Chapter 8
Role of Bacterial Consortia in Bioremediation of Textile Recalcitrant Compounds

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Abstract The increasing industrial demand for remediating the textile wastewater in an effective way has led to the pervasive acceptance of bioremediation. Bioremediation techniques such as bioaccumulation, biosorption, bioaugmentation, and biodegradation utilize the biological systems to treat the textile effluents containing the recalcitrant dye molecules. Bioremediation is known to be environmentally reliable and is an alternative to the conventional decomposition techniques with the prerequisite to fulfill the efficacy and economic viability. Among the aforementioned bio-remedial measures, biodegradation of the textile dyes is the trustworthy industrial application. Biodegradation of dyes can be achieved using single bacterial strains and co-cultures/consortia. The consortial systems are proven to be advantageous over a single strain as they involve an inductive synergistic mechanism among the co-existing strains. As a result of this co-metabolism, there is a formation of different intermediate metabolites such as toxic aromatic amines which are furthermore mineralized by the other bacterial strains in the consortia.

Keywords Bioremediation · Biodegradation · Bacterial consortia
Textile effluent · Mineralization · Recalcitrant

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1 Introduction: Textile Industrial Sector—An Overview

The first inception of dyeing was the wall paintings of Altamira cave, Spain, during 1500–900 BC. The twentieth century evidenced the exponential use of synthetic dyes which replaced the natural ones to a larger scale (Welham 2000). Globally, India stands next to China and Turkey in supplying textiles to the European Union (EU) with a share of approximately 8.1%. Indian textile industry is one of the major export sectors with several diversified units adding to the major country's economy (Goswami 1990). Twenty-seven percentage of the foreign exchange earnings are from the textiles export, contribute about 14% to the industrial production with 3% to the gross domestic product (GDP) of the country and have increased from 3.5 to 4.0% in the last four years. The cumulative global foreign direct investment (FDI) in Indian textile sector from 2000–01 to 2014–15 was approximately 1.5 billion USD, and India's share in global FDI in 2014 was 3%. The size of India's textile market in 2014 was 99.0 billion USD, which is expected to become 226 billion USD by 2023 at a compound annual growth rate (CAGR) of 8.7% which was revealed in the World investment report published in the year 2016 by United Nations, Geneva.

India has several advantages in the textile sector as there is an abundant availability of the concerned raw materials. As the industry requires intensive labor, India is having the advantage of the dense population; the textile industry adds 21% to the total employment either directly or indirectly. India hosts around 2324 textile industries which include 83 composite and 2241 semi-composite industries. Tamil Nadu has 741 industries with 739 belonging to semi-composite processing units and two composite mills. Gujarat stands next to Tamil Nadu with 523 textile industrial units.

The main contribution to wastewater which arises from the textile industries is during dyeing processes, chemical fiber production, and wool scouring. Table 1 shows the water required during the dyeing processes per day. The major environmental issue arises from wet processing, where huge tonnes of dyes are lost in the effluents during dyeing operations.

Table 1 Water required for different textile operations

S. no.	Wet processes	Water required (L/kg)	Solution pH
1	Sizing/slashing	4.35	7.0–9.5
2	Desizing	11.75	6.0–8.0
3	Scouring/ kiering	32.5	10.0–13.0
4	Bleaching	40–48	6.0–6.2
5	Mercerizing	24.5	12.0–3.0
6	Dyeing	105	10.5–11.5

The integrated textile industry is engaged in the production of yarn, fabric, and finished goods from raw fibers and extensively utilizes different variety of dyes (Pandey et al. 2007). It is obvious that the demand for textile dyes prolongs with the increasing population. The pervasive use of dyestuffs is mainly attributed to the simplicity in synthesis, diverse chemical structures, high molar extinction coefficients, and fastness to light and wetness (Zollinger 2003).

Textile industry consumes a large volume of water and chemicals for textile processing. Most of these dyes escape the conventional wastewater treatment, and they show greater stability to light, temperature, and water. The textile effluents are highly colored, and their characteristics mainly depend on the different chemical constituents of the starting materials used in different dyeing steps. The composition of the textile mill effluent (TME) is influenced by the presence of organic and inorganic compounds such as colored materials, surfactants, toxicants, and chlorinated compounds, thus making them persistent environmental pollutants. TME is generally characterized by different water quality parameters such as chemical oxygen demand (COD), biochemical oxygen demand (BOD), pH, intense color, and dissolved solids. Usually, TMEs have BOD/COD ratios around 1:4, describing their non-biodegradable nature (Bilińska et al. 2016).

2 Textile Dyes and Its Toxicity

The textile dyes have phenyl aromatic ring structures that are ionic in nature, and the color intensity of the dye molecules is due to the transition between the distinct molecular orbitals. The chromophores and auxochromes are responsible for intensifying color and they are known to have greater affinities towards each other (Peters and Freeman 1991). The Society of Dyers and Colorists, UK, in association with American Association of Textile Chemists and Colorists (AATCC) published the classification of dyes in the Color Index (C.I.) based on the structure and applications. Table 2 elaborates the degree of fixation onto the support and characteristics of the dyes.

2.1 Dyes and Their Applications

The azo dyes have extensive applications in textile fabrication and have azo with sulfonic (SO_3^{-1}) electron withdrawing groups generating electron deficiency in the molecules, thus making them less susceptible to oxidative catabolism and are hardly biodegraded under aerobic conditions (Sen et al. 2016). The anthraquinone-based reactive dyes are water-soluble dyes used for coloring wool and silk as they have a greater affinity toward these fibers without the aid of auxiliary binding agents. The anthraquinone-based disperse dyes lack water-solubilizing groups and are usually adsorbed by fibers having hydrophobic groups with the aid of mordants. The

Table 2 Characteristics and the estimated fixation of dyes onto the support

S. no.	Dye	Characteristic features	Support	Degree of fixation (%)
1	Acid	Negatively charged and binds with the cationic groups of the fiber	Polyamide	89–95
2	Reactive	Forms a covalent bond with OH, NH, or SH group	Cellulose	50–90
3	Metal complex	Forms strong complexes with metals and dyes	Wool	90–98
4	Direct	Binds to fiber by Van der Waals forces of attraction	Cellulose	70–95
5	Basic	Positively charged and binds with the anionic groups of the fiber	Acrylic	95–100
6	Disperse	Sparingly soluble and penetrates through the fibers	Polyester	90–100
7	Vat	Insoluble and gives soluble leuco derivatives upon reduction and is reoxidized upon exposure to air	Cellulose	80–95
8	Sulfur	Hetero-polyaromatic compounds containing sulfur	Cellulose	60–90

anthraquinone-based vat dyes are known for their brilliant colors and fastness to light and are insoluble in water. The leuco derivative of these dyes (soluble vat) is absorbed by the fiber and is then converted to the insoluble form (Salabert et al. 2015). Sulfonated phthalocyanine dyes are non-volatile, highly water-soluble, and thermally unstable. The sulfonated aromatics are hydrophilic in nature and remain impermeable through the cell membrane, thus making them as recalcitrant compounds. The nitro-substituted sulfonates in the benzene ring are highly persistent than the unsubstituted sulfonates (Lade et al. 2015). Triphenylmethane (TPM) dyes are colorants that find applications in textile, medicine, and laboratory as stains. They have a complex aromatic molecular structure with additional phenyl rings resisting biodegradation. The resonance-stabilized ring structures impart intense color to the fabrics and make them less susceptible to microbial attack (Mohanty et al. 2016).

2.2 *Toxicity of Dyes and Aromatic Amines*

TMEs containing the dyes and their intermediates when discharged as untreated/ partially treated effluents into aqueous ecosystems shall obstruct sunlight penetration, thereby disturbing the photosynthetic activity of the phytoplanktons and deteriorate the dissolved oxygen concentration. It also imparts unpleasant color to the water bodies, leading to the loss of aesthetic values and also adds toxicity to aquatic life systems. The toxicity is mainly due to the presence of trace metals and other auxiliary chemical compounds. The industrial personnel exposed to the dyestuffs are prone to high rates of the development of urinary bladder cancer (Burkinsha 2016). The risk of cancer increases with exposure to certain aromatic amines which are used as precursors in the dye-manufacturing units. Generally, during azo-dye degradation, the cleavage in the azoic group results in the liberation of aromatic amines which are toxic and carcinogenic. The discharge of toxic textile wastewater causes drastic change to the ecosystem, and therefore, it is necessary to treat these TMEs prior disposing them to the environment (Lade et al. 2015).

3 Need for the Best Available Techniques

The textile industries face a great stress to ensure environmental safety and environmental protection activities by inculcating the ways to reduce the generation of waste, treatment of wastewater, and the use of non-polluting dyestuffs. It is mandatory for the textile industries to abide by the rules and regulations of Environment Protection Act (EPA), 1986, the legislation including Water (Prevention and Control of Pollution) Act, 1974, and Water Cess Act, 1978. Larger textile industries generate adequate funds to implement the best available techniques (BAT) for effluent treatment. But it is impossible for small-scale textile units to own an effluent treatment plant because of the exorbitant costs involved in commissioning and setting up the plant. In order to facilitate this, wastewater treatment using common effluent treatment plants (CETPs) is considered as an option. India had only one CETP till 1990 in Hyderabad, and in 1991, Ministry of Environment and Forest (MoEF), Government of India, took an initiative to support the CETPs financially to ensure environmental safety without compensating the economic growth. By 2005, around 88 CETPs were established and the number of CETPs increased to 1191 across the country. Among them, 148 CETPs belong to Tamil Nadu and 187 belong to Maharashtra.

The burgeoning numbers of textile units with the voluminous effluent generation, the issues such as scarcity of space, lack of technical human resource and high cost pose as the serious constraints to abate water pollution, thus resulting in the inappropriate wastewater management (Mishra 2016). Despite the recommendations on the cleaner production technologies and waste reduction techniques, these textile units remain to be highly polluting (Khan and Malik 2014). The different conventional physicochemical treatment techniques and their mechanism for remediating the textile-dyeing effluents are shown in Table 3.

The decolorization efficiency is considerably better, but the aforementioned physicochemical techniques face severe drawbacks such as being economically unfeasible and inability to eliminate the pollutant and their intermediates (Moradeeya et al. 2017; Karthikeyan et al. 2014; Vidhyadevi et al. 2014). These techniques are not very suitable due to their high initial capital and operational costs and they also generate considerable amounts of sludge causing secondary pollution problems, thereby subsequently demanding other treatment options.

Table 3 Conventional physico-chemical treatment techniques

S. no.	Technique(s)	Mechanism
1	Adsorption	The adsorbate gets adsorbed onto the adsorbent surface by physical or chemical forces
2	Membrane filtration	The hydraulic pressure drives the desired separation through the semi-permeable membrane
3	Ion exchange	The removal of ions from aqueous solution by replacing another ionic species using natural and synthetic ion exchangers
4	Coagulation	A coagulant aid is added to the wastewater for destabilizing the colloidal particles, which helps in the agglomeration
5	Flocculation	Flocculation forms larger flocs of the destabilized particles which can be easily removed
6	Ozonation	It is a tertiary treatment for decolorization in which ozone activates H_2O_2
7	Fenton's oxidation	Fe^{2+} salts and H_2O_2 are used to treat the wastewater, and the reaction takes place in the acidic pH, which results in the formation of strong hydroxyl radical and ferric iron. The decolorization is due to the sorption of the dissolved dyes to the formed flocs
8	Photochemical degradation	Degradation is achieved by hydroxyl radical generation during the UV/H_2O_2, UV/TiO_2, UV/O_2, and UV/Fenton's processes, and the molecule is degraded to CO_2 and H_2O
9	Electrolysis	Dyes react on the basis of applied electric current passing through the electrodes. This technique involves electro-coagulation, electro-flotation, and redox electrochemical reactions

4 Bioremediation

Bioremediation techniques utilize the biological systems to treat the pollutants and are environmentally reliable and an alternate to conventional decomposition. These techniques usually involve bioaccumulation, biosorption, bioaugmentation, and biodegradation. Bioaccumulation is defined as the ability of the viable biomass to accumulate the pollutants, which is based on the tolerance and uptake capacities of the biomass. The limitation of this technique is that the microbial growth is inhibited when the pollutant concentrations are too high for bioaccumulation and such microbial cells require metabolic energy (Robinson et al. 2001). Biosorption usually involves the adsorption phenomena, where the pollutants (adsorbate) are adsorbed onto regenerative and eco-friendly adsorbents/biosorbents. The limitation of this process is that it cannot be used for handling voluminous effluents because of the problems associated with the disposal of adsorbed biomass (Kuhad et al. 2004). Bioaugmentation is the process of introducing selected species which may be endogenous or exogenous to a complex ecosystem with pollutants (Joshi et al. 2017; Cronje et al. 2002). The limitation of bioaugmentation technique is that the introduced bacterial strain may fail to grow or survive as they undergo some competitive inhibition with the environmental pollutant (Herrero and Stuckey 2014; El Fantroussi and Agathos 2005). Biodegradation is an economical and effective way of treating wastewater as it is inexpensive, eco-friendly, and environmentally compatible and has less sludge-producing properties (Saratale et al. 2011).

4.1 Phyto-remediation

Phyto-remediation is considered as a green and safe approach to mitigate the problem of pollution and is less disruptive to the environment. The treatment processes involve mechanisms like hyper-accumulation, rhizo-degradation and phyto-stabilization. Several plant species belonging to glycophytes such as *Salsola vermiculata*, *Brassica juncea*, *Typhonium flagelliforme*, *Blumeamal colmii*, *Glandularia pulchella,* and *Portulaca grandiflora* are known to exhibit potential ability to degrade dyes (Kabra et al. 2011). Phyto-remediation is suitable only for sites contaminated with lower concentrations of the pollutant. The limitation of this technique is that the plants require a longer time to remediate and the fate of the intermediates is unknown. Additionally, the plant species employed for remediating the pollutants may find difficulty in growing in water or the soils contaminated with the xenobiotic pollutants.

4.2 Enzyme-Aided Biodegradation

Enzymes are a better option for bio-remediating the environmental contaminants, and the oxidoreductive enzyme systems comprise oxidases and reductases that are involved in the degradation of several environmental pollutants (de Gonzalo et al. 2016). Enzymes like oxidase, reductase, and methylase are known to catalyze bio-transformations of dyes (Kabra et al. 2011). Generally, bacterial cells involve the oxidation and reduction of the chemical bonds by the enzymes mainly belonging to oxidoreductases. These enzymes may be extracellular or intracellular, depending on their type and growth pattern of the bacterial cells. The oxidoreductases help in detoxification of xenobiotic compounds (Mahmood et al. 2016).

Lignin-degrading enzymes such as lignin peroxidase (LiP) and manganese peroxidase (MnP) are known to have a potential application in bioremediation of diverse pollutants. LiP (E.C. 1.11.1.14) is a plant peroxidase containing a heme group and utilizes H_2O_2 as co-factor for oxidizing the phenolic group (Dawkar et al. 2009). MnP (E.C. 1.11.1.13) catalyzes the oxidation of phenolic contaminants, and the reaction is mainly dependent upon the divalent manganese and buffers used (de Gonzalo et al. 2016).

Laccase (EC 1.10.3.2) consists of four histidine copper-binding domains and is the most commonly used enzyme for biodegradation of textile dyes and PAHs (Balaji et al. 2016). It has the ability to degrade the substrates having high redox potential and helps in the removal of hydrogen atom from the hydroxyl group of the substituted mono- and polyphenolic compounds (Akkaya et al. 2016). Tyrosinase (EC1.14.18.1) is a monophenol mono-oxygenase which catalyzes the phenol oxidation with the help of molecular oxygen rather than H_2O_2. The catalysis occurs in two steps such as hydroxylation and oxidation. They are known to have the dual enzyme activities such as cresolase and catecholase (Mahmood et al. 2016).

Azoreductase (E.C. 1.7.1.6) catalyzes the reductive cleavage of azo bonds to release the aromatic amines (Khan and Malik 2016). They are categorized into flavin-dependant and flavin-independent azoreductases on the basis of their function (Rawat et al. 2016). Triphenylmethane reductase is a dinucleotide-binding motif-containing enzyme and is induced during the degradation of TPM dyes (Kim et al. 2008). The veratryl alcohol oxidase (EC 1.1.3.7) is another oxidative enzyme induced by the microbial system during the dye degradation and helps in the cleavage of the phenyl rings (Bourbonnais and Paice 1988).

The limitation of the enzyme-based biodegradation is that these enzymes are prone to denaturation at high temperatures; their activity gets lowered when exposed to higher concentrations of pollutants (Seenuvasan et al. 2017). The production and purification of these enzymes are relatively expensive and require controlled environmental conditions (Seenuvasan et al. 2014). To overcome these limitations and in order to increase the enzyme activity, immobilization of the enzymes onto suitable support matrices are done (Seenuvasan et al. 2013).

4.3 Microorganisms-Aided Biodegradation

Microorganisms bear the versatile capacity to remove the pollutants from wastewater by biodegrading the recalcitrant compounds (Mahmood et al. 2016). This is done by screening the microorganisms for the functionality of the target contaminants. Microbial cell-aided biodegradation is more advantageous on the features like occurrence, ability to adapt, cost-effectiveness with the ease of cultivation and manipulation, rapid growth unlike plants, and considerable selectivity toward the environmental pollutants (Komal et al. 2017). Thus, the abovesaid traits make these microbial cells more beneficial when compared with the other bio-remedial tools. The microbial systems utilize enzymes which may be intracellular or extracellular for the degradation of pollutants (Kumar et al. 2016a). The microbial systems can be mutated and genetically engineered for effective bioremediation.

4.3.1 Biodegradation Using Fungi

Ligninolytic fungal systems have the ability to degrade different xenobiotic compounds with the help of oxidases and reductases for the cleavage of hetero-polyaromatic moieties. Certain noteworthy fungal strains such as

Phanerochaete chrysosporium, *Aspergillus niger*, *Aspergillus terricola*, *Pycnoporus sanguineus*, *Trametes versicolor*, *Iperx lacteus,* and *Funalia trogii* are known to degrade distinct dyes (Sen et al. 2016).

4.3.2 Biodegradation Using Yeasts

Yeasts are a class of organisms belonging to fungi and are known to grow faster than the fungal strains with resistance to unfavorable environmental conditions. The yeasts employ putative enzymic mixtures for the biodegradation of dyes. *Saccharomyces cerevisiae*, *Trichosporon beigelii*, *Candida tropicalis*, *Candida zeylanoides*, *Candida lipolytica*, *Kluyveromyces marxianus*, *Galactomyces geotrichum*, *Debaryomyces polymorphus,* and *Issatchenkia occidentalis* are known to degrade different dyes (Jadhav et al. 2007). The use of yeast strains is limited due to their longer hydraulic retention time and other process conditions (Sathya et al. 2017).

4.3.3 Biodegradation Using Algae

Algae are photosynthetic organisms thriving in the marine ecosystems, and the algal biomasses are generally used in stabilization ponds which have an ability to induce azoreductase for the azo-dye degradation. *Chlorella pyrenoidosa*, *C. sorokiniana*, *C. vulgaris*, *Lemnaminus cula*, *Scenedesmus obliquus*, *Oscillateria tenuis*, *Closterium lunula*, *Cosmarium* sp, and *Spirogyra* sp. are the algal strains known to biodegrade different dyes into aromatic amines and other intermediates (Patil et al. 2011).

4.3.4 Biodegradation Using Actinomycetes

Actinomycetes are filamentous bacteria, and dye degradation using actinomycetes is more advantageous than fungal treatment. Reports are available for the biodegradation of distinct classes of dyes like *Streptomyces krainskii* SUK-5, *Nocardia corallina,* and *N. globerula* (Mane et al. 2008). Dye decolorization using actinomycetes is limited because such cells require a longer retention/induction time for decolorizing the dyes and the dye molecules get adsorbed onto the biomass rather than getting degraded (Bagewadi et al. 2011).

4.3.5 Biodegradation Using Bacteria

Bacterial cells are known to decolorize and degrade dyes under aerobic, anaerobic, and anoxic conditions. Dye degradation using bacterial culture is faster, cheaper, and efficient when compared with other the biological systems. The bacterial cultures used for dye degradation are either in their pure form or mixed cultures consisting of identified or unidentified strains (Sakthipriya et al. 2016).

5 Dye Degradation by Pure Bacterial Strains

Pure bacterial cultures or strains belonging to the genus such as *Bacillus*, *Pseudomonas*, *Enterobacter*, *Proteus*, *Aeromonas*, *Klebsiella*, and *Achromobacter* are known to effectively decolorize and degrade the dyes. The use of pure bacterial strains ensures reproducible observations having the merit of being easily interpreted using the biochemical and molecular biological analyses. Pure bacterial strains are known for their ability to degrade dyes and their use is highly advantageous as they give reproducible observations that can be interpreted easily. Dye degradation using a single bacterial strain shows remarkable efficiency in the aerobic, anaerobic, and anoxic conditions (Kumar et al. 2016b).

The contaminated sites harbor a diversified category of microorganisms that are well-adapted to survive in the presence of pollutants and are usually known to develop traits, capable of consuming or assuming the contaminants for their survival (Karthikeyan et al. 2017). These indigenous strains are more effective, advantageous and are termed as extremophiles as they usually adapt themselves to the biotic and abiotic stresses for their survival. The metabolic system of the surviving microorganisms adapts an alternative to routine systems, and this phenomenon is known as acclimation. At lower dye concentrations, the acclimated microbes exhibit negative inhibition, while at higher dye concentrations, the microbial strains get acclimated to a greater extent (Kumar et al. 2015). This is well-perceived by researchers, and some of the salient features of bacterial strain isolation are ease of screening, eco-friendly and economically viable, producing lesser sludge with metabolites of mineralized nature (Kumar et al. 2017b).

6 Dye Degradation by Mixed Bacterial Consortia

The mixed bacterial cultures are composed of identified and unidentified strains indigenous to different environmental pollutants. In a mixed bacterial consortium/culture, the individual bacterial strains attack the dye molecules at different positions to form the intermediate metabolites usually of low molecular weight fractions. The bacterial consortial systems are advantageous over the individual bacterial cultures as they involve an inductive, synergistic mechanism among the co-existing strains. The intermediate products are usually aromatic amines, and the consortial strains release certain enzymes which act on these amines and decompose them to simpler products (Ayed et al. 2010). Table 4 gives a snapshot of the research work on dye degradation by the mixed bacterial population and bacterial consortium comprising identified strains for the degradation of dyes.

Table 4 Application of bacterial consortia comprising of mixed culture and individual identified strains in dye degradation

S. no.	Bacterial consortia	Name of the dye	References
1	Bacterial consortium RVM11.1 comprising seven different isolates	Reactive violet 5	Moosvi et al. (2005)
2	Bacterial consortium comprising *B. cereus* (BN-7), *P. putida* (BN-4), *P. fluorescence* (BN-5), and *Stenotrophomonas acidaminiphila* (BN-3)	Acid red 88	Khehra et al. (2005)
		Acid red 119	
		Acid red 97	
		Acid blue 113	
		Reactive red 120	
3	Bacterial consortium (NJ38, NJ1, NJLC1, and NJLC3) comprising of gram-negative and gram-positive bacterial isolates	Direct RED 81	Junnarkar et al. (2006)
4	Mixed culture	Reactive black 5	Mohanty et al. (2006)
5	Isolated halophilic and halotolerant bacteria	Remazol black B	Asad et al. (2007)
		Maxilon blue	
		Sulphonyl scarlet BNLE	
		Sulphonyl blue TLE	
		Sulphonyl green BLE	
		Remazol black N	
		Entrazol blue IBC	
5	Consortium of *E. coli* DH5α and *P. luteola*	Reactive red 22	Chen and Chang (2007)
6	Consortium comprising *A. faecalis*, *Sphingomonas sp. EBD*, *B. subtilis*, *B. thuringiensis,* and *Enterobacter cancerogenus*	Direct blue 15	Kumar et al. (2007)
7	Consortium of *Enterobacter* sp., *Serratia* sp., *Yersinia* sp., and *Erwinia* sp.	Reactive red 195	Jirasripongpun et al. (2007)
8	Bacterial consortium JW-2 comprising *Paenibacillus polymyxa*, *Micrococcus luteus,* and *Micrococcus* sp.	Reactive violet 5R	Moosvi et al. (2007)
9	Consortium comprising *Pseudomonas aeruginosa* and *Bacillus circulans* and NAD1 and NAD6 isolates	Reactive black 5	Dafale et al. (2008)

(continued)

Table 4 (continued)

S. no.	Bacterial consortia	Name of the dye	References
10	Bacterial consortium TJ-1 comprising *Aeromonas caviae*, *Proteus mirabilis,* and *Rhodococcus globerulus*	Acid orange 7	Joshi et al. (2008)
11	Bacterial consortium DMC comprising *Pseudomonas aeroginosa* PAO1, *Stenotrophomonas maltophila,* and *Proteus mirabilis*	Direct black 22	Mohana et al. (2008)
12	Consortium SKB-II comprising *B. vallismortis* and *B. megaterium*	Congo red Brodeaux Ranocid fast blue Blue BCC	Tony et al. (2009a, b)
13	Consortium comprising *B. vallismortis*, *B. pumilus*, *B. cereus*, *B. subtilis,* and *B. megaterium*	Direct red 28	Tony et al. (2009a, b)
14	Consortium-GR comprising *Proteus vulgaris* and *Miccrococcus glutamicus*	Scarlet R	Saratale et al. (2009)
		Green HE4BD	Saratale et al. (2010)
15	Consortium DAS comprising three *Pseudomonas* sp.	Reactive orange 16	Jadhav et al. (2010)
16	Consortium-IV comprising *Sphingobacterium* sp. ATM, *B. odysseyi* SUK3, and *P. desmolyticum* NCIM 2112	Orange 3R	Tamboli et al. (2010)
17	Consortium comprising *S. paucimobilis*, *B. cereus* ATCC14579, and *B. cereus* ATCC11778	Methyl orange	Ayed et al. (2010)
18	Mixed bacterial strains from CETPs	Mixed dyes	Rajeswari et al. (2011)
19	Consortium comprising *Providencia* sp. SDS and *Pseudomonas aeuroginosa* strain BCH	Red HE3B	Phugare et al. (2011)
20	Mixed culture SB4	Reactive violet 5R	Jain et al. (2012)
21	Consortium GG-BL comprising *Galactomyces geotrichum* MTCC 1360 and *Brevibacillus laterosporus* MTCC 2298	Rubine GFL	Waghmode et al. (2012)
22	Consortium-AVS comprising *Kocuria rosea* MTCC 1532, *Pseudomonas desmolyticum* NCIM 2112, and *Micrococcus glutamicus* NCIM 2168	Methylene blue Acid Blue 15	Kumar et al. (2012)
23	Consortium comprising *P. putida*, *B. subtillis,* and *P. aeruginosa*	Acid Blue	Shah (2014)

(continued)

Table 4 (continued)

S. no.	Bacterial consortia	Name of the dye	References
24	Acclimated mixed culture	Reactive black HEBL	Kumar et al. (2014)
25	Acclimated mixed bacterial culture	Acid red 88	Kumar et al. (2015)
26	Consortium BMP1/SDSC/01 comprising *Bacillus* sp., *B subtilis*, *B.* cereus, *B. mycoides*, *Pseudomonas* sp., and *Micrococcus* sp.	Azo dyes	Mahmmod et al. (2015)
27	Consortium comprising *Proteus* spp., *Pseudomonas* spp., and *Acinetobacter* spp.	Methyl red Carbol fuchsin	Joshi et al. (2015)
28	Consortium ETL-A comprising *B. subtilis*, *Stenotrophomonas* sp., *P. stutzeri,* and *P. aeruginosa*	Reactive orange M_2R	Shah (2016)
29	Consortium comprising *Bacillus* sp. L10, *B. flexus* strain NBN2, *B. cereus* strain AGP-03, *B. cytotoxicus* NVH 391-98	Direct Blue 151 Direct Red 31	Lalnunhlimi and Krishnaswamy (2016)
30	Microbial Community	Actual textile wastewater	Forss et al. (2017)
31	Concocted bacterial consortium comprising *Achromobacter xylosoxidans* strain APZ, *K. pneumoniae* strain AHM, and *B. mannanilyticus* strain AVS	Textile mill effluent	Kumar et al. (2017c)

The consortial systems are proven to be advantageous over a single bacterial strain as they involve an inductive synergistic mechanism among the co-existing strains. Azo-dye degradation usually involves the cleavage of the azo bond that occurs to release the aromatic amines, and these amines are oxidized to reactive electrophilic species that covalently bind to the deoxyribonucleic acid (DNA), leading to severe toxicity and mutagenicity (Pandey et al. 2007). However, the advantageous bacterial consortia are favorable for the mineralization of the liberated aromatic amines (Lade et al. 2015; Kumar et al. 2017a).

7 Futuristic Scope of Bacterial Consortia-Aided Bioremediation

The bacterial consortium catalyzing the bio-transformation of dyes and effluents would lead to the detoxification and mineralization that would provide an insight into a strategic textile industrial wastewater treatment. The non-toxic and mineralized products of dyes and effluents would eliminate the threat of secondary pollution problems when they are disposed to the environment. The demand for the best available technologies for remediating the problems of textile colorants and effluents can be justified by employing the bacterial consortium for bio-transforming the dyes and mineralizing the liberated aromatic amines which are expected to result in the economic viability. Furthermore, the bio-transformation yielding the products of detoxified and mineralized nature can be tailored to selectively downstream these products. By implementing the effective concoction of the bacterial consortium, the scope and marketability of the processes in the wastewater treatment would be ameliorated. As for the pursuit of bacterial consortia-aided bioremediation, this beneficial phenomenon would be extended by immobilizing the bacterial consortium onto the suitable supports that would ease the separation of bacterial cells from the treated effluents which could be a potential lead for designing the pilot plant assembly.

8 Conclusions

The biodegradation of textile dyes is a user-friendly bio-remedial approach to mitigate the impacts and toxicities of the intermediate metabolites. The biodegradation of textile dyes using bacterial strains and their consortial systems provides an efficient and trustworthy way to mineralize and detoxify the dyes. These systems utilize inducible consortial oxidoreductases for the detoxification and mineralization into least/reduced toxic metabolites. Presently, the design of such consortial systems is gaining pervasive importance as they work under adverse conditions. Further, tailoring of process parameters is required for utilizing the bacterial consortia for making the process viable and serving the necessity of environmental safety and health.

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