Application of Extremophilic Microorganisms in Decolorization and Biodegradation of Textile Wastewater

M.A. Amoozegar, M. Mehrshad and H. Akhoondi

1 Introduction

The release of colored wastewater from textile industries in the ecosystem has been a great environmental as well as public health concern over the decades. Textile industry is a promising market due to the customer's increasing demand for new products. To fulfill these demands, textile industries are using selective dyestuffs among 100,000 different commercially available dyes (Husain 2006). Over 20–40 % of the dyes used in textile industries released to the environment via effluent discharge (Song et al. 2008) which causes serious environmental problems. However, growing importance of green practices encourages the adaption of microbe-based wastewater treatment technologies for textile effluents (Christie 2007). Several physical, chemical and physicochemical methods have been used for textile wastewater treatment, but each of them has their own advantages and disadvantages. Physico-chemical methods of wastewater treatment are not only costly methods, but also, some cases, very difficult to apply. Biological degradation and decolorization using microorganisms, on the contrary, provides inexpensive, effective, and specific, less energy intensive and eco-friendly methods for textile wastewater treatment (Robinson et al. 2001).

M.A. Amoozegar (✉) · M. Mehrshad · H. Akhoondi
Extremophiles Laboratory, Department of Microbiology, Faculty of Biology and Center of Excellence in Phylogeny of Living Organisms, College of Science, University of Tehran, Tehran, Iran
e-mail: amoozegar@ut.ac.ir

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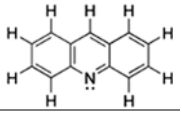
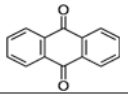
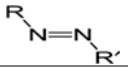
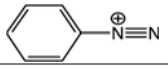
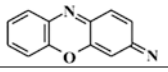
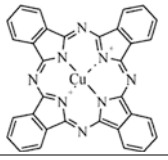
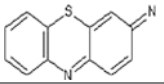
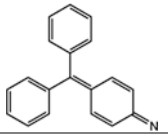
2 Textile Dyes

Textile industry is a growing sector which, in turn, uses of textile dyes in a large quantity (Dos Santos et al. 2007). Around 100,000 commercially available dyes can be classified according to their chromophoric groups, reactive groups, or even their applications (Husain 2006; Dos Santos et al. 2007). Considering their chromophoric groups, they fall into nine major classes as reflected in Table 1 (Rodríguez Couto 2009).

Azo dyes constitute more than half of commercial dyes available in the market. Any synthetic organic dyes, that contain nitrogen in azo group (–N=N–) as part of their molecular structures, fall into this class of dyes. Now-a-days more than 2000 different azoic dyes are being used in different industries and most of them are also

Table 1 Chromophoric groups of textile dyes

Chromophoric group	Structure
Acridine	
Anthraquinone	
Azo	
Diazonium	
Nitro	
Oxazine	
Phthalocyanine	
Thiazine	
Triarylmethane	

used in textile industries (Amoozegar et al. 2011). Textile process consists of several steps. Dying and scouring steps are the main sources of color in wastewaters and effluents (Dos Santos et al. 2007).

3 Textile Wastewater Effluents Properties

Industrial effluents treatment approaches should be designed in a way to meet the goals of protecting the assimilative capacity of surface waters; saving different kinds of life; preserving or restoring the aesthetic and recreational value of surface waters and protecting human beings from adverse effects of deteriorating water quality conditions. Selection among different wastewater treatment facilities is based on the knowledge of different factors, like physical, chemical and biological characteristics of wastewater, the quality of water reservoirs (rivers, ponds, streams, etc.) must be maintained in which the wastewater is to be released or the quality that the wastewater should meet environmental standards after treatment for reuse for various purposes. The main physical characteristics of industrial wastewaters are their solid content, color, odour and temperature. However, chemical characteristics of wastewaters are divided into two main classes: organic and inorganic characteristics. Inorganic chemicals, that enable us to choose the proper method for the wastewater treatment, are varying according to the wastewater origin. In organic factors include free ammonia, organic nitrogen, nitrites, nitrates, organic and inorganic phosphorous, chloride, sulphate, heavy metals, hydrogen sulphide, oxygen, methane and carbon dioxide. In order to assess the organic content of wastewaters, biological oxygen demand (BOD), chemical oxygen demand (COD), total organic compound (TOC) and volatile organic compounds (VOC) need to be determined carefully, as they have a great impact on choosing proper biological treatment technology. Typical characteristics of textile industry wastewater are presented in Table 2 (Al-Kdasi et al. 2004).

The textile industries wastewaters are a complex mixture of salts, acids, heavy metals, organochlorine-based pesticides, pigments, dyes etc. Dyes and dyestuff are of primary importance in textile manufacturing. In discriminate release of colored

Table 2 Composite textile industry wastewater characteristics

Parameters	Values
pH	7.0–9.0
Biochemical oxygen demand (mg l^{-1})	80–6,000
Chemical oxygen demand (mg l^{-1})	150–12,000
Total suspended solids (mg l^{-1})	15–8,000
Total dissolved solids (mg l^{-1})	2,900–3,100
Chloride (mg l^{-1})	1,000–1,600
Total kjeldahl nitrogen (mg l^{-1})	70–80

textile effluents to the environment HAS undesired impact on neighboring receptor water bodies because of presence of toxic reactive dyes and dark coloration. Due to environmental and health effects of dyes released in textile industry wastewater made the textile wastewater decolorization a subject to scientific scrutiny (Christie 2007).

Textile dyeing industries are facing problems to meet the green practices standards for safe discharge of wastewater due to complex nature and hard-to-treat by conventional methods. Therefore, in recent years, biological decolorization, using microorganisms capable of decolorizing and detoxifying the synthetic dyes, has been considered as a promising and environmentally benign method (McMullan et al. 2001).

4 Microbial Degradation of Textile Dyes

Amongst different decolorization methods for textile wastewaters; the biological methods seem to be most applicable. Bacteria, fungi and yeasts could be used based on their ability to decolorize dyes in the wastewater through aerobic, anaerobic or anaerobic/ aerobic systems. Among different techniques for wastewater decolorization, the live or dead microbial biomass adsorption has a great significance in biorecovery of dyes after decolorization of the effluents (McMullan et al. 2001). Some of microorganisms that are able to decolorize textile dyes, are of different taxonomic groups and their efficiency in dye removal has been summarized in Table 3. Some microbes show a very high efficiency in waste water decolorization which is attributed to their growth rate and versatile metabolism. However, harsh condition of wastewater effluents poses a limiting factor for mesophilic microorganisms to remediate the wastewaters properly. But the ability of extremophilic microorganism to survive in such harsh condition has some advantages over other mesophilic microorganisms for the bioremediation of colored wastewaters.

5 Extremophilic Microorganisms

Extremophiles are organisms that are adapted to grow optimally at or near to the extreme ranges of environmental variables. Most of them thrive under conditions that are clearly hostile from a human perspective. Extremophiles can fall in different categories based on single environmental extreme they survive. Different categories of extremophiles include acidophile, alkaliphile, endolith, halophile, hyperthermophile, hypolith, metallotolerant, oligotroph, piezophile, psychrophile, radioresistant, thermophile, toxitolerant and xerophile (Horikoshi 2011). Besides, there are many extremophiles which fall in two or more of above categories. They represent the polyextremophiles which refer to microorganisms adapted to two or more different environmental extremes (Rothschild and Mancinelli 2001).

Table 3 Different microbes used in microbial decolorization of textile dyes

Microorganisms	Dye (concentration)	Efficiency (time)	Medium NaCl content	Reference
Brevibacillus panacihumi strain ZB1,	Acid orange 7	98 % (2 h)		Bayet al. (2014)
Lysinibacillus fusiformis strain ZB2				
Enterococcus faecalis strain ZL				
Pseudomonas putida	Navy-Blue HER (100 mg l^{-1})	84.78 % (5 h)		Preethi et al. (2014)
Bacillus subtilis				
Escherichia coli				
Enterobacter sp. SXCR	Congo red (200 mg l^{-1})	100 % (93 h)		Prasad and Aikat (2014)
Saccharomyces cerevisiae	Congo Red			Kumar et al. (2013)
Lactobacillus sporogenes				
Deinococcus radiodurans R1	Malachite green (200 mg l^{-1})	97.20 %		Lv et al. (2013)
Micrococcus sp. strain BD15	Malachite Green (100 mg l^{-1})			Du et al. (2013)
Shewanella oneidensis MR-1	Mixture containing methyl orange (10 mM) and naphthol green B (10 mM)	>95 % (25 h)		Cao et al. (2013)
Shewanella aquimarina	Acid red 27 (200 μM)	100 % (5 h)	50 g l^{-1}	Meng et al. (2012)
Pleurotus ostreatus	Crystal violet (20 mg l^{-1})	92 % (10 days)		Kunjadia et al. (2012)
Staphylococcus sp. NIU-K1	Reactive black 5 (200 mg l^{-1})	>50 % (7 days)	60 g l^{-1}	Chen et al. (2011)
	Reactive blue 160 (200 mg l^{-1})			
	Reactive red 198 (200 mg l^{-1})			

(continued)

Table 3 (continued)

Microorganisms	Dye (concentration)	Efficiency (time)	Medium NaCl content	Reference
Exiguobacterium sp. NIU-K2	Reactive black 5 (200 mg l^{-1})	>50 % (7 days)	60 g l^{-1}	Chen et al. (2011)
	Reactive blue 160 (200 mg l^{-1})			
	Reactive red 198 (200 mg l^{-1})			
Exiguobacterium sp. NIU-K4	Reactive black 5 (200 mg l^{-1})	>50 % (7 days)	60 g l^{-1}	Chen et al. (2011)
	Reactive blue 160 (200 mg l^{-1})			
	Reactive red 198 (200 mg l^{-1})			
Klebsiella sp. P11	Reactive black 5 (200 mg l^{-1})	>50 % (7 days)	60 g l^{-1}	Chen et al. (2011)
	Reactive blue 160 (200 mg l^{-1})			
Comamonas sp. UVS	Reactive Blue HERD (50 mg l^{-1})	98 % (6 h)		Jadhav et al. (2011)
Halomonas sp. IP8	Cibacron Black (50 mg l^{-1})	60 % (8 h)	50 g l^{-1}	Pourbabee et al. (2011)
Bacillus cereus	Reactive red195 (200 mg l^{-1})	96 % (20 h)		Modi et al. (2010)
Pseudomonas sp.	Reactive Blue 13 (200 mg l^{-1})	83.2 % (70 h)		Lin et al. (2010)
Pseudomonas aeruginosa	Remazol Orange (200 mg l^{-1})	94 % (24 h)		Sarayu and Sandhya (2010)
Micrococcus glutamicus NCIM 2168	Reactive Green 19 (50 mg l^{-1})	100 % (42 h)		Saratale et al. (2009)
Enterobacter EC3	Reactive Black 5 (1,000 mg l^{-1})	92.56 % (36 h)		Wang et al. (2009b)
Mutant *Bacillus* sp. ACT2	Congo Red (3,000 mg l^{-1})	12–30 % (37–48 h)		Gopinath et al. (2009)
Lactobacillus acidophilus	Water and oil soluble azo dyes (6 mg l^{-1})	86-100 % (36 h)		Chen et al. (2009a, b)
Lactobacillus fermentum				

(continued)

Table 3 (continued)

Microorganisms	Dye (concentration)	Efficiency (time)	Medium NaCl content	Reference
Geobacillus stearothermophilus UCP 986	Orange II (0.050 mM)	96–98 % (24 h)		Evangelista-Barreto et al. (2009)
Aeromonas hydrophila	Reactive Red 198 (300 mg l^{-1})	60.20 %		Hsueh et al. (2009)
	Reactive Black 5 (300 mg l^{-1})	80.90 %		
	Reactive red 141 (300 mg l^{-1})	66.50 %		
	Reactive blue 171 (300 mg l^{-1})	36.00 %		
	Reactive Yellow 84 (300 mg l^{-1})	33.70 %		
Aeromonas hydrophila	Reactive Red 141 (3,800 mg l^{-1})	100 % (48 h)		Chen et al. (2009a)
Mutant *Escherichia coli* JM109 (pGEX-AZR)	Direct Blue 71 (150 mg l^{-1})	100 % (12 h)		Jin et al. (2009)
Bacillus sp. VUS	Navy blue 2GL (50 mg l^{-1})	94 % (18 h)		Dawkar et al. (2009)
Citrobacter sp. CK3	Reactive red 180 (200 mg l^{-1})	96 % (36 h)		Wang et al. (2009a)
Acinetobacter calcoaceticus NCIM-2890	Direct brown MR (50 mg l^{-1})	91.3 % (48 h)		Ghodake et al. (2009)
Bacillus sp.	C.I. Reactive orange 16 (100 mg l^{-1})	88 % (24 h)		Telke et al. (2009)
Enterococcus gallinarum	Direct black 38 (100 mg l^{-1})	100 % (20 days)		Bafana et al. (2009)
Pseudomonas sp. SU-EBT	Congo red (1,000 mg l^{-1})	97 % (12 h)		Telke et al. (2009)
Brevibacillus laterosporus MTCC 2298	Golden yellow HER (50 mg l^{-1})	87 % (48 h)		Gomare et al. (2009)
Bacillus sp.	Congo red (100-300 mg l^{-1})	100 % (24-27 h)		Kannappan et al. (2009)
Sphingomonas paucimobilis	Malachite green	100 % (24 h)		Ayed et al. (2009)

(continued)

Table 3 (continued)

Microorganisms	Dye (concentration)	Efficiency (time)	Medium NaCl content	Reference
Pseudomonas sp. SUK1	Reactive Red 2 (100 mg l^{-1})	95 % (18 h)		Kalyani et al. (2008)
Vibrio harveyi strain TEMS1	Acid black 210 (100 mg l^{-1})	93.9 % (24 h)	5 g l^{-1}	Ozdemir et al. (2008)
	Acid black 24 (100 mg l^{-1})	39.4 % (24 h)		
	Acid blue 7 (100 mg l^{-1})	4 % (24 h)		
	Acid green 20 (100 mg l^{-1})	16.3 % (24 h)		
	Acid yellow 36 (100 mg l^{-1})	1.5 % (24 h)		
Rhizobium radiobacter MTCC 8161	Reactive red 141 (50 mg l^{-1})	90 % (48 h)		Telke et al. (2008)
Comamonas sp. UVS	Direct red 5B (1,100 mg l^{-1})	100 % (13 h)		Jadhav et al. (2008)
Exiguobacterium sp. RD3	Navy blue HE2R (50 mg l^{-1})	91 % (48 h)		Dhanve et al. (2008)
Shewanella putrefaciens strain AS96	Reactive blazck-5 (100 mg l^{-1})	100 % (6 h)	40 g l^{-1}	Khalid et al. (2008b)
	Direct red-81 (100 mg l^{-1})	100 % (8 h)		
	Acid red-88 (100 mg l^{-1})	100 % (8 h)		
	Disperse orange-3 (100 mg l^{-1})	100 % (8 h)		
Pseudomonas sp. SUK1	Red BLI (50 mg l^{-1})	99.28 %		Kalyani et al. (2009)
	Reactive Navy blue RX (50 mg l^{-1})	85.33 %		
	Reactive Red M5B (50 mg l^{-1})	92.33 %		
	Reactive red 6BI (50 mg l^{-1})	97.30 %		
	Reactive red HE18 (50 mg l^{-1})	93.49 %		
	Reactive red HE3B (50 mg l^{-1})	93.47 %		

(continued)

Table 3 (continued)

Microorganisms	Dye (concentration)	Efficiency (time)	Medium NaCl content	Reference
	Reactive orange HE2R (50 mg l^{-1})	99.29 %		
	Reactive orange M2R (50 mg l^{-1})	90.50 %		
Comamonas sp. UVS	Direct red 5B	100 % (13 h)		Umesh et al. (2008)
Coriolus versicolor f. *antarcticus*	Malachite green			Diorio et al. (2008)
Bacillus fusiformis KMK5	Disperse blue 79 (1,500 mg l^{-1})	100 % (48 h)		Kolekar et al. (2000)
	Acid orange 10 (1,500 mg l^{-1})			
Trametes pubescens	Reactive black 5			Enayatzamir et al. (2008)
Schizophyllum sp.	Congo red			Li and Jia (2008)
Phanerochaete chrysosporium	K-2BP			Gao et al. (2008)
Trametes pubescens	Reactive black 5			Rodríguez Couto et al. (2008)
Aspergillus fumigatus	Reactive blue 19			Wang and Hu (2008)
Clostridium bifermentans SL186	Reactive red 3B-A (100 mg l^{-1})	>90 % (36 h)		Joe et al. (2008)
	Reactive black 5 (100 mg l^{-1})			
	Reactive yellow 3G-P (100 mg l^{-1})			
Halomonas sp. GTW	Reactive brilliant red K-2BP (100 mg l^{-1})	100 % (24 h)	150 g l^{-1}	Guo et al. (2008a)
	Acid red G (50 mg l^{-1})	100 % (24 h)		
	Acid Red B (50 mg l^{-1})	100 % (24 h)		
	Acid scarlet GR (50 mg l^{-1})	90 % (24 h)		
	Acid black 10B (50 mg l^{-1})	90 % (24 h)		
	Reactive brilliant red X-3B (50 mg l^{-1})	60 % (24 h)		

(continued)

Table 3 (continued)

Microorganisms	Dye (concentration)	Efficiency (time)	Medium NaCl content	Reference
Shewanella decolorationis strain S12	Fast acid red GR (150 μM)	100 % (10 h)	5 g l^{-1}	Xu et al. (2007)
Gracilibacillus sp. GTY	Acid red B (100 mg l^{-1})	100 % (96 h)	150 g l^{-1}	Salah Uddin et al. (2007)
Halomonas sp. D2	Remazol black B (50 mg l^{-1})	72 % (96 h)	50 g l^{-1}	Asad et al. (2007)
	Remozal black N (50 mg l^{-1})	82 % (96 h)		
	Sulphonyl green BLE (50 mg l^{-1})	94 % (96 h)		
	Sulphonyl scarlet BNLE (50 mg l^{-1})	72 % (96 h)		
	Sulphonyl blue TLE (50 mg l^{-1})	56 % (96 h)		
	Maxilon blue (50 mg l^{-1})	37 % (96 h)		
	Entrazol blue IBC (50 mg l^{-1})	21 % (96 h)		
	Mixyure of above seven dyes (50 mg l^{-1})	100 % (120 h)		
Halomonas sp. A3	Remazol black B (50 mg l^{-1})	56 % (96 h)	50 g l^{-1}	Asad et al. (2007)
	Remozal Black N (50 mg l^{-1})	87 % (96 h)		
	Sulphonyl green BLE (50 mg l^{-1})	97 % (96 h)		
	Sulphonyl Scarlet BNLE (50 mg l^{-1})	60 % (96 h)		
	Sulphonyl blue TLE (50 mg l^{-1})	85 % (96 h)		
	Maxilon Blue (50 mg l^{-1})	46 % (96 h)		
	Entrazol blue IBC (50 mg l^{-1})	41 % (96 h)		
	Mixyure of above seven dyes (50 mg l^{-1})	100 % (120 h)		
Shewanella decolorationis S12	Acid red GR (150 mM)	100 % (68 h)		Xu et al. (2007)

(continued)

Table 3 (continued)

Microorganisms	Dye (concentration)	Efficiency (time)	Medium NaCl content	Reference
Halomonas sp. Gb	Remazol black B (50 mg l^{-1})	64 % (96 h)	50 g l^{-1}	Asad et al. (2007)
	Remozal black N (50 mg l^{-1})	82 % (96 h)		
	Sulphonyl green BLE (50 mg l^{-1})	95 % (96 h)		
	Sulphonyl scarlet BNLE (50 mg l^{-1})	74 % (96 h)		
	Sulphonyl blue TLE (50 mg l^{-1})	56 % (96 h)		
	Maxilon blue (50 mg l^{-1})	55 % (96 h)		
	Entrazol blue IBC (50 mg l^{-1})	32 % (96 h)		
	Mixyure of above seven dyes (50 mg l^{-1})	100 % (120 h)		
Fomes sclerodermeus	Malachite green			Papinutti et al. (2006)
Funa liatrogii	Acid black 52			Park et al. (2006)
Trametes hirsuta	Bromophenol blue			Rodríguez Couto et al. (2006)
	Methyl orange			
	Poly R-478			
Irpex lacteus	Reactive orange 16			Tavčar et al. (2006)
Rhodopseudomonas palustris AS1.2352	Reactive brilliant red	90 % (24 h)		Liu et al. (2006)
	X-3B			
Dichomitus squalens	Remazol brilliant blue R			Šušla et al. (2007)
	Reactive orange16			
	Copper(II) phthalocyanine			
Trametes hirsuta	Phenol red			Domínguez et al. (2005)
Pleurotus sajor-caju	Real textile effluen			Kamida et al. (2005)

(continued)

Table 3 (continued)

Microorganisms	Dye (concentration)	Efficiency (time)	Medium NaCl content	Reference
Phanerochaete chrysosporium	Direct black 38			Pazarlioglu et al. (2005)
	Direct brown 2			
	Direct red 23			
	Direct blue 15			
	Direct orange 26			
	Direct green 6			
	Tartrazine			
	Chrysophenin			
	Congo red			
Phanerochaete chrysosporium	Methyl violet			Radha et al. (2005)
	Acid orange			
	Acid red 114			
	Vat magenta			
	Methylene blue			
	Acid green			
Funa liatrogii	Reactive black 5			Mazmanci and Ünyayar (2005)
Pseudomonas aeruginosa NBAR12	Reactive blue 172	83 % (42 h)		Bhatt et al. (2005)
	(500 mg l^{-1})			
Trametes hirsuta	Lissamine green B			Rodríguez Couto and Sanromán (2005)
Phanerochaete sordida	Basic bue 22			Ge et al. (2004)
Bjerkandera adusta	Reactive black 5			Mohorčič et al. (2004)

(continued)

Table 3 (continued)

Microorganisms	Dye (concentration)	Efficiency (time)	Medium NaCl content	Reference
Trametes versicolor	Carpet dye effluent			Ramsay and Goode (2004)
Trametes hirsuta	Indigo carmine			Rodríguez Couto et al. (2004a,b)
	Lanaset marine			
Trametes hirsuta	Sella solid blue			Rodríguez Couto and Sanromán (2004)
Pleurotus pulmonarius	Remazol brilliant blue			Tychanowicz et al. (2004)
	Ethyl violet			
	Methyl violet			
	Methyl green			
	Brilliant cresyl blue			
	Methylene blue			
	Poly R-478			
	Congo red			
	Trypan blue			
	Amido black			
Aeromonas hydrophila	Red RBN (3,000 mg l^{-1})	90 % (8 h)		Chen et al. (2003)
Irpex lacteus	Remazol			Kasinath et al. (2003)
	Brilliant blue R			
Trametes versicolor	Acid Fuchsine			Rodríguez Couto et al. (2003)
	Indigo Carmine			
	Congo red			
Citrobacter sp.	Azo and triphenylmethane dyes (5 mM)	100 % (1 h)		An et al. (2002)
Trametes versicolor	Amaranth			Shin et al. (2002)
Paenibacillus azoreducens	Remazol black B (100 mg l^{-1})			Meehan et al. (2001)

(continued)

Table 3 (continued)

Microorganisms	Dye (concentration)	Efficiency (time)	Medium NaCl content	Reference
Phanerochaete chrysosporium	Poly R-478	98 % (24 h)		Rodriguez Couto et al. (2000)
Coriolus versicolor	Everzol			Kapdan et al. (2000)
	turquoise blue G			
Pseudomonas luteola	Reactive red 22			Chang and Lin (2000)
Desulfovibrio desulfuricans	Reactive orange 96	95 %		Yoo et al. (2000)
	Reactive red 120			
Sphingomonas sp. BN6	Acid azo dyes			Russ et al. (2000)
	Direct azo dyes			
	Amaranth			
Proteus mirabilis	RED RBN (1,000 mg l^{-1})	95 % (20 h)		Chen et al. (1999)
Trametes versicolor	Poly R-478			Leiding et al. (1999)
Bacteroides fragilis	Amaranth, orange II (100 mg l^{-1})	95 %		Bragger et al. (1997)
	Tartrazine (100 mg l^{-1})			
K1ebsi1e11a pneumonia R5-13	Methyl red (100 mg l^{-1})	100 % (168 h)		Wong and Yuen (1996)
Pycnoporus cinnabarinus	Remozal brilliant			Schliephake and Lonergan (1996)
	Blue R			
Pseudomonas cepacia 13NA	Acid orange 12	90 % (68 h)		Ogawa et al. (1986)
	Acid orange 20			
	Acid ted 88			
Pseudomonas sp.	Orange I (1,000 mg l^{-1})	90 % (35 h)		Kulla et al. (1983)
	Orange Il (1,000 mg l^{-1})			
Aeromonas hydrophila var 24 B	Various azo dyes (10-100 mg l^{-1})	50-90 % (24 h)		Idaka et al. (1978)

The exploration of extremobiosphere targets at discovery of extremophile microorganisms with new metabolisms, natural products, biocatalysts and other services (Schiraldi and De Rosa 2002).

Extremophilic microorganisms have many applications in biotechnology, medicine and industry. Extremozymes are one of the most important products of extremophiles not only because of their industrial application, but also because they can also be used as a model system for the study of stabilization and enzyme activation mechanisms of protein structure-functional properties (Demirjian et al. 2001). Enzymes of thermophilic, hyperthermophilic, alkaliphilic and psycrophilic groups of extremophilic microorganisms are the most promising for industrial applications (Van Den Burg 2003). Highly thermostable hydrolases, like cellulases, amylases, pectinases, chitinases, xylanases, lipases, proteases, pullulanases, glucose isomerases, alcohol dehydrogenases, and esterases with broad industrial application can be extracted from thermophilic and hyperthermophilic microorganisms. Some other kinds of thermostable enzymes, like DNA polymerase, DNA ligase, restriction enzymes and phosphatase with application in molecular biology and medicine, are also produced by extremophilic microorganisms (Gomes and Steiner 2004; Egorova and Antranikian 2005). Psychrophilic microorganisms with hydrolases, like B-glucanases, pectinases, cellulases, and proteases, have some potential applications in the waste treatment and food industry, while cold adapted enzymes are of emerging interest in the detergent production industries (Cavicchioli et al. 2011). Alkaliphilic microorganisms are source of enzymes which are stable at high pH values. Some examples of these enzymes with application in industrial sector are elastase and keratinase in cosmetic industries and some other hydrolases, like cellulases, proteinases, amylases, lipases with application in detergent production industries. Some of extremophilic microbial enzymes have the potential to be used in the biosensor systems (D'Auria et al. 2002).

Along with these enzymes, other biologically active substances and biopolymers of extremophiles have also put their mark on industry and medicine, osmoprotectant compounds, like ectoin and betain, bacteriorhodopsin (Oesterhelt and Stoeckenius, 1973; Trivedi et al. 2011), β-carotene (León et al. 2003; Lamers et al. 2008), halocins and microhalocins (Haseltine et al. 2001; O'connor and Shand 2002) and long-chained poly unsaturated fatty acids are some examples of biologically active substances of extremophiles with biotechnological applications. Extremophiles are also source of useful biopolymers (Barbara et al. 2012) like bioplastics (Lu et al. 2009) and exopolysaccharides (Nicolaus et al. 2010). Gas vesicle and liposomes of some halophilic bacteria can be used for vaccine development (Stuart et al. 2001, 2004).

One of the most interesting applications of extremophilic microorganisms is their potential in bioremediation. Bioremediation is one of the most effective and successful cleaning techniques for removal of toxicants from polluted environments (Kumar et al. 2011). There are some strains of psychrophilic (Aislabie et al. 2006) and halophilic microorganisms (Nicholson and Fathepure 2004, 2005; Liebgott et al. 2007; Feng et al. 2012) which have been reported to degrade hydrocarbon compounds. These strains have the potential to be used for oil spill or oilfield

remediation. Heavy metals are one of the most important environmental concerns, as their accumulation through food chain can cause serious health problems. Some halophilic microorganisms have been reported with the ability to remediate heavy metal pollution through absorption. Hence, they can be used as biological agents for removal of heavy metals from highly saline industrial wastewaters (Popescu and Dumitru 2009; Francis et al. 2000; Amoozegar et al. 2012). Exploring extremophilic microbial potential for bioremediation purposes will result in using organisms that have a high tolerance to the environmental harsh conditions of salinity and high temperature for in situ and ex situ remediation in bioreactors (Kumar et al. 2011).

6 Extremophilic Microorganisms and Textile Dyes

In discriminate release of colored wastewater into the environment has become today a serious ecological obstacle. Therefore, green practices are tried to assort a proper decolorization or degradation approaches for the colored industrial effluents before releasing them to the environment. Extremophilic microorganisms are one of the most attractive biological tools for bioremediation in the harsh condition of most effluents. Factors, like pH, temperature, salinity, and dye concentration have a great effect on dye removal by microorganisms.

In most cases, sodium concentrations above 3,000 ppm moderately inhibit most of microbial activities except for halotolerant and halophilic microbes which can tolerate or may require salt to be active (Anjaneya et al. 2011). Halophilic microorganisms can be found in hypersaline environment which are widely distributed around the world. These microorganisms are a group of extremophiles which not only cope with salinity as an environmental extreme (Oren 2011), but also subjected to other kinds of extreme conditions, like high pH values, high or low temperature, low oxygen availability, pressure, heavy metals and/ or other toxic compounds (Oren 2002). Based on optimal growth with respect to the NaCl concentration, halophilic microorganisms fall into two physiological groups which include extreme halophiles (optimal growth at 2.5–5.2 M NaCl) and moderate halophiles (optimal growth at 0.5–2.5 M NaCl). Besides, there are some non-halophilic microorganisms with optimal growth in medium with less than 0.2 M NaCl concentration, but also they are able to tolerate high concentration of NaCl and hence defined as halotolerant microbes (Kushsner and Kamekura 1988).

In textile dyeing process, different salts are used for different purposes which include separating organic contaminants, inducing dyestuff precipitation, and mixing with concentrated dyes to standardize them. Addition of sodium hydroxide into dye bath to increase the pH could be another reason for elevated Sodium level (Khalid et al. 2008a). High salt concentration could decrease the decolorization process because of inability of microorganism to be active in this condition. Therefore, halophilic and halotolerant microorganisms can be only useful in this respect.

Fig. 1 Decolorization of azo dye, remazol black B by *Halomonas* sp. D2. The *right tube* contains decolorization medium without inoculation and the *left tube* is inoculated with the strain and it shows decolorization after 96 h incubation

Exiguobacterium acetylicum, *Exiguobacterium indicum* and *Staphylococcus gallinarum* are able to decolorate Reactive Black 5 dye in medium containing 60000 ppm NaCl (Chen et al. 2011). Halotolerant *Exiguobacterium* sp. has the ability to efficiently decolorize azo dye X-3B at 15 % (w/v) NaCl (Tan et al. 2009). Three halophilic and halotolerant strains of the genus *Halomonas* have been reported with the high ability of azo dye decolorization (Fig. 1) in a wide range of NaCl concentration (up to 20 % w/v), temperature (25–40 °C) and pH (5–11) after 5 days of incubation (Asad et al. 2007).

Halomonas sp. strain GTW, which was isolated from the coastal sediments, is able to grow well and completely decolorize K-2BP (98 %) at 30 °C (Guo et al. 2008a). Azo dye decolorization has been also reported with *Shewanella aquimarina*, which is able to grow at up to 7 % (w/v) NaCl (Meng et al. 2012). Further, research also showed that *Shewanella putrefaciens* strain AS96 could be effective for treatment of colored industrial wastewater containing high salt concentration up to 60 (g l^{-1}) NaCl (Khalid et al. 2008b). *Psychrobacter alimentarius* strain KS23 and *Staphylococcus equorum* strain KS26 which were isolated from seawater sediment, were able to decolorize three reactive dyes including Reactive Black 5, Reactive Golden Ovifix, and Reactive Blue BRS in medium with range of 0–100 g l^{-1} NaCl concentration (Khalid et al. 2012). A halophilic strain was isolated from a solar sea-saltern in Turkey and found to be resistant against Lanaset Navy R and Lanaset Brown B dyes. According to 16S rRNA gene sequence analysis, the strain C-22 belongs to the genus *Halobacillus* which was the first report for its ability of this genus in azo-metal complex dyes decolorization (Demirci et al. 2011). A novel halotolerant bacterium *Gracilibacillus* sp. GTY was isolated, showing the ability of dye decolorization by growing and resting cells, as well as by extracted azo reductase. This strain was able to grow in the media with 15 % (w/v) of NaCl. Decolorization efficiency of the strain grown in very low, or high concentrations did not suggest that salt concentrations controlled the

production of azo reductase (Salah Uddin et al. 2007). Decolorization of Acid Black 210 by a *Vibrio harveyi* TEMS1, isolated from coastal seawater of Turkey, has been also studied. Decolorization studies were performed in medium with 5 g l^{-1} NaCl concentration (Ozdemir et al. 2008). *Shewanella algae* and *Shewanella marisflavi*, isolated from marine environments, demonstrated better azo dye decolorization ability as compared to their strains isolated from non-saline sources. *S. algae* and *S. marisflavi* are able to decolorize amaranth dye at up to 100 (g l^{-1}) NaCl or Na_2SO_4 (Liu et al. 2013). The moderately halotolerant bacterial strain *Bacillus firmus* effectively decolorized Polar red B (an azo dye) in synthetic saline wastewater medium. Decolorization occurred in a wide range of sodium chloride (1–6 %, w/v), dye (5–100 mg l^{-1}) and at pH range of 6–10 after 24 h of incubation. Cell immobilization studies of this strain clearly indicated that color removal was significantly higher in immobilized cell systems especially at salt concentrations higher than 4 % (Ogugbue et al. 2011).

Thermophilic microorganisms are a group of extremophiles which are able to thrive and grow at high temperatures from 45 to 122 °C. Many of thermophiles belong to the domain *Archaea* (Brock 1967). Thermophilic microbes are among well studied extremophiles, as their enzymes are well suited for industrial processes (Prieur 2007). Based on advantages of these organisms, natural and artificial hot environments have been widely screened for novel thermophilic microorganisms and bioactive compounds (Torkamani et al. 2008; Kublanov et al. 2009). The biggest disadvantage of such microorganisms for biotechnological application is higher equipment corrosion and liquid evaporation which haven't been properly tackled for large scale operations. Eight thermophilic consortia were separated from Spain's northwest hot springs with the ability of Reactive Black 5 dye decolorization at 65 °C. From these consortia, 3 bacterial strains were isolated which showed closest similarity to *Anoxybacillus pushchinoensis*, *Anoxybacillus kamchatkensis* and *Anoxybacillus flavithermus* (Deive et al. 2010; Sanromán et al. 2010). *Anoxybacillus rupiensis* is a thermophilic bacterium which was isolated from hot springs of Maharashtra state in India. When reddish-black effluents of dyeing unit of a textile factory in Aurangabad, Maharashtra with the pH of 10.5 were subjected to this bacterium for decolorization, the results showed 75 % decolorization through degradation at 60 °C in eight days (Gursahani and Gupta 2011). Batch assays of mesophilic (30 °C) and thermophilic (55 °C) anaerobic consortia were studied for decolorization of Reactive Red 2 and Reactive Orange 14 azoic dyes. The contribution of fermentative and methanogenic microorganisms in both temperatures was also evaluated. Results revealed that the application of thermophilic anaerobic treatment was an interesting option for the reductive decolorization of azo dyes compared to mesophilic conditions (Dos Santos et al. 2005). Two facultative anaerobic bacteria consortia and a bacterial isolate DTB showed the ability of decolorization of textile colored discharge effluents. Both cultures were able to grow and decolorize the effluents at elevated temperatures up to 60 °C. These isolated bacteria can be used for textile colored wastewater treatment which is normally discharged at elevated temperatures (Banat et al. 1997).

Alkaline-adapted microorganisms can be divided into two main groups which include; alkaliphiles and alkalitolerants. The term alkaliphiles is restricted to microorganisms that require alkaline media for growth and their optimum growth rate could be observed in at least two pH units above neutrality. Alkalitolerants are able to grow at pH values more than 9 or 10, but their optimum growth rates occur around neutrality or less (Grant and Tindall 1986; Jones et al. 1994). One of the most important characteristic of textile wastewater effluents is their alkalinity. Using alkaliphiles is inevitable for bioremediation process, because they are adapted to sustain in the harsh conditions of dyeing process. An obligate alkaliphilic bacterium *Bacillus cohnii* MTCC 3616 was used for textile azo dye Direct Red-22 aerobic decolorization, showing 95 % efficiency for decolorization at 37 °C and pH 9 in 4 h incubation under static conditions. The decolorization occurred in a broad pH range (7–11), temperature (10–45 °C) and salinity (1–7 %) (Prasad and Rao 2013). Alkaliphilic bacterial strain, *Bacillus badius*, isolated from a lake in India, showed high potential towards the degradation of azo dyes up to 100 mg l^{-1} in 24 h under aerobic condition. Azoreductase enzyme, which is able to cleave azo and nitro groups of various compounds, has also been purified from this strain (Misal et al. 2011). *Clostridium bifermentans* strain SL186 was isolated from a contaminated site and investigated for Reactive Red 3B-A, Reactive black 5 and Reactive Yellow 3G-P dyes decolorization. The bacterium retained decolorizing activity over a wide range of pH values (6–12) with optimum activity at pH 10 (Joe et al. 2008).

7 Polyextremophilic Microorganisms and Textile Dyes

Extremophilic microorganisms are able to live under different types of stressful conditions which provide them an opportunity to extend habitable space on earth which can support essential biological processes like cell growth and main metabolism. It is important to note that there are some kinds of extremophiles that are adopted to grow optimally under multiple stress factors, known as polyextremophiles. The term polyextremophiles was first coined by Rothschild and Mancinelli (2001) to describe this group of micro-organisms. In comparison to other types of microorganisms that will die or become dormant in harsh conditions, extremophiles and polyextremophiles are able to grow with active metabolism in the environmental harsh conditions, as they have application in such environments. Different types of polyextremophiles are adopted to different combinations of environmental extremes i.e. high temperature and low pH, high temperature and high pH, high temperature and high pressure, low temperature and low pressure and high salt concentration and high pH. The chemolithotrophic archaum *Sulfolobus acidocaldarius* can easily flourish at 75 °C at pH 2–3, thus showing adaptation to grow in high temperature and low pH (Reysenbach et al. 2006). The archaum *Thermococcus alcaliphilus*, which is able to grow at 90 °C and at pH 10.5, was first isolated from shallow marine hydrothermal springs (Keller et al., 1995). *Thermococcus barophilus*, which flourishes at 100 °C and needs 15–17.5 MPa at the

highest temperature, is an example of polyextremophiles at high temperature and high pressure extremes (Marteinsson et al., 1999). Most of deep sea bacteria are adapted to low temperature (2–4 °C) and high pressure (50–110 MPa) as polyextremophiles. Soda lakes are the source of haloalkaliphilic microorganisms like *Natronobacterium gregoryi* which can thrive in high pH and high salt concentrations (Tindall et al. 1984). These are some examples of poly environmental extremes which were explored for polyextremophilic life. Culture independent methods revealed microbial life in the environmental extremes wherein we don't have expectation of life (Antunes et al. 2011; Stock et al. 2012). This helps us to understand the true shape of habitable space on earth.

We are indirectly benefitted by extremophilic and polyextremophilic microorganisms which are used in biotechnology and bioremediation (Rothschild and Manicelli 2001). Many of industrial wastes have harsh conditions which make extremophiles and polyextremophiles a good choice for their treatment before releasing them into the environment. Understanding the physical, geochemical and biological limits of life is an emerging biotechnological interest in view of applications of extremophiles, polyextremophiles and their biomolecules in industrial processes and waste treatments (Podar and Reysenbach 2006; Taylor et al. 2012).

Textile colored effluent is one of the complex industrial effluents wherein microorganisms, which are used for their decolorization, are subjected to a harsh condition due to the high salinity, alkaline pH and high temperature of the effluents (McMullan et al. 2001; Kandelbauer and Guebitz 2005). Extremophilic microorganisms, which are naturally adapted to this harsh condition, are a perfect choice for treatment of the wastewaters. As these effluents have a combination of environmental extremes, polyextremophilic microorganisms attracted the attention of scientists and became the subject of scientific scrutiny for finding new highly capable microorganisms for textile colored wastewater treatment.

There are some examples of polyextremophilic microorganisms which have been able to decolorize textile wastewaters. Four fungal strains, isolated from environmental samples, were assayed for their ability for Brown GR dye decolorization. These strains belonged to the genus *Aspergillus* which showed the highest decolorization efficiency at pH 4 and 2 % (w/v) NaCl concentration (Singh et al. 2013).

A moderately halophilic and alkalitolerant bacterium was isolated from the salty effluents of textile industries in central Iran with remarkable azo dyes decolorizing ability over wide ranges of pH (7–11) and temperature (25–45°C), in presence of NaCl and Na_2SO_4 (0.5–1.5 M) under both anaerobic and aerobic conditions (Fig. 2). According to 16S rDNA sequence similarity analysis, this strain belonged to the genus *Halomonas* with the highest similarity to *Halomonas axialensis* (Pourbabaee et al. 2011).

Bacillus sp. strain SF was isolated from wastewater drain of textile finishing company and showed growth at pH 9.3–10 and 60–65 °C temperature. This alkali-thermophilic microorganism has the ability of azo dye decolorization. An

Fig. 2 Microbial decolorization of textile dyes by *Halomonas* sp. strain IP8. From left to right tube *T1* contains decolorization medium with remazol black B without inoculums and *T2* tube is the same medium after decolorization with *Halomonas* sp. strain IP8; tube *T3* contains decolorization medium with remazol black GF without inoculums and *T4* tube is the same medium after decolorization with *Halomonas* sp. strain IP8 and *T5* tube contains Cibacron Red 6B and *T6* tube shows decolorization of dye by *Halomonas* sp. strain IP8

NADH-dependent azoreductase was found to be responsible for the decolorization of azo dyes, showing optimum range of 8 to 9, and the temperature 80 °C for maximum activity (Paar et al. 2001; Maier et al. 2004).

8 Conclusion

Proper decolorization of colored wastewater effluents of textile industries is a major environmental concern. Amongst different chemical, physical and biological treatment methods, the biotechnological approaches based on microorganisms, are the most effective and environmental friendly methods. Different strains of microorganisms have shown the ability of textile dye decolorization. One of the most important factors, which have a great impact on the setting of a proper bioremediation plant for textile wastewater, is the effluent characteristics, high salinity, temperature and alkalinity. Extremophilic microorganisms and their bioactive molecules have been found to have a great potential for treatment of textile wastewaters. Most of researches concerning extremophilic microorganisms for bioremediation of textile waste waters have focused on their ability in decolorization, but their final products haven't been examined properly. Finding the microbial enzymes and genes responsible for decolorization in extremophilic microorganisms and using them for bioremediation is a future perspective.

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