis absorbance around 280 nm tracks dissolved organic content.
- **How catalysts are characterised.** In the 2020 paper, XRD confirmed the anatase phase, TEM measured particle size, FTIR identified surface hydroxyl groups and BET measured surface area and pore structure.
- **Adsorption and photocatalysis as separate stages.** In the 2020 paper, BFA-TiO_2 removed 61% of COD in the dark stage, against 13% for plain TiO_2. During UV irradiation, plain TiO_2 removed a further 34% and BFA-TiO_2 only 10%, because the composite contains less TiO_2.
- **Measuring energy efficiency.** Electrical energy per order (EEO) is the energy needed to reduce a pollutant by one order of magnitude in 1 m^3 of water, calculated as $EEO = P \times t \times 1000 / (V \times \log(Ci/Cf))$. A lower value means a more efficient process.
- **Comparing advanced oxidation processes.** In the 2023 paper, photo-Fenton removed the most COD but left residual iron and dark colour. UV/TiO_2 raised the BOD:COD ratio from 0.1 to 0.8, making the water suitable for downstream biological treatment, and the catalyst kept its crystal structure after reuse.
- **Limits of oxidation.** None of the methods removed dissolved ions such as sodium, calcium and magnesium, so the sodium absorption ratio remained above the limit for irrigation water.

I wrote down questions as I read, then narrowed them to those about how the process actually worked, which I could not answer from the papers alone.

Discussions with Dr. Bhargava

Dr. Bhargava and I discussed the papers over several conversations, and he answered the questions I had prepared. The most useful parts were about how the process behaves in practice, beyond what the results tables show.

- **Reactor design and UV penetration depth.** I asked how the UV path length changes when a reactor is scaled up. He explained that the correct term is penetration depth: the distance through the water over which UV light stays effective, which is about 4 inches for the lamp they use. It depends on the lamp's power, source and wavelength. UV intensity falls off with distance because the water, its colour and the suspended TiO_2 particles absorb and scatter the light. Beyond that depth, the catalyst receives too little light to generate radicals. A larger plant therefore cannot just use a bigger tank. It needs the water to pass close to the lamps, and the flow rate then sets how long each volume of water spends in the irradiated zone. Penetration depth and flow rate together set the reactor geometry and the reaction kinetics.

- **Emulsified oil as a radical scavenger.** I asked whether oil and grease affected the TiO_2. He explained that the plant's oil skimmer removes floating oil, but emulsified droplets stay suspended and take part in scavenging reactive oxygen species. Hydroxyl radicals are highly reactive and non-selective, so they attack whatever organic matter is nearby. Every radical used up by an oil droplet is one that does not reach a dye molecule. This means the composition of the whole effluent, not just the target pollutant, determines how efficient the treatment is.

- **Mixed effluent from many units.** The 2023 study used effluent from a plant serving 11 textile units. He explained that effluent from a single dye process is easier to treat. A mix contains many different dyes, auxiliaries, additives and reactants, so the treatment has to be more robust. Each of these competes for radicals, and inorganic ions common in textile effluent, such as chloride and carbonate, can also quench them. The composition also changes from day to day as different units discharge different batches. A process for a common plant has to work across that variation, not just under ideal lab conditions.

- **Why bagasse fly ash improved the catalyst.** I asked how adding the ash during the sol-gel step changed the catalyst. He explained that it increased the porosity and BET surface area of the nanoparticles, which raised their adsorption capacity. This explained the 2020 results: the composite captured far more pollutants in the dark stage than plain TiO_2. Hydroxyl radicals are short-lived and react close to where they form, so holding pollutants on the catalyst surface keeps them near where the radicals are produced. The trade-off is that the composite contains less TiO_2 per gram, which is why its photocatalytic step alone was weaker.

These discussions filled in practical details about running the process that are not covered in the published papers.

Influence on My Own Research

Reading these papers and discussing them with Dr. Bhargava inspired me to do my own research in water treatment.

I decided to focus on heavy metal removal. The papers showed that advanced oxidation breaks down organic pollutants but does not remove dissolved ions. Heavy metals cannot be degraded either, so they have to be captured, for example by adsorption. My project, Computation-Guided Discovery of Agricultural Waste-Derived Biosorbents for Sustainable Heavy-Metal Remediation studies sustainable materials for removing heavy metals from water.

The project was published in the *Oxford Journal of Student Scholarship* and received a CREST Gold Award.

My project, Development of Trichoderma as an Alternative to Chemicals, at Bateli Tea Estate in Assam, isolated a strain from the estate's own soil, scaled up production to 39,700 litres a year, and reduced the estate's chemical fungicide costs by 84%.

It also received a CREST Gold Award.