Microbial remediation of triphenylmethane dyes contaminated wastewater: A review

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Abstract: Extensive dependence of textile and other industries on the synthetic dyes have made these chemicals a necessary evil nowadays. Among all classes of dyes, triphenylmethane dyes (TPMs) are most common and unfortunately most hazardous. The wastewater originated from various industries is usually found to contain a major portion of TPMs along-with other synthetic dyes, inorganic and organic contaminant which lead to serious environmental consequences. In this regard, microbial remediation of such synthetic chemicals seems to be a very robust, cost effective and environment friendly strategy. Microbial remediation exploits the enzymatic capabilities of microorganisms (bacteria, fungi or microalgae) to cope with recalcitrant synthetic dyes and other chemicals. The remediation of TPMs can occur either by the phenomenon of adsorption onto the microbial systems or through the degradation by the enzymatic or metabolic mechanisms of the microbe under optimized conditions. Both of the two ways convert the toxic chemicals to harmless and friendly products. Biodegradation or bioremediation of pollutants can be achieved through various living organisms such as plants and algae. But the current review only focuses on the remediation of TPMs by microbes such as bacteria, yeast and fungi. The factors such as pH, temperature, inoculum size, dye concentration etc. which have profound effect on optimization of degradation of TPMs, can never be neglected and hence they are discussed in detail in the present study. In this way we claim that the present article will provide deep insights into the current consequences of TPMs and related toxicants being added to our environment. Further, an emphasis on the implementation of bioremediation to get rid of such chemicals from our waters would be helpful to enhance the interest of researchers and scientists already working on the same theme.

Keywords: Biodegradation, wastewater, triphenylmethane, TPMs, Microorganism

1. Introduction

Since the beginning of the industrial riot in the 19th century, a great upheaval has been faced by our planet. Environmental pollution is a serious drawback of the industrial revolution and that has grown into a global problem and is maliciously affecting our air, our soil and our water ecosystems. The pollution of our environment is linked directly to human and environmental health. A tremendous increase in the global population combined with rapid economic development greatly contributed to the increased demands of production, consumption and mobility of synthetic chemicals. Currently, a countless number of different chemicals are available on the global market (Charuaud et al., 2018; Schröder et al., 2007).
Of all the chemicals, the synthetic dyes are becoming major pollutants of concern. It has been documented that about 20%, of dyes produced globally, is being discharged into the aquatic systems by the textile industries as a result of incomplete coloring of the required stuff (Mittal et al., 2009; Kant, 2012). Notably, the part of ecosystem that is most badly affected by the synthetic dyes is the “water” which serves as an ultimate sink for these chemicals and, therefore, this precious resource is very adversely being affected by the release of toxic dyes and other chemical pollutants into it converting it to “wastewater”. A number of different varieties of man-made dyes are being employed for innumerable industrial applications which contribute a significant part in building the wastewater.

Ultimately, the incessant use of synthetic dyes in domestic, industrial and agricultural sectors is leading to widespread contamination of environment and serious harm to non-target organisms and ecosystems (Carvalho, 2017; Klaine et al., 1988; Kimbrough et al., 2008; Olaniran et al., 2011). While in the environment, it is not necessary that all the dyes are degraded or destroyed. Most of them are converted to persistent and more toxic metabolites which can resist the biological and non-biological degradation (Singh et al., 2017; Chishiti et al., 2013). Moreover, most of the dyes and their metabolites have higher water solubility; hence they quickly leach to the water ecosystems causing detrimental effects on aquatic life (Zuccato et al., 2010; Bradford et al., 2018).

Due to being predominant tool of industrial applications, synthetic dyes have emerged as serious xenobiotic and an environmental contaminants which reach the soil and water bodies through the sewages of petroleum refineries, herbicide manufacturing, phenolic resin manufacturing, textile industries and petrochemicals companies (Pradeep et al., 2015; Mittal et al., 2009; Mota et al., 2021). The uncontrolled discharge of textile effluents into water bodies may cause a variety of acute and chronic health effects in humans and other life forms (Ajaz et al., 2020). Furthermore, the dyes present in the domestic or industrial waste/effluents pave the ways to several serious ecological concerns such as increase in the oxygen consumption followed by a scarcity of oxygen affecting the photosynthetic capacity of the ecosystem which consequently disturbs the food chain and food webs (Scarlett et al., 2015; Pinheiro et al., 2010; Jadhav et al., 2006).

Several reports describe the genotoxic and mutagenic effect of synthetic dyes and their metabolites which interfere with reproductive system of vertebrates and invertebrates (Punzi, 2015; Ventura-Camargo et al., 2016).

Synthetic dyes are of various types and grouped on the basis of differences in their chemical structure and mainly according to the types of chromophore group so that the industry employing a dye can get an idea of the reaction of the dye with the other compounds (Benkhaya et al., 2020; Berradi et al., 2019; Gordon et al., 1987). Grouping based on different chromophores of dyes include azodyes, anthraquinones, phthalocyanine, nitrated dyes, nitrosated dyes, diphenylmetane and triphenylmethane dyes (Singh, 2002). The current review aims to describe increasing havocs associated with the extensive use of TPMs in different industries.

2. TPMs – applications and consequences

Triphenylmethane dyes are aromatic xenobiotic compounds with molecular structures based upon the structure of the triphenylmethane hydrocarbons. They have weak resistance to light & bleaching chemicals and are extensively used in textile and non-textile industries such as copying papers, in printing inks and in leather industries (Thetford et al., 2013; Mani et al., 2018). The triphenylmethane dyes and their derivatives are amongst the primitive dyeing chemicals synthesized by the man, an applied method that was solely developed for the manufacture of fuchsin which is a best biological stain as well as a
good disinfectant (Wang et al., 2011; Berradi et al., 2019). Several other affiliates of TPMs were also discovered before the complete understanding of their chemical compositions. For example, Crystal violet, the most important member of TPMs, was introduced in late eighteenth century. The colors usually include reds, violets, blues, and greens.

Because of the extensive and wide range of applicability of TPMs, they have become a frequent component of the industrial effluents which can cause poisoning by skin absorption, inhalation and ingestion which can result in harmful health effects and lethality in living organisms. Frequent exposures to even minute concentrations of TPMs may cause dangerous physiological disorders, metal confusion and other related illnesses in human beings. Moreover, they also damage terrestrial and aquatic flora & fauna thus disturbing the whole ecosystem (Rathi et al., 2021; Yang et al., 2011; Chawla et al., 2014).

Owing to their consequences, TPMs dyes are considered as the priority and one of the most dangerous synthetic dyes. Malachite green was previously widely used in food industry as additive, as parasiticide, and as fungicide in food products (Roy et al., 2020). Unfortunately it has been reported to be very toxic due to its recalcitrant nature to biological degradation/remediation processes and, therefore, it was banned in many countries and Food and Drug Administration (FDA, USA) listed it a priority chemical carcinogenicity testing (Srivastava et al., 2004).

Acute exposure to TPMs causes carcinogenicity, mutagenicity and associated serious health problems in humans, animals and aquatic life (Maheshwari et al., 2021; Liu et al., 2021; Al Prol, 2019). A major and inevitable consequence of water contamination is the polluted agriculture sector. Much of the water we use for irrigation comes from ground water reservoirs, canals and through the rains. Therefore, the crops are exposed to wastewater which variety of toxic synthetic dye residues along-with various other kinds of toxicants which is becoming a leading cause of everyday increasing health issues of organisms and the ecosystem (Singh et al., 2021b; Przystaś et al., 2012). All these concerns imply that elimination of TPM dyes and other toxic pollutants along-with their metabolites from the aquatic ecosystem to alleviate their hazardous burden.

3. Bioremediation/decolourization of TPM dyes

In past, many conventional approaches including photo-degradation, chemical degradation, and incineration were applied for the elimination of toxic synthetic dyes and related toxic chemicals from the environment but most of these methods were found to be expensive, environmental un-friendly and inefficient for smaller concentrations. Therefore, biological remediation for the treatment of wastewaters seem to be the most feasible strategy for remediation of environmental contaminants (Sweety, 2018; Thengodkar et al., 2010).

Bioremediation is not a novel technology, nevertheless, is becoming priority remediation approach in recent decades because of being practical and safe. Further, it is becoming a robust and highly acceptable technology for remediating land and aquatic sites contaminated with various kinds of hazardous organic materials (Lefevre et al., 2016). Owing to extensive and continuous discharge of TPMs in the environment most microorganisms developed natural resistance to the toxic effects of these dyes and started utilizing them as the source of carbon and energy (Pandey et al., 2007; Khan et al., 2013; Lellis et al., 2019). The importance of the microorganisms in bioremediation of dyes and other pollutants of environmental concerns lies in their diversity; ubiquity and metabolic flexibility which make them use diverse ecological conditions. Many microorganisms may grow in diverse media because of their excellent capacity of adaptation and mutation. Furthermore, microorganisms have been found to possess tremendous potential to acquire capacities of xenobiotic degradation when exposed to these xenobiotic for long periods.
Microorganisms can survive in almost any kind of the environmental conditions if an appropriate source of energy and carbon is available (Hassan et al., 2020).

TPMs have been found very recalcitrant and difficult to be eliminated from the environment and therefore, to date, very few bacteria have been known to degrade such chemicals. Many researchers quoted the anaerobic or aerobic degradation of TPMs by bacteria (Zhang et al., 2012; Yatome et al., 2008; Ayed et al., 2010), fungi (Casas et al., 2009; Yang et al., 2011; Bumpus et al., 1988a) or microalgae (Abd Ellatif et al., 2021; Singh et al., 2021a). Moreover, plants have also been reported as potent degraders of the TPMs (Ayele et al., 2021). Ado et al., (2018) isolated and characterized extracellular laccase enzyme from Trametes fungus which was very much effective against several synthetic dyes including TPMs. Laccases from various fungal genera such as Agaricus, Myceliophthora, Trametes, Neurospora, Coriolus, Rhizonia, Aspergillus, Cerrena and Phlebia have been extensively documented to play a great role in decolorization or removal dyes from the wastewaters. Previously, Kwasniewska, (1985) demonstrated that oxidative red yeasts Rhodotorulae sp. and Rhodotorulae rubra had a high biodegradation potential against Crystal violet dye. In addition, Bumpus et al., (1988b) showed that TPMs undergo extensive biodegradation in ligninolytic cultures of Phanerochaete chrysosporium. The efforts continued and ability of wild mushrooms was also acknowledged to decolorize Crystal violet, Malachite green and bromophenol blue (Kang et al., 2014).

Just like fungal species/enzymes bacteria have also been extensively used for the treatment of TPMs contaminated wastewater, however, bacteria are found comparatively friendlier, easier to culture and more beneficial for human welfare purposes. Therefore, much attention has been paid towards bacterial degradation of TPMs such as crystal violet, malachite green, phenol red etc. which are routinely used in textile, paper and pulp industries (Ayed et al., 2009; Cheriaa et al., 2012; Mathur et al., 2012). A bacterial strain Castellaniella denitrificans SA13P was isolated from tank of tannery effluents treatment plants and was found very efficient in degrading malachite green which is one of the very toxic, carcinogenic and mutagenic member of TPMs (Chawla et al., 2014). More recently, Bacillus cereus and Stenotrophomonas maltophilia have been reported as excellent outfits for the degradation of TPMs in the wastewaters ((Wang et al., 2021; Alaya et al., 2021). Authors further quoted that the isolates could be used as potential tool for the bioremediation of contaminated wastewater. Bacteria with their diverse metabolic capabilities are offering a world of services for the benefit of mankind. A halo-thermotolerant bacterial strains Bacillus subtilis B2d and B. licheniformis B3e have been reported to be effective for enhanced degradation of TPMs such as crystal violet and malachite green (Jakhrani et al., 2021a). Bacterial degradation of TPMs is not a new sector and a number of researchers have already achieved the credit of exploiting the extensive metabolic capabilities of many different bacteria to cope with such toxic pollutants. For example Pseudomonas pseudomalle (Yatome et al., 2008), Bacillus subtiliss (Yatome et al., 1991; Mishra et al., 2018) and Nocardia corallina was reported to degrade Crystal violet (Yatome et al., 1993).

3.1 Factors affecting the biological degradation/bioremediation of TPMs

It is well known that nutrient and cultural conditions are the key factor in controlling the mechanisms involving the enzymatic reactions (Jabeen et al., 2015). The optimization of the growth conditions and the microbial media composition for the degradation of TPMs is one of the major factor involved in achieving the enhanced and robust remediation (Jasinska et al., 2015). TPMs degradation by the microorganisms has been documented to be regulated by various physic-chemical factors including temperature, pH, presence/absence/concentration of glucose of other co-metabolic substrates, structure of TPM derivative and media composition etc. (Myers et al., 2016; Jakhrani et al., 2021b).
As TPMs are very recalcitrant colorants brought into the environment, so they need optimization of different environmental parameters which affect their degradation. Chen et al., (2015b) provided a report showing the effect of fungal biomass, initial dye concentrations and oxygen requirements on the degradation of cotton blue, crystal violet, methyl violet and malachite green by a white rot fungus Coriolopsis sp. They further explained that the amount of biomass had a pronounced influence on the degradation of TPMs.

Increasing the biomass was proportional to increase in TPM degradation within a short duration provided the growth medium is not depleted. This concept is dependent on the initial concentration of the dyes and as well as on type and species of microbes used. As Saratale et al., (2006) demonstrated that 200 and 500 mg/L TPM dyes were efficiently decolourized by 10 g of Aspergillus ochraceus in a period of 24 h. While 50 mg/L of TPM was degraded by 0.5 g of Penicillium ochrochloron sufficiently (93%) in a period of 2.5 h (Shedbalkar et al., 2008).

Initial concentration of dye has a profound effect on the degradation of TPMs and it has been mostly reported that increasing the initial concentration of the dyes retards the biodegradation process. This may be due to the presence of toxic sulfonic acid groups on the aromatic rings of such chemical compounds (Khan et al., 2013). Increased concentration of dye means increased toxicity to the degrading microorganisms hence their growth is inhibited and so the degradation process is stunted (Zhang et al., 2012). Furthermore, (Parshetti et al., 2006) indicated that higher concentration of Malachite green was toxic to degrading culture of Kocuria rosea. Moreover, Malachite green and Crystal Violet have been reported to cause a prominent reduction in biomass of Dichomitus squalens even at smaller concentrations (Eichlerová et al., 2006). They further documented that this decrease in biomass directly deceased the removal of dyes from water.

The pH and the temperature are two of the main parameters which control the process of degradation or decolourization of TPMs. Because of their use in industrial processes, these dyes are structured in a way to resist the action of microbes. Therefore, the optimal pH for color removal by microbes usually ranges from 6.0 to 10 (Chen et al., 2015a; Chen et al., 2016). Temperature significantly affects the stability of the dye structure and the enzymatic activity of the microbes. Hence, it is also an important parameter involved in the remediation of wastewater. Many reports document the gradual increase in the rate of decolourization and degradation of TPM dyes (and other synthetic dyes) with the increase of temperature until an optimum temperature is reached (Saratale et al., 2006). At higher than optimal temperature, the biomass starts decreasing and so the degradation of the substrate (Garg et al., 2020; Saratale et al., 2009).

Another important factor is the media conditions and the time of addition of dye to the microbial culture. Li et al., (2014) documented that decolonization duration of crystal violet and methyl violet by Rhodococcus qingshengii were shorter in liquid media compared to that in the static medium. They further added that the time of addition of dye to the same microbial culture mattered significantly. When they added dyes 24 h after the growth of culture, they found efficient removal of the dyes. Similar observations have been quoted by (Kalme et al., 2007; Kalyani et al., 2009).

Biological degradation or decolourization of dyes/chemicals is the result of enzymatic activities of the microbes which are very sensitive to fluctuations in the environmental parameters and physiology of the degrading organism. Therefore, while demonstrating the microbial potential of bioremediation, the intrinsic and extrinsic factors must be considered at priority to get maximum level of success.
4. Future Recommendations

The current review can serve as a useful source to enhance the mindfulness on present research on bioremediation of TPMs and related chemicals. However, this research sector still has potential discrepancies which must be met to successfully cope with such environmental contaminants. Few recommendations are as follow:

1. The microbes are no doubt, good degraders of the low concentrations of TPMs and related chemicals but increased concentrations of such toxicants show the adverse effects on microbial cells and lead to destruction of the biomass and hence these tiny creatures would not support the further detoxification of the environment. In this regard, it is better to collaborate with phytoremediation technologies. Therefore, the so called “microbe assisted phytoremediation” can be an excellent option for the enhanced bioremediation toxic chemicals from the environments.

2. Further research is required to fish out the mechanisms of degradation of such chemicals through microbes so that the genomics and metabolomics approaches can be applied to enhance the microbial potential for the toxicity elimination.

3. More research and insights into the enzymatic actions involved in microbial remediation of pollutants is required to get clear understanding of microbial remediation mechanisms.

4. Pathways of degradation of each member of the different classes of TPMs must be elaborated so as to get the knowledge of fate of these toxic entities in the environment.

5. Although, the research is still going on the microbial genes involved in the TPM degradation, but this aspect is of utmost importance and should be elaborated effectively and on priority so as to understand the microbial potential for a specific pollutant and flexibility of microbial genome to be exploited for genetic engineering approaches.

5 Conclusion

Indiscriminate and extensive use of triphenylmethane dyes has created many unavoidable and serious health concerns of human and other life forms. In recent years, a little attention is given towards the removal of dyes from the water resources which are aggravating the aquatic ecosystem and consequently the whole food chain is contaminated. Hence the researchers have been very successful in isolating various capable microorganisms which could degrade the TPM dyes. However, a little more attention towards the dye elimination from water would result in a better cleaned and green environment. As whole life of the planet is directly or indirectly associated with the water. If the water resources are remediated, associated food chains and food webs will be free of contamination and hence the health of living beings will be improved. In this regard, this review can play a vital role for the future studies to simulate the interest of researchers in the field of TPMs remediation and can pace a great step towards the development of a green environment.

References


