Research Article

Laccase- Incorporated Nanoparticles: Advances in Nanobiocatalyst Design and Multidisciplinary Applications

O S Nimmi[1*], Shilpa H[1], Padmapriya Venkatesan[2], D. Roselin Jenifer[3], Gowtham G[4], Yamini Priya.V[2], Sowmiya G[2], Ruban P[1]

[1]Department of Biotechnology, Nehru Arts and science College, Thirumalayampalayam, Coimbatore, Tamil Nadu 641105, India
[2]Department of Microbiology and Biotechnology, Faculty of Arts and Science, Bharath Institute of Higher Education and Research, 173, Agaram Main Road, Selaiyur, Tambaram, Chennai - 600073, Tamil Nadu.
[3]Department of Biotechnology, Sathyabama Institute of Science and Technology, Chennai- 600119, Tamil Nadu.
[4]Department of Biotechnology, Faculty of Arts, Science, commerce and management, Karpagam Academy of Higher Education, Coimbatore 641 021
Email: *O S Nimmi – nimmiosm@gmail.com

Abstract

Laccase is a flexible multicopper oxidase which has been studied for use in a variety of sectors including environmental, industrial, food, medical and biotechnology. Although, there is rapid development in studying the practical uses of laccase, issues surrounding poor reusability, stability, and a short lifespan still exist. The entrapment of laccase in nanoparticles has been proven to be a viable method to increase the effectiveness of laccase and its enzymes. The laccase nanoparticles exploit the adjustable chemistry, high surface area and great electrical characteristics of laccase. A host of advanced biocatalysts have proven their potential in a number of industries including food, medical diagnostics, medicine, medical, pharmaceuticals, bioenergy, intelligent food packaging, bioelectronics, biosensors, and waste water treatment. The enhancement of electron transfer, controlled immobilization of enzymes, and simplified recovery of laccase bound to metallic, polymeric, magnet, and carbon nanoparticles, sustains the green technology goals.

Keywords: Laccase, Nanoparticles, Green chemistry, Nano biocatalyst, Biosensors, Enzyme immobilization.

Introduction

Multi copper oxidases, peroxidases, and oxidases can be found in nearly every industry including pharmaceuticals, food, textiles, paper, and even in environmental biotechnology (Bilal et al, 2019). With increases in demand for safe and sustainable processing, laccases are becoming increasingly commercially valuable as oxidative enzymes. Laccases are referred to as brown oxidases, as a subclass of oxidases, and also as an enzyme with a specific type of electrochemical reaction of oxidation; laccases oxidize a substrate, and in the process, lose an electron and, via a 4 electron (4-eu) pathway, reduce and make water (Singh et al, 2018). This behavior explains how laccases and certain phenolic and aromatic amine xenobiotics, laccases and some other oxidases can operate with no by-products, which in laccases, is explaining the most fundamental principle of green chemistry (Bilal et al, 2019). In the textile industry, laccases are used for the decolorization of dyes. They also serve a variety of purposes including the treatment of waste water, the synthesis of organics, the creation of biofuels, the sensing of bios, and the utilization of biomass of lignocellulosic materials (Marlina et al, 2021).

Yoshida was the first person to describe the presence of laccases when researching phenolic compounds from the Japanese lacquer tree (Rhus vernicifera) in the year 1883. There is no shortage of scientific descriptions of laccases and their functions within the study of fungal communities. In particular, laccases produced by white-rot fungi are instrumental in the degradation of lignin (Baldrian, 2006; Couto, S. R.; Herrera, 2006). Evolving laccases and organism classification seem to differ in some bacterial and higher plant and certain insect groups (Janusz et al, 2017). While laccases are produced by the fungi of the basidiomycetes, the basidiomycete fungi have been the subjects of most of the laccase investigations, particularly due to their distinctive redox and substrate versatility (Mate et al, 2015). There is a growing understanding as a result of the fusion of contemporary molecular and protein engineering and genomics of laccases and their possible commercial applications (Pollegioni et al, 2016; Ruiz-Dueñas, F. J.; Martínez, 2020).

Unbound laccases do come with disadvantages that make them combustable: operational stability is low and they are not reusable. Free laccases run lnc efficiently with extreme pH, temperature, and organic solvents (Bilal et al, 2017; Lima et al, 2016). Despite operational stability and entrapment improving through the use of nanotechnology, numerous questions remain. Laccases are solid catalysts. Moreover, nanomaterials enhance not only the engineered surface area and chemistry for mass and chemical transfer but

also for operational stability, catalytic potency, and the reuse of solid laccase catalysts (Su et al, 2021). Among the most sophisticated catalytic solid laccase systems are those with various biocompatible nanostructures and laccase, including metallic and metal oxide nanoparticles, carbon and carbon-based magnetic nanoparticles, polymer and magnetic nanoparticles, hybrid nanocomposites, and laccase with biocompatible nanostructures (Bilal et al, 2021; Zhao et al, 2020; Gao et al, 2023). Bridging laccases with nanotechnology and engineering/biochemistry minimizes the numerous biocatalytic systems' challenges at the systemic level.

BIOCHEMICAL PROPERTIES OF LACCASE

Laccase has possible applications in different industries and biotechnologies based on its biochemical properties, including optimum pH and temperature, stability, kinetics, and redox mediators. Such factors may differ, impact catalytic and operational efficiencies, and are a function of proximate source, molecular make up and reaction conditions of the enzyme (Baldrian, 2006; Janusz et al, 2017). Apart from the specific oxidizable substrate, the source of laccase also impacts on the laccase pH value. Laccases have a broad range of operational pH. Fungal laccases perform optimally in the range of pH 3.0 to 5.0 in the presence of phenolic substrates (Baldrian, 2006). Some of the behaviours of fungal laccases may be attributed to the electron transfer at the type 1 copper site. In addition, phenoxy radicals tend to be more stable in an acidic environment (Mate and Alcalde, 2015). On the other hand, bacterial and plant laccases show optimum activity at pHs 6 to 9. This particular feature is advantageous when laccases are used in various applications, including textile, pulp and paper, and wastewater treatment industries, which are typically alkaline (Singh et al, 2020).

Temperature, too, has an influence on the activity of laccases. Most laccases have optimal activity at temperatures between 40 and 50 °C, but certain thermophilic bacteria operate at temperatures exceeding 70 °C (Janusz et al, 2017). Extreme temperatures, however, can cause the misalignment of the copper and protein subunits, causing an irreversible loss of function of the enzyme (Pollegioni et al, 2016).

The robustness of laccases is especially useful to numerous industrial applications. More economical laccase variants tend to suffer more from extremes of pH, thermal instability, and elemental inhibition (Mate and Alcalde, 2015). While fungal laccases tend to be more stable in the presence of acid, they tend to possess relatively low activity at high pH. On the other hand, even under extreme pH, salinity, and certain organic solvents, bacterial laccases tend to have high relative activity (Singh et al, 2018). Animal laccases tend to exhibit Michaelis-Menten type of kinetics.

The particularities of substrate specificity also include its size, electrostatic charge, and concealment of the T1 copper site and so on (Zhang et al, 2020). The substrate oxidation limit of laccases is determined by high redox potential or by the size.Laccase-mediator systems, in some cases, exhibit a form of redox versatility. Although, because of redox activators, small mediators might provide and electric pathway to the enzyme and the substrate, which would otherwise be blocked (Bilal et al, 2021). The implementations of mediators in laccase-mediator systems do come at their own issues. These include high cost, unregulated pollution, instability of the mediators, and increased pollution. Use of unbound laccase, or nano laccase, is to enhance efficiency and is more eco-friendly (Kumar et al, 2023; Wang et al, 2024).

SOURCES OF LACCASE

Numerous different varieties of organisms can produce laccases, including a range of bacteria, fungi, animals, and even some plants that are considered multicopper oxidases. While laccases can be produced by laccase-inducing organisms in a range of environments, laccases produced by fungi, laccase-inducing plants, laccase-inducing bacteria, and laccase-inducing insects are most economically valuable. Laccase-producing bacteria, laccase-producing fungi, and laccase-producing organisms are the most economically valuable and are the most diverse. The highly diverse laccase-producing fungi and bacteria dominate laccase-producing fungi and laccase-producing bacteria industries (Reinhammar, 2018; Younus et al, 2025).

The white-rot and brown-rot basidiomycete fungi genera are the most well-characterized groups producing laccases, particularly Laccase-producing fungi, which, alongside laccase-producing basidiomycetes, are some of the most well-characterized organisms producing laccases (Deshmukh et al, 2025). Laccases are made by fungi in the form of glycoproteins that are produced and secreted extracellularly. Fungi laccases are active against a variety of polymeric subunits (positive and negative) across all the classes of phenols and non-phenols. The redox potentials shown by laccase-encoding fungi laccases are very diverse as well (Vallejo et al, 2025).

Vallejo et al. note the presence of laccase-encoding multigene families in all fungi species including Lentinula, Timothy, Phanerochaete, Pleurotus, and Ganoderma. Laccase production is most active under conditions that are mesophilic and of moderate acidity (Vallejo et al, 2025). There are laccase-producing fungi which have shown optimal growth and laccase activity in conditions which are outside the usual mesophilic range. The laccases of Aspergillus and Penicillium species are said to have a lower redox potential but are produced commercially more easily because of lesser growth and lesser requirements for genetic manipulation (Sharma et al, 2025; Huang et al, 2024; Algahmadi et al, 2024). Hence, fungal laccases are used in most of the industrial processes like pulp biobleaching, textile dye decolorization, wastewater treatment, biosensing, and green biosynthesis (Rodríguez-Couto et al, 2019; Magalhães et al, 2024).

The enzymes of bacteria have been the most commercially studied and exploited laccases for biotechnological applications. Bacteria, as explained by Chauhan et al., have shown robust and greater stability in alkaline environments (pH, temperature, salinity, and organic solvents) (Chauhan et al, 2017). Species of Bacillus, Streptomyces, Pseudomonas and Thermus are neutral to alkaline, and their high thermostability coupled with their typically lower redox potential makes them bioremediation, biofuel and nanobiotechnology (Akram et al, 2022). Laccases are the enzymes of plants which polymerize the Xeno-substrates of monolignols.

These are endoenzymes that polymerize the lignin in the secondary cell walls of the plants (structural components of the plant's defense tissues) (Liao et al, 2023; Chen et al, 2025). Laccase-1 and 2 are insect laccases involved in cuticle sclerotization, pigmentation, and components of the cellular immunity and are used in natural polymerization and designing of biomimetic materials and cannot be used for industrial purposes directly (Asano et al, 2014; Liu et al, 2018; Clark et al, 2021).

Table 1: Classification of Laccase Sources and Their Industrial Significance

Source	Representative organisms	Optimum pH	Major characteristics	Major applications	Reference
Fungi	Trametes versicolor, Pleurotus ostreatus, Ganoderma lucidum	3.0–5.0	High redox potential, extracellular enzyme	Bioremediation, textile dye degradation, pulp bleaching	Baldrian (2006); Janusz et al. (2017); Sharma et al. (2025)
Bacteria	Bacillus, Streptomyces, Pseudomonas, Thermus	6.0–9.0	Thermostable, alkali tolerant	Wastewater treatment, biofuel production	Chauhan et al. (2017); Akram et al. (2022)
Plants	Rhus vernicifera, Populus trichocarpa	5.0–7.0	Lignin polymerization	Plant development, lignification	Liao et al. (2023); Chen et al. (2025)
Insects	Bombyx mori, Plutella xylostella	~6.0–7.0	Cuticle sclerotization and pigmentation	Biomimetic materials	Asano et al. (2014); Liu et al. (2018)

LIMITATIONS OF FREE LACCASE

The most important issues regarding the use of free soluble laccases in inustrial processes are the poorly working and the loss of function of the enzyme at the high temperatures, extreme pH and long process times that are common in industry. Operational life spans can be shortened by any number of factors. Common instances of this are enzyme depletion by reaction intermediates, by the processing pH, and by the need for product replenishment (Zhao et al, 2020). Because free laccases cannot be recovered and reused, the processes being reused become more volatile, as with processes like dye degradation and waste water treatment that involve free laccases. The laccases are also affected by heavy metals and organics that disrupt the electron transfer from Ni and Cu, as well as by the halides that are known to be laccase inhibitors (Wang et al, 2024). Free laccases also cannot use mediators, and therefore cannot process large, non-native substrates. Because industry often involves very high temperatures and the use of free laccases, these processes also become non-viable, which is one of the reasons that the use of immobilization and nanobiocatalyst are so popular (Zhao et al, 2020).

Table 2: Comparative Characteristics of Free and Immobilized Laccase Systems

Parameter	Free Laccase	Nano-Immobilized Laccase	Reference
Operational stability	Low	High	Bilal et al. (2017); Zdarta et al. (2023)
Thermal stability	Poor	Improved	Datta et al. (2017); Bilal et al. (2023)
pH tolerance	Narrow	Broad	Sheldon and van Pelt (2015); Ribeiro et al. (2024)
Reusability	Single use	Multiple catalytic cycles	Kumar et al. (2023);

			Zhao et al. (2020)
Recovery	Difficult	Easy (especially magnetic nanoparticles)	Rashid et al. (2022); Villalonga et al. (2025)
Catalytic efficiency	Moderate	Enhanced	Li et al. (2024); Mate and Alcalde (2024)
Industrial applicability	Limited	High	Wang et al (2024)

NANOTECHNOLOGY IN IMMOBILIZATION OF LACCASE

The length of time, reusability, and stability problems of laccase systems and nanotechnology para and the impact of combined laccase systems and nanotechnology has been documented (Alvarado-Ramírez et al, 2021). Various magnetic and silica nanostructures, laccase-graphene oxide nanofibers, other nanofibers, and various polymeric derivatives of these materials have been used for the laccase nanoscale and microscale immobilization. These micro and nanostructures materials lessen the potential for laccase to fold on itself and constrain the microenvironment (Mahmoodi et al, 2014; Lateef et al, 2015; Deniz et al, 2022). With the optimum microenvironment, nanocarriers, the conditions for substrate accessibility, catalysis, and enzyme loading. Economically, and reusable laccase nanomaterials, magnetic, and laccase nano-immobilized laccase. Of surrendered laccase nanocarriers, the best for control and orientation was, according to Alvarado-Ramírez et al, entrapment (Alvarado-Ramírez et al,2021). The use of laccase nanotechnology immobilization is economically feasible in most of the processes in which laccases perform functions in biocatalysis, bioremediation, and in the biosensors; laccases perform vital functions (Dong et al, 2023; Ren et al, 2020).

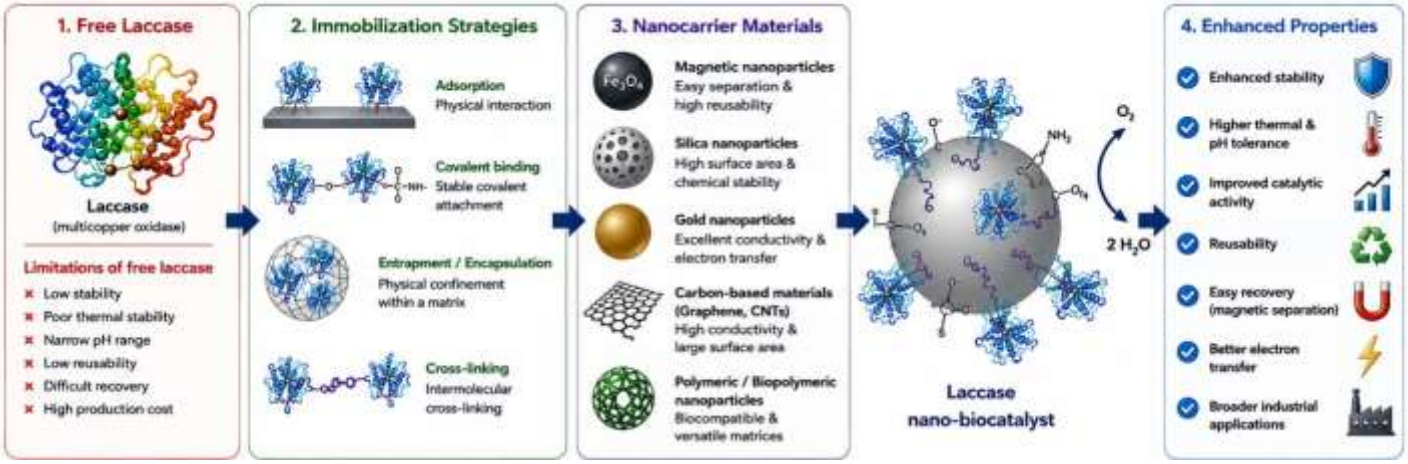


Figure 1: Schematic overview of laccase immobilization on nanoparticles illustrating the limitations of free laccase, major immobilization strategies, representative nanocarriers, and the resulting improvements in catalytic performance, stability, and reusability.

METHODS FOR SYNTHESIS OF NANOPARTICLES

The techniques used in the synthesis of nanoparticles determine the particles' dimensions, shape, surface chemistry, biocompatibility, etc. These characteristics are all crucial for effective laccase immobilization. Patil et al. reported that nanoparticle synthesis methods are typically divided into three categories: physical, chemical, and green methods (Patil et al, 2021).

Physical Methods

Methods that do not involve chemicals as such, and use purely physical means rely upon top-down approaches and the use of mechanical/physical methods to break samples down to the nanoscale, from bulk to nanoparticles. Such methods include ball milling, laser ablation, evaporation–condensation and sputtering (Jagdeo, 2023). Although ball milling can be scaled up easily, the nanoparticles produced are often not uniform which leads to the potential problem of not having the proper enzyme loading (Wirunchit et al, 2021). Amongst the other methods laser ablation is the most applicable to sensitive biological systems as the nanoparticles produced are chemically pure and optimal for enzyme immobilization (Kim et al, 2017; Mansoureh and Parisa, 2018). Since physical methods are usually associated with high costs because of the high quantity of specialised equipment and the high amount of energy required, additional surface modifications are needed as the nanoparticles produced are usually (Jagdeo, 2023).

Chemical Methods

Because the intrinsic physical characteristics of nanoparticles such as dimensions, form, and surface chemistry can be fine-tuned, most methods to immobilize laccase involve some type of chemical synthesis. Some of the synthesis methods include chemical reduction, co-precipitation, sol-gel, and polymerization. Because of the rapid growing field of laccase immobilization on porous iron oxide nanoparticles, it is pertinent to mention that it was also co-precipitation that was most widely used in the formation of highly magnetic,

easily collectable, and reusable laccase (Hachem et al, 2022). Chemical reduction is of at most importance in the construction of metal-Au (and Ag) nanoparticles which are predominantly used in biosensors. Sahoo et al. explains the use of polymeric microspheres, which are formed by interface polymerization or ionic gelation, and are hydrophilic in nature, as offering an advantageous environment for the utilization of laccase as well as being biocompatible (Sahoo et al, 2021). Careful selection and purification of reagents is, without a doubt, the result of the use of hazardous chemicals and/or solvents (Hachem et al, 2022).

Green Synthesis Methods

The use of biological systems and natural compounds as reducing and stabilizing agents in green chemistry is another area that improves sustainability. Successful synthesis of nanoparticles for laccase immobilization has been achieved with polyphenol- and flavonoid-containing plant extracts and with microorganisms, including bacteria, fungi, and algae. There have also been positive reports during synthesis with the biopolymers chitosan, alginate, cellulose, and starch (Ali et al, 2015; Nasrollahzadeh et al, 2019; Warkara and Meena, 2022). Although there have been positive reports regarding the biocompatibility and environmental safety of the nanoparticles, size and reproducibility are still concerns (Samuel et al, 2022).

TYPES OF NANOMATERIALS USED FOR IMMOBILIZATION OF LACCASE ENZYME

Recent advances in the encapsulation of laccase nanomaterials have laccase increased activity, catalytic efficiency, and reusability. For instance, nanosilver, gold, and platinum nanoparticles enhance conductivity and biocompatibility. These nanoparticles promote electron transfer in laccase biosensors, and laccase bioelectrochemical systems. Iron oxides (Fe_3O_4, γ-Fe_2O_3), as well as titanium oxides, zinc oxides, cerium oxides, and manganese dioxides are among the materials attributed mechanical and chemical stability, along with surface hydroxides that bond, chemically, to laccase. Iron oxides (Fe_3O_4) nanomaterials are particularly beneficial, as the laccase that is covalently bonded to the material can, the use of a magnet, be removed and reused (Rashid et al, 2022; Muthuvelu et al, 2020; Kadam et al, 2022; Si et al, 2024; Villalonga et al, 2025; Wang et al, 2024).

Core-shell magnetic silica and nanomagnetic mesosphere silicate are praised for their chemical stability. Silicate nanomagnetic mesospheres have been cited as magnets in the positive, as has Zhao (Zhao et al, 2022). When grouped mesoporous silica and multifunctional mesoporous silica, the magnetic microspheres mesospheres silica nanocomposites exhibit the same stability and permeability characteristics as silicate magnetic nanocomposites (Patel et al, 2014).

Numerous carbon nanomaterials exhibit remarkable tensile strength, as well as remarkable conductance and catalytic abilities, and carbon biochar nanoparticles, carbon nanodots, carbon nanotubes, nano-graphenes (graphene oxide, reduced graphene oxide, grapheme), and even conductive oxides. The properties of graphene oxide and laccase (Adamian et al, 2021). The primary focus will thus be on composite nanomaterials, more specifically, those that integrate magnetic nanomaterials, layered nanomaterials, and synthetic and naturally occurring polymers like chitosan, alginate, cellulose, starch, dextran, poly(lactic acid), poly(vinyl alcohol), polyaniline and stogether with the more complicate synergistic effects of the additional electrostatic interactions (Alsaiari et al, 2021; Gupta et al 2025).

Table 3: Types of Nanocarriers for Laccase Immobilization and Their Applications

Nanomaterial	Major characteristics	Typical application	Reference
Fe_3O_4 magnetic nanoparticles	Magnetic separation, high reusability	Wastewater treatment	Rashid et al. (2022); Zhao et al. (2020)
Silica nanoparticles	High surface area, chemical stability	Enzyme immobilization	Patel et al. (2014); Zhao et al. (2022)
Gold nanoparticles	Excellent conductivity and biocompatibility	Biosensors	Patil et al. (2021); Li et al. (2024)
Graphene oxide / Carbon nanotubes	High electrical conductivity	Bioelectrocatalysis, biosensors	Adamian et al. (2021)
Chitosan nanoparticles	Biocompatible, biodegradable	Food packaging, biocatalysis	Rashid et al. (2022)
Polymeric nanoparticles	High enzyme loading and stability	Industrial biocatalysis	Sahoo et al. (2021)

PROPERTIES OF LACCASE NANOCOMPOSITES

Among recent entrants of biocatalysts innnovation are nanocomposites biocatalysts using laccase and new designed nanomaterials (Mate and Alcalde, 2024). One of the benefits of biocatalysts is their longer operational shelf life. Due to laccase support is nanostructured, laccase is less susceptible to irreversible denaturation. In addition, these composites are not subjected to the operational inflexibility and reuse limitations of previous nanomaterials (Bilal et al, 2023). Compared to other dissociated catalysts, nanomaterials offer better surface area and porosity, and with dissociated catalysts better substrate accessibility, and higher catalytic

efficiencies, the extent of catalytic action is enhanced (Zhang et al, 2023; Ribeiro et al, 2024). In comparison to unbound laccase, laccase nanocomposites offer greater mass transfer and less diffusion of reacted biocatalysts, thus enhancing biocatalyst response time. According to Kumar et al, there appears to be an association of reduced enzymatic leaching to increased oriented and more laccase bonded to the functionalized nanocarriers (Kumar et al, 2023). In certain laccase nanocomposites, Li et al. report of increased electrical conductivity, and improved resistance to some classes of inhibitors. Due to the unique attributes of such composites, they can be applied in various domains, including but not limited to, environmental remediation, the production of sensors, sustainable bioprocessing, and biocompatible electrodes (Li et al, 2024).

EFFECT OF NANOPARTICLES ON PROPERTIES OF LACCASE

Certain types of nanomaterials used in conjunction with laccases may solve, or at least ameliorate the problem of free enzymes in bioconversion systems, although free enzymes present a myriad of problems (Mate and Alcalde, 2017; Bilal et al, 2019). The laccase free enzyme instability issue is one of those problems. The microenvironment created by the nanomaterials may protect the enzyme microenvironment from extreme pH, temperature, and organic solvents that cause enzyme denaturation. This microenvironment may allow enzymes to withstand extreme pH and elevated temperature, enhancing its commercial and industrial applications (Datta et al, 2017; Sheldon and van Pelt, 2015; Zdarta et al, 2018). The cost and operational implications of modifying laccases and using magnetophoresis, (removal of laccase via magnets), as a controllable biocatalyst, may integrate with process and function multiple reaction cycles with negligible loss of laccase activity, as described by (Kumar et al, 2023; Asgher et al, 2017).

Laccases catalyze enzyme reactions; one way to obtain better reaction rates is to place them within magnetically responsive nanoparticles with optimal pore size and an ideal surface to volume ratio, increasing the enzyme's surface and interaction with the substrate (Zdarta et al, 2023; Bilal Iqbal, 2020). Of all nanoparticles, the most functional modification is offered by polymers that encapsulate laccase conjugated to the polymers.

This method offers the highest laccase positional control, the best reduction of laccase leaching from the nanoparticles, and the best promotion of laccase encapsulation. Laccase nanoparticles coupled with biosensors and other areas of electrochemistry are very promising (Gupta et al, 2016; Li et al, 2024). The enzyme laccase is, with respect to certain inhibitors such as halides and metal cations, less inhibited (Santos et al, 2015; Ribeiro et al, 2024). Of all disciplines, laccase and nanoparticles composites are especially promising for biosensors and electrochemistry (Li et al, 2024; Gupta et al, 2016). Like other conductive nanomaterials, such as graphene oxide, metal nano parts, and carbon nanotubes, accelerate electron transfer from laccase to the electrode.

APPLICATIONS OF NANO-ENABLED LACCASE SYSTEMS

Industrial and biotechnological applications

The first nano-biocatalysts were created with laccase systems by coupling laccase enzymes to laccase-immobilized nanostructured supports (Arduini et al, 2022; Bilal et al, 2019). Laccase systems span a variety of technological and biotechnological fronts. Environmentally, they rapidly and effectively mitigate phenolic, synthetic dye, endocrine disrupting, and pharmaceutical contaminants in wastewater (Singh et al, 2020; Gasser et al, 2014). Since nano-immobilized laccase systems are reliable, they are consistent in straightforward continuous treatment systems, extreme changes in pH and temperature, and in the presence of heavy metals and organic solvents (Sharma et al, 2021; Zdarta et al, 2018). In the textile and paper industries, the application of nanostructured laccases to decolor dyes, biobleach the pulp, and in a chemically disruptive manner, alter the chemically fibro disruptive pulp (Yang et al, 2023; Chauhan et al, 2017).

The use of biosensors with bioelectrochemical applications of laccase with conductive nanomaterials like carbon nanotubes, metal nanoparticles, graphene oxide showed improved detection of phenolic compounds, glucose, and other analytes due to better electron transfer between laccase and the electrodes (Rodríguez-Delgado et al, 2015; Tiwari et al, 2020). Nano-immobilized laccase enhances the safety and the quality of food and pharmaceuticals, since laccase detoxifies mycotoxins and synthesizes antioxidants, and laccase modifies bioactive compounds (Faccini et al, 2019; Bilal et al, 2020). In biopolymer and packaging technologies, laccase-nano composites enhance the functionality of active packaging systems, and add antimicrobial and antioxidant properties to sustain and prolong food shelf life (Bilal et al, 2020; Zdarta et al, 2018). Nano-enabled systems for laccase are commercially scalable and economically viable due to having great substrate accessibility, a high surface to volume ratio, and resistance to inhibitors (Zdarta et al, 2018; Jesionowski et al, 2015). The combination of laccase and nanotechnology, especially in the environmental, biomedical, and industrial fields, strengthens the utilization of biocatalysis as a more environmentally friendly and sustainable paradigm in the technologies of the future (Arikan et al, 2024; Bilal et al, 2021).

Applications in the food industry

Bilal et al. and Zdarta et al. report the application of nanotechnology in the food sector which improves the stability, efficiency, and reusability of laccase (Zdarta et al, 2023). The operational lifespan of laccase is boosted by the nanomaterials; silica, gold and polymers,

which provide protection from temperature, pH, and proteolytic enzymes (Sharma et al, 2021; Jesionowski et al, 2015). Another application is the stabilization and clarification of some beverages. Laccase can reduce the enzymatic browning which occurs when phenolic compounds are present and turbidity (Faccini et al, 2019; Minussi et al, 2016). In baking, the nano-laccase systems (Yang etal, 2022; Selinheimo et al, 2017) increase the texture of the bread by means of controlled oxidative crosslinking of phenolic compounds and proteins and also enhance the rheology of flour and dough, and reinforce the gluten network. The use of nano-laccase in the processing of dairy is also reported by many authors with the improvement of the solubility and functionality of the modified whey proteins (Mate and Alcalde, 2024). In addition, nano-laccase has been found to unregulatedly reduce undesired off-flavors due to phenolic oxidation (Bilal and Iqbal, 2020; Abdel-Moneim et al, 2023).

From the point of view of the dairy processing industry, antimicrobial laccase conjugate nanoparticles are, probably, an answer to the phenomena of Fos coagulation, which would be useful to extend the shelf-life of dairy products (Zhang et al, 2023). Laccase nanoparticles could also function as biosensors to assess/track the quality of the food (Arduini et al, 2022; Rodríguez-Delgado et al, 2015). The incorporation of laccase and nanomaterials and the reduction of chemical preservatives in food processing is very recent and remains of high interest (Bilal et al. 2021; Zdarta et al. 2023).

Medical and Pharmaceutical Applications

There is an increasing trend in the use of biocatalysts of laccase, encapsulated in nanocarriers in the pharmaceutical and medical fields. They are more catalytically active, biochemically more stable, and more readily reusable (Zdarta et al, 2023; Bilal et al, 2021). Numerous encapsulated laccase nanocarriers, which are more useful in preventing the denaturation of the enzyme within more complex biophysical constructs at physiological temperatures.

For example, some examples of nanocarriers include the encapsulated laccase magnet, gold and silica, and other polymers (Sharma et al, 2021; Jesionowski et al, 2015). When it comes to the biocatalyst laccase, in the drug development process it is less toxic than the chemical and biocide-releasing methods used in the industry for targeted and stereoisomer oxidation (Bilal et al, 2020; Rodríguez Couto and Toca Herrera, 2016).

As laccase-nanoparticle conjugates used in prodrug activation and drug delivery, the oxidation caused by the triggered enzyme acts on the drug released to alter the therapeutic effect, there are new potentials for this in as some literature describe (Kumari et al, 2018; Arikan et al, 2024). Also, laccase-carrying nanoparticles used for their combined antimicrobial and anticancer properties are (El-Saadony et al, 2023; Singh et al, 2018). Laccase-integrated distributed sensors have been used for the rapid and selective detection of biosensors and the markers of drugs and toxins (Arduini et al, 2022; Rodríguez-Delgado et al, 2015).

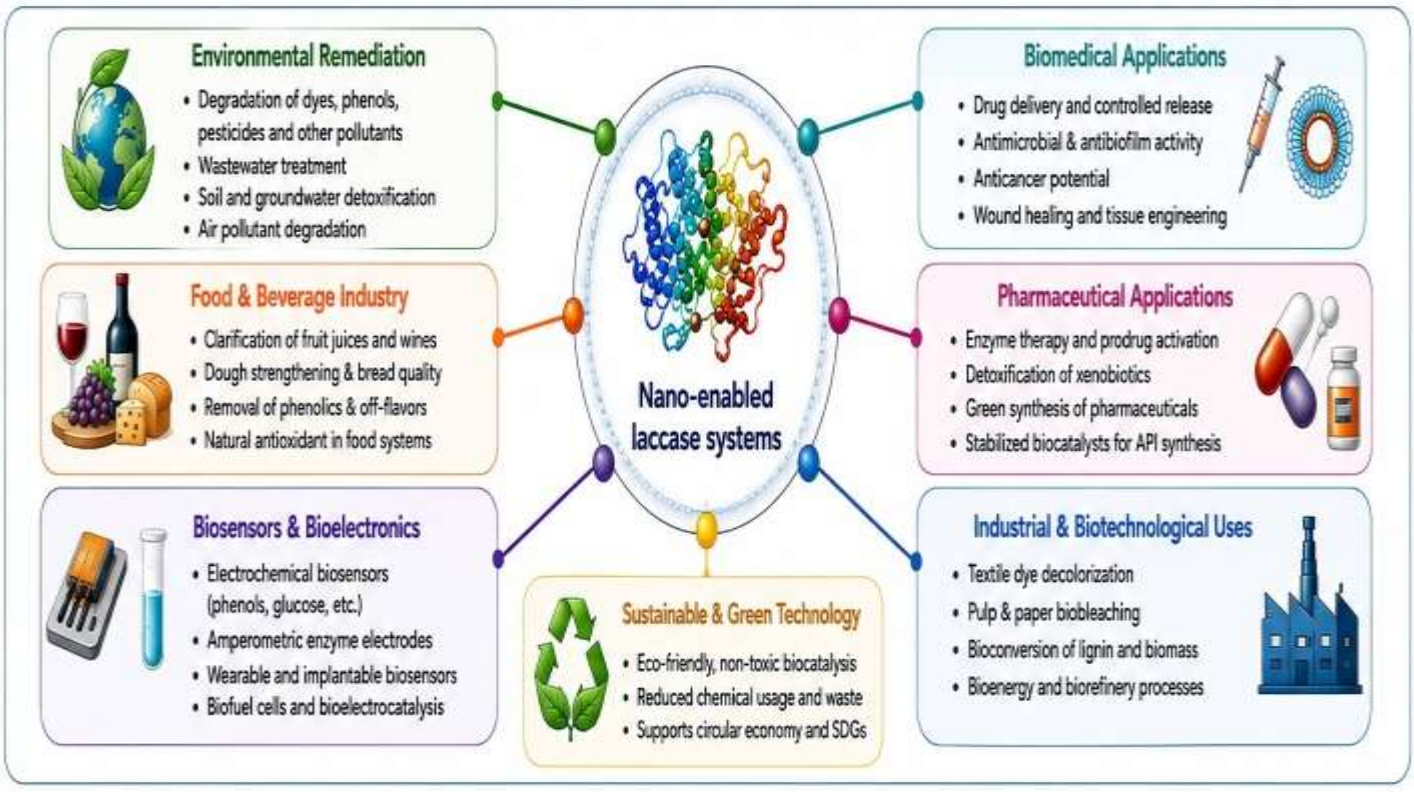


Figure 2. Multidisciplinary applications of nano-enabled laccase systems in environmental remediation, food processing, biosensing, biomedical engineering, pharmaceutical technologies, industrial biotechnology, and sustainable biocatalysis.

CONCLUSION

One of the best promising combinations of nanotechnology and enzymology is the incorporation of laccase into nanoparticles. These nanoparticles, in addition to being multifunctional, can also possess a number of helpful characteristics in various aspects of industry and biotechnology. Along with laccase's improved stability, laccase's limitations and laccase's reusability will boost overall catalytic efficiency. Dependable performance will be shown, even in exceptionally complicated and extreme reactivity. Regulatory safety, cost, and scalability will be easily overcome by the trends in the field of laccase redesign, the immobilization methods, and the nanomaterials. Responsive smart systems will be of extreme importance, as will commercially and societally laccase nanobiocatalysts. Strong innovation will also be supported in many fields of technology, especially in the extremely important field of sustainability.

ACKNOWLEDGEMENT

The authors have no acknowledgements to declare.

REFERENCES

1. Bilal, M.; Asgher, M.; Iqbal, H. M. N. Nanostructured Materials for Laccase Immobilization: A Review. Int. J. Biol. Macromol. 2019, 131, 856–867.
2. Singh, R.; Singh, P.; Shukla, P. Oxidative Enzymes in Biotechnological and Industrial Applications. 3 Biotech 2018, 8, 159. https://doi.org/10.1007/s13205-018-1188-6.
3. Marlina, S.; Rahman, R. N. Z. R. A.; Salleh, A. B.; Basri, M. Laccase in Lignocellulosic Biomass Valorization: Current Trends and Future Prospects. Biotechnol. Biofuels 2021, 14, 58. https://doi.org/10.1186/s13068-021-01912-6.
4. Baldrian, P. Fungal Laccases—Occurrence and Properties. FEMS Microbiol. Rev. 2006, 30 (2), 215–242. https://doi.org/10.1111/j.1574-4976.2005.00010.x.
5. Couto, S. R.; Herrera, J. L. T. Industrial and Biotechnological Applications of Laccases: A Review. Biotechnol. Adv. 2006, 24 (5), 500–513. https://doi.org/10.1016/j.biotechadv.2006.04.003.
6. Janusz, G.; Pawlik, A.; Świderska-Burek, U.; Polak, J.; Sulej, J.; Jarosz-Wilkołazka, A.; Paszczyński, A. Laccase Properties, Physiological Functions, and Evolution. Int. J. Mol. Sci. 2017, 18 (6), 1389. https://doi.org/10.3390/ijms18061389.
7. Mate, D. M.; Alcalde, M. Laccase Engineering: From Rational Design to Directed Evolution. Biotechnol. Adv. 2015, 33 (1), 25–40. https://doi.org/10.1016/j.biotechadv.2014.12.007.
8. Pollegioni, L.; Tonin, F.; Rosini, E. Lignin-Degrading Enzymes. FEBS J. 2016, 283 (16), 2964–2978. https://doi.org/10.1111/febs.13755.
9. Ruiz-Dueñas, F. J.; Martínez, A. T. Microbial Degradation of Lignin: How a Bulky Recalcitrant Polymer Is Efficiently Recycled. Microb. Biotechnol. 2020, 13 (6), 1528–1546. https://doi.org/10.1111/1751-7915.13624.
10. Bilal, M.; Asgher, M.; Iqbal, H. M. N.; Hu, H.; Zhang, X. Bio-Catalysis and Bioremediation by Laccase Immobilized on Nanostructured Materials: A Review. Int. J. Biol. Macromol. 2017, 97, 267–278. https://doi.org/10.1016/j.ijbiomac.2017.01.045.
11. Lima, C. G. S.; de Lima, T. M.; Paixão, M. W.; Corrêa, A. G. Enzyme Stability and Operational Challenges in Industrial Biocatalysis. Chem. Soc. Rev. 2016, 45 (21), 5369–5407. https://doi.org/10.1039/C6CS00196A.
12. Su, H.; Zhang, L.; Wang, Y. Advances in Nanomaterials for Enzyme Immobilization and Stabilization. Catalysts 2021, 11 (3), 352. https://doi.org/10.3390/catal11030352.
13. Bilal, M.; Jing, Z.; Zhao, Y.; Iqbal, H. M. N. Immobilized Oxidative Enzymes for Sustainable Biomedical and Environmental Applications. Sci. Total Environ. 2021, 770, 145187.
14. Zhao, J.; Hu, Q.; Wang, X. Magnetic Nanoparticle-Assisted Immobilization of Laccase for Enhanced Recyclability. Bioresour. Technol. 2020, 307, 123221. https://doi.org/10.1016/j.biortech.2020.123221.
15. Gao, S.; Wang, Y.; Li, X.; Zhang, Y. Nanocomposite-Based Enzyme Immobilization for Enhanced Catalytic Stability and Reusability. Bioresour. Technol. 2023, 369, 128383. https://doi.org/10.1016/j.biortech.2022.128383.
16. Singh, G.; Arya, S. K.; Bhalla, T. C. Immobilized Laccase for Bioremediation of Emerging Pollutants. J. Environ. Manage. 2020, 268, 110662.
17. Zhang, L.; Zhou, M.; Dong, S. Bioelectrocatalysis of Laccase and Its Applications in Biofuel Cells. Biosens. Bioelectron. 2020, 151, 111980. https://doi.org/10.1016/j.bios.2019.111980.
18. Kumar, A.; Sharma, K.; Singh, R.; Kumar, R. Magnetic Nanoparticle-Assisted Laccase Immobilization for Enhanced Reusability and Bioremediation Efficiency. Bioresour. Technol. 2023, 369, 128391. https://doi.org/10.1016/j.biortech.2022.128391.
19. Wang, Y.; Zhao, X.; Liu, H.; Zhang, Y. Magnetic Nanoparticle-Assisted Immobilization of Laccase for Electrochemical Detection of Phenolic Compounds. Anal. Chim. Acta 2024, 1294, 341615. https://doi.org/10.1016/j.aca.2024.341615.
20. Reinhammar, B. Laccase. In Copper Proteins and Copper Enzymes; CRC Press: Boca Raton, FL, 2018; pp 1–36.

21. Younus, H.; Khan, M. A.; Khan, A.; Alhumaydhi, F. A. Eco-Friendly Biocatalysts: Laccase Applications, Innovations, and Future Directions in Environmental Remediation. Catalysts 2025, 15 (10), 921.
22. Deshmukh, A.; Sattikar, P.; Sukhatankar, A.; Wakade, G.; Kumbhar, P.; Kommoju, P. R. Optimized Laccase Production from the White-Rot Fungi Pleurotus ostreatus and Trametes versicolor. Protein Expression Purif. 2025, —, 106813.
23. Vallejo, J. L.; Vallejos, S.; Trigo-López, M.; García, J. M.; Busto, M. D. Optimization and Stability of a Reusable Laccase–Polymer Hybrid Film for the Removal of Bisphenol A in Water. Environ. Technol. Innov. 2025, 38, 104093.
24. Sharma, R.; Salwan, R.; Kour, N.; Sharma, K.; Sharma, V. Decoding the Distribution, Structure–Function–Redox Potential Relationship and Recent Advances in Fungal Laccases: A Systematic Approach. Bioprocess Biosyst. Eng. 2025, —, 1–24.
25. Huang, J.; Wang, J.; Chen, L. Z.; He, J. L.; Wu, Y. P.; Cui, X. P.; Mei, M. N.; Li, Y. Y. Improved Expression of Cerrena unicolor Laccase in Aspergillus niger via Combined Strategies and Its Applications. Biochem. Eng. J. 2024, 209, 109371.
26. Algahmadi, A.; Mohammed, A. E.; Alfadda, A. A.; Alanazi, I. O.; Alwehaibi, M. A.; Joy, S. S.; Al-Shaye, D.; Benabdelkamel, H. Proteomics of Penicillium chrysogenum for a Deeper Understanding of Lead (Pb) Metal Bioremediation. ACS Omega 2024, 9 (24), 26245–26256.
27. Rodríguez-Couto, S. Fungal Laccase: A Versatile Enzyme for Biotechnological Applications. In Recent Advancement in White Biotechnology through Fungi; Springer International Publishing: Cham, 2019; pp 429–457.
28. Magalhães, F. F.; Pereira, A. F.; Cristóvão, R. O.; Barros, R. A.; Faria, J. L.; Silva, C. G.; Freire, M. G.; Tavares, A. P. Recent Developments and Challenges in the Application of Fungal Laccase for the Biodegradation of Textile Dye Pollutants. Mini-Rev. Org. Chem. 2024, 21 (6), 609–632.
29. Chauhan, P. S.; Goradia, B.; Saxena, A. Bacterial Laccase: Recent Update on Production, Properties, and Industrial Applications. 3 Biotech 2017, 7 (5), 323.
30. Akram, F.; Ashraf, S.; Haq, I. U.; Shah, F. I.; Aqeel, A. Eminent Industrial and Biotechnological Applications of Laccases from Bacterial Source: A Current Overview. Appl. Biochem. Biotechnol. 2022, 194 (5), 2336–2356.
31. Liao, B.; Wang, C.; Li, X.; Man, Y.; Ruan, H.; Zhao, Y. Genome-Wide Analysis of the Populus trichocarpa Laccase Gene Family and Functional Identification of PtrLAC23. Front. Plant Sci. 2023, 13, 1063813.
32. Chen, L. Y.; Diao, Y.; Ma, J. H.; Zhang, X. X.; Li, R.; Liu, Y.; Tang, H. T.; Wang, Z.; Gao, S.; Xu, R. H.; Kang, Z. S. Genome-Wide Identification of the Laccase Gene Family in Wheat (Triticum aestivum L.) during Fusarium pseudograminearum Infection. Plant Sci. 2025, —, 112894.
33. Asano, T.; Taoka, M.; Yamauchi, Y.; Everroad, R. C.; Seto, Y.; Isobe, T.; Kamo, M.; Chosa, N. Re-Examination of an α-Chymotrypsin-Solubilized Laccase in the Pupal Cuticle of the Silkworm Bombyx mori: Insights into the Regulation System for Laccase Activation during the Ecdysis Process. Insect Biochem. Mol. Biol. 2014, 55, 61–69.
34. Liu, Z. G.; Wang, H. H.; Xue, C. B. Molecular Identification and Enzymatic Properties of Laccase2 from the Diamondback Moth Plutella xylostella (Lepidoptera: Plutellidae). J. Integr. Agric. 2018, 17, 2310–2319.
35. Clark, M.; Tepper, K.; Petroll, K.; Kumar, S.; Sunna, A.; Maselko, M. Bioremediation of Industrial Pollutants by Insects Expressing a Fungal Laccase. ACS Synth. Biol. 2021, 11 (1), 308–316.
36. Alvarado-Ramírez, L.; Rostro-Alanis, M.; Rodríguez-Rodríguez, J.; Castillo-Zacarías, C.; Sosa-Hernández, J. E.; Barceló, D.; Iqbal, H. M.; Parra-Saldívar, R. Exploring Current Tendencies in Techniques and Materials for Immobilization of Laccases—A Review. Int. J. Biol. Macromol. 2021, 181, 683–696.
37. Mahmoodi, N. M.; Arabloo, M.; Abdi, J. Laccase-Immobilized Manganese Ferrite Nanoparticle: Synthesis and LSSVM Intelligent Modeling of Decolorization. Water Res. 2014, 67, 216–226.
38. Lateef, A.; Adeeyo, A. O. Green Synthesis and Antibacterial Activities of Silver Nanoparticles Using Extracellular Laccase of Lentinus edodes. Not. Sci. Biol. 2015, 7 (4), 405–411.
39. Deniz, S. A.; Goker, S.; Toppare, L.; Soylemez, S. Fabrication of D–A–D Type Conducting Polymer, Carbon Nanotubes, and Silica Nanoparticle-Based Laccase Biosensor for Catechol Detection. New J. Chem. 2022, 46 (32), 15521–15529.
40. Dong, C. D.; Tiwari, A.; Anisha, G. S.; Chen, C. W.; Singh, A.; Haldar, D.; Patel, A. K.; Singhania, R. R. Laccase: A Potential Biocatalyst for Pollutant Degradation. Environ. Pollut. 2023, 319, 120999.
41. Ren, D.; Wang, Z.; Jiang, S.; Yu, H.; Zhang, S.; Zhang, X. Recent Environmental Applications of and Development Prospects for Immobilized Laccase: A Review. Biotechnol. Genet. Eng. Rev. 2020, 36 (2), 81–131.
42. Patil, S.; Basu, A.; Tiwari, A. Nanomaterial-Enabled Laccase Biosensors: Recent Developments. Sens. Actuators B Chem. 2021, 329, 129123. https://doi.org/10.1016/j.snb.2020.129123.
43. Jagdeo, K. R. Physical Methods for Synthesis of Nanoparticles. In Nanochemistry; CRC Press: Boca Raton, FL, 2023; pp 66–76.
44. Wirunchit, S.; Gansa, P.; Koetniyom, W. Synthesis of ZnO Nanoparticles by Ball-Milling Process for Biological Applications. Mater. Today Proc. 2021, 47, 3554–3559.
45. Kim, M.; Osone, S.; Kim, T.; Higashi, H.; Seto, T. Synthesis of Nanoparticles by Laser Ablation: A Review. KONA Powder Part. J. 2017, 34, 80–90.

46. Mansoureh, G.; Parisa, V. Synthesis of Metal Nanoparticles Using Laser Ablation Technique. In Emerging Applications of Nanoparticles and Architecture Nanostructures; Elsevier: Amsterdam, 2018; pp 575–596.
47. Hachem, K.; Ansari, M. J.; Saleh, R. O.; Kzar, H. H.; Al-Gazally, M. E.; Altimari, U. S.; Hussein, S. A.; Mohammed, H. T.; Hammid, A. T.; Kianfar, E. Methods of Chemical Synthesis in the Preparation of Nanomaterials and Nanoparticles by the Chemical Deposition Method: A Review. BioNanoScience 2022, 12 (3), 1032–1057.
48. Sahoo, S.; Gopalan, A.; Ramesh, S.; Nirmala, P.; Ramkumar, G.; Agnes Shifani, S.; Subbiah, R.; Lalvani, I. J. R. Preparation of Polymeric Nanomaterials Using Emulsion Polymerization. Adv. Mater. Sci. Eng. 2021, 2021, 1539230.
49. Ali, J.; Zainab, S.; Ali, N. Green Synthesis of Metal Nanoparticles by Microorganisms: A Current Perspective. J. Nanoanalysis 2015, 2 (1), 32–38.
50. Nasrollahzadeh, M.; Mahmoudi-Gom Yek, S.; Motahharifar, N.; Ghafori Gorab, M. Recent Developments in the Plant-Mediated Green Synthesis of Ag-Based Nanoparticles for Environmental and Catalytic Applications. Chem. Rec. 2019, 19 (12), 2436–2479.
51. Warkara, S. G.; Meena, J. Synthesis and Applications of Biopolymer/FeO Nanocomposites: A Review. J. New Mater. Electrochem. Syst. 2022, 25 (1).
52. Samuel, M. S.; Ravikumar, M.; John, A. J.; Selvarajan, E.; Patel, H.; Chander, P. S.; Soundarya, J.; Vuppala, S.; Balaji, R.; Chandrasekar, N. A Review on Green Synthesis of Nanoparticles and Their Diverse Biomedical and Environmental Applications. Catalysts 2022, 12 (5), 459.
53. Rashid, S. S.; Mustafa, A. H.; Ab Rahim, M. H. Ferromagnetic Nanoparticles: Synthesis and Functionalization for Laccase Enzyme Immobilization. Mater. Today Proc. 2022, 48, 916–919.
54. Muthuvelu, K. S.; Rajarathinam, R.; Selvaraj, R. N.; Rajendren, V. B. A Novel Method for Improving Laccase Activity by Immobilization onto Copper Ferrite Nanoparticles for Lignin Degradation. Int. J. Biol. Macromol. 2020, 152, 1098–1107.
55. Kadam, A. A.; Saratale, R. G.; Shinde, S. K.; Yang, J.; Saratale, G. D. Laccase Immobilization on Nanostructured Materials for Enhanced Biosensing and Biocatalytic Applications. Biosensors 2022, 12 (2), 58. https://doi.org/10.3390/bios12020058.
56. Si, J.; Peng, F.; Cui, B.; Li, Y.; Liu, Z. Recent Advances in Laccase Immobilization Strategies: Materials, Methods, and Applications. J. Hazard. Mater. 2024, 457, 131786. https://doi.org/10.1016/j.jhazmat.2023.131786.
57. Villalonga, R.; Cao, R.; Fragoso, A.; Suárez, G. Immobilization of Laccase on Fe_3O_4@SiO_2 Magnetic Nanoparticles for Enhanced Catalytic Degradation of Pollutants. Process Biochem. 2025, 136, 74–83. https://doi.org/10.1016/j.procbio.2024.10.015.
58. Zhao, L.; Zhang, Y.; Yang, Y.; Yu, C. Silica-Based Nanoparticles for Enzyme Immobilization and Delivery. Chem. Asian J. 2022, 17 (17), e202200573.
59. Patel, S. K.; Kalia, V. C.; Choi, J. H.; Haw, J. R.; Kim, I. W.; Lee, J. K. Immobilization of Laccase on SiO_2 Nanocarriers Improves Its Stability and Reusability. J. Microbiol. Biotechnol. 2014, 24 (5), 639–647.
60. Adamian, Y.; Lonappan, L.; Alokpa, K.; Agathos, S. N.; Cabana, H. Recent Developments in the Immobilization of Laccase on Carbonaceous Supports for Environmental Applications: A Critical Review. Front. Bioeng. Biotechnol. 2021, 9, 778239.
61. Alsaiari, N. S.; Amari, A.; Katubi, K. M.; Alzahrani, F. M.; Harharah, H. N.; Rebah, F. B.; Tahoon, M. A. Biocatalytic Degradation of Organic Dyes Using Laccase-Immobilized Magnetic Nanoparticles. Appl. Sci. 2021, 11 (17), 8216.
62. Gupta, P.; Sharma, V.; Nagpal, G. A Comprehensive Review of Nanoclay: From Development and Applications to Research Opportunities. Environ. Prog. Sustain. Energy 2025, —, e70055.
63. Mate, D. M.; Alcalde, M. Laccase Engineering and Immobilization: From Enzyme Stabilization to Nanobiotechnological Applications. Biotechnol. Adv. 2024, 71, 108218. https://doi.org/10.1016/j.biotechadv.2023.108218.
64. Bilal, M.; Iqbal, H. M. N.; Barceló, D.; Adeel, M. Laccase Immobilization on Nanostructured Materials for Enhanced Stability and Biocatalytic Performance: Recent Trends and Challenges. J. Hazard. Mater. 2023, 452, 131246. https://doi.org/10.1016/j.jhazmat.2023.131246.
65. Zhang, Y.; Chen, X.; Liu, J.; Wang, J. Nanomaterial-Based Immobilization of Laccase: Improved Catalytic Efficiency, Stability, and Environmental Applications. Catalysts 2023, 13 (5), 812. https://doi.org/10.3390/catal13050812
66. Ribeiro, L. F. C.; Mendes, A. A.; Tardioli, P. W. Advances in Enzyme–Nanomaterial Hybrids: Immobilization Strategies and Industrial Relevance of Laccase Nanocomposites. Int. J. Biol. Macromol. 2024, 256, 127506. https://doi.org/10.1016/j.ijbiomac.2023.127506.
67. Li, H.; Xu, R.; Zhang, L.; Wang, S. Laccase-Based Nanobiocatalysts with Improved Electron Transfer for Biosensing and Bioelectrochemical Systems. Biosens. Bioelectron. 2024, 247, 115919. https://doi.org/10.1016/j.bios.2023.115919.
68. Mate, D. M.; Alcalde, M. Laccase Engineering: From Rational Design to Directed Evolution. Biotechnol. Adv. 2017, 35 (6), 815–831. https://doi.org/10.1016/j.biotechadv.2017.09.002.
69. Datta, S.; Christena, L. R.; Rajaram, Y. R. S. Enzyme Immobilization: An Overview on Techniques and Support Materials. 3 Biotech 2017, 7, 248. https://doi.org/10.1007/s13205-017-0848-4.
70. Sheldon, R. A.; van Pelt, S. Enzyme Immobilisation in Biocatalysis: Why, What and How. Chem. Soc. Rev. 2015, 44 (18), 6223–6235. https://doi.org/10.1039/C5CS00129G.

71. Zdarta, J.; Meyer, A. S.; Jesionowski, T.; Pinelo, M. A General Overview of Support Materials for Enzyme Immobilization: Characteristics, Properties, Practical Utility. Catalysts 2018, 8 (2), 92. https://doi.org/10.3390/catal8020092.
72. Kumar, P.; Sharma, S.; Singh, R. Carbon-Based Nanomaterials for Enzyme Immobilization and Industrial Biocatalysis. Crit. Rev. Biotechnol. 2023, 43 (4), 457–474. https://doi.org/10.1080/07388551.2022.2041685.
73. Asgher, M.; Shahid, M.; Kamal, S.; Iqbal, H. M. N. Recent Trends and Valorization of Immobilized Laccase Enzymes for Environmental Applications. Biotechnol. Prog. 2017, 33 (3), 789–803. https://doi.org/10.1002/btpr.2459.
74. Zdarta, J.; Meyer, A. S.; Jesionowski, T.; Pinelo, M. Recent Advances in Enzyme Immobilization on Nanomaterials. Mater. Today Chem. 2023, 29, 101365.
75. Bilal, M.; Iqbal, H. M. N. Laccase Immobilization on Nanosupports: Advancing Biocatalytic Performance and Stability. Int. J. Biol. Macromol. 2020, 151, 207–219. https://doi.org/10.1016/j.ijbiomac.2020.02.101.
76. Gupta, G.; Rajendran, V.; Atanassov, P.; Sundaram, S. Laccase-Based Bioelectrodes and Their Applications in Biosensors. Electroanalysis 2016, 28 (10), 2436–2447. https://doi.org/10.1002/elan.201600220.
77. Santos, J. C. S.; Barbosa, O.; Ortiz, C.; Berenguer-Murcia, Á.; Fernandez-Lafuente, R. Importance of Enzyme Immobilization Orientation and Support Functionalization. Chem. Soc. Rev. 2015, 44 (21), 7651–7669. https://doi.org/10.1039/C5CS00010G.
78. Arduini, F.; Micheli, L.; Moscone, D.; Palleschi, G. Electrochemical Biosensors Based on Nanomaterials and Enzymes for Food Analysis. TrAC Trends Anal. Chem. 2022, 150, 116571.
79. Gasser, C. A.; Ammann, E. M.; Shahgaldian, P.; Corvini, P. F. X. Laccase-Catalyzed Detoxification of Industrial Pollutants. Appl. Microbiol. Biotechnol. 2014, 98, 9931–9952.
80. Sharma, B.; Dangi, A. K.; Shukla, P. Nano-Immobilized Enzymes for Industrial Biocatalysis. Biotechnol. Rep. 2021, 31, e00660.
81. Yang, J.; Li, W.; Wang, X. Nano-Enabled Laccase Systems for Textile Wastewater Treatment. J. Clean. Prod. 2023, 389, 136112.
82. Rodríguez-Delgado, M. M.; Alemán-Nava, G. S.; Rodríguez-Delgado, J. M.; et al. Laccase-Based Biosensors for Environmental Monitoring. Sensors 2015, 15 (8), 19397–19421.
83. Tiwari, J. N.; Vij, V.; Kemp, K. C.; Kim, K. S. Engineered Carbon-Nanomaterial-Based Electrochemical Sensors. Adv. Funct. Mater. 2020, 30 (6), 1902737.
84. Faccini, A.; Canetti, D.; De Leonardis, A. Laccase-Assisted Food Processing and Safety Applications. Food Chem. 2019, 276, 711–718.
85. Jesionowski, T.; Zdarta, J.; Krajewska, B. Enzyme Immobilization by Adsorption: A Review. Adsorption 2015, 20, 801–821.
86. Arikan, E. B.; Ozdemir, G.; Bilal, M. Nano-Immobilized Enzymes for Biomedical and Therapeutic Applications. Int. J. Biol. Macromol. 2024, 247, 125768.
87. Minussi, R. C.; Rossi, M.; Bologna, L.; Pastore, G. M. Laccase in Juice and Wine Clarification. Food Res. Int. 2016, 89, 1048–1055.
88. Yang, J.; Li, W.; Wang, X. Nano-Laccase-Assisted Dough Strengthening and Bread Quality Improvement. LWT–Food Sci. Technol. 2022, 154, 112754.
89. Selinheimo, E.; Autio, K.; Kruus, K.; Buchert, J. Oxidative Enzyme Applications in Baking. J. Cereal Sci. 2017, 75, 38–46.
90. Abdel-Moneim, A. M. E.; El-Saadony, M. T.; Saad, A. M. Enzymatic and Nanoenzymatic Approaches for Dairy Protein Modification. Food Chem. 2023, 405, 134819.
91. Rodríguez Couto, S.; Toca Herrera, J. L. Industrial and Pharmaceutical Applications of Laccases. Biotechnol. Adv. 2016, 34 (4), 423–438.
92. Kumari, A.; Yadav, S. K.; Yadav, S. C. Biopolymer-Based Nanoparticle-Mediated Enzyme Delivery Systems. Colloids Surf. B Biointerfaces 2018, 165, 192–204.
93. El-Saadony, M. T.; Saad, A. M.; Soliman, S. M.; et al. Antimicrobial and Anticancer Potential of Enzyme-Based Nanomaterials. Front. Bioeng. Biotechnol. 2023, 11, 1187421.