

The present study has attempted to develop a microbial-based indigenous pilot-scale technology that can efficiently treat the undiluted textile effluent with minimum additives for supporting microbial growth. To begin with, a visit to leading textile industry was undertaken to understand the functioning of the different wet operational units, types of effluents/wastes generated, and identify the problems associated with the effluent treatment process. Various effluents generated from different wet operations were procured and characterized. A novel microbial consortium enriched from Pre-treatment range (PTR) effluent was used to optimize the process of decolourization under extreme conditions with minimum inputs. With PTR effluent as a carbon source and only 0.5 g L⁻¹ yeast extract as external input, the process enabled 70-73% colour reduction (from 1910-1930 to 516-555 hazen) in dyeing unit wastewater. Unhindered performance at higher temperatures (30 °C-50 °C) and wide pH range (7-12) makes this process highly suitable for the treatment of warm and extremely alkaline textile effluents. No significant difference was observed in the decolourization efficiency for effluents from different batches (Colour: 1647-4307 hazen; pH-11.5-12.0) despite wide variation in nature and concentration of dyes employed. Long term (60 d) continuous mode performance monitoring at hydraulic retention time of 48 h in lab-scale bioreactor showed consistent colour (from 1734-1980 to 545-723 hazen) and chemical oxygen demand (1720-2170 to 669-844 mg L⁻¹) removal and consistently neutral pH of the treated water. This developed anaerobic process shows a significant advancement by uncovering the ability of native microbial consortium to reliably treat dye laden textile wastewater without any dilution or pre-treatment and with minimum external inputs.

Next, the speculation of molecular mechanism for azo dye degradation using the microbial consortium was done by understanding the role of oxido-reductase enzymes followed by deciphering the functional genes and their corresponding proteins. For this, decolourization of 100 mg L⁻¹ reactive blue 13 (RB13) was done using same consortium at optimized condition and the results showed ~92.67% decolourization at 48 h of incubation. The fourier-transform infrared spectroscopy (FTIR), high performance liquid chromatography (HPLC) and gas chromatography–mass spectrometry (GCMS) analysis were performed to identify the metabolites formed during RB13 degradation, followed by hypothesizing the metabolic pathway. The GC-MS analysis showed formation of 1,4-dihydronaphthalen-1-ol and 1,3,5-triazin-2-amine as the final degraded compounds after enzymatic breakdown of RB13 dye. The activity of different oxido-reductase enzymes was determined, and the results showed that NADH DCIP reductase and azo reductase had higher activity than other enzymes (veratryl alcohol oxidase, and aldehyde dehydrogenase). It clearly indicated the degradation was initiated with the enzymatic cleavage of azo bond (–N=N–) of RB13. Further, the functional genes were annotated against the database of clusters of orthologous groups (COGs) and kyoto encyclopedia of genes and genomes (KEGG). It provided the valuable information about the role of crucial functional genes and their corresponding proteins correlated with dominant bacterial species in degradation of RB13.

Further, an on-site anaerobic biological reactor integrated with activated carbon filter (ACF) and ultra-filtration (UF) unit termed as AN-ACF-UF process was installed and used for the decolourization of fresh textile effluent at the industrial premises. The anaerobic reactor containing the developed microbial consortium was fed with a mixed inlet consisting of coloured and PTR effluents in a ratio of 70:30 (v/v). The anaerobic unit was run in a continuous mode for 32 d with a hydraulic retention time of 2 d. The treated effluent from the anaerobic unit was fed into the ACF unit at 0.7 mL min⁻¹. Finally, the outlet from the ACF unit was fed into the UF unit. The AN-ACF-UF process was effective in decolourizing 91 ± 3 % of the colour in textile effluent mixture. The phytotoxicity test (germination test) on *Vigna radiata* using the treated effluent did not show any significant difference (p > 0.05) between control (92 ± 1 % germination) and treated effluent group (83 ± 1 % germination). The recovered salt which contained high concentration of sodium salt (349.70 mg g⁻¹ of salt) was reused for pad batch process in dyeing unit of textile industry. The results showed a shift towards red-yellow zone of CIELab colour space. However, this colour shift did not interfere with the dyeing process and could be used for darker shade. It creates an inner loop recycling of recovered salts within the industrial operations and eliminates the cost required

for the disposal of salt generated from the multi effect evaporator i.e., MEE salt (coloured salt). However, the AN-ACF-UF prototype system was conducted in lab-scale system and still lacked residual COD reduction from the treated effluent. Moreover, it required frequent backwash of ACF and UF due to poor sludge retention in anaerobic bioreactor. To overcome these limitations, an improved pilot scale sequential microbial-based anaerobic-aerobic reactor technology (SMAART) was designed and operated for the treatment of real textile effluent in the industrial premises in continuous mode for 180 days. The sequential treatment technology SMAART consists of specific treatment units, i.e., an anaerobic unit with a membrane module (to improve sludge retention) integrated with the aerobic unit (for effective COD reduction) followed by the polishing steps (activated carbon columns). The results showed an average \square 95% decolourization along with \sim 92% reduction in the chemical oxygen demand establishing the resilience against fluctuations in the inlet parameters and climate conditions. Moreover, the pH of treated effluent was also reduced from alkaline range (11.05 ± 0.75) to neutral range (7.76 ± 0.22) along with turbidity reduction from 44.16 ± 7.82 NTU to 0.14 ± 0.08 NTU. A comparative life cycle assessment (LCA) of SMAART with the conventional activated sludge process (ASP) showed that ASP caused 41.5% more negative impacts on environment than SMAART. Besides, ASP had 46.15% more negative impact on human health, followed by 42.85% more negative impact on ecosystem quality as compared to SMAART. This was attributed to less electricity consumption, absence of pre-treatment units (cooling and neutralization) and less volume of sludge generation (\sim 50%) while using SMAART. Hence, integration of SMAART within the industrial effluent treatment plant could achieve minimum waste generation in pursuit of sustainability.