Water Practice & Technology

IWA PUBLISHING

Water Practice & Technology Vol 17 No 12, 2570 doi: 10.2166/wpt.2022.143

Decolorization of methyl red using *Bacillus thuringiensis* RI16 strain: Enhanced bacterial treatment by SPB1 biosurfactant addition

Ines Mnif[a,b,*], Raouia Fendri[c] and Dhouha Ghribi[c,d,e]

[a] Laboratory of Biochemistry and Enzymatic Engineering of Lipases, National Engineering School of Sfax, Sfax, Tunisia
[b] Faculty of Science of Gabes, University of Gabes, Gabes, Tunisia
[c] Higher Institute of Biotechnology of Sfax, University of Sfax, Tunisia
[d] Laboratory of Plant Improvement and Agro-Ressources Valorization, National Engineering School of Sfax, Sfax, Tunisia
[e] Bioreactor coupled to an ultra filtra, National Engineering School of Sfax, University of Sfax, Sfax, Tunisia
*Corresponding author. E-mail: inesmnif2011@gmail.com

ABSTRACT

In this work, we evaluate the ability of a novel isolated bacteria identified as *Bacillus thuringiensis* RI16 (KM111604) to decolorize methyl red. Results showed its efficiency for the treatment of azo-dye-contaminated wastewaters under static conditions at pH values ranging from 7 to 9. The isolated bacteria could tolerate higher doses of dyes as it was able to decolorize up to 1000 mg/L. For better methyl red decolorization, we evaluate the potential use of *Bacillus subtilis* SPB1-derived lipopeptide biosurfactant. The study showed its ability to accelerate the decolorization rate and slightly maximized the decolorization efficiency at an optimal concentration of 0.025%. Compared with synthetic surfactants, the bacterial surfactant was more efficient as we observe a drastic decrease and an inhibition of methyl red decolorization by cetyl trimethylammonium bromide (CTAB) and sodium dodecyl sulfate (SDS) additions. Also, studies ensured that methyl red removal by this strain could be due to extracellular enzymatic activities. SPB1 biosurfactant could improve enzyme activities and/or enzyme synthesis and diffusion.

Key words: *Bacillus thuringiensis*, biodecolorization, biosurfactants, methyl red

HIGHLIGHTS

- *B. thuringiensis* RI16 for methyl red biodecolorization under static conditions and neutral and alkaline pH values.
- *B. subtilis* SPB1-derived lipopeptide-enhanced methyl red decolorization.
- Inhibition of methyl red decolorization by CTAB and SDS additions.
- Tween 80 enhanced methyl red decolorization.
- Improvement of color removal-related enzymes' activities and/or enzymes' synthesis and diffusion by SPB1 biosurfactant.

ABBREVIATION

BioS biosurfactant

INTRODUCTION

A wide variety of compounds can be found in textile effluent. In the Color Index, there are more than 8000 chemical products associated with the dyeing process ranging from inorganic compounds and elements to polymers and organic products (Priyanka *et al.* 2022). The most abundant are non-biodegradable synthetic dyes, pigments, hydrocarbons and heavy metals (Ardila-Leal *et al.* 2021; Al-Tohamy *et al.* 2022). Synthetic dyes include several structural varieties of dyes, such as acidic, reactive, basic, disperse, azo, diazo, anthraquinone-based and metal-complex dyes (Ardila-Leal *et al.* 2021; Al-Tohamy *et al.* 2022). These chemicals are used for desizing, scouring, bleaching, dyeing, printing and finishing (Al-Tohamy *et al.* 2022). Also, in textile industries, during the dyeing process, up to 15% of the total textile dye remains unreacted and is directly lost in the effluents generating huge amounts of wastewaters (Ardila-Leal *et al.* 2021; Al-Tohamy *et al.* 2022).

Azo dyes are the largest synthetic chemicals extensively used in textile, food, plastic, printing, leather, cosmetics and pharmaceutical industries (Benkhaya *et al.* 2020). They are highly used in the industry for dyeing fabrics (Ngo & Tischler 2022). Generally, they are characterized by a nitrogen-to-nitrogen double bond –N = N–

(Benkhaya *et al.* 2020). As they have poor exhaustion properties, nearly 10–15% of the dyestuff used remains unbound to the fiber, synthetic dyes are released into the environment leading to ecotoxicity risk, direct and indirect toxic effects and potential danger of bioaccumulation (Lellis *et al.* 2019; Ngo & Tischler 2022). First, the presence of dyes in water is highly visible and affects its transparency and esthetics impeding light penetration and reducing dissolved oxygen concentration (Lellis *et al.* 2019; Al-Tohamy *et al.* 2022; Ngo & Tischler 2022). Second, synthetic dyes can lead to the formation of tumors, cancers and allergies besides growth inhibition of bacteria, protozoan, algae, plants and different animals including human beings (Ardila-Leal *et al.* 2021). Having the ability to cause great damage to the environment and living organisms, an urgent need for their detoxification and/or elimination from the environment was developed recently (Ardila-Leal *et al.* 2021).

Numerous studies were developed including physical methods such as adsorption, ion exchange and membrane filtration and chemical methods such as coagulation-flocculation, electrochemical and advanced oxidation processes are used to treat dye-containing wastewater (Al-Tohamy *et al.* 2022). However, they are quite expensive and unable to completely remove the recalcitrant azo dyes and/or their organic metabolites (Al-Tohamy *et al.* 2022). Also, they generate significant amounts of sludge and toxic byproducts and metabolites during the treatment process that may cause secondary pollution problems and involve complicated procedures for their elimination and discharge (Al-Tohamy *et al.* 2022). So, biological treatment methods using microorganisms appear to be the best alternative to physicochemical methods since they are eco-friendly and cost-competitive (Lellis *et al.* 2019; Ngo & Tischler 2022). They involve the use of bacteria or fungi capable of dye decolorization either in pure culture or in consortia (Lellis *et al.* 2019; Abd El-Rahim *et al.* 2021). Recent studies reported the use of pure bacterial culture (Kalme *et al.* 2007; Dawkar *et al.* 2008; Ayed *et al.* 2010, 2011; Cai *et al.* 2012; Garg *et al.* 2012; Ng *et al.* 2014; Thakur *et al.* 2014; Nair *et al.* 2017; Chittal *et al.* 2019; Khairun *et al.* 2019; Al-Tohamy *et al.* 2020), mixed bacterial culture (Fang *et al.* 2004; Moosvi *et al.* 2005; Joshi *et al.* 2008; Lalnunhlimi & Krishnaswamy 2016; Kamal *et al.* 2022), pure fungi (Chakraborty *et al.* 2013; Hadibarata *et al.* 2013; Zuleta-Correa *et al.* 2016), fungal consortium (Almeida & Corso 2019), yeast (Jadhav *et al.* 2007; Jafari *et al.* 2014) and algae (El-Sheekh *et al.* 2009; Ishchi & Sibi 2020) for dyes decolorization.

The ability of microorganisms to decolorize and metabolize azo dyes has long been known, and the use of bioremediation-based technologies for treating textile wastewater has attracted interest (Ngo & Tischler 2022). Being cost-effective, environmentally friendly and producing low sludge, biological approaches are very advantageous (Ngo & Tischler 2022). Methyl red (2-(N,N-dimethyl-4-aminophenyl)azobenzenecarboxylic acid), also called C.I. Acid Red 2, is one of the most frequently used secondary diazo dyes well known by their ecotoxicity (Benkhaya *et al.* 2020; Ngo & Tischler 2022). Numerous microbial strains were reported to have the ability to degrade azo dyes especially methyl red, including bacteria (Ayed *et al.* 2011; Ng *et al.* 2014; Abd El-Rahim *et al.* 2021; Ngo & Tischler 2022), fungi (Zuleta-Correa *et al.* 2016; Abd El-Rahim *et al.* 2021), cyanobacteria (Dellamatrice *et al.* 2017), yeast (Al-Tohamy *et al.* 2020) and algae (El-Sheekh *et al.* 2009; Ishchi & Sibi 2020). The increasing interest in bacteria is a result of their potential to degrade and mineralize most textile dyes effectively; bacteria also have a rapid growth rate and are straightforward to culture (Ayed *et al.* 2011). In addition, biological treatment methods involving the use of bacteria belonging to *Bacillus* strains were highly discussed to treat azo dyes (Thakur *et al.* 2014; Nair *et al.* 2017; Khairun *et al.* 2019; Ngo & Tischler 2022; Pinheiro *et al.* 2022). In this aim, this study will discuss the ability of a *Bacillus thuringiensis* RI16 (KM111604) strain to decolorize the azo-dye methyl red. In this regard, the present study aims to investigate, primarily, the potential of a hydrocarbon-degrading bacterium *B. thuringiensis* RI16 (KM111604) to decolorize the azo-dye methyl red. Subsequently, we studied the efficiency of *Bacillus subtilis* SPB1 lipopeptide biosurfactant (BioS) in the improvement of the dye bioremoval process.

MATERIALS AND METHODS

Microorganism strain

A *B. thuringiensis* RI16 (KM111604) strain was used for the study of the biodecolorization of the azo-dye methyl red. It was isolated and identified in our previous study for its ability to degrade diesel oil (Mnif *et al.* 2015a). A wild-type strain of *B. subtilis* SPB1 (HQ392822) was used to produce BioS (Ghribi *et al.* 2012). As presented in our previous work, the lipopeptide BioS was composed mainly of different Surfactin isoforms with molecular weights of 1007, 1021 and 1035 Da, Iturin isoforms with molecular weights of 1028, 1042 and 1056 Da and Fengycin isoforms with molecular weights of 1432 and 1446 Da along with two new clusters of lipopeptide isoforms

having molecular weights of 1410 and 1424 Da and 973 and 987 Da (Mnif *et al.* 2016). Mass spectroscopic analysis served to identify the lipopeptides BioS after acid precipitation and purification (Mnif *et al.* 2016).

Culture conditions and preparation of the purified lipopeptide preparation

Culture conditions for BioS production were carried out as described by Mnif *et al.* (2021a, 2021b, 2021c). They were incubated for 2 days at 37 °C and 150 rpm. At the end of the cultivation, the culture was centrifuged at 10,000 rpm and 4 °C for 20 min to remove bacterial cells. Hence, BioS were extracted from the supernatant-free cells as described in the next section. Lipopeptide BioS were partially purified during three consecutive cycles of acid precipitation–dissolution as described in our previous work (Mnif *et al.* 2021a, 2021b, 2021c). In fact, each time, the pellet formed by acid precipitation was suspended in alkaline water at a concentration of 4 mg/mL and the pH was readjusted to 8 with NaOH 1 N. The supernatant was collected by centrifugation at 10,000 rpm and 4 °C for 20 min followed by second acid precipitation. The final pellet formed was washed three times with acid water (pH = 2), dissolved in distilled water at a concentration of 10 mg/mL, pH adjusted to 8 with NaOH 1 N and lyophilized. This serves as crude lipopeptide preparation to enhance the decolorization efficiency (Mnif *et al.* 2015a, 2015b, 2015c).

Growth medium and decolorization of dye solution

The decolorization of methyl red was studied at different concentrations of the mentioned dyes (50, 200, 500, 750 and 1000 mg/L) in 250-mL Erlenmeyer flasks containing 50-mL mineral salt medium (MSM). The pH of the medium was adjusted to 7 as described by Ayed *et al.* (2011). The inoculum was prepared in an LB medium. *B. thuringiensis* RI16 strain was streaked on a nutrient agar slant and incubated overnight at 37 °C. After that, one loop of cells was dispensed in 50-mL LB medium (250-mL Erlenmeyer flasks) and incubated in a shaker at 150 rpm and 37 °C ($\pm$ 0.5) overnight. Flasks were inoculated by the newly isolated strain at a final optical density of 600 nm corresponding to 0.2. The culture was incubated under shaking conditions (150 rpm) and at static conditions at 37 °C for 24 h. Color removal was quantified after 4, 8 and 24 h of incubation. The resultant culture was centrifuged for 10 min at 10,000 rpm and the cell pellet was washed twice in sterile saline solution (9‰) and re-suspended in the liquid culture medium (Mnif *et al.* 2015a).

In order to study the effect of pH on biodecolorization efficiency, methyl red decolorization was studied at different pH values ranging from 5 to 9. pH of the MSM was adjusted before dye addition and inoculation. Results were expressed as residual activity toward the biodecolorization at a neutral pH value. It is calculated according to this formula:

$$\text{Residual activity (\%)} = \frac{\text{Biodecolorization at different pH value}}{\text{Biodecolorization at neutral pH value}} \times 100 \quad (1)$$

Effect of SPB1 biosurfactant addition on methyl red biodecolorization

In order to study the effect of SPB1 lipopeptide addition on methyl red removal efficiency by the respective strain, various concentrations (0.025, 0.05, 0.075 and 0.1%) were added in the nutrient growth before incubation. The effect of SPB1 lipopeptide was compared to those of three different chemical surfactants, the anionic surfactant sodium dodecyl sulfate (SDS) (8.2 mM at 25 °C = 0.2364%) (Mukerjee & Mysels 1971); the cationic surfactant cetyl trimethylammonium bromide (CTAB) (0.89–0.93 mM at 25 °C = 0.0324–0.0338%) (Yaofeng 2009) and the nonionic surfactant polyoxyethylene-sorbitan monooleate; polysorbate 80 (Tween 80) (0.012 Mm at 25 °C = 0.00157%) (Chou *et al.* 2005).

Mechanism of microbial decolorization

In order to elucidate the mechanism of microbial decolorization of methyl red, decolorization tests were realized using living cells, dead cells and two enzymatic preparations of the respective decolorizing strain corresponding to extracellular enzymes in the supernatant and the intracellular enzymes present in the sonication product. Similar experiments were conducted by Jadhav *et al.* (2011), and Mohanty & Kumar (2021). In fact, *B. thuringiensis* RI16 was grown in LB medium overnight at 37 °C and 150 rpm. The supernatant was filter-sterilized using 0.2-μm membranes to remove residual cells and serve as extracellular enzyme preparation to measure enzymatic dye biodegradation. The resulting biomass was harvested by centrifugation (10,000 rpm, 20 min) and suspended in 50-mM potassium phosphate buffer (pH 7.4). The first prize of the biomass suspension was sonicated (30 s, 60

amplitude, 10 strokes) at 4 °C (Jadhav *et al.* 2011). After centrifugation, this extract was used as an intracellular enzyme source to quantify intracellular enzymatic dye biodegradation. A second prize of the biomass suspension was autoclaved and the resultant cellular debris was used as biosorbent material to quantify methyl red removal. A third part serves as active cells to quantify color removal resulting from decolorization and biodegradation. In total, four tests were realized in parallel; one is using living beings' cells, one using dead cells, one using bacterial supernatant and one using intracellular bacterial content. They were carried out in duplicate with and without the addition of SPB1 lipopeptide BioS at its optimal concentration determined in the result part. Biodecolorization efficiencies were measured for each trial.

Analytical methods

To measure decolorization, sampling was carried out at different time intervals from the inoculated decolorizing media. Withdrawn samples were clarified before absorbance measurements in order to prevent absorbance interference from the cellular or other suspended debris. Sample clarification was carried out by centrifugation at 10,000 rpm for 10 min and the absorbance of supernatants obtained was determined at the maximum absorption wavelength (λ_{max}) of methyl red (442 nm) using UV-vis spectrophotometer (Spectro UV-Vis Double Beam PC Scanning spectrophotomètre UVD-2960). Uninoculated culture media with and without added dyes were used as negative controls. The decolorization efficiency of different isolates was calculated according to Equation (2) (Ayed *et al.* 2010; Mnif *et al.* 2015b, 2015c):

$$\%\text{Decolorization (MR)} = \frac{(\text{Initial Absorbance (0 h)} - \text{Observed Absorbance } (t))}{\text{Initial Absorbance (0 h)}} \times 100 \quad (2)$$

RESULTS AND DISCUSSION

Methyl red decolorization under different culture conditions

Effect of initial dye concentration

The decolorization of methyl red was studied at various increasing concentrations of dye, i.e. from 100, 200, 300, 500, 750 and 1000 mg/L at both static and shaking conditions. A progressive increase of dye decolorization was observed during the first 24 h of incubation. After, no significant variation occurs (data not shown). It is well observed that the rate of decolorization decreased with increasing concentration of dye (Figures 1 and 2). Moreover, the time required for decolorization increase with increasing dyes' concentrations. Additionally, decolorization was more efficient at static conditions with more than 90% after 8 h of incubation in contrast to 60% at shaking conditions. Optimal decolorization efficiency was obtained at 200 mg/L methyl red under static conditions. Similar observations were also reported during the decolorization of reactive violet 5 (at 200 mg/L after 37 h) by a newly isolated bacterial consortium (Moosvi *et al.* 2005), the decolorization of the azo-dye acid orange 7 (at 200 mg/L after 16 h) by newly isolated consortium TJ-1 (Joshi *et al.* 2008), the decolorization of Brown 3REL (100% at static conditions after 8 h) by *Bacillus* sp. (Dawkar *et al.* 2008) and the

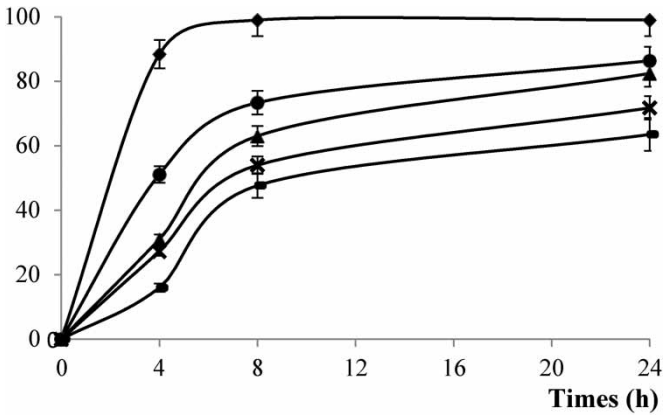

Figure 1 | Effect of dye concentration on the biodecolorization efficiency of methyl red at static conditions. —◆—: 200 mg/L; —●—: 300 mg/L; —▲—: 500 mg/L; —✕—: 750 mg/L; —•—: 1000 mg/L.

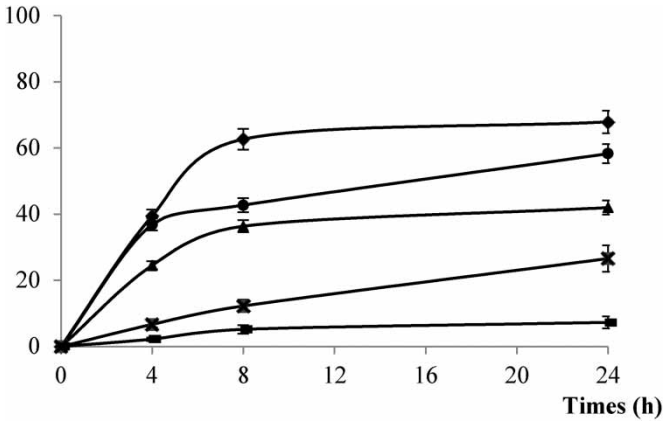

Figure 2 | Effect of dye concentration on the biodecolorization efficiency of methyl red at shaking conditions. —◆—: 200 mg/L; —●—: 300 mg/L; —▲—: 500 mg/L; —✕—: 750 mg/L; —▬—: 1000 mg/L.

decolorization of Congo Red (97% of 100 mg/L after 8 h of incubation) by *Pseudomonas* sp. SU-EBT (Telke *et al.* 2010). Uninoculated negative controls realized at the same conditions indicate that there was no biotic loss of methyl red within the increase of incubation time. In addition, the strain can tolerate higher doses of dyes as it can decolorize up to 1000 mg/L of dye and could be considered an efficient decolorizer of methyl red. Results are similar to those published by Ayed *et al.* (2011), Jafari *et al.* (2014) and Kamal *et al.* (2022) reporting an efficient biodecolorization of higher doses of azo dyes by selected bacterial strains and fungi. In contradiction, other studies reported the biodecolorization of lower concentrations of azo dyes (Jadhav *et al.* 2007; Chittal *et al.* 2019; Al-Tohamy *et al.* 2020). Generally, higher doses of azo dyes higher than 500 mg/L can cause toxicity to living cells and decrease decolorization efficiency (Shi *et al.* 2021; Ngo & Tischler 2022). In some cases, even moderate concentration of the azo-dye caused a drastic decrease of decolorization efficiency. For example, only 15% decolorization percentage of Direct Blue-6 by *Pseudomonas desmolyticum* NCIM 2112 was observed at 250-mg/L dye concentration (Kalme *et al.* 2007).

Effect of static and shaking conditions

Results presented in Figures 1 and 2 indicated that the strain could decolorize methyl red under both static and shaking conditions, but the decolorization under static conditions appeared to be significantly higher. In fact, as shown in Figures 1 and 2, the decolorization of methyl red (100–1000 mg/L) under shaking condition by *B. thuringiensis* RI12 cannot exceed 76% with very weak biodecolorization at high dye concentration. However, under static conditions, a complete biodecolorization was obtained for doses between 50 and 200 mg/L with 82.41% when working in the presence of 500 mg/L. Results are similar to many literature studies reporting high microbial decolorization of azo dyes under static conditions (Fang *et al.* 2004; Telke *et al.* 2010; Garg *et al.* 2012). Also, Cai *et al.* (2012) reported efficient azo-dye biodegradation under static conditions. However, several studies reported the efficient biodecolorization of methyl red under shaking conditions (Ayed *et al.* 2011).

Effect of pH on methyl red decolorization

Having a great influence on dye structure and microbial growth, pH could affect biodecolorization and biodegradation efficiency. Therefore, it was recognized as an important factor for the biodecolorization process (Shah *et al.* 2013; Nair *et al.* 2017; Lalnunhlimi & Krishnaswamy 2016). As shown in Figure 3, the optimal pH for methyl red biodecolorization range from 7 to 9. Therefore, it was obvious that neutral and basic conditions higher than 7 were favorable for the decolorization of methyl red. A drastic decrease in biodecolorization efficiency was observed when operating at acidic pH conditions lower than 7. Results are similar to those published by Shah *et al.* (2013) and Nair *et al.* (2017) showing preferential azo dyes biodegradation at neutral pH values. However, Lalnunhlimi & Krishnaswamy (2016) and Kamal *et al.* (2022) show favorable decolorization of azo dyes (Direct Blue 151 and Direct Red 31) at alkaline conditions. Gou *et al.* (2009) reported efficient azo-dye biosorption at acidic pH values of 4 or 5 by fungal-bacterial co-cultures. *Bacillus* spp. shows optimum decolorization of Remazol Black-B from pH 5 to 7 (Shah *et al.* 2013). Also, Chakraborty *et al.* (2013) and Senthilkumar *et al.* (2014) reported a maximal azo dyes biotreatment at pH 5.

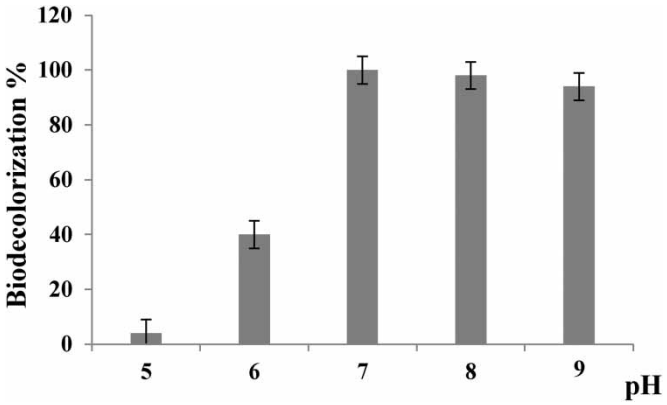

Figure 3 | Effect of initial pH values on biodecolorization efficiency.

Effect of SPB1 lipopeptide biosurfactant addition on dye biodecolorization

B. thuringiensis RI16 strain could decolorize the textile azo-dye methyl red efficiently under static conditions. Surfactant-enhanced decolorization technology is one of the feasible approaches to improve textile dye removal from wastewater. So, in order to upgrade the biodecolorization efficiency in the course of time, different concentrations of SPB1 lipopeptide BioS (0.025; 0.05; 0.075; 0.1 and 0.15%) were added before culture inoculation (Figure 4). In fact, SPB1 BioS was characterized by its high emulsification activity (Ghribi *et al.* 2012) and was demonstrated to enhance *in situ* (Mnif *et al.* 2014) and *ex situ* hydrocarbon biodegradation (Mnif *et al.* 2015a). Moreover, the described BioS stimulate methyl orange and malachite green biotreatment by *Aeromonas veroni* and *Citrobacter sedlakii*, respectively (Mnif *et al.* 2015b, 2015c). Results in Figure 3 show a significant enhancement of decolorization percentage when using 0.025% BioS. A gradual decrease of decolorization proportion was observed. It rose from 62 to 81%, from 78 to 93.69% and from 91.47 to 97.69% after 4, 8 and 24 h, respectively. When adding 0.05% SPB1 BioS, biodecolorization percentages were similar to those without BioS addition. For superior doses, an inhibition of biodecolorization was observed and SPB1 BioS addition seems to have a deleterious effect on decolorization efficiency. The dose-dependent effect on biodecolorization efficiency was also observed by Kristensen *et al.* (2007), Champagne *et al.* (2010), Gül & Dönmez (2012) and Ruta & Juozas (2013). Therefore, we can assume that an optimal concentration of BioS of about 0.025% accelerates the decolorization rate and maximizes the decolorization efficiency. Thus, it could save energy and lower costs are required for the treatment technique by shortening the incubation period. These findings are similar to those described by Jadhav *et al.* (2011) and Gül & Dönmez (2012). Furthermore, as dye biodecolorization efficiency enhancement by chemical surfactants addition was highly described in many literature reviews (Gül & Dönmez 2011, 2012); the effect of SPB1 BioS was compared to those of synthetic surfactants Tween 80,

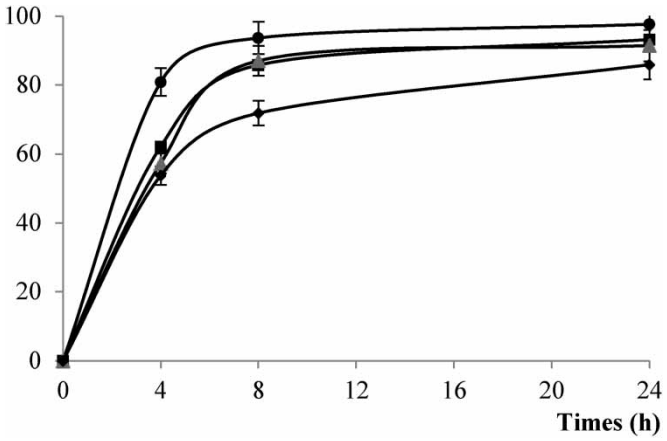

Figure 4 | Effect of the addition of SPB1 BioS on methyl red biodecolorization. —■—: Without BioS; —●—: +0.025% BioS; —▲—: +0.05% BioS; —◆—: +0.15%BioS.

CTAB and SDS at its optimal concentration (0.025%). In fact, many authors described that they could improve synthetic dyes solubilization through their incorporation within their micelle structure and therefore their microbial treatment (Tehrani-Bagha & Holmberg 2013). When added at a concentration of 0.025%, results showed a drastic decrease and a total inhibition of methyl red decolorization by CTAB and SDS additions. These results remembered those published by Liu *et al.* (2012). In fact, due to their chemical nature and toxic effect, we can suppose that they can disturb membrane cells integrity inhibiting; therefore, their growth and biological activities and consequently lead to the inhibition of decolorization rate (Kapadia Sanket & Yagnik 2013), whereas, the nonionic surfactant Tween 80 did not have any negative effect on methyl red biodecolorization. Results are similar to those published by Hadibarata *et al.* (2013), reporting the enhancement of microbial decolorization of an Azo Dye Reactive Black 5 using white-rot fungus *Pleurotus eryngii* by Tween 80 addition. Also, Liu *et al.* (2006) and Zenz Zeng *et al.* (2006) reported an increase of certain enzyme activities by Tween 80 addition. Remember, due to their natural origin, biodegradability and higher efficiency in extreme conditions could be the best alternative to chemical surfactant addition in promoting the treatment and eliminating contaminants. Actual results show the higher efficiency of SPB1 lipopeptide BioS as an enhancer of methyl red biotreatment compared to the reported chemical emulsifiers.

Mechanism of bacterial decolorization of methyl red

Decolorization of the dye solution may take place in two ways: either adsorption on the microbial biomass or enzymatic biotreatment of the dyes (Pinheiro *et al.* 2022). When conducting biodecolorization using different preparation, efficient decolorization was observed using living cells of *B. thuringiensis* RI12 and extracellular supernatant of the strain (data not presented). However, no decolorization was observed by the application of the dead cells and intracellular enzymatic preparation. Therefore, these results indicate that methyl red removal by this strain can be due to extracellular enzymatic activities. Other studies reported the enzymatic biotreatment of certain azo dyes (Liu *et al.* 2020; Singh *et al.* 2020; Ardila-Leal *et al.* 2021; Ngo & Tischler 2022; Vishani & Shrivastav 2022). However, many reports described the adsorptive removal of azo-dye using bacteria, fungi and yeast (Almeida & Corso 2019; Öztürk *et al.* 2020; Ngo & Tischler 2022; Pinheiro *et al.* 2022). Studies with and without BioS addition were also conducted when treating methyl red with living cells and extracellular enzymatic preparation. Results indicated the enhancement of methyl red biodecolorization in both cases due to the addition of 0.025% BioS. Regarding the preliminary results showing the enhancement of methyl red biodecolorization by the addition of SPB1 bioemulsifier, we can propose an enhancement of bacterial growth and, therefore, methyl orange biodecolorization due to the fact that this BioS is biodegradable and could be used as a primary and more accessible carbon source to initiate microorganisms' growth (Bautista *et al.* 2009; Mnif *et al.* 2015b). Also, we can propose that the BioS improve enzyme production and, therefore, their biological activities. Similar results are described by Liu *et al.* (2017) and Oliva-Taravilla *et al.* (2020) and reporting the improvement of enzyme production by the addition of lipopeptides and rhamnolipids, respectively. Moreover, we can assume that the addition of SPB1 BioS may increase bacterial membrane permeability as reported in other studies (Vaidyanathan *et al.* 2014; Kaczorek *et al.* 2018) facilitating the enzymes diffusion. Regarding the enhancement of methyl red biodecolorization when using textracellular enzymatic preparation, we can assume that the bioemulsifier can activate decolorizing enzymes. In fact, recent studies reported the promotion of enzyme activities by chemical surfactants addition. As reported by Singh & Singh (2017), laccase activity was improved by Triton X-100 and Tween 20. Similarly, as described by Bento *et al.* (2020), surfactant-based ionic liquids improve the efficiency of laccase to degrade indigo carmine. Additionally, Britos *et al.* (2018) proved the improvement of laccase activity by ionic surfactant addition. Also, Tween 80 increased the cellobiohydrolase and endoglucanase activities from 63.0 and 76.7% to 123.2 and 103.1%, respectively (Ying *et al.* 2021), and Tween 20 enhanced cellulose activity (Wang *et al.* 2020). Similarly, Jadhav *et al.* (2011) showed the intensified effects of rhamnolipid on the enzymes involved in the dye degradation process and the stimulatory effect on lignin peroxidase (increased by 324.52%) and Veratryl alcohol oxidase (increased by 100%) were much eminent. Also, Liu *et al.* (2008) and Liang *et al.* (2010) reported 161.98 and 86% increase in the activity of lignin peroxidase in the presence of dirhamnolipid, respectively. Moreover, Zhou *et al.* (2011) and Liu *et al.* (2012) reported the improvement of laccase production and phenol biodegradation by rhamnolipid addition. Similar findings describing the improvement of diverse enzymes activities through dirhamnolipid addition were reported (Shao *et al.* 2017; Oliva-Taravilla *et al.* 2020; Gayathiri *et al.* 2022).

Also, we can assume a stabilizing effect on enzymes enhancing, therefore, their activities. Similarly, Ji *et al.* (2009) reported the stabilizing effect of laccase by Triton X-100 addition. Also, *P. aeruginosa* BSZ-07 rhamnolipid BioS was demonstrated to stimulate rice straw hydrolysis bioprocess by *Trichoderma reesei* ZM4-F3, a cellulose decomposing fungus, through increasing the activity of *β*-glucosidase and stabilizing Cel7A activity (Zhang *et al.* 2009).

CONCLUSION

B. thuringiensis RI16 showed excellent potential for bioremediation application as it can decolorize up to 1000 mg/L of methyl red dye at neutral and basic pH values. Results were better under static conditions and for lower dye concentrations. When elucidating the mechanism of dye removal, biodecolorization of methyl red can result from enzymatic activities. The addition of SPB1 BioS at 0.025% increased the biotreatment yields significantly. It seems to activate the extracellular enzymes involved in dye biodecolorization. However, chemical surfactants addition seems to have a deleterious effect on biodecolorization efficiency. The addition of SPB1 bioemulsifier reduced energy costs by reducing effective decolorization time, and BioS-stimulated bacterial decolorization method may provide a highly-efficient, inexpensive, and time-saving procedure in the treatment of textile effluents.

ACKNOWLEDGEMENTS

This work was supported by grants from the Tunisian Ministry of Higher Education, Scientific Research and Technology. It is a part of a research project on Biosurfactant Production, Characterization and Application.

FUNDING

Funding for this research work was granted by the Ministry of Higher Education and Research of Tunisia.

CONSENT FOR PUBLICATION

All authors read the final manuscript and approved its submission to Water Practice and Technology.

AVAILABILITY OF DATA AND MATERIALS

The data sets supporting the conclusions of this article are included in the article.

AUTHORS CONTRIBUTIONS

All authors directly participated in the planning, execution, or analysis of this study. All authors read and approved the final manuscript.

DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

CONFLICT OF INTEREST

The authors declare there is no conflict.

REFERENCES

Abd El-Rahim, W.-M., Moawad, H., Abdel Azeiz, A. Z. & Sadowsky, M. J. 2021 Biodegradation of azo dyes by bacterial or fungal consortium and identification of the biodegradation products. *The Egyptian Journal of Aquatic Research* **47**(3), 269–276.

Almeida, E. J. R. & Corso, C. R. 2019 Decolorization and removal of toxicity of textile azo dyes using fungal biomass pelletized. *International Journal of Environmental Science and Technology* **16**, 1319–1328.

Al-Tohamy, R., Sun, J., Fareed, M. F., Kenawy, E.-R. & Ali, S. S. 2020 Ecofriendly biodegradation of Reactive Black 5 by newly isolated *Sterigmatomyces halophilus* SSA1575, valued for textile azo dye wastewater processing and detoxification. *Scientific Reports* **10**, 12370.

Al-Tohamy, R., Ali, S. S., Li, F., Okasha, K. M., Mahmoud, A.-G. Y., Elsamahy, T., Jiao, H., Fu, Y. & Sun, J. 2022 A critical review on the treatment of dye-containing wastewater: ecotoxicological and health concerns of textile dyes and possible remediation approaches for environmental safety. *Ecotoxicology and Environmental Safety* **231**, 113160.

Ardila-Leal, L. D., Poutou-Piñales, R. A., Pedroza-Rodríguez, A. M. & Quevedo-Hidalgo, B. E. 2021 A brief history of colour: the environmental impact of synthetic dyes and removal by using laccases. *Molecules* **26**, 3813.

Ayed, L., Achour, S., Khelifi, E. & Cheref, A. 2010 Use of active consortia of constructed ternary bacterial cultures via mixture design for Congo Red decolorization enhancement. *Chemical Engineering Journal* **162**, 495–502.

Ayed, L., Mahdhi, A., Cheref, A. & Bakhrouf, A. 2011 Decolorization and degradation of azo dye methyl red by an isolated *Sphingomonas paucimobilis*: biotoxicity and metabolites characterization. *Desalination* **274**, 272–277.

Bautista, F. L., Sanz, R., Molina, M. C. & Gonzalez, N. 2009 Effect of different non-ionic surfactants on the biodegradation of PAHs by diverse aerobic bacteria. *International Biodeterioration and Biodegradation* **63**, 913–922.

Benkhaya, S., M'rabet, S. & El Harfi, A. 2020 Classifications, properties, recent synthesis and applications of azo dyes. *Heliyon* **6**(1), e03271.

Bento, R. M. F., Almeida, M. R., Bharmoria, P., Freire, M. G. & Tavares, A. P. M. 2020 Improvements in the enzymatic degradation of textile dyes using ionic-liquid-based surfactants. *Separation and Purification Technology* **235**(18), 116191.

Britos, C. N., Gianolini, J. E., Portillo, H. & Trelles, J. A. 2018 Biodegradation of industrial dyes by a solvent, metal and surfactant-stable extracellular bacterial laccase. *Biocatalysis and Agricultural Biotechnology* **14**, 221–227.

Cai, P.-J., Xiao, X., He, Y.-R., Li, W.-W., Chu, J., Wu, C., He, M.-X., Zhang, Z., Sheng, G.-P., Hon-Wah Lam, M., Xu, F. & Yu, H.-Q. 2012 Anaerobic biodecolorization mechanism of methyl orange by *Shewanella oneidensis* MR-1. *Applied Microbiology and Biotechnology* **93**, 1769–1776.

Chakraborty, S., Basak, B., Dutta, S., Bhunia, B. & Dey, A. 2013 Decolorization and biodegradation of Congo red dye by a novel white rot fungus *Alternaria alternata* CMERI F6. *Bioresource Technology* **147**, 662–666.

Champagne, P.-P., Nesheim, M. E. & Ramsay, J. A. 2010 Effect of a non-ionic surfactant, Merpol, on dye decolorization of Reactive blue 19 by laccase. *Enzyme and Microbial Technology* **46**, 147–152.

Chittal, V., Gracias, M., Anu, A., Saha, P. & Rao, K. V. B. 2019 Biodecolorization and biodegradation of Azo Dye Reactive Orange-16 by marine *Nocardiopsis* sp. *Iranian Journal of Biotechnology* **17**(3), e1551.

Chou, D. K., Krishnamurthy, R., Randolph, T. W. & Carpenter, J. F. 2005 Effects of Tween 20 and Tween 80 on the stability of Albutropin during agitation. *Journal of Pharmaceutical Science* **94**, 1368–1381.

Dawkar, V. V., Jadhav, U. U., Jadhav, S. U. & Govindwar, S. P. 2008 Biodegradation of disperse textile dye Brown 3REL by newly isolated *Bacillus* sp. VUS. *Journal of Applied Microbiology* **105**, 14–24.

Dellamatrice, P. M., Silva-Stenico, M. E., de Moraes, L. A. B., Fiore, M. F. & Monteiro, R. T. R. 2017 Degradation of textile dyes by cyanobacteria. *Brazilian Journal of Microbiology* **48**(1), 25–31.

El-Sheekh, M. M., Gharie, M. M. & Abou-El-Souod, G. W. 2009 Biodegradation of dyes by some green algae and cyanobacteria. *International Biodeterioration and Biodegradation* **63**, 699–704.

Fang, H., Wenrong, H. & Yuezhong, L. 2004 Biodegradation mechanisms and kinetics of azo dye 4BS by a microbial consortium. *Chemosphere* **57**, 293–301.

Garg, S. K., Tripathi, M., Singh, S. K. & Tiwari, J. K. 2012 Biodecolorization of textile dye effluent by *Pseudomonas putida* SKG-1 (MTCC 10510) under the conditions optimized for monoazo dye orange II color removal in simulated minimal salt medium. *International Biodeterioration and Biodegradation* **74**, 24–35.

Gayathiri, E., Prakash, P., Karmegam, N., Varjani, S., Awasthi, M. K. & Ravindran, B. 2022 Biosurfactants: potential and eco-friendly material for sustainable agriculture and environmental safety – a review. *Agronomy* **12**, 662.

Ghribi, D., Abdelkefi-Mesrati, L., Mnif, I., Kammoun, R., Ayadi, I., Saadaoui, I., Maktouf, S. & Chaabouni-Ellouze, S. 2012 Investigation of antimicrobial activity and statistical optimization of *Bacillus subtilis* SPB1 biosurfactant production in solid-state fermentation. *Journal of Biomedecine and Biotechnology* **2012**, 373682.

Gou, M., Qu, Y. & Zhou, J. 2009 Azo dye 400 decolorization by a new fungal isolate, *Penicillium* sp. QQ and fungal-bacterial cocultures. *Journal of Hazardous Materials* **170**, 314–319.

Gül, U. D. & Dönmez, G. 2011 Effect of surfactants on Remazol Blue bioremoval capacity of *Rhizopus Arrhizus* strain growing in molasses medium. *Fresenius Environmental Bulletin* **20**, 2677–2683.

Gül, U. D. & Dönmez, G. 2012 Effects of dodecyl trimethyl ammonium bromide surfactant on decolourization of remazol blue by a living *Aspergillus versicolor* strain. *Journal of Surfactant and Detergent* **15**, 797–803.

Hadibarata, T., Adnan, L. A., Mohd Yusoff, A. R., Yuniarto, A., Meor, R., Ahmad Zubir, M. F., Khudhair, A. B., The, Z. C. & Naser, M. A. 2013 Microbial decolourization of an azo dye reactive black 5 using White-Rot Fungus *Pleurotuseryngii* f032. *Water, Air and Soil Pollution* **224**, 1595.

Ishchi, T. & Sibi, G. 2020 Azo dye degradation by *Chlorella vulgaris*: optimization and kinetics. *International Journal of Biological Chemistry* **14**, 1–7.

Jadhav, J. P., Parshetti, G. K., Kalme, S. D. & Govindwar, S. P. 2007 Decolorization of azo dye methyl red by *Saccharomyces cerevisiae* MTC 463. *Chemosphere* **68**, 394–400.

Jadhav, M., Kalme, S., Tamboli, D. & Govindwar, S. 2011 Rhamnolipi from Pseudomonas desmolyticum NCIM-2112 and its role in the degradation of Brown 3REL. *Journal of Basic Microbiology* **51**, 385–396.

Jafari, N., Soudi, M. R. & Kasra-Kermanshahi, R. 2014 Biodecolorization of textile azo dyes by isolated yeast from activated sludge: *Issatchenkia orientalis* JKS6. *Annals of Microbiology*. doi:10.1007/s13213-013-0677-y.

Ji, G., Zhang, H., Huang, F. & Huang, X. 2009 Effects of nonionic surfactant Triton X-100 on the laccase-catalyzed conversion of bisphenol A. *Journal of Environmental Science* **21**, 1486–1490.

Joshi, T., Iyengar, L., Singh, K. & Garg, S. 2008 Isolation, identification and application of novel bacterial consortium TJ-1 for the decolourization of structurally different azo dyes. *Bioressource Technology* **99**, 7115–7121.

Kaczorek, E., Pacholak, A., Zdarta, A. & Smułek, W. 2018 The impact of biosurfactants on microbial cell properties leading to hydrocarbon bioavailability increase. *Colloids Interfaces* **2**, 35.

Kalme, S. D., Parshetti, G. K., Jadhav, S. U. & Govindwar, S. P. 2007 Biodegradation of benzidine based dye direct Blue-6 by *Pseudomonas desmolyticum* NCIM 2112. *Bioressource Technology* **98**, 1405–1410.

Kamal, I. M., Abdeltawab, N. F., Ragab, Y. M., Farag, M. A. & Ramadan, M. A. 2022 Biodegradation, decolorization, and detoxification of di-azo dye direct Red 81 by halotolerant, alkali-thermo-tolerant bacterial mixed cultures. *Microorganisms* **10**, 994.

Kapadia Sanket, G. & Yagnik, B. N. 2013 Current trend and potential for microbial biosurfactants. *Asian Journal of Experimental and Biological Science* **4**(1), 1–8.

Khairun, K., Hanis, A., Muhammad Nasri, A. R., Wan Farahiyah, W. K. & Mohd Rabani, M. Y. 2019 Bacterial degradation of azo dye congo red by *Bacillus* sp. *Journal of Physics: Conference Series* **1529**(2), 022048.

Kristensen, J. B., Borjesson, J., Bruun, M. H. & Tjerneld, F. 2007 Use of surface active additives in enzymatic hydrolysis of wheat straw lignocellulose. *Enzyme and Microbial Technology* **40**, 888–895.

Lalnunhlimi, S. & Krishnaswamy, V. 2016 Decolorization of azo dyes (Direct Blue 151 and Direct Red 31) by moderately alkaliphilic bacterial consortium. *Environmental Microbiology* **47**(1), 39–46.

Lellis, B., Fávaro-Polonio, C. Z., Pamphile, J. A. & Polonio, J. C. 2019 Effects of textile dyes on health and the environment and bioremediation potential of living organisms. *Biotechnology Research and Innovation* **3**(2), 275–290.

Liang, Y.-S., Yuan, X.-Z., Zeng, G.-M., Hu, C.-L., Zhong, H., Huang, D.-L., Tang, L. & Zhao, J.-J. 2010 Biodelignification of rice straw by *Phanerochaete chrysosporium* in the presence of dirhamnolipid. *Biodegradation* **21**(4), 615–624.

Liu, J., Yuan, X., Zeng, G., Shi, J. & Chen, S. 2006 Effect of biosurfactant on cellulase and xylanase production by *Trichoderma viride* in solid substrate fermentation. *Process Biochemistry* **41**, 2347–2351.

Liu, X.-L., Zeng, G.-M., Tang, L., Zhong, H., Wang, R.-Y., Fu, H.-Y., Liu, Z.-F., Huang, H.-L. & Zhang, J.-C. 2008 Effects of dirhamnolipid and SDS on enzyme production by *Phanerochaete chrysosporium* in submerged fermentation. *Process Biochemistry* **43**, 1300–1303.

Liu, Z.-F., Zeng, G.-M., Zhong, H., Yuan, X.-Z., Fu, H.-Y., Zhou, M.-F., Ma, X.-L., Li, H. & Li, J.-B. 2012 Effect of dirhamnolipid on the removal of phenol catalyzed by laccase in aqueous solution. *World Journal of Microbiology and Biotechnology* **28**, 175–181.

Liu, J., Zhu, N., Yang, J., Yang, Y., Wang, R., Liu, L. & Yuan, H. 2017 Lipopeptide produced from *Bacillus* sp. w112 improves the hydrolysis of lignocellulose by specifically reducing non-productive binding of cellulases with and without CBMs. *Biotechnology for Biofuels* **10**, 301.

Liu, S., Xu, X., Kang, Y., Xiao, Y. & Liu, H. 2020 Degradation and detoxification of azo dyes with recombinant ligninolytic enzymes from Aspergillus sp. with secretory overexpression in *Pichia pastoris*. *Royal Society Open Science* **7**(9), 200688.

Mohanty, S. S. & Kumar, A. 2021 Enhanced degradation of anthraquinone dyes by microbial monoculture and developed consortium through the production of specific enzymes. *Scientific Reports* **11**(1), DOI:10.1038/s41598-021-87227-6.

Mnif, I., Ayedi, Y., Ellouze-Chaabouni, S. & Ghribi, D. 2014 Treatment of diesel- and kerosene-contaminated water by *B. subtilis* SPB1 biosurfactant-producing strain. *Water Environment Research* **86**, 707–716.

Mnif, I., Mnif, S., Sahnoun, R., Maktouf, S., Ayedi, Y., Ellouze-Chaabouni, S. & Ghribi, D. 2015a Biodegradation of diesel oil by a novel microbial consortium: comparison between co-inoculation with biosurfactant-producing strain and exogenously added biosurfactants. *Environmental Science and Pollution Research* **22**, 14852–14861.

Mnif, I., Maktouf, S., Fendri, R., Kriaa, M., Ellouze, S. & Ghribi, D. 2015b Improvement of methyl orange dye biotreatment by a novel isolated strain, *Aeromonas veronii* GRI, by SPB1 biosurfactant addition. *Environmental Science and Pollution Research* **23**(2), 1742–1754.

Mnif, I., Fendri, R. & Ghribi, D. 2015c Malachite green bioremoval by a newly isolated strain *Citrobacter sedlakii* RI11; enhancement of the treatment by biosurfactant addition. *Water Science and Technology* **72**(8), 1283–1293.

Mnif, I., Grau-Campistany, A., Coronel-León, J., Hammami, I., Triki, M. A., Manresa, A. & Ghribi, D. 2016 Purification and identification of *Bacillus subtilis* SPB1 lipopeptide biosurfactant exhibiting antifungal activity against *Rhizoctonia bataticola* and *Rhizoctonia solani*. *Environmental Science and Pollution Research International* **23**, 6690–6699.

Mnif, I., Bouallegue, A., Bouassida, M. & Ghribi, D. 2021a Surface properties and heavy metals chelation of lipopeptides biosurfactants produced from date lour by *Bacillus subtilis* ZNI5: optimized production for application in bioremediation. *Bioprocess and Biosystems Engineering*. https://doi.org/10.1007/s00449-021-02635-2.

Mnif, I., Rajhi, H., Bouallegue, A., Trabelsi, N. & Ghribi, D. 2021b Characterization of lipopeptides biosurfactants produced by a newly isolated strain *Bacillus subtilis* ZNI5: potential environmental application. *Journal of Polymers and The Environment*. doi:10.1007/s10924-021-02361-6.

Mnif, I., Bouallegue, A., Mekki, S. & Ghribi, D. 2021c Valorization of date juice by the production of lipopeptide biosurfactants by a *Bacillus mojavensis* BI2 strain: bioprocess optimization by response surface methodology and study of surface activities. *Bioprocess and Biosystems Engineering*. https://doi.org/10.1007/s00449-021-02606-7.

Moosvi, S., Keharia, H. & Madamwar, D. 2005 Decolourization of textile dye Reactive Violet 5 by a newly isolated bacterial consortium RVM 11.1. *World Journal of Microbiology and Biotechnology* **21**, 667–672.

Mukerjee, P. & Mysels, K. J. 1971 *Critical Micelle Concentration of Aqueous Surfactant Systems*, Vol. 36. US Government Printing Office, Washington, DC.

Nair, L. K., Begum, M. & Ragunathan, R. 2017 Biodegradation of azo dyes using *Bacillus megaterium* and its phytotoxicity study. *Journal of Environmental Science, Toxicology and Food Technology* **11**(7), 12–20.

Ng, I.-S., Chen, T., Lin, R., Zhang, X., Ni, C. & Sun, D. 2014 Decolorization of textile azo dye and congo red by an isolated strain of the dissimilatory manganese-reducing bacterium *Shewanella xiamenensis* BC01. *Applied Microbiology and Biotechnology* **98**, 2297–2308.

Ngo, A. C. R. & Tischler, D. 2022 Microbial degradation of azo dyes: approaches and prospects for a hazard-free conversion by microorganisms. *International Journal of Environmental Research and Public Health* **19**(8), 4740.

Oliva-Taravilla, A., Carrasco, C., Jönsson, L. J. & Martín, C. 2020 Effects of biosurfactants on enzymatic saccharification and fermentation of pretreated softwood. *Molecules* **25**, 3559.

Öztürk, A., Bayol, E. & Abdullah, M. I. 2020 Characterization of the biosorption of fast black azo dye K salt by the bacterium *Rhodopseudomonas palustris* 51ATA strain. *Electronic Journal of Biotechnology* **46**, 22–29.

Pinheiro, L. R. S., Gradíssimo, D. G., Xavier, L. P. & Santos, A. V. 2022 Degradation of azo dyes: bacterial potential for bioremediation. *Sustainability* **14**, 1510.

Priyanka, J. V., Rajalakshmi, S., Kumar, P. S., Krishnaswamy, V. G., Al Farraj, D. A., Elshikh, M. S. & Abdel Gawwad, M. R. 2022 Bioremediation of soil contaminated with toxic mixed reactive azo dyes by co-cultured cells of *Enterobacter cloacae* and *Bacillus subtilis*. *Environmental Research* **204**, 112136.

Ruta, I. G. & Juozas, K. 2013 Effects of rhamnolipid 496 biosurfactant JBR and synthetic surfactant surfynol 465 on the peroxidase-catalyzed oxidation of 2-naphthol. *Journal of Environmental Science* **25**, 1431–1440.

Senthilkumar, S., Perumalsamy, M., Prabhu, H. J. & Thajudin, N. 2014 Optimization of process parameters for efficient decolorization of Congo red by novel fungus *Curvularia* sp. using Box–Behnken design. *Desalination and Water Treatment* **54**, 1708–1716.

Shah, M. P., Patel, K. A., Nair, S. S. & Darji, A. M. 2013 Optimization of environmental parameters on microbial degradation of reactive black dye. *Journal of Bioremediation and Biodegradation* **4**, 183.

Shao, B., Liu, Z., Zhong, H., Zeng, G., Liu, G., Yu, M., Liu, Y., Yang, X., Li, Z., Fang, Z., Zhang, J. & Hao, C. 2017 Effects of rhamnolipids on microorganism characteristics and applications in composting: a review. *Microbiological Research* **200**, 33–44.

Shi, Y., Yang, Z., Xing, L., Zhang, X., Li, X. & Zhang, D. 2021 Recent advances in the biodegradation of azo dyes. *World Journal of Microbiology and Biotechnology* **37**, 137.

Singh, A. & Singh, R. K. 2017 Effect of surfactants on lignin modifying enzyme activity of *Ganoderma* species KX879638 and *Lentinus* species KY006984 under solid state fermentation. *African Journal of Microbiology Research* **11**(41), 1520–1527.

Singh, G., Dwivedi, S. K. & Mishra, J. 2020 Role of fungal enzymes in the removal of azo dyes. *Microorganisms for Sustainability* **11**, 231–257.

Tehrani-Bagha, R. & Holmberg, K. 2013 Solubilization of hydrophobic dyes in surfactant solutions. *Ali Reza Tehrani-Bagha and Krister Holmberg: Materials* **6**, 580–608.

Telke, A. A., Joshi, S. M., Jadhav, S. U. & Shah, D. 2010 Decolorization and detoxification of congo red and textile industry effluent by an isolated bacterium *Pseudomonas* sp. SU-EBT. *Biodegradation* **21**, 283–296.

Thakur, J. K., Paul, S., Dureja, P., Annapurna, K., Padaria, J. C. & Gopal, M. 2014 Degradation of sulphonated azo dye Red HE7B by *Bacillus* sp. and elucidation of degradative pathways. *Current Microbiology* **69**(2), 183–191.

Vaidyanathan, S., Orr, B. G. & Banaszak Holl, M. M. 2014 Detergent induction of HEK 293a cell membrane permeability measured under quiescent and superfusion conditions using whole cell patch clamp. *The Journal of Physical Chemistry B* **118**, 2112–2123.

Vishani, D. B. & Shrivastav, A. 2022 Chapter 19 - enzymatic decolorization and degradation of azo dyes. In: Shah, M. P., Rodriguez-Couto, S. & Kapoor, R. T. (eds). *Development in Wastewater Treatment Research and Processes; Innovative Microbe-Based Applications for Removal of Chemicals and Metals in Wastewater Treatment Plants*. Elsevier, The Netherlands. pp. 419–432.

Wang, W., Wang, C., Zahoor Chen, X., Yu, Q., Wang, Z., Zhuang, X. & Yuan, Z. 2020 Effect of a nonionic surfactant on enzymatic hydrolysis of lignocellulose based on lignocellulosic features and enzyme adsorption. *ACS Omega* **5**(26), 15812–15820.

Yaofeng, W. 2009 Encapsulation of myoglobin in a cetyl trimethylammonium bromide micelle in vacuo: a simulation study. *Biochemistry* **48**, 1006–1015.

Ying, W., Xu, Y. & Zhang, J. 2021 Surfactants protect the activities of endoglucanase and cellobiohydrolase from gas-liquid interface. *Industrial Crops and Products* **171**, 113958.

Zenz Zeng, G.-M., Shi, J.-G., Yuan, X.-Z., Liu, J., Zhang, Z.-B., Huang, G.-H., Li, J.-B., Xi, B.-D. & Liu, H.-L. 2006 Effects of Tween 80 and rhamnolipid on the extracellular enzymes of *Penicillium simplicissimum* isolated from compost. *Enzyme and Microbial Technology* **39**, 1451–1456.

Zhang, Q., He, G., Wang, J., Cai, W. & Xu, Y. 2009 Mechanisms of the stimulatory effects of rhamnolipid biosurfactant on rice straw hydrolysis. *Applied Energy* **86**, 233–237.

Zhou, M.-F., Yuan, X.-Z., Zhong, H., Liu, Z.-F., Li, H., Jiang, L.-L. & Zeng, G.-M. 2011 Effect of biosurfactants on laccase production and phenol biodegradation in solid-state fermentation. *Applied Biochemistry and Biotechnology* **164**(1), 103–114.

Zuleta-Correa, A., Merino-Restrepo, A., Jiménez-Correa, S., Hormaza-Anaguano, A. & Cardona-Gallo, S. A. 2016 Use of white rot fungi in the degradation of an azo dye from the textile industry. *Dyna* **83**(198), 128–135.

First received 5 June 2022; accepted in revised form 25 October 2022. Available online 14 November 2022