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LACCASE: A ROBUST ENZYME FOR BIOTECHNOLOGICAL ADVANCEMENT

***[1]Shehu Aisha Abbas, [2]Afiya Hamisu, [3]Fatima Farouk Umar and [3]Zainab Muhammad Mahmud**

[1]Department of Biological Science, Aminu Kano College of Islamic and Legal Studies
[2]Department of Biological Science, Northwest University, Kano
[3]Department of Biological Science, Yusuf Maitama Sule Federal University of Education, Kano

*Corresponding authors' email: asa99939@gmail.com Phone: +2348038880568

ABSTRACT

Laccase, a highly adaptable and resilient enzyme, has become a crucial component in various biotechnological applications due to its remarkable catalytic capabilities and ability to interact with a wide range of substrates. This enzyme's versatility has led to its utilization in numerous processes, including the cleanup of pollutants through bioremediation, the production of biofuels, food processing, and innovative biomedical applications. A comprehensive examination of laccase reveals its unique molecular properties, diverse sources, and classification, as well as its significant roles in different industries. Furthermore, recent advancements and potential future directions in laccase research highlight its vast potential to propel sustainable biotechnological innovations. By harnessing the power of laccase, researchers and industries can develop more efficient and environmentally friendly solutions. As a vital enzyme in modern biotechnology, laccase is poised to transform various fields and contribute to a more sustainable future. Its potential applications are vast, and continued research and development are expected to unlock new opportunities for this enzyme. With its impressive capabilities and broad range of applications, laccase is an enzyme that holds significant promise for driving positive change in various industries and shaping a greener future.

Keywords: Laccase, Biotechnology, Biocatalysis, Sustainable technology, Organic synthesis

INTRODUCTION

Laccase enzymes, classified under the family of enzymes known as multi-copper oxidases, are versatile biocatalysts found in various organisms, including fungi, bacteria, insects and plants (Adamian *et al.,* 2021). These enzymes have received considerable interest because of their varied roles in nature, extending from lignin degradation to pigment formation and detoxification processes (Kyomuhimbo and Brink, 2023). Laccases catalyze the oxidation of a vast array of substrates through the reduction of oxygen molecules to water, utilizing copper ions as cofactors in the process. The potential to act on both aromatic and non-aromatic compounds under mild conditions makes them particularly valuable for industrial applications (Kyomuhimbo and Brink, 2023). Indeed, laccases have found utility in biofuel production, textile dye removal, and wastewater treatment, among other fields (Surwase *et al.,* 2016).

Laccase (EC 1.10.3:2), found in a range of species, from fungi to higher plants and bacteria, is a multi-copper enzyme enabling the oxygen reduction to water, without the intermediate formation of hydrogen peroxide. It also oxidizes an electron donor. Its broad applicability and utilization of oxygen make it valuable in biotechnology (Kyomuhimbo & Brink, 2023).

Laccase, an enzyme found in various organisms, was initially discovered in Japanese lacquer tree, *Rhusvernicifera*. It is commonly present in nature, spanning across a wide array of organisms including angiosperms, arthropods, microbial species, certain insects and notably in fungi. In specific plants, laccases are predominantly observed in cabbage, turnips, potatoes, pears, apples and various vegetables (Singh & Gupta, 2020). Laccase are abundant and serve various biological functions such as breaking down lignin, contributing to pathogenicity, detoxification processes, cellular morphogenesis, and spore generation. They were categorized as blue oxidases under the enzyme commission classification scheme, also known as oxidative enzymes. Laccases catalyze the oxidation of a diverse array of substrates, including phenolic and non-phenolic compounds, aromatic amines, diphenols, and aliphatic amines, depending solely on molecular oxygen for electron acceptance (Surwase *et al.*, 2016).

The laccase catalytic reaction takes place at room temperature, utilizing molecular oxygen as a secondary substrate, which is reduced through a mechanism involving a four-electron mediator. It operates without the need for cofactors, and the only by-product produced is water (Kyomuhimbo & Brink, 2023). Because of their increased stability and impressive ability to work with a wide variety of substrates, they are highly valuable biocatalysts for numerous biotechnological uses (Bilal et al., 2019). Due to being extracellular in nature, laccases can withstand high concentrations of pollutants in the substrate (Bebik *et al.*, 2020).

The subset of laccases known as blue laccases usually need the occurrence of small molecules called mediators to oxidize substances that are typically targeted by laccases. These mediators can be either natural or synthetic, including complex biopolymers like lignin (Kudanga and Le Rose-Hills, 2014). The capacity to generate laccase through cost-effective and straightforward means renders it highly sought after in a range of industrial and ecological settings, encompassing chemical synthesis, the breakdown of hazardous organic substances, immunoassays and biosensors (Areskogh & Henriksson, 2011). This review aims to encapsulate and present the foremost biotechnological uses of laccases, focusing on their emerging and prominent uses as a flexible biocatalyst.

Molecular Properties of Laccase Enzyme

Laccase functions as a multi-copper enzyme, with its molecular structure consisting of three domains enclosing four copper atoms. These copper atoms are typically categorized into three types, comprising the catalytically active domains of the enzyme: type 1 and type 2 each possess a single copper atom, while type 3 contains two copper atoms

(Sidy & Kumar, 2017). The type 1 copper (T1) is a single copper ion located within domain 3, where it binds to histidine, cysteine, and often methionine residues. Type 2 and type 3 coppers (T2 and T3) form a trinuclear copper cluster positioned at the junction of domains 1 and 3, with coordination to histidine. A tripeptide of histidine-cysteine-histidine links T1 to T2/T3, while a disulfide bond between cysteine residues connects domains 1 and 2, as well as domains 1 and 3. Additionally, an extensive loop connects domain 2 and 3, contributing to the stability of the structure (Ba *et al.,* 2013).

The process of converting substrates by laccase begins within the T1 domain, electrons from the reducing substrate are harvested and relayed one by one to the T2/T3 cluster through the His-Cys-His ligand. At the T2/T3 site, the stored electrons facilitate the oxygen reduction to form water (Baldrian, 2006).

Sources of Laccase

Fungal Laccases

Bertrand was the first to identify a fungal laccase, noting its role in causing color alteration in mushrooms from the *Boletus* genus upon exposure to air. Since then, several fungi have been identified as major producers of laccase, with white rot fungi being exceptionally notable in this regard (Arregui *et al.,* 2019).

Fungal laccases play roles in multiple applications including sporulation, pigment synthesis, formation of fruiting bodies, defense against stress, plant disease development, and degradation of lignin (Acalde, 2007).

Bacterial Laccases

The initial detection of laccase activity in bacteria occurred in 1993 with *Azospirillum lipoferum*, extracted from the rhizosphere region of rice (Arregui *et al.*, 2019).

Over time, laccases have been progressively identified in various bacterial genera including *Bacillus, Streptomyces, Klebsiella, Pseudomonas*, *Yersinia, Proteobacterium, Marinomonas,* and others (Singh, 2011). In their natural environment, bacterial laccases participate in pigment formation, morphological changes, detoxification of toxins, and defense mechanisms against oxidative stress and UV radiation (Singh, 2011). The bacterial laccase exhibits remarkable stability across diverse environmental conditions, demonstrating both thermostability and resistance to fluctuations in pH levels (Jeyabalan *et al.*, 2023).

Plant Laccases

The initial laccase identified and documented from plants originated from the Japanese lacquer tree *Toxicodendron vernicif-luum* (Rhusvernicifera) (Yoshida, 1883). Plant laccases exhibit molecular structures and reaction mechanisms that are similar to those of fungal laccases (Arregui *et al.,* 2019). Plant laccases have been linked to the biosynthesis and polymerization processes of lignin (Tobimatsu and Schuetz, 2019), growth extension and the reaction to stress (Arrengui *et al.,* 2019). However, there have been no documented instances of industrial application to date (Wang, 2015).

Insect Laccases

Insect laccases are noted for their significant involvement in cuticle hardening and coloration, alongside various functions including wound recovery and the development and upkeep of the immune system (Du *et al.*, 2017).

Classes of Laccase

Three classes are commonly recognized for laccases: Low $E^{o'}$ laccases (<+460mV), which are usually found in plants and bacteria, and have a 4^{th} ligating Met residue at the T1 copper site; medium $E^{o'}$ laccases (from 460 to 710mV), which are usually detected in ascomycetes and other lignin-degradation fungi that share similar eco physiological niches, and a non-linking Leu residue found at the T1 copper site; and high $E^{o'}$ laccases (>+710mV), which are usually reported in white-rot basidiomycetes, and have a non-linking Phe residue at this site (Arregui *et al.,* 2019).

Properties of Laccase

Monomeric, dimeric, and tetrameric glycoproteins make up the majority of laccases. Copper-holding ability, thermal durability, vulnerability against proteolytic breakdown, and secretion are all significantly influenced by glycosylation. After being purified, laccase enzymes show a great deal of variability. The composition of the growing medium affects the glycoprotein's glycosylation content and composition (Shraddha *et al.,* 2011).

Roles of Laccase

Biodegradation

Lignin, a complex polymer in plant cell wall, is notoriously difficult to break down due to its complex structure. Laccase enzymes, along with other ligninolytic enzymes like peroxidases, play a crucial role in decomposing lignin into simpler compounds. This break down process is essential for carbon and nutrient cycling in ecosystems, as it allows microorganisms to access the nutrients trapped within lignin (Giardina *et al.*, 2010)

Detoxification

Laccases possess the capacity to oxidize a large variety of pollutants and xenobiotics, transforming them into less harmful or more biodegradable compounds. This detoxification process is valuable in environments contaminated with industrial pollutants, pesticides, and other harmful compounds (Camarero *et al.,* 2007).

Synthesis

Some fungi and bacteria utilize laccase enzymes to synthesize melanin, a pigment found in animals, plants and microorganisms. Melanin serves various functions, including protection against UV radiation, regulating temperature, and acting as a defense mechanism against pathogens and predators (Singh *et al.*, 2011).

Mediation of biochemical reactions

Laccase enzymes catalyze the oxidation of diverse substrates by decreasing molecular oxygen levels to form water. This wide-ranging substrate tolerance makes laccases versatile biocatalysts in various biotechnological applications. For example, they are employed in biofuel production to break down lignocellulosic biomass, in bioremediation to degrade environmental pollutants, and in the food industry for processes like wine stabilization (Shleeva *et al.*, 2019).

Bio catalysis in organic synthesis

Laccases are increasingly utilized in organic synthesis reactions because of their power to catalyze a range of transformations with minimal severity. This biocatalytic approach offers advantage compared to conventional chemical synthesis methods, featuring enhanced selectivity, gentler reaction parameters, and minimized ecological impacts (Salvachua *et al.*, 2019).

Applications of Laccase

Because of their versatility and ability to employ oxygen gas as an electron acceptor molecule, laccases have garnered interest as biocatalysts in a variety of biotechnological applications (Kyomuhimbo & Brink, 2023). In the biotechnology sector, laccase has many potential uses, such as environmental effluent detoxification, wine and fruit juice stain prevention, oxidation reactions involving synthetic dyes and their compounds, biological cleanup, and lignin removal of natural bleaching processes for cellulose materials. In addition to being used in pharmaceutical research for medical diagnosis, laccase is also applied in cosmetics to lessen the negative effects of certain drugs, such as anticancer drugs, and in the elimination of certain toxic plant metabolites, such as insecticides, vegetation control agents, and other reactive materials from the soil (Singh & Gupta, 2020).

Food

Laccase is used in the food business because it promotes both similar and dissimilar unit polymer synthesis processes. They can be applied in fruit processing, baking, wine and beer fining stabilization, food sensory parameter improvement, and sugar beet pectin gelation. Wine's flavor, color, and gustatory experiences are all influenced by the high concentration of phenolic chemicals they contain. Therefore, laccase can extract polyphenols selectively to prevent any unintended changes to the wine's gustatory and olfactory qualities (Osma *et al.*, 2010).

Additionally, *T.versicolor* laccase was trapped in coconut fibres (CF) and glutaraldehyde-activated. Using the laccase-glutaraldehyde-CF matrix, apple juice's original color was enhanced by 61%, and 29% of its turbidity was eliminated (Mate & Alcalde, 2016). Liquid waste from olive oil mills, which contains a large percentage of extremely poisonous phenols, has also been treated extensively with laccase (Jeyabalan *et al.,* 2023).

In a study on food allergies, Lv *et al.* (2019) employed propyl gallate as a mediator to crosslink *Paralichthysolivaceus* parvalbumin using laccase from *Coriolus versicolor.* Indirect ELISA analysis and Western blotting demonstrated that parvalbumin's IgG binding capacity had decreased, which was consistent with structural alterations. Parvalbumin was more resistant to gastrointestinal digestion following laccase treatment, as demonstrated by in vitro digestion.

In another study, in order to create stabilized emulsions, α-lactalbumin (α LA) was crosslinked using a commercially available laccase derived from *Aspergillus sp.* and ultrasound. The α- LA has strong foaming and emulsifying qualities, but weak gelation activity. The operational, molecular and viscoelastic characteristics of the α-LA emulsified gel were significantly impacted by the combined use of ultrasound pretreatment and laccase crosslinking (Qayum *et. al.*, 2021)

Papermaking and pulp processing

In the biopolpation process, laccases have the capacity to break down lignin and remove lignin from wood fibres, kraft pulp fibres, and chlorine-free. When laccases are combined with mediators, pulp can be delignified more readily. The non-phenolic compounds remaining after oxygen delignification can be oxidized using mediators, and the mediator molecule in its oxidized state then oxidizes lignin subunits that will not otherwise be laccase substrates (Dana *et al.*, 2017). Furthermore, pitch and dyes can be eliminated through the use of laccase-mediated processes on wood products (Dana *et al.,* 2017). Laccases are useful for binding paperboard and fiber particles (Pannu and Kapoor, 2014). Large amounts of brightly colored black liquid, containing poisonous chlorinated derivatives of lignin degradation such as chlorophenols and chloro aliphatics, are produced by pulp and paper mills. The highly alkaline effluents from paper mills change the pH level of the surrounding soil and water bodies when they are realized (Dana *et al.*, 2017).

Weldesenbet *et al*. (2013) has described bio-bleaching Kraft pulp with laccase, xylanase, and/or mannanase. The kappa number decreased by 32.6% when mannanase was utilized in conjunction with a laccase mediator system, and by 40% when the triple enzyme was used.

Textile industry

Due to its ability to degrade the dyes commonly used in textiles, laccase is seen to be a viable solution to the problem of textile effluent (Pannu and Kapoor, 2014). Additionally, cellulose and laccase are utilized in stone washing to limit harm to the outside fibres while shielding the inner ones (Montazer and Maryan, 2008). In order to produce a brighter shade and to lessen blot after stone washing, it can also be used to decolorize dyed fabrics (Maryan and Montazer, 2009). Malachite Green (MG), a triphenylmethane dye used in aquaculture to manage protozoan and fungal illness in farmed fish, can be decolored using laccase. The food, pharmaceutical, and textile sectors also employ MG (Dana *et al.*, 2017).

To explore the underlying mechanisms of decolorization when using fungal system, Rodriguez *et al*. (1999) used sixteen distinct strains of white rot fungus to assess the decolorization of twenty-three industrial colors. Even though aryl alcohol oxidase, manganese peroxidase, and laccase biochemical activities were observed in untreated extracts from solid-state cultures, only the laccase activity was found to be connected to the colour removal. After that, two *Trameteshispida* different laccase isoenzymes were observed, and their capacity to degrade dye was assessed. Of the 23 industrial dyes examined, 11 could be decolored *in vitro* by the refined enzymes. It was frequently discovered that fungal species with higher laccase concentrations were more effective at removing dye when compared to other fungal systems.

Pharmaceuticals

Pharma-tech businesses use laccase, a biomolecule with specificity, to synthesize complex medical substances like antibiotics, sedatives, anesthetics, and anti-inflammatories (Maestre-Reyna *et al.*, 2015). According to research conducted by Sacher *et al.* (2008), three widespread pharmaceutical pollutants found in wastewater, namely carbamazephine, diclofenac, and sulfamethoxazole, were investigated for their ability to be broken down by Tvlcc5 laccase. The results indicated that while carbamazephine remained largely unaffected, sulfamethoxazole and diclofenac showed significant effects, breaking down by 51.1% and 46.8%, respectively. When the laccase mediator ABTS was added, Tvlcc5's effectiveness was much enhanced. Within an hour of incubation, sulfamethoxazole and diclofenac underwent complete degradation. Nevertheless, carbamazephine was unaffected.

Cosmetics

Laccase-based skin-lightening cosmetics have been produced recently; these cosmetics might be safer and milder than existing hair dyes. Deodorants, tooth gel, mouth rinse, detergent, soap, and diapers with lower irritation potential007A can all be made utilizing protein-engineered laccase (Pannu and Kapoor, 2014).

Jeon *et al.* (2010), produced stable colors by hetero- and homopolymerizing natural phenolic monomers using a laccase. i.e., components of hair coloring products.

Bioremediation

The biodegradation of toxic waste and bioremediation of contaminated soil are two processes that employ microorganisms that produce laccases (Acalde *et al.*, 2006). Bacterial laccase, which is pH and thermostable, is extremely stable in a variety of environmental settings. Therefore, despite its low redox potential, bacterial laccase is the best option for sustainable remediation in natural environments (Jeyabalan *et al.,* 2023). Through the oxidative enzymatic coupling of pollutants, laccases have also been shown to be helpful in the elimination of hazardous chemicals, resulting in the formation of insoluble complex structures. It was also noted that phenols, in particular, and other persistent environmental contaminants were degrading (Kunamneni *et al.*, 2007).

Industrial effluent from diverse sources such as the transformation of coal, the processing of petroleum, the manufacturing of organic compounds and the creation of olive oil, containing phenolic compounds (Aggelis *et al.,* 2003). It was discovered that immobilized laccase was effective in eliminating phenolic and chlorinated phenolic contaminants (Ehlers and Rose, 2005). Laccase are being investigated by biotechnologists as one of the most eco-friendly instruments for the transformation of phenol-based and non-phenol-based chemicals and green remediation of environmental hazards because of their ability to depolymerize and break down lignin (Kameshwar & Qin, 2017).

In a study, Nadarogla *et al.* (2019), employed magnetic chitosan nanoparticles with covalently immobilized laccase enzyme to decolorize a variety of manufactured dyes. The results of the study shown that even after ten rounds of reusability, the immobilized laccase has the potential to maintain roughly 47% of its relative activity. For the azo dyes Evans Blue, Direct Blue 15 (DB15), RB15, and Acid Red 37 (AR37), it demonstrated a greater removal capacity.

In another study, the elimination of tetracycline hydrochloride and ciprofloxacin hydrochloride was achieved by using immobilized laccase on carbon nanospheres with hollow mesoporous structure. It was noted that the immobilized enzyme's removal rate for tetracycline hydrochloride only decreased following five cycles of experimentation, suggesting its enhanced durability (Shoa *et al*., 2019).

Waste treatment

By oxidatively transforming hydroxylated intermediates containing heterocycles and polycyclic aromatic hydrocarbons, cleaving aromatic rings, or directly chlorinating chemicals, laccase can convert poisonous, resistant substances into less harmful, more degradable derivatives (De Salas & Camarero, 2021). Laccase can be used to detoxify wastewater from the food, fabric, dye, and publishing sector that are high in phenols and aromatic amines (Madhavi & Lele, 2009).

For example, when a mixture of enzymes derived from fungi with laccase was added to biomass obtained from wineries (along with an ultrasonic pretreatment), the amount of time needed for fungal degradation was reduced, and chemicals with economic value, like gallic acid, lactate, and glycolic acid, were created (De Salas & Camarero 2021).

Organic synthesis

Many problems plague the organic synthesis of molecules, such as reagent toxicity, laborious multi-step reactions, and expensive chemical costs. Laccases have been suggested to be useful in synthetic chemistry for the synthesis of complex polymers and pharmaceuticals, and they could prove to be highly beneficial in this regard (Sahay, 2021).

It was discovered in 2005 that fungal laccase (EC 1.10.3.2) from *Myceliophthera thermophila* and extracellular laccase C from *Trametes sp.* (EC 1.10.3.2) catalyzed the formation of aminoquinones. In sodium salt of acetic acid, buffer pH 5 (laccase enzyme derived from *T. spec*) or citrate-phosphate, buffer pH 7 (laccase enzyme derived from M. thermophila), only four diaminobenzoquinones were synthesized utilizing a molar ratio of up to 5:1 of first-order amine to hydroquinones without the use of a co-solvent. The production of mono-aminobenzoquinones and combination of the latter and diaminobenzoquinone was encouraged by this approach. Starting from primary aromatic amines, alkylated hydroquinones, or *p*-dihydroxylated benzoic acid derivatives, both mono-and deaminated quinones can be produced with high efficiency (Wellington, 2011).

Biosensor

Laccase is widely used for the electrocatalytic reduction of oxygen and has been utilized in the construction of biosensors for phenolic substrates. In contrast to peroxidase biosensors, laccase biosensors oxidize phenolic substrates without the need for hydrogen peroxide. Tyrosinase-based biosensors have issues with limited enzyme longevity and substantial enzyme activity suppressed by reaction products. As a result, laccase is a strong alternative that could be used in biosensors to detect phenolic chemicals (Gupta *et al.*, 2003).

The use of nano composites in biosensors is a rapidly growing area of study. For the purpose of determining catechol, Chen *et al.* (2006) created a novel composite material consisting of laccase and gold nanoparticles (AuNPs), cross-linked zein ultrafine fibres (CzuFs) using zein, a naturally occurring biodegradable protein polymer. The findings indicated that direct electron transfer (DET) was responsible for the biosensor's excellent detection sensitivity.

In another study, a bi-enzyme horseradish peroxidase/laccase method was employed by Tang *et al.* (2017) to quickly and accurately determine the density of *E.coli.* Because the amount of polyphenolic chemicals produced by the *E.coli* metabolism of salicylic acid (SA) depends on the density of the bacteria, the biosensor was used to detect *E.coli* density by enzymatic oxidation of polyphenols using laccase/HRP.

Nanobiotechnology

The creation and/or manipulation of nanoparticles for a variety of industries is one area in which the prospective laboratory uses of laccases expand into nanotechnology. Recently, it was revealed that lignin may be oxidized enzymatically to create nanosized colloidal particles for a variety of uses. Similarly, hybrid nanoflowers incorporating laccase as a nano biocatalyst for color degradation could be created. For instance, the adsorption of laccase on carbon nanotubes resolved the technical issues with the application of laccase for the rate of xenobiotic removal, leading to increased enzyme performance as well as high-thermal-stability and psychlophilic stability (Zerva *et al.*, 2019).

Li *et al.* (2017) used carbon nanotubes, laccase, graphite oxide, copper phosphate, and a simple one-pot method in mild circumstances to create the 3D hybrid nanoflower-like structural assembly. The hybrid nanoflowers that were created showed enhanced laccase activity and a very high enzyme loading. When copper phosphate was present, laccase hybrid nanoflowers showed higher Km and Kcat values than free laccase, indicating better electron transfer rate between

laccase enzyme and CNT molecules. Efficiently, the crystal violet and neutral red dyes were destroyed by laccase hybrid nanoflowers.

Disinfection

When using laccase-iodide (LIS) instead of straight iodine for disinfection, there are number of benefits. When handling, storing, and transporting iodine salt, it is safer than iodine itself. To control the liberation of iodine from the solution container, the amount of laccase in LIS can be readily changed. Pools, drinking water, and other surfaces can be sanitize using LIS. Minor wounds can also be disinfected with it (Sondhi *et al.*, 2023).

Limitations and Challenges

It still needs to be accomplished to produce laccases in an effective large quantity for industrial use. Several industrial and scientific initiatives over the years have focused on the efficient and economical manufacturing of laccase. Regarding productivity and yield, there are numerous issues with laccase production in their natural hosts. Slow growth rate and poor productivities are detrimental to the manufacture of enzymes in submerged continuous culture, particularly for high Eo laccases, which are often obtained from basidiomycetes. There are other technical challenges that prevent the creation of these enzymes, like the rheological changes in the culture brought on by the fungal growth, and the extraction and laccase purification from the cultural broth is an expensive and time-consuming process (Zerva, 2019). Low stability, low productivity, and restricted reusability are the main issues preventing laccase from being produced and used industrially (Adamian *et al.*, 2021).

Numerous attempts have been made to address these problems. For instance, careful culture media optimization can significantly impact the amount of laccases produced by white-rotting fungi. Schneider *et al.* (2018) adjusted the medium's carbon and nitrogen sources in detail using a rotatable central composite experimental design technique in order to maximize laccase production from *Marasmiellus Palmivorus.*

Non-native gene expression of bacterial laccases in eukaryotic hosts can also enhance laccase synthesis. After process optimization, the mutant protein expression *Bacillus licheniformis* Ls04 laccase created by site-directed mutagenesis produced a final titer of 347 uL, 2.1 times higher activity in P-pastoris (Wang *et al.,* 2017). The expense of redox mediators and insufficient enzyme stocks are the main barriers to the commercial use of laccases. It is anticipated that laccases will be competitive with other methods like elemental chlorine-free (ECF) and completely chlorine-free (TCF) bleaching because to the significant progress achieved in recent years towards solving these issues.

CONCLUSION

Heralded as a powerful enzyme for biotechnological progress, laccase is at the front of sustainable innovation. Its many uses include a wide range of industries, including biomedical engineering and environmental cleanup. Laccase promises to transform industries by providing eco-friendly solutions as we further explore its catalytic potential, advancing our progress towards a more sustainable and environmentally friendly future. Undoubtedly, realizing laccase's full potential will lead to revolutionary breakthroughs and a world full of biotechnological marvels via ongoing research and development.

In conclusion, laccase is revealed to be more than just an enzyme, rather, it is a ray of hope for the pursuit of sustainable development. Its eco-friendliness, stability, and adaptability make it a fundamental component of biotechnological innovation. Laccase presents a promising way to satisfy the needs of an expanding population, handle environmental issues, and push the boundaries of science and technology as we traverse the difficulties of the modern world. Laccase has the potential to trigger a paradigm shift towards a more harmonious human-environment relationships with concerted efforts towards research, collaboration, and implementation. This could pave the way for a future in which biotechnological advancements are synonymous with sustainability and prosperity for all.

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