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Review Article

LIGNINOLYTIC PEROXIDASES: SOURCES AND APPLICATIONS

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ABSTRACT

Ligninolytic extracellular enzymes including lignin peroxidase and manganese peroxidase have high redox potential and many biotechnological applications. The prospective applications of lignin peroxidase and manganese peroxidase span through a lot of sectors like textile industry, paper and pulp industry, dermatology, biorefinery and bioremediation. They have wide range of applications due to their versatility in degradation of phenolic and non-phenolic compounds. Over the years, ligninolytic extracellular enzymes have been studied but still research on these peroxidases seems to be lagging behind as compared to other peroxidases. Thereby, a documentation of sources and applications of lignin peroxidases and manganese peroxidases has been given in this review.

Keywords: Lignin, Peroxidases, White Rot Fungi, Delignifiers.

1. INTRODUCTION

Most of the plants including woody and non-woody comprises of lignocellulose as their main component in their cell wall. Over the years the utilization of this lignocellulosic biomass for the production of value added products has been increased, due to their abundance and renewable nature. There are many different categories of lignocellulosic material which includes waste biomass, energy crops which are generated from industrial practices which in turn generate agricultural wastes, wood waste and pulp waste. These wastes, either generated by industrial or agricultural practices, pose a great threat to the environment due to their poor and improper waste management. Due to this reason, environment is at a very high risk due to the threat caused by them. By keeping all these points in mind, we require such a technique that can use these wastes to produce industrially important products. So, either these ligninolytic wastes can be exploited for the production of value added products or microbial activities on this waste can generate industrially important enzymes, organic acids, ethanol, polysaccharides, vitamins etc [1]. Major focus is on the production of enzymes due to their wide range of industrial and biotechnological applications. In other words we can say that industrially important enzymes are in great need. But the cost of production of these important enzymes is very high. So, there is a need to use an alternative cheaper technique for their production. In the search of cheaper technique, there is a cost reduction strategy which can be applied to the production of the enzyme and that strategy is to produce these enzymes on the lignocellulosic material which includes waste biomass. There are several advantages of using this waste biomass as they are always available, abundantly present and are renewable in nature. By using this strategy, two main problems can be tackled. Firstly, the lignocellulosic waste biomass can be exploited, which otherwise was causing pollution, and secondly cost of enzyme production can be reduced to a greater extent as it requires waste biomass as substrate. Consequently, large variety of lignocellulosic waste has been employed for the production of enzymes e.g. rice straw and wheat straw have been used for the production of lignin peroxidase and manganese peroxidase [2, 3].

Lignin provides hydrolytic stability and rigidity to plant's cell walls. Also, lignin traps and provides unavailable monosaccharides, disaccharides, oligosaccharides and polysaccharides necessary for fermentation. Lignin is very important for the plant's survival and its difficulty to degradation is due to its (1) cross linkages with polysaccharides via ester and ether linkages and (2) molecular architecture, in which there is a complicated 3-D network having ether and C-C bonds produced by various non-phenolic phenyl propanoid units [4].

To remove the lignin recalcitrance to degradation, there are several pretreatment technologies which have been

developed to distort the cross linkages which will provide polysaccharides (cellulose and hemicelluloses) easily accessible for enzymatic hydrolysis [5]. Some of these pretreatment methods include ammonia fiber explosion, acid and alkaline hydrolysis, ozonolysis, steam explosion and oxidative delignification [6]. These methods are being used for quite a long time but there are several disadvantages also. These methods (1) are quite expensive, (2) requires high energy inputs, (3) generate compounds that may be inhibitory to fermentation, (4) releases toxic chemicals which ultimately lead to corrosion problems which further lead to material loss [6]. Therefore, there is a need of such a method which can overcome these disadvantages. So, biological method of degradation of lignin may be used as an alternative method [7]. In biological method, we make use of microorganisms or microbial enzymes. This method is comparatively cheaper and environmental-friendly. However, as any other method, it also has some limitations. Main demerit of this method is that it may result in lower product yield [8].

Wood rotting organisms have been extensively studied for lignin degradation. Much of the literature has established that white rot fungi are the best delignifiers, majorly because of their ability to produce extracellular oxidative enzymes which lead to lignin degradation. As a result of degradation of lignocellulosic biomass, many potent and industrially important extracellular enzymes are produced. The lignocellulosic extracellular oxidative enzymes include heme peroxidases which are lignin peroxidases, manganese peroxidases and versatile peroxidases. Other than these, there are some other accessory enzymes whose function is to generate hydrogen peroxide which is further required by peroxidases. These accessory enzymes include aryl oxidase and glucose oxidase [9]. These enzymes have high redox potential and ability to degrade phenolic and non-phenolic compounds. Due to these properties, they can be employed in biopulping, bioremediation, biorefinery and textile industry [10]. Therefore, due to their broad range of applications, interest in these ligninases for biotechnological purpose continues. Thereby, this review presents the sources and the applications of lignin peroxidase and manganese peroxidase.

2. PEROXIDASES

Peroxidases are oxidoreductase in nature. They carry out both oxidation and reduction. It catalyzes the reduction of peroxides, like hydrogen peroxide and the oxidation of both organic and inorganic compounds [11]. Particularly, peroxidase acts as an electron donor which further binds to other substrates and breaks them into harmless components. Peroxidase catalyzes the following reaction:

$$\text{Substrate} + H_2O_2 + 2e^- \longrightarrow \text{Oxidised Substrate} + H_2O$$

Peroxidases are widely present in nature. They are vastly produced by animals, plants and micro organisms like bacteria, fungi. It consists of heme and non-heme peroxidases. The difference between these two groups is the presence of prosthetic group (protoporphyrin IX heme) which is present in heme peroxidases and absent in non-heme peroxidases [12]. Further classification of peroxidases is presented in Fig. 1.

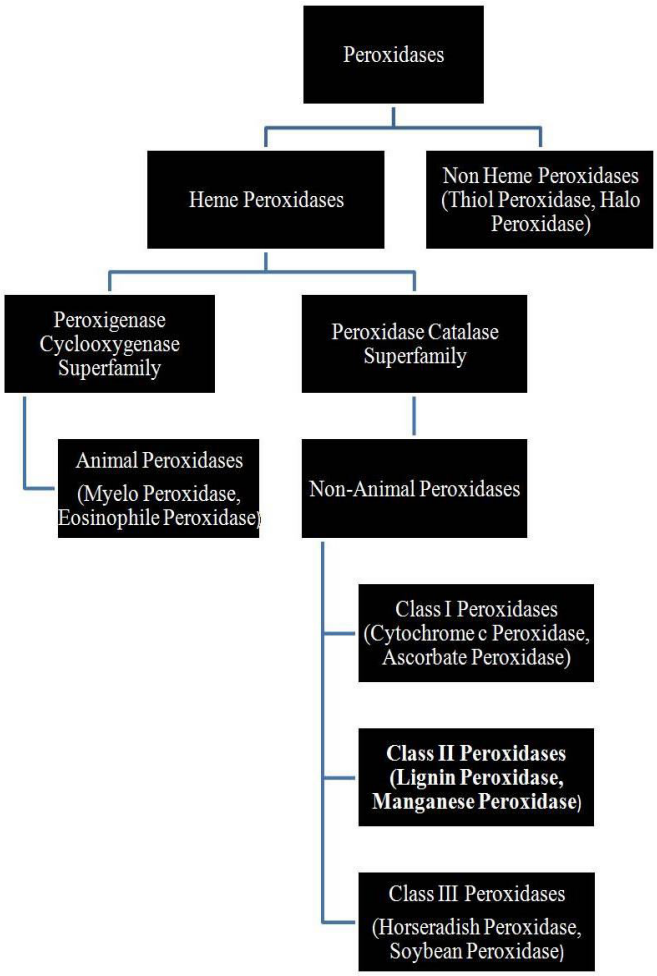

Fig. 1: Classification of peroxidases

Out of all these enzymes presented in Fig.1, lignin peroxidase and manganese peroxidase are of great importance. These peroxidase acts on different components. Lignin peroxidase acts on non-phenolic components which constitutes about 90% of lignin [13]. Lignin peroxidase can also acts on phenolic components

[14]. Manganese peroxidase acts on phenolic component of lignin. Manganese peroxidase can also acts on non phenolic components with the help of mediators [15]. The focus of this review is on lignin peroxidase and manganese peroxidase due to their mode of action and their wide range of emerging applications.

2.1. Lignin peroxidase

Lignin peroxidase belongs to the family of oxidoreductase, which acts on a peroxide as acceptor (peroxidases). It employs one cofactor, heme. It was first discovered in fungus *Phanerochaete chrysosporium* [16]. Lignin peroxidase plays an important role in lignin biodegradation using hydrogen peroxide. Lignin peroxidase is an extracellular heme protein, dependent of hydrogen peroxide, with high redox potential and low optimum pH [17-20]. Lignin peroxidase forms a globular structure of size about 50 × 40 × 40 Å [19]. The lignin peroxidase motif contains eight major and minor helices, and three β sheets [21]. The catalytic cycle of lignin peroxidase is comparable to that of heme peroxidases. However, there are some structural differences between lignin peroxidase and other heme peroxidases. The molecular weight range, isoelectric point range of lignin peroxidase has been reported as 38 kDa to 43 kDa and 3.3 to 4.7 respectively [22]. Lignin peroxidase is capable of oxidizing a variety of reducing substrates including polymeric substrates [23]. Due to their high redox potentials and their enlarged substrate range lignin peroxidase have great potential for application in various industrial processes [20]. Lignin peroxidase shows little substrate specificity, reacting with a wide variety of lignin model compounds and even unrelated molecules [24]. It is able to oxidize methoxylated aromatic rings without a free phenolic group, which further generates cation radicals that can react by a variety of pathways, which includes ring opening, demethylation and phenol dimerisation [18]. The catalytic cycle of lignin peroxidase involves three steps (Fig. 2).

1. The first reaction step is the oxidation of the resting ferric enzyme [Fe (III)] by hydrogen peroxide (H_2O_2) as an electron acceptor resulting in the formation of compound I oxo-ferryl intermediate.
2. In the second step, the oxo-ferryl intermediate is reduced by a molecule of substrate such as non-phenolic aromatic substrate which donates one electron to compound I to form the second intermediate, compound II (deficient of one electron).
3. In the third step, there is subsequent donation of a second electron to compound II by the reduced substrate, there by returning lignin peroxidase to the resting ferric oxidation state which indicates the completion of the oxidation cycle [15].

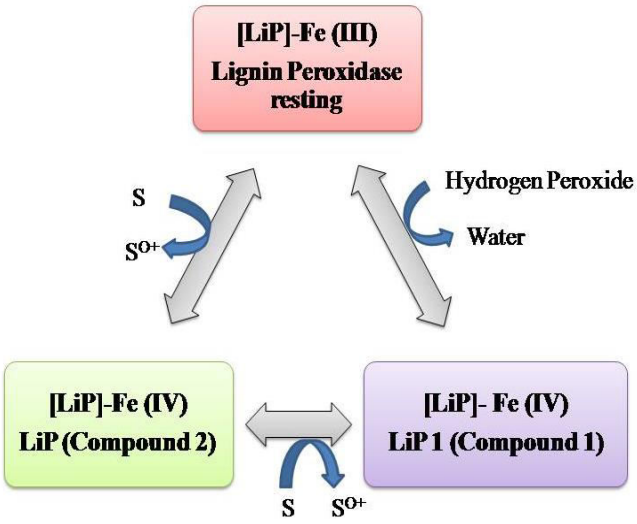

Fig. 2: Catalytic reaction of lignin peroxidase

2.1.1. Sources of lignin peroxidase

Lignin peroxidase is mainly involved in the lignin biodegradation. Lignin degradation is caused by fungi as well as several bacterial species (Table 1). Fungi are more efficient in the breakdown of lignin than bacteria because in bacteria, process of delignification is slower and more limited [25]. Among the microbes, degradation of lignin has been intensively studied in fungi especially white rot fungi, but there are also reports of bacteria that can break down lignin (Table 1). There are three classes of lignin-degrading bacteria which are: Actinomycetes, α-Proteobacteria and γ -Proteobacteria [7]. These microbes are widely distributed in natural ecosystems worldwide and occur both in terrestrial and aquatic habitats. Their branching growth, production of aerial or substrate mycelia and morphogenetic development resembles to that of filamentous fungi. Due to their potential of production of secondary metabolites and extracellular enzymes, these bacterial species are the decomposers of lignocelluloses in soils [26- 28]. Several bacterial species have been identified as lignin degraders like *Acinetobacter* sp. [29], *Streptomyces* sp. [30], *Klebsiella pneumonia*, *Pseudomonas putida*, *Ochrobacterium tritici* [31]. All these findings suggest that bacterial degradation of lignin is important than previously thought. But bacteria are not

the only source, fungi particularly white rot fungi is the main decomposer of lignin [32]. The number of fungal species which are lignin biodegraders lignin is not known exactly; but Gilbertson reported that there are approximately 1600 to 1700 species of wood-degrading fungi [33]. Wood-degrading fungi mostly live as saprotrophs on wood in the natural and human-affected ecosystems. It has also been shown that some coprophilic fungi (e.g. *Panaeolus papilionaceus*, *Coprinopsis friesii*) produce ligninolytic enzymes such as peroxidases [34]. Wood-rotting fungi are primary lignin degraders and are capable of mineralization of lignocellulosic material, which is the abundant plant product which accounts for 25% of organic matter, in the biosphere [7]. The saprophytic fungi are of three types: (i) white rot fungi (ii) brown rot fungi and (iii) soft rot fungi. These groups can be further categorised into (iv) litter-decomposing and (v) coprophilic fungi that also degrades lignin [35]. All these fungi are able of decomposing lignin, but only white rot has the ability to degrade it completely into carbon dioxide and water [35]. Polyporales and Agaricales represent white rot fungi. Among brown rot fungi, *Gloeophyllum trabeum* has been studied the most [35]. In nature, white rot fungi occur more often on hardwood of angiosperms whereas brown rot fungi more often attack softwoods and are usually found in coniferous ecosystems [25]. Some of the fungi producing lignin peroxidases are *P. Chyrosporium* [36], *T. versicolor* [37], *P. radiata* [38], *Panus* sp. [39]. Major sources of lignin peroxidase have been summarized in Table 1.

Table 1: Sources of lignin peroxidases

Bacterial Sources	Reference
Acinetobacter calcoaceticus	29
Thermobifida fusca	40
Nocardia autotrophica	41
Microbacterium sp, *Brucella melitensis*, *Ochrobactrum* sp,	42
Streptomyces coelicolor, Arthrobacter globiformis, Rhodococcus jostii RHA1, Pseudomonas putida mt-2	43
Streptomyces viridosporus T7A	30
Bacillus megaterium	44
Serratia sp. JHT01, *Serratia liquefacien* PT01, *Pseudomonas chlororaphis* PT02, *Stenotrophomonas maltophilia* PT03 and *Mesorhizobium* sp. PT04	45
Pandoraea spp.	46
Klebsiella pneumoniae, Pseudomonas putida ,*Ochrobactrum tritici*	31
Rhodococcus josti	47
Fungal Sources	
P. chrysosporium	36
Polyporus ostreiformis	48
T. versicolor	37
Trametes hirsute, Stereum gausapatum	49
P. coccineus, P. sanguineus and *Perenniporia medulla-panis*	39
Phlebia radiata	38]
D. confragosa, F. fomentarius and *Trametes gibbosa*	50
Bjerkandera adusta	51
Pycnosporus spp.	52
Nigrospora sp., *Curvularia lunata*	53
Pleurotus ostreatus	54
Penicillium spp.	55
Ganoderma lucidium	56
Aspergillus terreus	57
Cunninghamella elegans	58

2.1.2. Applications of lignin peroxidase

Generally, peroxidases have been applied in soil detoxification [59], biopulping and biobleaching [25, 60-63], development of biosensors to determine the presence of hydrogen peroxide and other related compounds [64] and in the development of skin-lightening cream [65]. Some of these applications are yet to be commercialized. Biopulping, an alternative to

chemical pulping, is one of the oldest applications of peroxidases [66]. Recently, the applications of lignin peroxidase have extended to the development of dermatological products such as skin lightening agents. Most remarkable of these products are Melanozyme™ (lignin peroxidase based product) which is marketed as "elure™, a skin brightening cream" and Luminase for the treatment of hyperpigmentation which are caused by sun spots or age spots and skin brightening. Lignin peroxidase used in the development of these skin-lightening products has been derived from *P. chrysosporium*. Some of their applications are delignification of feedstock for ethanol production [67]. Ethanol is a good alternative to fossil fuel and the use of lignocellulosic biomass is the cheap source of feedstock for production of ethanol. Delignification is an important step in the bioconversion of lignocellulose to ethanol. Biological method of delignification is a promising strategy due to its higher product yield and low energy demand. Another application of lignin peroxidase is the coal depolymerization and degradation of xenobiotics [68]. Some of the xenobiotics are active components of pesticides, herbicides, dyes which are commonly found in industries. Thereby, accumulation of these harmful chemicals in the soil, water, and air contaminates the environment. Therefore, effective removal of these environmental pollutants is very important to take care of the environment as well as of the public health. So, to tackle this problem, we can make use of extracellular peroxidases, from ligninolytic microbes, which are known to play an important role in the degradation of xenobiotic compounds [69]. Lignin peroxidases from both fungi and bacteria, has been reported to mineralize different types of recalcitrant compounds. Lignin peroxidases also have prospects in drug discovery. Lignin peroxidase also helps in silver nanoparticles syntheses [70] which are antibacterial in nature [71, 72]. As we already know that lignin peroxidase acts as melanin degrader thereby acting as skin brightening agent. So, this property of lignin peroxidase can be used in conjuction with silver nanoparticles to make a drug that may act against melanin and hence decreasing the microbial load. Apart from these, there are several other applications of lignin peroxidases which have been summarized in Table 2.

Table 2: Applications of lignin peroxidase

Industry	Applications	References
Food Industry	Production of natural aromatic flavours	73
	Production of vanillin	74, 75
	Production of flavor compound	76
Pulp and Paper industry	Bleaching of high quality paper pulps	25
	Biobleaching of chemical pulp	60
	Decolorizing Kraft pulp mill effluents	61-63
	Paper pulp delignification	77
Textile industry	Decolorizing synthetic dyes	78-82
	Degradation of textile dyes	83
	Bioremediation of textile wastewater	84
	Decolorization of azo, triphenyl methane, heterocyclic, and polymeric dyes	85
	Textile effluent treatment and dye decolorization	82
Bioremediation	Polycyclic aromatic hydrocarbon (PAH) degradation	86
	Mineralization of recalcitrant aromatic compounds	87
Cosmetic industry	Skin lightening agent	65
Other applications	Commercial development of biosensors for polymeric phenol or lignin	88
	Delignification of feedstock for ethanol production	82
	Coal depolymerization	82
	Decolorization of synthetic melanin	89, 90
	Decolorization of human hair melanin	91
	Cytotoxicity reduction property	92
	Degradation of carbamazepine and diclofenac	93

2.2. Manganese peroxidase

Manganese peroxidase (MnP) belongs to oxidoreductases, those acting on peroxide as acceptor. It employs one cofactor, heme. It requires calcium ions for their activity. Manganese peroxidase was discovered in 1985 in fungus *Phanerochaete chyrososporium* [94]. Major function of manganese peroxidase is the biodegradation of lignin. For this, basidiomycetes secretes manganese peroxidase. Manganese peroxidase secretes manganese ions which further oxidizes phenolic compounds in lignin to form radicals [96].

Manganese peroxidase has same tertiary structure as that of lignin peroxidase as they both are class II peroxidases, but it contains disulfide bridges like that of class II peroxidases. MnP contains 11-12 α-helices, number of helices depends upon the species it is produced in. Stablization of MnP is achieved by 10 cysteine amino acid residues which form disulfide bonds. The active site contains a heme cofactor which is bound by two Ca^{2+} ions, one above and one below the heme. There are 357 amino acid residues in the manganese peroxidase of *P. chrysosoporium* [95].

There is a series of irreversible redox reactions in the catalysis of manganese peroxidase which follows a ping-pong mechanism and second order kinetics [95]. The catalytic cycle of manganese peroxidase is almost same as that of other peroxidase. In contrast to other peroxidase, it uses manganese ions (Mn) as electron donor (Fig. 3).

1. In the first step, H_2O_2 (Hydrogen peroxide) enters the active site of manganese peroxidase. The oxygen in H_2O_2 binds to an Fe (III) ion to form an iron peroxide complex [96]
2. In the second step, there is a breaking of oxygen-peroxide bond to form H_2O and a Fe(IV) oxo-porphyrin radical complex which leads to the transfer of two electrons from Fe^{3+} to peroxide. This oxidized intermediate complex is known as MnP Compound I [96]
3. In the third step, MnP Compound I then binds to a Mn(II) ion and forms Mn(III) and MnP Compound II. MnP II oxidizes another Mn(II) ion to Mn(III) and this Mn(III) is reduced by the reaction of H+ ions and the oxygen (iron bound). This reforms the Fe(III) ion in the heme and releases a second water molecule [96].

Most manganese peroxidases follow this classic catalytic cycle but still there are also other deviations from this traditional catalytic cycle. MnP Compound I can oxidize free Mn(II) and other aromatic compounds [97].

The main function of Mn^{3+} ions produced here is the oxidation and degradation of lignin [99]. For this, basidiomycetes secrete manganese peroxidase, not Mn^{3+}. This manganese peroxidase enzyme then goes outside the fungal cell and forms Mn^{3+} ions. These ions then oxidize phenolic components in the lignin directly. This oxidation leads to the formation of some radicals, which in turn oxidizes with lignin in the presence of oxygen to form water [100]. Formation of different radicals, in the presence of different substrates, by manganese peroxidase is given in Fig. 4 [96].

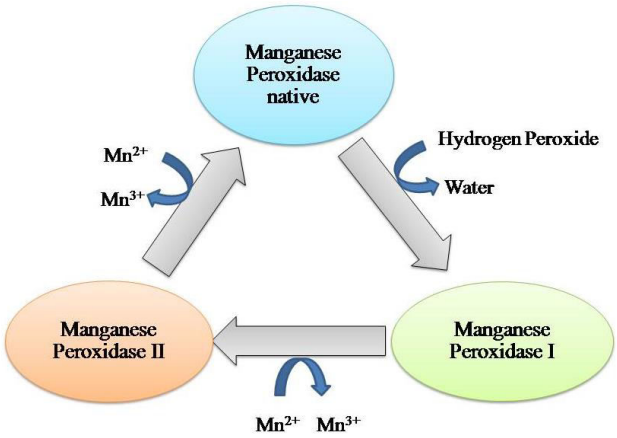

Fig. 3: Catalytic cycle of manganese peroxidase

2.2.1. Sources of manganese peroxidase

Manganese peroxidase is naturally found in fungi especially white rot fungi *P. chrysosporium*, *T. versicolor*, *Irpex* sp. and many other species [101]. Apart from white rot fungi, production of manganese peroxidase has also been reported from filamentous fungi like *Aspergillus* [57], *Fusarium* [102]. White rot fungi is the main source of manganese peroxidase. *C. subvermispora* has been greatly studied for its lignin degrading system as it produces high level of manganese peroxidase and is the most promising candidate for biopulping [103]. *Pleurotus erygnii* also secretes high level of manganese peroxidase [104]. During the treatment of kraft pulp with *T. versicolor* mangenese peroxidase was the main ligninolytic enzyme [105]. *P. radiata* manganese peroxidase isoforms had a molecular mass of 50 kDa [106]. Manganese peroxidase from *N. frowardii* forms only one manganese peroxidase isozyme with a molecular mass of 54 kDa [107]. Some bacterial species has also been reported to produce this enzyme. Some of the bacterial sources are *K. pneumonia, S. enteric, E.*

aerogenes, E. cloaceae etc [108]. By all these examples, we can say that there are many white rot fungi which are capable of producing a high level of manganese peroxidase which can be further used for industrial applications. There are also some of the bacterial species which are capable of producing it. Hence, we can say that there are some known sources of manganese peroxidase; still many of the sources are unknown. There is a need to explore those sources which have not been explored yet. Some of the sources of manganese peroxidase have been summarized in table 3.

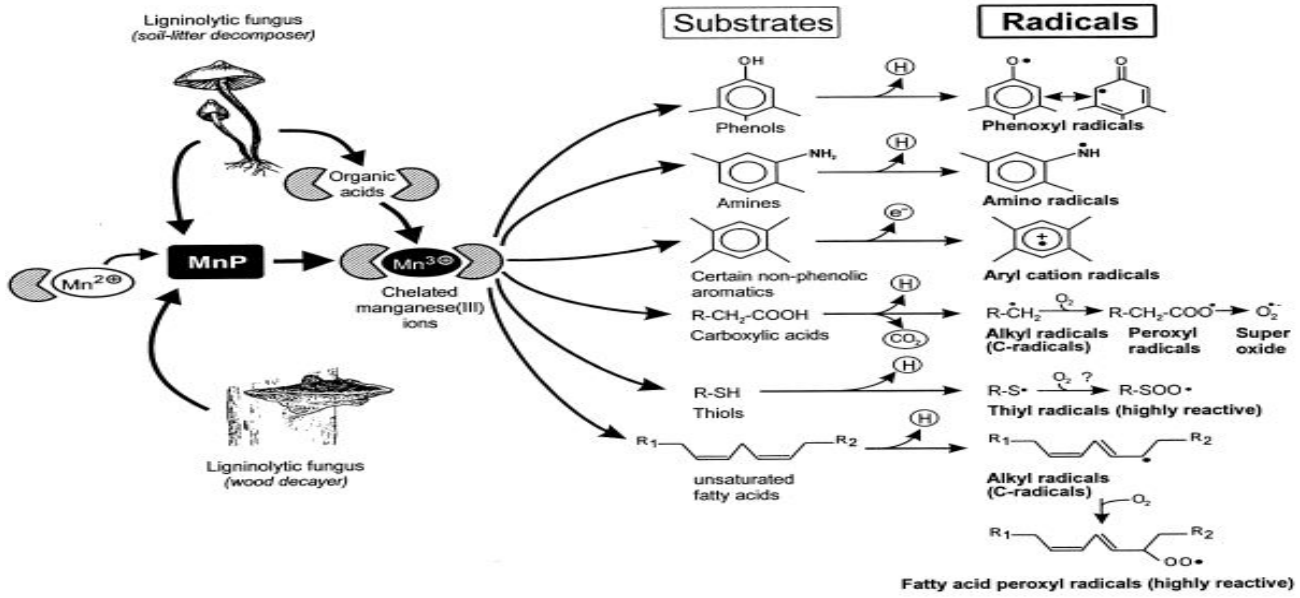

Fig. 4: Production of different radicals by manganese peroxidase [96]

Table 3: Sources of manganese peroxidase

Bacterial Sources	References
Klebsiella pneumonia, *Salmonella enteric*, *Enterobacter aerogenes*, *Enterobacter cloaceae*	108
Acinetobacter baumanii	109
Bacillus pumilus and *Paenibacillus* sp.	110
Bacillus subtilis	111
Raoultella ornithinolytica, *Ensifer adhaerens*	112
Fungal Sources	
Fusarium spp.	102
Nematoloma frowardii	107
Bjerkandera spp.	113
Abortiporus biennis	106
Agaricus bisporus	114
Stropharia rugosoannulata	115
Pleurotus spp.	116-120
Physisporinus vitreus	121
Panaeolus sphinctrinus	34
Auricularia	122
Ceriporiopsis subvermispora	123
C. subvermispora, P. chrysosporium, T. versicolor, D. squalens, Stereum ostrea, I. lacteus.	101,56
Aspergillus terreus	57
Pleurotus ostreatus	54
Ganoderma spp.	124
Cerrena spp.	125
Sparassis latifolia	126
Trametes villosa, Merulius sp., *Kuehneromyces mutabils, Heterobasidion annosum, Hypholoma fasciculare, Dichomitus squalens, Cyathus stercoreus*	127, 96

2.2.2. Applications of manganese peroxidase

Manganese peroxidase (MnP) is an iron-containing enzyme that oxidizes Mn^{2+} to Mn^{3+}, which can then directly oxidize a variety of organic substrates including various dyes, lignin, and phenolic compounds [61]. Manganese peroxidase is a relatively very interesting and useful enzyme. In nature, the fungus that contains this enzyme is responsible for decomposing dead trees and other organic matter. The mechanism of action of MnP is that it adds oxygen to its bonds and breaks the lignin. In similar way, fungi eat the sugars which are found in dead trees. Oxidation and degradation of lignin is the major task of Mn(III) ions produced by MnP. For this purpose, white rot fungi secrete MnP and this enzyme functions outside of the fungal cell. Then there is production of Mn(III) ions from MnP. Function of these Mn(III) ions is the oxidation of phenolic compounds in lignin. Mn(III) ions also oxidizes unsaturated fatty acids and some organic sulfur compounds [96]. This oxidation forms radicals, which in the presence of oxygen, can oxidize lignin. Manganese ion can degrade lignin by catalyzing alkyl-aryl cleavages and α-carbon oxidation in phenols. Manganese peroxidase is a less studied peroxidase as compared to lignin peroxidase, still there are many reports suggesting wide applications of this enzyme. It can be used in dye decolorization and dye degradation [128-130]. It can also decolorize textile dye containing effluents [61-63]. Apart from this, there is a chemical named Diuron, which is a commercial herbicide. But high exposure to diuron shows toxicity to mammals. It causes depression of mammal's central nervous system. Manganese peroxidase has been reported to degrade this herbicide [131]. Manganese peroxidase produced by the white rot *Bjerkandera adusta* was used for polymerization of acrylamide [132]. The decomposition of polyacrylamide was completed at 520°C, this suggests that polyacrylamide can be used as a thermoplastic resin.

Potential applications for MnP include dye decolorization, bioremediation, biomechanical pulping, pulp bleaching. Apart from these applications, MnP can also b used in biorefineries to produce high value chemicals from residual lignin and in pulp and paper side-streams [63,107, 133]. Due to the slow growth and low productivity of native enzyme producers, applications of MnP are limited and there is lack of an efficient recombinant production process [96]. Some of the applications of manganese peroxidase have been summarized in Table 4.

Table 4: Applications of manganese peroxidase

Industry	Applications	References
Food Industry	Production of natural aromatic flavours	73
	Production of vanillin	74,75
	Production of flavor compounds	76
Pulp and paper industry	Decolorizing Kraft pulp mill effluents	61-63
	Improvement in pulp properties	133,134
Textile industry	Decolorization and degradation of synthetic dyes	128, 130.135
Bioremediation	Degradation of DDT, TNT, PAH, styrene.	80, 136-139
	Degradation of nitroaromatic compounds	140
	Degradation of melanoidine	141
	Degradation of arsenic containing warfare agents	142
	Degradation of organo pollutants	96
Other applications	Polymerization of acrylamide	132
	Development of biosensors based on DET, effective biofuel cells, and selective bioorganic synthesis	143

3. CONCLUSION

This review summarizes the available, recent and important reports on the mode of action, properties, available sources and important industrial applications of lignin peroxidase and manganese peroxidase. These peroxidases have been reported to be produced by a variety of microorganisms like bacteria, fungi. Among different microbes, only white rot fungi have the natural ability to decay lignin so they are the potent producer of these peroxidases. In view of the articulated sources and prospective applications of both peroxidases, the exploration of the underexplored microbial diversity for

novel peroxidases with enhanced capabilities is required. Besides, there is a need of peroxidases which can work at wide range of pH and temperature so they can have better catalytic activity. This could be achieved by screening indigenous strains or by protein engineering. In addition, limited large scale industrial applications of these peroxidases are due to the lack of large scale production of highly active enzymes. This limitation can be overcome by high-yield production of recombinant peroxidases, with increased activity and stability which would be advantageous in terms of cost-effectiveness. Last but not the least, deeper understanding of these peroxidases will facilitate the development of novel applications.

Conflict of Interest

The authors declare they have no competing interests.

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