microorganisms

MDPI

Review

Fungal Laccase Production from Lignocellulosic Agricultural Wastes by Solid-State Fermentation: A Review

Feng Wang [1,2,*], Ling Xu [1,2], Liting Zhao [3,4], Zhongyang Ding [3,4,*], Haile Ma [1,2] and Norman Terry [5]

1 School of Food and Biological Engineering, Jiangsu University, Zhenjiang 212013, China; lxu@ujs.edu.cn (L.X.); mhl@ujs.edu.cn (H.M.)
2 Institute of Food Physical Processing, Jiangsu University, Zhenjiang 212013, China
3 Key Laboratory of Carbohydrate Chemistry and Biotechnology, Ministry of Education, School of Biotechnology, Jiangnan University, Wuxi 214122, China; 7160201043@vip.jiangnan.edu.cn
4 Jiangsu Provincial Research Center for Bioactive Product Processing Technology, Jiangnan University, Wuxi 214122, China
5 Department of Plant and Microbial Biology, University of California, Berkeley, CA 94720, USA; nterry@berkeley.edu
* Correspondence: fengwang@ujs.edu.cn (F.W.); zyding@jiangnan.edu.cn (Z.D.); Tel./Fax: +86-511-8878-0201 (F.W.); +86-510-8591-8221 (Z.D.)

Received: 11 November 2019; Accepted: 6 December 2019; Published: 9 December 2019

Abstract: Laccases are copper-containing oxidase enzymes found in many fungi. They have received increasing research attention because of their broad substrate specificity and applicability in industrial processes, such as pulp delignification, textile bleaching, phenolic removal, and biosensors. In comparison with traditional submerged fermentation (SF), solid-state fermentation (SSF) is a simpler technique for laccase production and has many advantages, including higher productivity, efficiency, and enzyme stability as well as reduced production costs and environmental pollution. Here, we review recent advances in laccase production technology, with focus on the following areas: (i) Characteristics and advantages of lignocellulosic agricultural wastes used as SSF substrates of laccase production, including detailed suggestions for the selection of lignocellulosic agricultural wastes; (ii) Comparison of fungal laccase production from lignocellulosic substrates by either SSF or SF; (iii) Fungal performance and strain screening in laccase production from lignocellulosic agricultural wastes by SSF; (iv) Applications of laccase production under SSF; and (v) Suggestions and avenues for future studies of laccase production by fungal SSF with lignocellulosic materials and its applications.

Keywords: laccase; solid-state fermentation; lignocellulosic agricultural wastes; application

1. Introduction

Laccases (EC 1.10.3.2) are multicopper oxidoreductase enzymes with the ability to oxidize a broad range of structurally differing substrates (e.g., monophenols, polyphenols, aminophenols, methoxyphenols, aromatic amines) along with the simultaneous reduction of molecular oxygen to water [1,2]. They were first described in *Toxicodendron vernicifluum* (Japanese lacquer tree; formerly called *Rhus vernicifera*) and subsequently in a wide variety of organisms, including bacteria, insects, and fungi (notably, white rot fungi) [3]. Laccases display broad substrate specificity and are applied in many industrial and environmental technology areas, including in textile effluents (decolorization, detoxification), paper production (biobleaching, biopulping), and biopharmaceuticals (transformation of antibiotics, steroids) [4–6]. Their ability to remove xenobiotic substances and generate polymeric

products makes them useful in bioremediation processes [7,8]. However, their application in biotechnological processes has been limited because of high production costs resulting from low enzyme activity and low yield. Increasing research attention has been paid to effective laccase production strategies associated with increased activity and reduced cost [9,10].

Laccase production is highest for white rot fungi (Basidiomycetes). In the past, submerged fermentation (SF) has been the most commonly used technology for the production of most enzymes, including laccase [11]. SF results in homogeneous distribution of nutrients, which can result in the full contact and absorption of nutrients by cultured microorganisms. However, there has been a trend during the past decade towards the increasing use of solid-state fermentation (SSF) for the production of certain enzymes [7,12]. In SSF, the desired microorganism is grown in the near or complete absence of free water, using an inert or natural substrate as solid support [13,14]. In comparison with SF, SSF more closely simulates the microorganism's natural environment and has numerous advantages such as being a simpler technique, having lower energy consumption and less pollution as well as higher product recovery [15–18]. However, the common drawbacks of SSF have also been observed in laccase production, including difficulties in scaling up and large batch-to-batch variation [19,20]. Substrates used for SSF are typically lignocellulosic wastes that contain carbon, nitrogen, and various mineral elements (K, Mg) needed for microorganism growth, enzyme production, and metabolite synthesis [21]. Fungi, particularly white rot fungi, have a strong ability to degrade lignin and cellulosic substances. Many research groups have attempted to improve laccase production by screening fungal strains based on the choice of lignocellulosic waste and optimization of the medium [22–24].

Worldwide, ~200 billion tons of agricultural waste are generated each year [25]. Lignocellulose, the major source of agricultural waste, is regarded as a low-cost nutrient substitute for laccase production in SSF systems in comparison with other complex nutrient sources [26]. Lignocelluloses contain three major polymers (cellulose, hemicellulose, lignin) and can be directly depolymerized by laccase as natural substrates [22,27]. Besides serving as a nutrient source, certain lignocellulosic wastes contain natural inductive substances, such as flavonoids and phenolic compounds, which can be applied directly in SSF to enhance fungal laccase production [28–30]. The majority of agricultural waste is used as livestock feed, fuel, and in paper production, or (regrettably) burned or left to rot, contributing to environmental pollution and resource waste. Efficient bioconversion of lignocellulose is, thus, an important goal in agricultural waste resource utilization. One review highlighted the potential of lignocellulosic materials to be used in different applications involving biofuels, enzymes, chemicals, pulp and paper, animal feed, and composites [31]. A variety of lignocellulosic residues associated with agriculture (e.g., sunflower seed hulls, sugarcane bagasse, sawdust waste, apple pomace, cotton stalks) have been studied in this regard [20,32–36]. There have been more than 20 review papers published since 2010, and different topics about laccase have been summarized and discussed, including characteristics, expression and regulation, molecular design, production, and applications. Among these publications, Rodriguez-Couto reviewed the production of ligninolytic enzymes by SSF, discussed an SSF bioreactor design for ligninolytic enzyme fermentation, and compared the laccase production of SF and SSF at the reactor scale [19,37]. The physicochemical characteristics and composition of agroindustrial biomass were summarized by Iqbal et al. (2014), where laccase production from lignocellulosic materials and its application in delignification were included [38]. Recently, the regulation of laccase expression and laccase-mediated bioremediation of pharmaceuticals were highlighted by Yang et al. (2017) [39], and the potential of the strategies used for laccase enhancement were updated by Bertrand et al. (2017) [40]. Here, we review the recent status of laccase production technology using lignocellulosic agricultural wastes by fungal SSF, including characteristics and selection of substrates, comparison of SSF and SF in laccase production, screening of fungal strains, and potential applications of laccase production by SSF.

2. Laccase Production from Lignocellulosic Agricultural Wastes by SSF

2.1. Lignocellulosic Agricultural Wastes

Agricultural waste provides carbon and nitrogen nutrients, which are excellent substrates for fungal growth and laccase production in SSF [41,42]. In general, the most abundant and least expensive lignocellulosic agricultural waste source is crop straw (e.g., from rice, wheat, or corn). Another abundant source (~180×10^6 tons/year worldwide) is bagasse, the dry fibrous material remaining after the extraction of juice from sugarcane [43]. Lignocellulose is composed mainly of cellulose, hemicellulose, and lignin. Lignocellulose composition of agricultural waste varies depending on the source and should be evaluated before the waste is used as a fermentation substrate. The compositions of lignocellulosic wastes commonly used in SSF were summarized by Rodriguez-Couto and Sanromán (2005) [37]. Besides lignocellulose, certain agricultural wastes (e.g., banana skin) are rich in sugars that are also easily metabolized by microorganisms or can be used as a supporting material because of their physical integrity [44]. Therefore, lignocellulosic agricultural waste should first act as the support for the ligninolytic enzyme production, and it can then be a substrate provider for microbes depending on its components. Besides the typical composition of cellulose, hemicellulose, and lignin, the other components, such as sugar, crude protein, and metal ions, should also be analyzed before the lignocellulosic agricultural waste is utilized. This is because those components can affect fungal growth and enzyme production.

Lignocellulose can be degraded by ligninolytic enzymes such as cellulase, hemicellulase, manganese peroxidase (MnP), laccase (Lac), and lignin peroxidase (LiP) [45]. In lignocellulose, cellulose is embedded in hemicellulose and lignin as long fibers. Lignin is a structurally complex aromatic heteropolymer and may promote impermeability by maintaining structure and thereby inhibit utilization of lignocellulose in SSF [46,47]. It was reported that the degradation of cellulose, hemicellulose, and lignin in lignocellulosic agricultural waste was less than 40% after laccase production by SSF [48]. In lignocellulosic agricultural waste, lignocellulose was not the dominant carbon source for laccase production by SSF. Therefore, an exogenous carbon source was often added to the culture medium of laccase SSF, or the other carbon sources in lignocellulosic agricultural waste could also be used as supplementary material.

Laccase-producing microbial strains are able to effectively degrade lignin because they release a powerful extracellular lignin-degrading enzyme system [49]. Lignocellulosic agricultural wastes are valuable substrates for laccase production as they have a high proportion of raw materials and contribute to improved efficiency. There is abundant evidence that lignin stimulates laccase production [50,51]. On the other hand, laccase production may be adversely affected by excessive lignin content. Gómez et al. found that laccase levels in barley bran cultures (1799.6 U/L) were almost 2-fold higher than those in chestnut shell cultures (959.8 U/L) [52]. Chen et al. evaluated residues of seven plant species as substrates for laccase production and observed maximal laccase activity (10,700 IU/g substrate) in rice straw cultures (lignin 10%–15% *w*/*w*) [22]. Laccase activity was also high (7593.3 IU/g substrate) in medium supplemented with water hyacinth (lignin 3.5% *w*/*w*). Moreover, several studies have shown that lignocellulose stimulates laccase production, presumably because of its high cellulose content. Srinivasan et al. reported stimulation of laccase production by cellulose in *Phanerochaete chrysosporium* [53]. Lignocellulosic residues shown to be effective substrates for laccase production in SSF are summarized in Table 1. Lignocellulosic waste is a good candidate for laccase production by SSF because it can function as support, a nutrient source, and as an inducer.

Table 1. Laccase production by different white rot fungi grown on different natural supports under solid-state fermentation (SSF) conditions.

Fungus	Support	Cultivation Vessel	Period (Day)	Enzyme Substrate	Laccase Activity	Reference
Pleurotus ostreatus	Sugarcane bagasse	Erlenmeyer flask (250 mL)	5	ABTS **	151.6 U/g	[33]
Ganoderma lucidum	Rice husks and straw	Polyethylene bags (2 L)	10	ABTS	10.927 U/g	[20]
	Sunflower seed hulls		5	ABTS	16.442 U/g	
Trametes pubescens	Sunflower seed	Immersion bioreactor (–)	21	ABTS	4000–6000 UI/L	[54]
Pseudolagarobasidium acaciicola	Wheat bran	Erlenmeyer flask (250 mL)	12	ABTS	535,000 U/g	[4]
Coriolopsis gallica	Sawdust waste	Erlenmeyer flask (250 mL)	15	2,6-Dimethoxyphenol	4880 U/L	[32]
Pleurotus ostreatus	Ammoniated corn straw	Fermentation tray (10.8 L)	20	ABTS	661 U/g	[55]
Trametes versicolor	Wheat straw	Erlenmeyer flask (250 mL)	9	ABTS	6364 ± 64 U/kg	[56]
	Oil palm trunk	Erlenmeyer flask (2 L)	28	2,6-Dimethoxyphenol	218.66 U/L	[57]
	Olive leaf	Erlenmeyer flask (250 mL)	12	ABTS	276.62 ± 25.67 U/gds	[58]
	Wheat bran and corn straw	Erlenmeyer flask (250 mL)	10	ABTS	32.09 U/g ds	[6]
	Steam-exploded pretreated cornstalk	Erlenmeyer flask (250 mL)	13	Catechol	2765.81 U/g	[48]
	Corncob waste	Erlenmeyer flask (50 mL)	14	ABTS	8.49 U/gdm	[14]
	Corn silage	Erlenmeyer flask (250 mL)	4	ABTS	180.2 U/L	[59]
	Apple pomace	Erlenmeyer flask (500 mL)	14	ABTS	49.16 ± 4.5 U/gds	[34]
	Pulp and paper solid waste				52.4 ± 2.2 U/gds	
	Alfa fibers				14.26 ± 0.8 U/gds	
	Sugarcane leaves	Erlenmeyer flask (250 mL)	17	Guaiacol	165 U/g	[60]
	Wheat straw				150 U/g	
	Rice straw				145 U/g	
Pleurotus pulmonarius	Wheat bran	Erlenmeyer flask (250 mL)	10	ABTS	2860 ± 250 U/L	[61]
	Pineapple peel				2450 ± 230 U/L	
	Bagasse				2100 ± 270 U/L	
Cerrena unicolor	Spent mushroom substrate	Glass tubes (141 mL)	20	Syringaldazine	44,363.22 U/g	[62]
	Oat husks	Mixed bench-scale bioreactor (20 L)	19	ABTS	28.2 U/g DM *	[63]
Aspergillus niger	Prickly palm cactus husk	Erlenmeyer flask (–)	12	Syringaldazine	9023.67 UI/L	[64]
Funalia trogii	Kudzu vine root	Erlenmeyer flask (250 mL)	14	ABTS	42.5 IU/g	[15]
Daedalea flavida and *Phlebia radiata*	Cotton stalks	Petri plate (–)	15	ABTS	14.19 ± 0.85 IU/g	[35]
Coriolus versicolor	Sweet sorghum bagasse	Erlenmeyer flask (250 mL)	16	ABTS	205.01 ± 10.1 U/g	[50]
Rhizopus sp.	Prickly palm cactus husk	Erlenmeyer flask (–)	3	Syringaldazine	1.65 U/g	[65]
Marasmiellus palmivorus	Pineapple leaves	Erlenmeyer flask (250 mL)	5	ABTS	667.4 ± 13 IU/mL	[10]
Pycnoporus sanguineus	Wheat bran and corncob	Erlenmeyer flask (250 mL)	8	ABTS	138.6 ± 13.2 U/g	[5]
Trametes versicolor	Brewer's spent grain	Erlenmeyer flask (500 mL)	12	ABTS	10,108 ± 157.4 IU/g	[66]
		Plastic tray bioreactor (12 L)			13,506.2±138.2 IU/g	
Trametes hirsuta	Pine wood chips/orange peels (1:1)	Rotary drum bioreactor (20 L)	35	ABTS	10498 U/L *	[67]

* The enzyme activity was calculated based on the original data from the reference; ** ABTS: 2,2′-azino-bis-(3-ethylbenzthiazoline-6-sulfonic acid); –: No information of the vessel volume was provided in the reference.

2.2. Supplemental Nutrients

Lignocellulosic wastes are useful substrates in fermentation processes, but supplemental nutrients (carbon and nitrogen sources) are required to promote fungal growth during early stages [3]. Studies of laccase production have generally used defined media [68]. Carbon sources in the medium play an important role in laccase production because they can promote mycelial growth and induce transcription of the laccase gene [69]. In *P. chrysosporium*, ligninolytic gene expression was triggered only by depletion of carbon-based nutrients [68]. Tavares et al. showed that initial glucose concentration was the factor most important for laccase production in *Trametes versicolor*, and that initial concentration of 11 g/L resulted in maximal laccase production (11,403 U/L) [70]. In recent years, there has not been much research on the effect of the carbon source on laccase production because its influence matrix is basically clear. However, the impact of nitrogen sources is highly controversial for the production of ligninolytic enzymes from different organisms [71]. Some strains require excess nitrogen to protect the enzyme, while others are only induced by nitrogen starvation [72]. From some studies, we can also see that organic nitrogen is more conducive to the production of laccase than inorganic nitrogen [33,58]. The carbon/nitrogen ratio is one of the key parameters for laccase production in lignocellulosic wastes. The optimal C/N ratio in laccase SSF varies due to differences in lignocellulosic resources and fungal strains [5,14,62]. Mineral supplements are also necessary for the growth of microorganisms. In particular, elemental phosphorus is crucial because it is part of the backbone of DNA, the carrier and transmitter of genetic information [3]. In the optimization of SSF laccase production by *Coriolopsis caperata*, statistical analysis of eight selected factors showed that KH_2PO_4 alone affected the overall production of laccase by 2.84% [3]. The dependence of laccase activity in different fungal species on the carbon and nitrogen source in the medium is shown in Table 2, which indicates that laccase production can be improved by the modification of supplemental nutrients, particularly carbon/nitrogen sources.

Table 2. Effect of carbon and nitrogen source on laccase production using lignocellulosic agricultural wastes by SSF.

Species	Support	Carbon/Nitrogen Source	Concentration	Laccase Activity	Reference
Pleurotus ostreatus	Dry, ground mandarin peels Grapevine sawdust	Glucose Maltose	0.333 g/mL	4.80 ± 0.08 U/L 6.9 ± 0.4 U/L	[73]
Pseudolagarobasidium acaciicola	Decayed wood	Glucose	0.775 g/L 0.6625 g/L 0.55 g/L	379,000 U/gs 535,000 U/gs 479,000 U/gs	[4]
P. ostreatus	Sawdust	Glucose	5 g/L 10 g/L 15 g/L	10.90 ± 0.36 U/g dry wt 19.42 ± 0.14 U/g dry wt 26.00 ± 0.98 U/g dry wt	[74]
P. ostreatus	Sugarcane bagasse	Yeast extract $(NH_4)_2SO_4$	6.4 g/L 2.5 g/L	151.6 U/g 9.942 U/g	[33]
Trametes hirsuta	Kiwifruit	NH_4Cl	0.150 g/L 0.400 g/L 0.600 g/L	1079.8–1139.8 U/L * 359.9–479.9 U/L * 839.8–959.8 U/L *	[75]
P. ostreatus	*E. benthamii* and bagasse of cassava	$(NH_4)_2SO_4$ Saltpetre soybean	0.111 g/gs	10.11 ± 1.04 U/g ds 13.0 ± 1.29 U/g ds 23.32 ± 2.33 U/g ds	[43]
Trametes versicolor	Olive leaves	NH_4NO_3 Yeast extract	20 g/L 1%	38.47 ± 3.12 U/gds 276.62 ± 25.6 U/gds	[58]
Daedaleopsis confragosa *D. tricolor*	Cherry sawdust	Peptone	0.9 mM	20,204.8 U/L 16,501.7 U/L	[76]

*: The enzyme activity was calculated based on the original data from the reference.

2.3. Potential Inducers

Certain lignocellulosic residues contain natural inducers that have the potential to enhance laccase productivity, reduce costs, and reduce pollution in SSF. In SSF of *Funalia trogii*, Kudzu vine root, in which flavonoids are the major phenolic compounds, is an effective substrate for laccase production (42.5 IU/g) [15]. In the SSF of *T. versicolor*, oleuropein and hydroxytyrosol from olive leaves acted as major inducers to increase laccase production (276.62 ± 25.67 U/g dry matter) [58]. The other flavonoid-rich agroindustrial residues, such as tata acti green tea leaves, 1% pulp and paper industry effluent (agro based), and 1% wine made from *Syzygium cumini*, have been demonstrated to improve the laccase production by SSF [29]. The phenolic compounds in steam-exploded cornstalk were beneficial for the induction of laccase expression by SSF [48]. Besides the natural inducers present in agricultural wastes, many single inducers have been added to media to increase laccase yield [50]. Aromatic inducers stimulated response signal recognition in white rot fungi, resulting in an intense biological response that induced secondary metabolism, leading to increased laccase concentration [77]. Other compounds, such as Tween 80 and veratryl alcohol, were used to enhance laccase production [34]. Xylidine was reported to increase laccase production more efficiently than copper [3]. The well-studied inducers of increased laccase production are summarized in Table 3. Table 3 shows that copper is an excellent inducer for laccase production when dosed as $CuSO_4$ to increase laccase production [78] because laccase is blue copper oxidase, containing four copper atoms per molecule, and the addition of copper may lead to the activation of the metal, resulting in the expression of laccase genes [34]. Unfortunately, most inducers known to date have disadvantages such as toxic effects, high production costs, and environmental pollution. Thus, the search for a natural inducer from the composition of lignocellulosic wastes used as substrates in SSF is a promising approach to address these disadvantages.

To select lignocellulosic wastes for laccase SSF, these key points need to be considered: (i) lignocellulosic wastes should be a suitable support, and potential carbon or nitrogen sources should be available for the fungi if possible; (ii) the composition of lignocellulosic waste, such as the C/N ratio and micro- and macronutrients, should be clear and defined; (iii) any potential inhibitors should be absent from the lignocellulosic waste; (iv) natural inducers are expected to be present in the lignocellulosic waste in addition to the fixed laccase inducer (lignin).

Table 3. Inducers applied in laccase production using lignocellulosic agricultural wastes by SSF.

Strain	Support	Inducer	Inducer Concentration	Laccase Activity	Reference
Pleurotus ostreatus	Bagasse	$CuSO_4$ and ferulic acid	150 µM 2 mM	86.8 U/g 167 U/g	[79]
Trametes versicolor	Apple pomace Pulp and paper solid waste Alfa fibers	$CuSO_4$	3 mmol/kg ds	49.16 ± 4.5 U/gds 52.4 ± 2.2 U/gds 14.26 ± 0.8 U/gds	[34]
Pycnoporus sanguineus	Wheat bran and corncob	$CuSO_4$	50 mmol/L	138.6 ± 13.2 U/g	[5]
Marasmiellus palmivorus	Pineapple leaves	$CuSO_4$	3 mM	627.7 IU/mL	[10]
Daedalea flavida	Cotton stalks	Cu^{2+} Gallic acid	0.5 mM/g	7.74 ± 0.45 IU/g 6.26 ± 0.55 IU/g	[80]
Coriolus versicolor	Sweet Sorghum bagasse	$CuSO_4$ Gallic acid Syringic acid	2.2 µmol/g 4.4 µmol/g 8.8 µmol/g	58.2 ± 4.3 U/g 42.1 ± 3.6 U/g 67.4 ± 7.7 U/g	[50]
Pycnoporus sanguineus	*Eichhornia crassipes* and sawdust	$CuSO_4$ and gallic acid	1.5 mM and 40 mM	32.02 U/g ds	[81]
Trametes versicolor	Corn silage	$CuSO_4$	0.1 mol/dm^3	1539.4 U/dm^3	[59]
Daedaleopsis tricolor	Cherry sawdust	Veratryl alcohol	0.5% *v*/*v*	27,610.92 U/L	[76]

3. Comparison of Laccase Production from Lignocellulosic Agricultural Wastes by SSF or SF

Two types of fungal cultivation have been developed: solid-state fermentation (SSF) and submerged fermentation (SF), both of which are commonly used methods for laccase production [82]. However, problems such as low-volume production and high cost remain unsolved, which hinder the wide application of laccase [48]. To solve these problems, researchers studied laccase production by SSF using lignocellulosic agricultural waste as a substrate (Table 1) because SSF is more compatible with the natural growth of the strain and the lignocellulosic substrates are inexpensive, readily available, and environmentally friendly [10,34]. However, it is well-known that scaling up of SSF still has some difficulties, especially for SSF bioreactors. Rodríguez Couto reviewed the development of SSF bioreactors producing laccase and other ligninolytic enzymes and emphasized the necessity of designing new bioreactors or improving existing bioreactors [19]. In that review, it was also mentioned that the SSF reactor has discontinuities and mass transfer limitations for oxygen. To improve the performance of SSF bioreactors, efforts have been made regarding the design of bioreactors. It was reported that a temporary immersion bioreactor was designed for laccase production from *Trametes pubescens* cultivated in sunflower seed hulls under SFF conditions, and no operational problems were detected in the cultivation [54]. However, the use of bioreactors for SSF is still not widespread, and only a few sterile large-scale solid-state bioreactors have been reported in laccase production by SSF. In recent years, many laccases have been produced by SSF using different lignocellulosic wastes as substrates, but few studies have been conducted on the bioreactor culture (Table 1). As shown in Table 4, laccase activity of 2600.33 ± 81.89 U/g was obtained in the steam-exploded cornstalk against 1241.07 ± 70.93 U/g in the untreated cornstalk [48]. Pretreatment of cornstalks with steam explosion increases the pore volume of the substrate, which facilitates nutrient availability for microbial growth and metabolism in the substrate [48,82,83]. Economou et al. (2017) reported good laccase production of 44,363.22 U/g by SSF using spent mushroom substrate in the culture media [62]. However, this result was obtained using a culture in a glass tube, and further scaled-up experiments were suggested for future study. In order to carry out large-scale laccase production by SSF, culture parameters should be investigated at a large scale, and some adjustments are necessary. Moilanen et al. (2014) found a change in laccase activity obtained for a large-scale laboratory culture [63]. Among the culture parameters, the water content is one of the key points for the scaling up of laccase production by SSF. The evaporation of water in a flask vs. bioreactor generally differs, resulting in varied laccase activity obtained at the different culture scales. A high water content in SSF probably resulted in decreased substrate porosity which, in turn, prevented efficient oxygen penetration [7].

Table 4. Maximal laccase activities obtained by different types of cultivation.

Support	Fungus	Scale of Cultivate	Type of Cultivation	Period	Laccase Activity	Reference
Rice bran	*Ganoderma lucidum*	Erlenmeyer flask (–)	SF SSF	28 d	100.13 U/mL 156.82 U/g	[84]
Wheat bran	*Pleurotus ferulae* co-cultured with *yeast*	Erlenmeyer flask (–)	SF	7 d	10,575 U/L	[85]
Oak sawdust	*Trametes versicolor*	Erlenmeyer flask (–)	SF	7 d	0.8 U/mL	[86]
Wheat bran	*Trametes versicolor*	Erlenmeyer flask (250 mL)	SF SSF	7 d 14 d	0.93 U/mL 1.54 U/mL	[87]
Wheat bran	*Cerrena unicolor*	Stirred bioreactor (120 L)	SF	12 d	416.4 U/mL	[82]
Wheat bran	*Cotylidia pannosa*	Erlenmeyer flask (–)	SF	77 h	13 U/mL	[88]
Food waste	*Ganoderma lucidum*	Bioreactor (15 L)	SF	8 d	54,000 U/L	[89]
Wheat straw	*Ganoderma applanatum*	Erlenmeyer flask (100 mL)	SF SSF	14 d	11,007 U/L 4000 U/L	[90]
Wheat bran	*Pleurotus ferulae*	Erlenmeyer flask (–)	SF	7 d	6832.86 U/L	[91]
Synthetic fiber	*Peniophora cinerea* *Trametes versicolor*	Stirred tank bioreactor (1.6 L)	SF	15 d 8 d	3500 U/L 75 U/L	[92]

* The enzyme activity was calculated based on the original data from the reference; –: No information of the vessel volume was provided in the reference.

Compared to the laccase production under SSF, the application of SF bioreactors seems to be more mature, and laccase production from lignocellulosic materials in SF could be conducted in large-scale bioreactors (Table 4). Lignocellulosic wastes, such as oak sawdust, rice bran, wheat bran, and other food waste, were used as natural, abundant, and cheap sources of nutrients and laccase inducers [85,86,89]. Based on the information in Tables 1 and 4, the culture period for laccase production in SF is generally shorter than that of SSF. It was indicated that food waste was suitable for laccase production, and the maximum laccase activity reached 54,000 U/L in a 15 L bioreactor after 8 days [89]. Laccase produced by *Pleurotus ostreatus* was significantly increased by the addition of apple pomace, where the maximal laccase production was increased to 114.64 U/mL with 2.5% (*w*/*v*) apple pomace compared with 76.81 U/mL of laccase production without apple pomace addition [93]. In fact, the mass proportion of lignocellulosic materials in SF medium was much lower than that in SSF medium, and their dominant role in SF is as an inducer. Although liquid fermentation with lignocellulosic materials reduces the cost of laccase production to a certain extent and is easier to carry out at a large scale, it does not definitively provide better laccase production (Table 4). In the case of laccase production from *Ganoderma applanatum* with rice bran, a maximal laccase activity of 11,007 U/L was achieved on the 14th day by SF, while a maximum laccase activity of 4000 U/L was observed in SSF [90]. It can be calculated that the laccase productivity was 2.75 U/g/day and 0.286 U/g/day under SF and SSF, respectively, where SF had better performance. However, opposing results were also observed. *Ganoderma lucidum* with rice bran under SF produced 100.13 U/mL of laccase after a 28-day incubation, whereas 156.82 U/g of laccase was obtained with the same culture period under SSF [84]. The laccase productivity was calculated to be 3.57 and 5.6 U/g/day, respectively. The enzyme production and incubation period varied in the laccase production from lignocellulosic raw materials by SF or SSF due to different fungal strains and different lignocellulosic substrates.

4. Fungal Strains Effective for Laccase Production from Agricultural Wastes

White rot fungi (species or strains of the phylum Basidiomycota) have a well-documented ability to degrade whole wood with high efficiency and a short fermentation time because they secrete various nonspecific extracellular enzymes (particularly LiP, MnP, and laccase) that break down lignin, cellulose, and hemicellulose [94,95]. There is an increasing research focus on the screening fungal strains suitable for laccase production in SSF.

Laccase production has been reported for numerous genera belonging to the fungal classes Deuteromycetes, Basidiomycetes, Agaricomycetes, and Hyphomycetes (Table 1). On the basis of the enzyme production patterns of an array of white rot fungal strains, Hatakka, in 1994, proposed their division into three categories: (i) lignin-MnP group; (ii) MnP-laccase group; (iii) LiP-laccase group [96]. Kuhar et al., in 2007, proposed the classification of white rot fungi into four groups based on the secretion of (i) laccase and two peroxidases (MnP, LiP); (ii) laccase and one peroxidase; (iii) laccase only; and (iv) peroxidase(s) only [97]. The mechanisms whereby fungi produce these various types of enzymes are unclear and are an important topic for future research.

White rot fungi are the most efficient naturally occurring producers of ligninolytic enzymes [2]. Massive LiP, MnP, and laccase activities were observed during SSF of *Coriolus versicolor* using sweet sorghum bagasse as a substrate [50]. The well-known laccase-producing fungal genera are *Pleurotus* (*P. ostreatus*, *P. pulmonarius*) and *Trametes* (*T. versicolor*, *T. hirsuta*) (Table 1). *T. versicolor* has been intensively studied and commercialized for laccase production. Besides strains of white rot fungi, *Aspergillus niger* is a good producer of all three major ligninolytic enzymes: laccase (9023.67 UI/L), LiP (2,234.75 UI/L), and MnP (8,534.81 UI/L) [64]. Generally, a higher degradation rate of lignocellulose in the SSF support results in a higher yield of ligninolytic enzymes. Therefore, using the degradation rate as an index is helpful for the screening of strains with a high laccase yield. Recently, a simple kinetic model was established to predict temporal fungal enzyme production by SSF on complex substrates, where maximal enzyme activity and incubation time for peak value of enzyme production can be estimated [98]. This strategy can be useful for the screening of fungi producing high yields of laccase

under SSF in specific lignocellulosic agricultural wastes and the selection of suitable lignocellulosic substrates by SSF within a certain fungal strain.

Novel fungi producing ligninolytic enzymes were isolated from different sources, such as sea grass, mud, herbaceous weed, and mangrove forests [99–102]. A marine-derived strain, *Pestalotiopsis* sp. J63, was isolated using a modified medium containing 4 mM guaiacol and exhibited high laccase activity of 10,700 IU/g substrate under SSF [22]. Hariharan and Nambisan isolated 15 fungal strains from dead tree trunks and leaf litters, and *G. lucidum* produced maximal production of ligninolytic enzymes by SSF using pineapple leaves as substrate [103]. Eugenio's group isolated 127 endophytic fungal strains from *Eucalyptus* trees, and 21 fungal strains possessed the ability of ligninolytic enzyme production, including a member of the family Dothioraceae [78].

Utilization of thermotolerant species may be advantageous for SSF because (i) culture is conducted under non-isothermal conditions, and (ii) the high invasive capacity of mycelia and modification of hyphal morphology under changing temperatures are desirable features in SSF [104]. The genus *Trametes* includes some thermotolerant strains, but few of them have been studied at temperatures above 30 °C. *Trametes trogii* LK13 cultured at 37 °C showed enhancement of laccase activity, mycelial growth rate, thermostability, and tolerance to organic solvents [105]. A temperature increase from 40 to 50 °C was detrimental to the fungus *Fusarium incarnatum* and reduced its laccase production [106]. Higher temperatures may also adversely affect metabolic activities of fungi by denaturing key enzymes [4]. The optimum incubation temperature for *Pycnoporus* sp. SYBC-L1 was 35 °C, which is much higher than those observed for most laccase-producing fungi [107]. For several isolated strains, such as *Neofusicoccum luteum*, *Neofusicoccum australe*, *Hormonema* sp., and *Pringsheimia smilacis*, a maximum temperature of 40 °C was recommended for biotechnological applications involving laccase production [78]. The above strains and others similar to them should be investigated further for the screening of desired laccase production properties, such as thermotolerance, a short fermentation period, and water stress tolerance.

Fungal strains with a high laccase yield from lignocellulosic agricultural wastes is another important key point for low-cost laccase production by SSF. Since the higher degradation rate of lignocellulose results in a higher yield of ligninolytic enzyme, potential laccase high-yield strains may be isolated from the natural site with fast composting of lignocellulosic wastes. Although thermotolerant species can prevent the thermogenesis inhibitory effect on cell growth, low laccase yield may also occur due to the deactivation of laccase resulting from high temperatures. Thus, a thermotolerant strain with a high yield of thermostable laccase can be the target of fungal screening for laccase SSF. At present, natural fungal strains are widely used in laccase production from lignocellulosic wastes by SSF. The construction of genetically modified strains is an alternative way to improve the laccase yield of SSF. Overexpression of homologous or heterologous genes encoding laccase and related ligninolytic enzymes may increase the utilization rate of lignocellulosic wastes and improve laccase production [108]. In addition, heterologous expression of thermostable laccase in a thermotolerant white rot fungi provides good potential for large-scale production of laccase by SSF.

5. Application of Laccase Production from Lignocellulosic Wastes by SSF

5.1. Lignin Degradation

An obstacle to the utilization of lignocellulosic waste is the stubbornness of lignin, in which cellulose fibrils are embedded, prevent the conversion of structural polysaccharides into fermentable sugars [109]. In recent reports, physical and chemical pretreatments have been reported to degrade lignin into lignocellulosic biomass within a short time (10–40 min) [110,111]. However, these physical or chemical methods have some disadvantages, including high energy consumption and difficult operating conditions [112,113]. Biological pretreatment is regarded as a better strategy for the delignification process of lignocellulosic biomass, which offers a lower energy cost alternative to chemical pretreatment for the reduction in recalcitrance towards cellulolytic enzymes [114,115]. The

high efficiency of biological pretreatment was because of the simultaneous production of ligninolytic enzyme systems including LiP, MnP, and laccase [116,117]. Most white rot fungi are used as biological reagents in solid-state fermentation to pretreat lignocellulosic waste, where mushroom production, lignin removal, and enzyme production may be carried out at the same time [118]. The effect of different biological pretreatments on structural components of lignocellulosic wastes is depicted in Table 5. In the SFF of *P. ostreatus* in sugarcane bagasse, the lignin content was reduced from 31.89% to 20.79% after 15 days due to laccase production [33]. A total of 27.83% lignin in cotton stalks was degraded by *Daedalea flavida* under SSF [35]. Lignin degradation of 63% and cellulose enrichment occurred in rice straw treated by *Pyrenophora phaeocomes*, with a final laccase activity of 10,859.51 IU/gds [116]. In addition, a maximum of 74% lignin degradation was observed after 30-day cultivation of *Trichoderma viride* in rice straw after optimizing culture parameters [112].

However, in fungal treatment of lignocellulosic wastes, cellulose degradation is generally accompanied by delignification [48]. To maximize the lignin degradation and selectivity, phenolic supplements were applied in the biological pretreatment of sweet sorghum bagasse by *C. versicolor*, and 45.8% lignin degradation was achieved [50]. In addition to investigating the phenolic compounds as laccase inducers, the potential for metal ions to improve the degradation selectivity in biological pretreatment was also examined. It was reported that Fe^{2+} had a stimulating effect on the lignin degradation of wheat straw by *Trametes gibbosa* and kept the cellulose degradation rate low when the Fe^{2+} concentration was 0.5 mM, providing better selectivity in lignin degradation [119]. To achieve a high lignin breakdown and low cellulolytic enzyme production, the fungal strain *C. versicolor* was selected for biological pretreatment of sweet sorghum bagasse, resulting in excellent cellulose recovery [109].

Table 5. Degradation of lignocellulosic structural components in biological pretreatments.

Support	Fungus	Laccase Activity	Degradation Rate (%, *w*/*w*)			Time (Day)	Reference
			Lignin	Cellulose	Hemicellulose		
Sweet sorghum bagasse	*Coriolus versicolor*	205.01 ± 10.1 U/g	45.80	9.81		20	[50]
Rice straw	*Pyrenophora phaeocomes*	10,859.51 IU/gds	63		51	40	[116]
Wheat bran	*Pleurotus ferulae*	68.9 U/L	62.1	35.6	62.6	19	[119]
Wheat bran	*Ganoderma lucidum*	–	58.5	–	–	–	
Sugarcane bagasse	*Trametes versicolor*	–	46	–	–	–	[120]
Rice straw	*Pleurotus ostreatus*	–	52	–	–	–	
Cotton stalk	*Daedalea flavida* and *Phlebia radiata*	~5 IU/g	35.13	–	–	20	[35]
Hardwoods	*Coniophora puteana* and *Trametes versicolor*	1.54 U/mL	–	30.2–38.7	–	42	[87]
Sugarcane bagasse	*Ceriporiopsis subvermispora*	–	48	–	–	60	[113]
Wheat straw	*Phlebia radiata*	–	9.9	–	–	21	[114]
Wheat straw	*Ganoderma applanatum*	3000 U/L	23.5	10	7	14	[90]
Oak sawdust		1800 U/L	20.5	15.05	13		
Steam-exploded cornstalk	*Trametes versicolor*	2600.33 ± 81.89 U/g	7.8	38.1	27.2	16	[48]
Cornstalk		1241.07 ± 70.93 U/g	4.2	23.2	16.9		
Rice straw	*Trametes viride*	–	74	–	–	30	[112]
Wheat straw	*Chaetomium*	–	45	–	–	–	[121]
Pearl millet straw	*globosporum*	–	48	–	–	–	

–: Not determined or no data provided in the reference.

The biological pretreatment of lignocellulosic biomass by SSF is selective, energy-saving, and effective under mild environmental conditions [114]. Biologically pretreated lignocellulosic materials are widely used in different areas, such as feed, pulp, and energy [90,122]. Sugar yield from the enzymatic hydrolysis of lignocellulosic wastes often increases after biological pretreatment due to lignin degradation. It was reported that enzymatic hydrolysis of pretreated sweet sorghum bagasse resulted in a higher fermentable sugar yield, which was ~2.43 times than that of the control [50]. The treatment by *P. phaeocomes* provided a 4.90-times increase in the sugars released from rice straw after hydrolysis [116]. The glucose yield after enzymatic saccharification of the biologically pretreated cotton stalks was increased more than 2-fold compared with that of the untreated control [35]. The delignification of lignocellulosic materials is important for cellulosic biofuel production, ruminant feed digestibility, and formation of paper products [123–125].

5.2. Dye Decolorization

Approximate 1 million tons of dye are produced globally each year, and nearly 50% of the dye is discharged into the waste stream or, eventually, into landfill [126]. The treatment of dye-containing wastewater is receiving serious attention worldwide because dyes can cause cancer, mutagenesis, chromosomal fractures, teratogenicity, and respiratory toxicity [32,127]. A variety of physicochemical methods are available for removing dyes, but they are expensive, inefficient, and not suitable for a wide variety of compounds [4]. Biological systems (microbes and produced enzymes) provide an environmentally friendly method for dye decolorization [128]. Among microorganisms, white rot fungi, a group of laccase-producing fungi, are very effective in decomposing synthetic dyes because the structure of dyes resembles the lignin in wood [129,130]. The maximal decolorization rates of 13.6 μmol/h/U laccase for reactive black 5 and 22.68 μmol/h/U laccase for reactive orange 16 were obtained by using the filtrate of *Cyathus bulleri* cultured on wheat bran [126]. The decolorization of malachite green by laccase from *Ganoderma* sp. reduced its toxicity and made it amenable for use in fungal growth [127]. Based on the reported studies, the factors affecting the decolorization of dyes included dye concentration, enzyme dosage, decolorization time, and intermediates, etc. Table 6 shows the effect of laccase produced by SSF on dye decolorization. The degree of decolorization may depend on the reaction rate, which is directly related to the dye's structure as well as its enzymatic activity and properties [131].

Table 6. Application of laccase produced by SSF in dye decolorization.

Strain	Support for SSF	Dye	Dye Concentration (mg/L)	Laccase Concentration	Time (h)	Decolorization Rate (%)	Reference
Pseudolagarobasidium acaciicola	Wheat bran	Violet P3P	100	10,000 U/mL	24	97.2	[4]
		Green ME4BL	100	20,000 U/mL		80.3	
		Blue 3R	100	10,000 U/mL		91.3	
Ganoderma sp.	Wheat bran	Malachite green	100	30 U/mL	16	~100	[127]
			200		20	~100	
			300		24	72	
			400		28	62	
			500		32	55	
Coriolopsis gallica	Sawdust	Reactive black	50	–	24	67	[32]
		Acid Orange 51	50			75	
Pycnoporus sanguineus	Wheat bran and corncob	Bromophenol blue	25	5 U/mL	2	90	[5]
		Remazol brilliant blue R	100			80	
		Reactive blue 4	100			60	
Trametes pubescens	Sunflower-seed shells	Remazol brilliant blue R	133.33	100 U/L	2	79.4	[54]
Trametes versicolor	Brewer's spent grain	Methyl green	7.5	100 U/L	24	87.7	[66]
		Aniline blue	25			78.48	
Ganoderma lucidum	Peach palm	Remazol brilliant blue R	50	53.94 U/L	32	93.97	[132]

–: No data provided in reference.

Although enzymatic treatments have many advantages, their decolorization time is generally long due to deactivation of the enzyme. Therefore, the shortcomings of physical, chemical, and biological methods have stimulated interest in developing a combined approach to minimize dye contamination of water and avoid secondary effects [14]. The adsorption process by lignocellulosic materials may be an alternative method for removing dyes from effluents [32]. Several studies have shown the potential for adsorption of different lignocellulosic materials [95,133]. The combination of the adsorption and the biological decolorization by SSF is likely to be a suitable method for dye removal and laccase production. Red 40 dye was adsorbed onto a low-cost waste product, followed by degradation by *T. versicolor* under SSF, and the maximum dye degradation was 96.04% [14]. Besides the above strategy, the lignocellulosic substrates after laccase production by SSF can also be good catalysts and adsorbents for dye decolorization. Since there is a low water content in SSF substrates, the fermented substrates can be dried for future application and stored for a long time. Through this method, part of the produced laccase will be immobilized on the fermented substrates, and the lignocellulosic material became more porous after SSF. Therefore, the stable immobilized laccase on the lignocellulosic support with a high specific surface area will be a good candidate for the treatment of dye wastewater. In our recent research, the dried culture residues from *T. versicolor* under SSF with tea residues exhibited high efficiency and good reusability in dye decolorization [134].

5.3. Phenolic Compound Degradation and Others

White rot fungi and laccase have shown great potential in treating phenolic compounds [135]. Bisphenol A (BPA) degradation was found to be accompanied by laccase production, and BPA can induce laccase. During the degradation of BPA by *T. versicolor* under SSF, laccase activity increased rapidly from day 6 to day 10 compared with the untreated control [6]. In addition, laccase-producing fungi were also used to remove other phenolic compounds. Phenol (1 mg/g) was completely degraded by *Penicillium simplicissimum* within 3 days [136]. *Hericium erinaceus* showed 47% total phenol decay associated with laccase and manganese peroxidase activities when it was cultured in olive mill wastewater, and a good mushroom yield was obtained from *H. erinaceus* SSF in olive mill byproducts [137].

Besides the above applications, there are other applications for the SSF of lignocellulosic materials. In fact, other enzymes or target metabolites can be produced simultaneously during the laccase production of SSF from lignocellulosic substrates. In addition to laccase, a bioflocculant and lignocellulase were also obtained in solid-phase-fermented oil palm trunks by *C. versicolor* [57]. Laccase produced from SSF was also used in the synthesis of gold nanoparticles [138].

6. Outlook

(1) Lignocellulosic agricultural wastes have been widely used in fungal laccase production by SSF due to their low cost and good prospects. Although different lignocellulosic wastes were tested for laccase production by fungi, the principles for the selection of lignocellulosic substrates are lacking. Since the main components of lignocellulosic substrates (lignin, cellulose, and hemicellulose) can be used as nutrients and inducers for fungal laccase production, the relationship between the main components and laccase production should be established and, at the same time, the mechanism may be revealed. This will be beneficial for the substrate selection of laccase SSF with lignocellulosic agricultural byproducts, where better substrates can be obtained at low cost (fewer selection experiments) and with high efficiency.

(2) Many natural inducers are present in lignocellulosic agricultural wastes. Hence, a possible direction for future research involves the exploration of natural inducers with high induction efficiency in relation to laccase production by SSF. In addition, the induction mechanism should be investigated for the high-efficient inducer, allowing better and cheaper inducers to be developed for the synthesis of laccase by SF or SSF.

(3) The information needed for effective large-scale production of laccase by SSF is still limited. More work is suggested involving the scaling up of fungal laccase production by SSF using lignocellulosic agricultural wastes. From this, the possible problems that exist in laccase SSF will be illustrated, and convincing evidence can be provided for improvement of the bioreactor structure and control system as well as a new design for the reactor used in laccase production by SSF. The above achievements will be fundamental for the future of industrial laccase production from lignocellulosic substrates by fungal SSF.

(4) In the screening of fungal strains used for laccase SSF from lignocellulosic wastes, a few methods have been established for the efficient screening of good laccase producers. However, traditional strain screening is still repetitive and time-consuming work. The method development and application, based on high-throughput screening, can be an alternative for the fungal strain selection with high laccase production by SSF with lignocellulosic wastes. Synthetic biology can also be a useful tool for the construction of thermotolerant strains with the production of thermostable laccase, which will provide good fungal producers of laccase by SSF at a large scale.

(5) Laccase production from lignocellulosic agricultural residues by fungal SSF has exhibited great potential in different application areas. In the biological pretreatment of lignocellulose waste, laccase-producing fungi under SSF are a good strategy. However, delignification efficiency and degradation selectivity are the key points for subsequent applications of lignocellulosic materials. For this purpose, the modification of medium composition has been tested, and good results were obtained. Fungal strains with a high production of thermotolerant laccase are also good candidates for the biological pretreatment of lignocellulose waste. In this case, the pretreatment can be conducted under high temperatures for lignin degradation, resulting in other enzymes becoming deactivated in this process. Deletion of the cellulase gene or inhibition of cellulase expression can also be possible strategies for improve degradation selectivity. Although the process and final product of laccase SSF with lignocellulosic wastes have shown good potential in wastewater treatment, their application is limited at the bench scale. For future studies, it is suggested that the application first be examined at a pilot scale, in addition to finding possible apparatus for its continuous application at a large scale.

7. Conclusions

Wide industrial application of laccase has been hampered by problems of high production cost and low yield. Various research approaches have been used in attempts to overcome these problems, e.g., co-culture, biosurfactants, and thermotolerant strains. Use of lignocellulosic wastes (which contain natural inducers) as fermentation substrates is a highly promising approach that reduces costs and environmental pollution. Screening for novel high-yielding strains for laccase production and genetic engineering strategies can also enhance laccase production by fungi under SSF. In addition to using various methods to increase laccase production from lignocellulosic wastes, the scaling up of laccase SSF and the application of laccase produced by SSF are also future research directions.

Author Contributions: All authors contributed text to the manuscript. W.F. generated the tables. All authors read and approved the final manuscript.

Funding: This work was financially supported by the National Natural Science Foundation of China (No. 31571822), the Natural Science Foundation of Jiangsu Province (No. BK20160493), the Social Development Project of Jiangsu Province (No. BE2017683), the China Postdoctoral Science Foundation (No. 2015M571691), the Senior Talent Scientific Research Initial Funding Project of Jiangsu University (No. 15JDG17 & 15JDG061), the 2015 International Postdoctoral Exchange Fellowship Program of China, the 2014 Excellent Key Young Teachers Project of Jiangsu University, and the Qing Lan Project of Jiangsu Province.

Acknowledgments: Not applicable.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Garrido-Bazán, V.; Téllez-Téllez, M.; Herrera-Estrella, A.; Díaz-Godínez, G.; Nava-Galicia, S.; Villalobos-López, M.Á.; Arroyo-Becerra, A.; Bibbins-Martinez, M. Effect of textile dyes on activity and differential regulation of laccase genes from *Pleurotus ostreatus* grown in submerged fermentation. *AMB Express.* **2016**, *6*, 93. [CrossRef] [PubMed]
2. Hernández, C.; Da Silva, A.M.F.; Ziarelli, F.; Perraud-Gaime, I.; Gutiérrez-Rivera, B.; García-Pérez, J.A.; Alarcon, E. Laccase induction by synthetic dyes in *Pycnoporus sanguineus* and their possible use for sugar cane bagasse delignification. *Appl. Microbiol. Biotechnol.* **2017**, *101*, 1189–1201. [CrossRef] [PubMed]
3. Nandal, P.; Ravella, S.R.; Kuhad, R.C. Laccase production by *Coriolopsis caperata* RCK2011: Optimization under solid state fermentation by Taguchi DOE methodology. *Sci. Rep.* **2013**, *3*, 1386. [CrossRef] [PubMed]
4. Thakur, S.; Gupte, A. Optimization and hyper production of laccase from novel agaricomycete *Pseudolagarobasidium acaciicola* AGST3 and its application in in vitro decolorization of dyes. *Ann. Microbiol.* **2015**, *65*, 185–196. [CrossRef]
5. Zimbardi, A.L.R.L.; Camargo, P.F.; Carli, S.; Neto, S.A.; Meleiro, L.P.; Rosa, J.C.; De Andrade, A.R.; Jorge, J.A.; Furriel, R.P.M. A high redox potential laccase from *Pycnoporus sanguineus* RP15: Potential application for dye decolorization. *Int. J. Mol. Sci.* **2016**, *17*, 672. [CrossRef]
6. Zeng, S.; Zhao, J.; Xia, L. Simultaneous production of laccase and degradation of bisphenol A with *Trametes versicolor* cultivated on agricultural wastes. *Bioprocess Biosyst. Eng.* **2017**, *40*, 1237–1245. [CrossRef]
7. Xin, F.; Geng, A. Utilization of horticultural waste for laccase production by *Trametes versicolor* under solid-state fermentation. *Appl. Biochem. Biotechnol.* **2011**, *163*, 235–246. [CrossRef]
8. Sharma, A.; Jain, K.K.; Jain, A.; Kidwai, M.; Kuhad, R.C. Bifunctional in vivo role of laccase exploited in multiple biotechnological applications. *Appl. Microbiol. Biotechnol.* **2018**, *102*, 10327–10343. [CrossRef]
9. Akpinar, M.; Ozturk Urek, R. Induction of fungal laccase production under solid state bioprocessing of new agroindustrial waste and its application on dye decolorization. *3 Biotech* **2017**, *7*, 98. [CrossRef]
10. Chenthamarakshan, A.; Parambayil, N.; Miziriya, N.; Soumya, P.S.; Lakshmi, M.S.K.; Ramgopal, A.; Dileep, A.; Nambisan, P. Optimization of laccase production from *Marasmiellus palmivorus* LA1 by Taguchi method of Design of experiments. *BMC Biotechnol.* **2017**, *17*, 12. [CrossRef]
11. Dey, T.B.; Chakraborty, S.; Jain, K.K.; Sharma, A.; Kuhad, R.C. Antioxidant phenolics and their microbial production by submerged and solid state fermentation process: A review. *Trends Food Sci Technol.* **2016**, *53*, 60–74.
12. Nguyen, K.A.; Wikee, S.; Lumyong, S. Brief review: Lignocellulolytic enzymes from polypores for efficient utilization of biomass. *Mycosphere* **2018**, *9*, 1073–1088. [CrossRef]
13. Rodríguez-Couto, S. A promising inert support for laccase production and decolouration of textile wastewater by the white-rot fungus *Trametes pubescesns*. *J. Hazard. Mater.* **2012**, *233*, 158–162. [CrossRef] [PubMed]
14. Jaramillo, A.C.; Cobas, M.; Hormaza, A.; Sanroman, M.A. Degradation of adsorbed azo dye by solid-state fermentation: Improvement of culture conditions, a kinetic study, and rotating drum bioreactor performance. *Water Air Soil Pollut.* **2017**, *228*, 205. [CrossRef]
15. Qiu, W.; Zhang, W.; Chen, H. Flavonoid-rich plants used as sole substrate to induce the solid-state fermentation of laccase. *Appl. Biochem. Biotechnol.* **2014**, *172*, 3583–3592. [CrossRef] [PubMed]
16. Akpinar, M.; Urek, R.O. Extracellular ligninolytic enzymes production by *Pleurotus eryngii* on agroindustrial wastes. *Prep. Biochem. Biotechnol.* **2014**, *44*, 772–781. [CrossRef] [PubMed]
17. Dai, C.H.; Ma, H.L.; He, R.H.; Huang, L.R.; Zhu, S.Y.; Ding, Q.Z.; Luo, L. Improvement of nutritional value and bioactivity of soybean meal by solid-state fermentation with *Bacillus subtilis*. *LWT Food Sci. Technol.* **2017**, *86*, 1–7. [CrossRef]
18. Jiang, H.; Wang, W.; Mei, C.L.; Huang, Y.H.; Chen, Q.S. Rapid diagnosis of normal and abnormal conditions in solid-state fermentation of bioethanol using fourier transform near-infrared spectroscopy. *Energy Fuels* **2017**, *31*, 12959–12964. [CrossRef]
19. Rodriguez-Couto, S.; Toca-Herrera, J.L. Laccase production at reactor scale by filamentous fungi. *Biotechnol. Adv.* **2007**, *25*, 558–569. [CrossRef]
20. Postemsky, P.D.; Bidegain, M.A.; González-Matute, R.; Figlas, N.D.; Cubitto, M.A. Pilot-scale bioconversion of rice and sunflower agro-residues into medicinal mushrooms and laccase enzymes through solid-state fermentation with *Ganoderma lucidum*. *Bioresour. Technol.* **2017**, *231*, 85–93. [CrossRef]

21. Hatvani, N.; Mécs, I. Production of laccase and manganese peroxidase by *Lentinus edodes* on malt-containing by-product of the brewing process. *Process Biochem.* **2001**, *37*, 491–496. [CrossRef]
22. Chen, H.Y.; Xue, D.S.; Feng, X.Y.; Yao, S.J. Screening and Production of Ligninolytic Enzyme by a Marine-Derived Fungal *Pestalotiopsis* sp. J63. *Appl. Biochem. Biotechnol.* **2011**, *165*, 1754–1769. [CrossRef] [PubMed]
23. Tišma, M.; Žnidaršič-Plazl, P.; Vasić-Rački, Đ.; Zelić, B. Optimization of laccase production by *Trametes versicolor* cultivated on industrial waste. *Appl. Biochem. Biotechnol.* **2012**, *166*, 36–46. [CrossRef] [PubMed]
24. Soumya, P.S.; Lakshmi, M.S.K.; Nambisan, P. Application of response surface methodology for the optimization of laccase production from *Pleurotus ostreatus* by solid state fermentation on pineapple leaf substrate. *J. Sci. Ind. Res. India* **2016**, *75*, 306–314.
25. Ren, N.; Wang, A.; Cao, G.; Xu, J.; Gao, L. Bioconversion of lignocellulosic biomass to hydrogen: Potential and challenges. *Biotechnol. Adv.* **2009**, *27*, 1051–1060. [CrossRef] [PubMed]
26. Huang, C.; Lai, C.; Zeng, G.; Huang, D.; Xu, P.; Zhang, C.; Cheng, M.; Wan, J. Manganese-enhanced degradation of lignocellulosic waste by *Phanerochaete chrysosporium*: Evidence of enzyme activity and gene transcription. *Appl. Microbiol. Biotechnol.* **2017**, *101*, 6541–6549. [CrossRef]
27. Kshirsagar, S.D.; Waghmare, P.R.; Loni, P.C.; Patil, S.A.; Govindwar, S.P. Dilute acid pretreatment of rice straw structural characterization and optimization of enzymatic hydrolysis conditions by response surface methodology. *RSC Adv.* **2015**, *5*, 46525–46533. [CrossRef]
28. Iandolo, D.; Piscitelli, A.; Sannia, G.; Faraco, V. Enzyme production by solid substrate fermentation of *Pleurotus ostreatus* and *Trametes versicolor* on tomato pomace. *Appl. Biochem. Biotechnol.* **2011**, *163*, 40–51. [CrossRef]
29. Sharma, A.; Gupta, V.; Khan, M.; Balda, S.; Gupta, N.; Capalash, N.; Sharma, P. Flavonoid-rich agro-industrial residues for enhanced bacterial laccase production by submerged and solid-state fermentation. *3 Biotech* **2017**, *7*, 200. [CrossRef]
30. Cabrera, R.; Lopez-Pena, D.; Asaff, A.; Esqueda, M.; Valenzuela-Soto, E.M. Bioavailability of Compounds Susceptible to Enzymatic Oxidation Enhances Growth of Shiitake Medicinal Mushroom (*Lentinus edodes*) in Solid-State Fermentation with Vineyard Prunings. *Int. J. Med. Mushrooms* **2018**, *20*, 291–303. [CrossRef]
31. Anwar, Z.; Gulfraz, M.; Irshad, M. Agro-industrial lignocellulosic biomass a key to unlock the future bio-energy: A brief review. *J. Radiat. Res.* **2014**, *7*, 163–173. [CrossRef]
32. Daâssi, D.; Zouari-Mechichi, H.; Frikha, F.; Rodríguez-Couto, S.; Nasri, M.; Mechichi, T. Sawdust waste as a low-cost support-substrate for laccases production and adsorbent for azo dyes decolorization. *J. Environ. Health Sci. Eng.* **2016**, *14*, 1. [CrossRef] [PubMed]
33. Karp, S.G.; Faraco, V.; Amore, A.; Letti, L.A.J.; Soccol, V.T.; Soccol, C.R. Statistical Optimization of Laccase Production and Delignification of Sugarcane Bagasse by *Pleurotus ostreatus* in solid-state fermentation. *BioMed Res. Int.* **2015**. [CrossRef] [PubMed]
34. Lonappan, L.; Rouissi, T.; Laadila, M.A.; Brar, S.K.; Galan, L.H.; Verma, M.; Suranripalli, R.Y. Agro-industrial produced laccase for degradation of diclofenac and identification of transformation products. *ACS Sustain. Chem. Eng.* **2017**, *5*, 5772–5781. [CrossRef]
35. Meehnian, H.; Jana, A.K.; Jana, M.M. Pretreatment of cotton stalks by synergistic interaction of *Daedalea flavida* and *Phlebia radiata* in co-culture for improvement in delignification and saccharification. *Int. Biodeterior. Biodegrad.* **2017**, *117*, 68–77. [CrossRef]
36. Zhang, W.M.; Wu, S.H.; Cai, L.Y.; Liu, X.L.; Wu, H.; Xin, F.X.; Zhang, M.; Jiang, M. Improved Treatment and Utilization of Rice Straw by *Coprinopsis cinerea*. *Appl. Biochem. Biotech.* **2018**, *184*, 616–629. [CrossRef]
37. Rodriguez-Couto, S.; Sanromán, M.A. Application of solid-state fermentation to ligninolytic enzyme production. *Biochem. Eng. J.* **2005**, *22*, 211–219. [CrossRef]
38. Iqbal, H.M.N.; Kyazze, G.; Keshavarz, T. Advances in the valorization of lignocellulosic materials by biotechnology: An overview. *Bioresources* **2013**, *8*, 3157–3176. [CrossRef]
39. Yang, J.; Li, W.; Ng, T.B.; Deng, X.; Lin, J.; Ye, X. Laccases: Production, Expression Regulation, and Applications in Pharmaceutical Biodegradation. *Front. Microbiol.* **2017**, *8*, 832. [CrossRef]
40. Bertrand, B.; Martínez-Morales, F.; Trejo-Hernández, M.R. Upgrading Laccase Production and Biochemical Properties: Strategies and Challenges. *Biotechnol. Prog.* **2017**, *33*, 1015–1034. [CrossRef]

41. Arias, M.; Blánquez, A.; Hernández, M.; Rodríguez, J.; Ball, A.; Jiménez-Morillo, N.T.; Gonzalez-Vila, F.J.; Gonzalez-Perez, J.A. Role of a thermostable laccase produced by *Streptomyces ipomoeae* in the degradation of wheat straw lignin in solid state fermentation. *J. Anal. Appl. Pyrolysis* **2016**, *122*, 202–208. [CrossRef]
42. Ijoma, G.N.; Selvarajan, R.; Tekere, M. The potential of fungal co-cultures as biological inducers for increased ligninolytic enzymes on agricultural residues. *Int. J. Environ. Sci. Technol.* **2019**, *16*, 305–324. [CrossRef]
43. Balat, M.; Balat, H.; Öz, C. Progress in bioethanol processing. *Prog. Energy Combust. Sci.* **2008**, *34*, 551–573. [CrossRef]
44. Osma, J.F.; Herrera, J.L.T.; Rodríguez-Couto, S. Banana skin: A novel waste for laccase production by *Trametes pubescens* under solid-state conditions. Application to synthetic dye decolouration. *Dyes Pigment.* **2007**, *75*, 32–37. [CrossRef]
45. Omar, F.N.; Hafid, H.S.; Samsu, B.A.; Map, M.; Abdullah, J. Oil palm fiber biodegradation: Physico-chemical and structural relationships. *Planta* **2017**, *246*, 567–577. [CrossRef]
46. Liu, J.; Wang, M.L.; Tonnis, B.; Habteselassie, M.; Liao, X.; Huang, Q. Fungal pretreatment of switchgrass for improved saccharification and simultaneous enzyme production. *Bioresour. Technol.* **2013**, *135*, 39–45. [CrossRef]
47. Zhang, C.; Liu, L.; Zeng, G.M.; Huang, D.L.; Lai, C.; Huang, C.; Wei, Z.; Li, N.J.; Xu, P.; Cheng, M. Utilization of nano-gold tracing technique: Study the adsorption and transmission of laccase in mediator-involved enzymatic degradation of lignin during solid-state fermentation. *Biochem. Eng. J.* **2014**, *91*, 149–156. [CrossRef]
48. Adekunle, A.E.; Zhang, C.; Guo, C.; Liu, C.Z. Laccase production from *Trametes versicolor* in solid-state fermentation of steam-exploded pretreated cornstalk. *Waste Biomass Valorization* **2017**, *8*, 153–159. [CrossRef]
49. Martani, F.; Beltrametti, F.; Porro, D.; Branduardi, P.; Lotti, M. The importance of fermentative conditions for the biotechnological production of lignin modifying enzymes from white-rot fungi. *FEMS Microbiol. Lett.* **2017**, *364*, 134. [CrossRef]
50. Mishra, V.; Jana, A.K.; Jana, M.M.; Gupta, A. Enhancement in multiple lignolytic enzymes production for optimized lignin degradation and selectivity in fungal pretreatment of sweet sorghum bagasse. *Bioresour. Technol.* **2017**, *236*, 49–59. [CrossRef]
51. Adekunle, A.E.; Guo, C.; Liu, C.Z. Lignin-Enhanced Laccase Production from *Trametes versicolor*. *Waste Biomass Valorization* **2017**, *8*, 1061–1066. [CrossRef]
52. Gómez, J.; Pazos, M.; Rodríguez-Couto, S.; Sanromán, M.Á. Chestnut shell and barley bran as potential substrates for laccase production by *Coriolopsis rigida* under solid-state conditions. *Braz. J. Microbiol.* **2005**, *68*, 315–319. [CrossRef]
53. Srinivasan, C.; Dsouza, T.; Boominathan, K.; Reddy, C. Demonstration of Laccase in the White-rot Basidiomycete *Phanerochaete chrysosporium* BKM-F1767. *Appl. Environ. Microbiol.* **1995**, *61*, 4274–4277. [PubMed]
54. Rodríguez-Couto, S. Production of laccase and decolouration of the textile dye Remazol Brilliant Blue R in temporary immersion bioreactors. *J. Hazard. Mater.* **2011**, *194*, 297–302. [CrossRef]
55. Liu, J.; Liu, B.; Zhan, L.; Wang, P.; Ju, M.; Wu, W. Solid-state fermentation of ammoniated corn straw to animal feed by *Pleurotus ostreatus* Pl-5. *BioResources* **2017**, *12*, 1723–1736. [CrossRef]
56. Albornoz, S.; Wyman, V.; Palma, C.; Carvajal, A. Understanding of the contribution of the fungal treatment conditions in a wheat straw biorefinery that produces enzymes and biogas. *Biochem. Eng. J.* **2018**, *140*, 140–147. [CrossRef]
57. Singh, P.; Sulaiman, O.; Hashim, R.; Peng, L.C.; Singh, R.P. Evaluating biopulping as an alternative application on oil palm trunk using the white-rot fungus *Trametes versicolor*. *Int. Biodeterior. Biodegrad.* **2013**, *82*, 96–103. [CrossRef]
58. Aydınoğlu, T.; Sargın, S. Production of laccase from *Trametes versicolor* by solid-state fermentation using olive leaves as a phenolic substrate. *Bioprocess Biosyst. Eng.* **2013**, *36*, 215–222. [CrossRef]
59. Bucić-Kojić, A.; Šelo, G.; Zelić, B.; Planinić, M.; Tišma, M. Recovery of phenolic acid and enzyme production from corn silage biologically treated by *Trametes versicolor*. *Appl. Biochem. Biotechnol.* **2017**, *181*, 948–960. [CrossRef]
60. Singh, J.; Kumar, P.; Saharan, V.; Kapoor, R.K. Simultaneous laccase production and transformation of bisphenol-A and triclosan using *Trametes versicolor*. *3 Biotech* **2019**, *9*, 129. [CrossRef]

61. Bazanella, G.C.D.; de Souza, D.F.; Castoldi, R.; Oliveira, R.F.; Bracht, A.; Peralta, R.M. Production of laccase and manganese peroxidase by *Pleurotus pulmonarius* in solid-state cultures and application in dye decolorization. *Folia Microbiol.* **2013**, *58*, 641–647. [CrossRef] [PubMed]
62. Economou, C.N.; Diamantopoulou, P.A.; Philippoussis, A.N. Valorization of spent oyster mushroom substrate and laccase recovery through successive solid state cultivation of *Pleurotus*, *Ganoderma*, and *Lentinula* strains. *Appl. Microbiol. Biotechnol.* **2017**, *101*, 5213–5222. [CrossRef] [PubMed]
63. Moilanen, U.; Winquist, E.; Mattila, T.; Hatakka, A.; Eerikäinen, T. Production of manganese peroxidase and laccase in a solid-state bioreactor and modeling of enzyme production kinetics. *Bioprocess Biosyst. Eng.* **2014**, *38*, 57–68. [CrossRef] [PubMed]
64. dos Santos, T.C.; Reis, N.; Silva, T.P.; Machado, F.D.P.; Bonomo, R.C.F.; Franco, M. Prickly palm cactus husk as a raw material for production of ligninolytic enzymes by *Aspergillus niger*. *Food Sci. Biotechnol.* **2016**, *25*, 205–211. [CrossRef]
65. dos Santos, T.C.; de Brito, A.R.; Bonomo, R.C.F.; Pires, A.J.V.; Aguiar-Oliveira, E.; Silva, T.P.; Franco, M. Statistical optimization of culture conditions and characterization for ligninolytic enzymes produced from *Rhizopus* Sp. using prickly palm cactus husk. *Chem. Eng. Commun.* **2017**, *204*, 55–63. [CrossRef]
66. Dhillon, G.S.; Kaur, S.; Brar, S.K. In-vitro decolorization of recalcitrant dyes through an ecofriendly approach using laccase from *Trametes versicolor* grown on brewer's spent grain. *Int. Biodeterior. Biodegrad.* **2012**, *72*, 67–75. [CrossRef]
67. Böhmer, U.; Frömmel, S.; Bley, T.; Müller, M.; Frankenfeld, K.; Miethe, P. Solid-state fermentation of lignocellulotic materials for the production of enzymes by the white-rot fungus *Trametes hirsuta* in a modular bioreactor. *Eng. Life Sci.* **2011**, *11*, 395–401. [CrossRef]
68. Wang, P.; Hu, X.; Cook, S.; Begonia, M.; Lee, K.S.; Hwang, H.M. Effect of culture conditions on the production of ligninolytic enzymes by white rot fungi *Phanerochaete chrysosporium* (ATCC 20696) and separation of its lignin peroxidase. *World J. Microbiol. Biotechnol.* **2008**, *24*, 2205–2212. [CrossRef]
69. Kaluskar, V.M.; Kapadnis, B.P.; Jaspers, C.; Penninckx, M.J. Production of laccase by immobilized cells of *Agaricus* sp.: Induction effect of xylan and lignin derivatives. *Appl. Biochem. Biotechnol.* **1999**, *76*, 161–170. [CrossRef]
70. Tavares, A.; Coelho, M.; Agapito, M.; Coutinho, J.; Xavier, A. Optimization and modeling of laccase production by *Trametes versicolor* in a bioreactor using statistical experimental design. *Appl. Biochem. Biotechnol.* **2006**, *134*, 233–248. [CrossRef]
71. Breen, A.; Singleton, F.L. Fungi in lignocellulose breakdown and biopulping. *Curr. Opin. Biotechnol.* **1999**, *10*, 252–258. [CrossRef]
72. Jing, D. Improving the simultaneous production of laccase and lignin peroxidase from *Streptomyces lavendulae* by medium optimization. *Bioresour. Technol.* **2010**, *101*, 7592–7597. [CrossRef] [PubMed]
73. Stajić, M.; Persky, L.; Friesem, D.; Hadar, Y.; Wasser, S.P.; Nevo, E.; Vukojevic, J. Effect of different carbon and nitrogen sources on laccase and peroxidases production by selected *Pleurotus* species. *Enzym. Microb. Technol.* **2006**, *38*, 65–73. [CrossRef]
74. Elisashvili, V.; Parlar, H.; Kachlishvili, E.; Chichua, D.; Bakradze, M.; Kokhreidze, N.; Kvesitadze, G. Ligninolytic activity of basidiomycetes grown under submerged and solid-state fermentation on plant raw material (sawdust of grapevine cuttings). *Adv. Food Sci.* **2001**, *23*, 117–123.
75. Rosales, E.; Rodríguez-Couto, S.; Ángeles Sanromán, M. Reutilisation of food processing wastes for production of relevant metabolites: Application to laccase production by *Trametes hirsuta*. *J. Food Eng.* **2005**, *66*, 419–423. [CrossRef]
76. Cilerdzic, J.; Galic, M.; Ivanovic, Z.; Brceski, I.; Vukojevic, J.; Stajic, M. Stimulation of Wood Degradation by *Daedaleopsis confragosa* and *D. tricolor*. *Appl. Biochem. Biotech.* **2019**, *187*, 1371–1383. [CrossRef]
77. Tavares, A.; Coelho, M.; Coutinho, J.; Xavier, A. Laccase improvement in submerged cultivation: Induced production and kinetic modelling. *J. Chem. Technol. Biotechnol.* **2005**, *80*, 669–676. [CrossRef]
78. Fillat, Ú.; Martín-Sampedro, R.; Macaya-Sanz, D.; Martín, J.A.; Ibarra, D.; Martínez, M.J. Screening of eucalyptus wood endophytes for laccase activity. *Process Biochem.* **2016**, *51*, 589–598. [CrossRef]
79. Li, H.; Zhang, R.; Tang, L.; Zhang, J.; Mao, Z. Manganese peroxidase production from cassava residue by *Phanerochaete chrysosporium* in solid state fermentation and its decolorization of indigo carmine. *Chin. J. Chem. Eng.* **2015**, *23*, 227–233. [CrossRef]

80. Meehnian, H.; Jana, A.K.; Jana, M.M. Effect of particle size, moisture content, and supplements on selective pretreatment of cotton stalks by *Daedalea flavida* and enzymatic saccharification. *3 Biotech* **2016**, *6*, 235. [CrossRef]
81. Wang, Z.; Liu, J.; Ning, Y.; Liao, X.; Jia, Y. *Eichhornia crassipes*: Agro-waster for a novel thermostable laccase production by *Pycnoporus sanguineus* SYBC-L1. *J. Biosci. Bioeng.* **2017**, *123*, 163–169. [CrossRef] [PubMed]
82. Songulashvili, G.; Spindler, D.; Jimenéztobón, G.A.; Jaspers, C.; Kerns, G.; Penninckx, M.J. Production of a high level of laccase by submerged fermentation at 120-L scale of *Cerrena unicolor* C-139 grown on wheat bran. *C. R. Biol.* **2015**, *338*, 121–125. [CrossRef] [PubMed]
83. Chen, H.Z.; He, Q. Value-added bioconversion of biomass by solid-state fermentation. *J. Chem. Technol. Biotechnol.* **2012**, *87*, 1619–1625. [CrossRef]
84. Kaur, H.; Kapoor, S.; Kaur, G. Application of ligninolytic potentials of a white-rot fungus *Ganoderma lucidum* for degradation of lindane. *Environ. Monit. Assess.* **2016**, *188*, 588. [CrossRef]
85. Wang, H.; Peng, L.; Ding, Z.Y.; Wu, J.Y.; Shi, G.Y. Stimulated laccase production of *Pleurotus ferulae* JM301 fungus by *Rhodotorula mucilaginosa* yeast in co-culture. *Process Biochem.* **2015**, *50*, 901–905. [CrossRef]
86. Bertrand, B.; Martínez-Morales, F.; Tinoco-Valencia, R.; Rojas, S.; Acosta-Urdapilleta, L.; Trejo-Hernández, M.R. Biochemical and molecular characterization of laccase isoforms produced by the white-rot fungus *Trametes versicolor* under submerged culture conditions. *J. Mol. Catal. B Enzym.* **2015**, *122*, 339–347. [CrossRef]
87. Irbe, I.; Elisashvili, V.; Asatiani, M.D.; Janberga, A.; Andersone, I.; Andersons, B.; Biziks, V.; Grinins, J. Lignocellulolytic activity of *Coniophora puteana* and *Trametes versicolor* in fermentation of wheat bran and decay of hydrothermally modified hardwoods. *Int. Biodeterior. Biodegrad.* **2014**, *86*, 71–78. [CrossRef]
88. Sharma, D.; Garlapati, V.K.; Goel, G. Bioprocessing of wheat bran for the production of lignocellulolytic enzyme cocktail by *Cotylidia pannosa* under submerged conditions. *Bioengineered* **2016**, *7*, 88–97. [CrossRef]
89. Wang, H.L.; Li, P.; Yang, Y.H.; Liu, Y.F. Overproduction of laccase from a newly isolated *Ganoderma lucidum* using the municipal food waste as main carbon and nitrogen supplement. *Bioprocess Biosyst. Eng.* **2015**, *38*, 957–966.
90. Ćilerdžić, J.; Stajić, M.; Vukojević, J. Degradation of wheat straw and oak sawdust by *Ganoderma applanatum*. *Int. Biodeterior. Biodegrad.* **2016**, *114*, 39–44. [CrossRef]
91. Ding, Z.Y.; Chen, Y.Z.; Xu, Z.H.; Peng, L.; Xu, G.H.; Gu, Z.H.; Zhang, L.; Shi, G.Y.; Zhang, K.C. Production and characterization of laccase from *Pleurotus ferulae* in submerged fermentation. *Ann. Microbiol.* **2014**, *64*, 121–129. [CrossRef]
92. Silvério, S.C.; Moreira, S.; Milagres, A.M.; Macedo, E.A.; Teixeira, J.A.; Mussatto, S.I. Laccase production by free and immobilized mycelia of *Peniophora cinerea* and *Trametes versicolor*: A comparative study. *Bioprocess Biosyst. Eng.* **2013**, *36*, 365–373. [CrossRef]
93. Park, Y.J.; Yoon, D.E.; Kim, H.I.; Kwon, O.C.; Yoo, Y.B.; Kong, W.S.; Lee, C.S. Overproduction of laccase by the white-rot fungus *Pleurotus ostreatus* Using Apple Pomace as Inducer. *Mycobiology* **2014**, *42*, 193–197. [CrossRef]
94. Elisashvili, V.; Kachlishvili, E. Physiological regulation of laccase and manganese peroxidase production by white-rot Basidiomycetes. *J. Biotechnol.* **2009**, *144*, 37–42. [CrossRef]
95. Kuhar, F.; Castiglia, V.; Levin, L. Enhancement of laccase production and malachite green decolorization by co-culturing *Ganoderma lucidum* and *Trametes versicolor* in solid-state fermentation. *Int. Biodeterior. Biodegrad.* **2015**, *104*, 238–243. [CrossRef]
96. Hatakka, A. Lignin-modifying enzymes from selected white-rot fungi: Production and role from in lignin degradation. *FEMS Microbiol. Rev.* **1994**, *13*, 125–135. [CrossRef]
97. Kuhar, S.; Kapoor, M.; Kapoor, R.; Sharma, K.K.; Singh, A.; Kuhad, R. Biodiversity of Ligninolytic Fungi. In *Lignocellulose Biotechnology: Future Prospects*; Kuhad, R.C., Singh, A., Eds.; IK International: New Delhi, India, 2007; pp. 37–53.
98. Diaz, A.B.; Blandino, A.; Webb, C.; Caro, I. Modelling of different enzyme productions by solid-state fermentation on several agro-industrial residues. *Appl. Microbiol. Biotechnol.* **2016**, *100*, 9555–9566. [CrossRef]
99. Adak, A.; Tiwari, R.; Singh, S.; Sharma, S.; Nain, L. Laccase production by a novel white-rot fungus *Pseudolagarobasidium acaciicola* LA 1 through solid-state fermentation of parthenium biomass and its application in dyes decolorization. *Waste Biomass Valorization* **2016**, *7*, 1427–1435. [CrossRef]
100. Bugni, T.S.; Ireland, C.M. Marine-derived fungi: A chemically and biologically diverse group of microorganisms. *Nat. Prod. Rep.* **2004**, *21*, 143–163. [CrossRef]

101. Jones, E.; Stanley, S.J.; Pinruan, U. Marine endophyte sources of new chemical natural products: A review. *Bot. Mar.* **2008**, *51*, 163–170. [CrossRef]
102. Raghukumar, C.; D'souza, T.; Thorn, R.; Reddy, C. Lignin-modifying enzymes of *Flavodon flavus* a basidiomycete isolated from a coastal marine environment. *Appl. Environ. Microbiol.* **1999**, *65*, 2103–2111.
103. Hariharan, S.; Nambisan, P. Optimization of lignin peroxidase, manganese peroxidase, and Lac production from *Ganoderma lucidum* under solid state fermentation of pineapple leaf. *BioResources* **2012**, *8*, 250–271. [CrossRef]
104. Ordaz, A.; Favela, E.; Meneses, M.; Mendoza, G.; Loera, O. Hyphal morphology modification in thermal adaptation by the white-rot fungus *Fomes* sp. EUM1. *J. Basic Microbiol.* **2012**, *52*, 167–174. [CrossRef]
105. Yan, J.; Chen, Y.; Niu, J.; Chen, D.; Chagan, I. Laccase produced by a thermotolerant strain of *Trametes trogii* LK13. *Braz. J. Microbiol.* **2015**, *46*, 59–65. [CrossRef]
106. Chhaya, U.; Gupte, A. Effect of different cultivation conditions and inducers on the production of laccase by the litter-dwelling fungal isolate *Fusarium incarnatum* LD-3 under solid substrate fermentation. *Ann. Microbiol.* **2013**, *63*, 215–223. [CrossRef]
107. Wang, Z.; Cai, Y.; Liao, X.; Zhang, F.; Zhang, D.; Li, Z. Production and characterization of a novel laccase with cold adaptation and high thermal stability from an isolated fungus. *Appl. Biochem. Biotechnol.* **2009**, *162*, 280–294. [CrossRef]
108. Jiao, X.Y.; Li, G.Q.; Wang, Y.; Nie, F.; Cheng, X.; Abdullah, M.; Lin, Y.; Cai, Y.P. Systematic Analysis of the *Pleurotus ostreatus* Laccase Gene (PoLac) Family and Functional Characterization of PoLac2 Involved in the Degradation of Cotton-Straw Lignin. *Molecules* **2018**, *23*, 880. [CrossRef]
109. Mishra, V.; Jana, A.K.; Jana, M.; Gupta, A. Fungal pretreatment of sweet sorghum bagasse with supplements: Improvement in lignin degradation, selectivity and enzymatic saccharification. *3 Biotech* **2017**, *7*, 110. [CrossRef]
110. Hideno, A. Short-time alkaline peroxide pretreatment for rapid pulping and efficient enzymatic hydrolysis of rice straw. *Bioresour. Technol.* **2017**, *230*, 140–142. [CrossRef]
111. Tang, C.L.; Shan, J.Q.; Chen, Y.J.; Zhong, L.X.; Shen, T.; Zhu, C.J.; Ying, H. Organic amine catalytic organosolv pretreatment of corn stover for enzymatic saccharification and high-quality lignin. *Bioresour. Technol.* **2017**, *232*, 222–228. [CrossRef]
112. Ghorbani, F.; Karimi, M.; Biria, D.; Kariminia, H.R.; Jeihanipour, A. Enhancement of fungal delignification of rice straw by *Trichoderma viride* sp. to improve its saccharification. *Biochem. Eng. J.* **2015**, *101*, 77–84. [CrossRef]
113. Machado, A.D.S.; Ferraz, A. Biological pretreatment of sugarcane bagasse with basidiomycetes producing varied patterns of biodegradation. *Bioresour. Technol.* **2017**, *225*, 17–22. [CrossRef]
114. Bule, M.V.; Chaudhary, I.; Gao, A.H.; Chen, S. Effects of extracellular proteome on wheat straw pretreatment during solid-state fermentation of *Phlebia radiata* ATCC 64658. *Int. Biodeterior. Biodegrad.* **2016**, *109*, 36–44. [CrossRef]
115. Kasprzycka, A.; Lalak-Kanczugowska, J.; Tys, J. Flammulina velutipes treatment of non-sterile tall wheat grass for enhancing biodegradability and methane production. *Bioresour. Technol.* **2018**, *263*, 660–664. [CrossRef]
116. Rastogi, S.; Soni, R.; Kaur, J.; Soni, S.K. Unravelling the capability of *Pyrenophora phaeocomes* S-1 for the production of ligno-hemicellulolytic enzyme cocktail and simultaneous bio-delignification of rice straw for enhanced enzymatic saccharification. *Bioresour. Technol.* **2016**, *222*, 458–469. [CrossRef]
117. Yamagishi, K.; Kimura, T.; Watanabe, T. Treatment of rice straw with selected *Cyathus stercoreus* strains to improve enzymatic saccharification. *Bioresour. Technol.* **2011**, *102*, 6937–6943. [CrossRef]
118. Ruqayyah, T.I.; Jamal, P.; Alam, M.Z.; Mirghani, M.E. Biodegradation potential and ligninolytic enzyme activity of two locally isolated *Panus tigrinus* strains on selected agro-industrial wastes. *J. Environ. Manag.* **2013**, *118*, 115–121. [CrossRef]
119. Knežević, A.; Stajić, M.; Vukojević, J.; Milovanović, I. The effect of trace elements on wheat straw degradation by *Trametes gibbosa*. *Int. Biodeterior. Biodegrad.* **2014**, *96*, 152–156. [CrossRef]
120. Ahmad, Z.; Asgher, M.; Hussain, F.; Randhawa, M.A. A novel approach to delignify lignocellulosic materials by using ligninolytic enzyme consortium. *Bioresources* **2016**, *11*, 10511–10527. [CrossRef]

121. Yadav, M.; Singh, A.; Balan, V.; Pareek, N.; Vivekanand, V. Biological treatment of lignocellulosic biomass by Chaetomium globosporum: Process derivation and improved biogas production. *Int. J. Biol. Macromol.* **2019**, *128*, 176–183. [CrossRef]
122. Muktham, R.; Taha, M.; Shahsavari, E.; Bhargava, S.K.; Bankupalli, S.; Ball, A.S. Pongamia pinnata seed residue—A low cost inedible resource for on-site/in-house lignocellulases and sustainable ethanol production. *Renew. Energy* **2016**, *103*, 682–687.
123. Yaghoubi, K.; Pazouki, M.; Shojaosadati, S.A. Variable optimization for biopulping of agricultural residues by *Ceriporiopsis Subvermispora*. *Bioresour. Technol.* **2008**, *99*, 4321–4328. [CrossRef]
124. Hayes, D.J.M. Mass and compositional changes relevant to biorefining, in Miscanthus × giganteus plants over the harvest window. *Bioresour. Technol.* **2013**, *142*, 591–602. [CrossRef]
125. Kuijk, S.J.A.V.; Sonnenberg, A.S.M.; Baars, J.J.P.; Hendriks, W.H.; Cone, J.W. Fungal treated lignocellulosic biomass as ruminant feed ingredient: A review. *Biotechnol. Adv.* **2015**, *33*, 191–202. [CrossRef]
126. Vats, A.; Mishra, S. Decolorization of complex dyes and textile effluent by extracellular enzymes of *Cyathus bulleri* cultivated on agro-residues/domestic wastes and proposed pathway of degradation of Kiton blue A and reactive orange 16. *Environ. Sci. Pollut. Res. Int.* **2017**, *24*, 1–13. [CrossRef]
127. Sharma, A.; Shrivastava, B.; Kuhad, R.C. Reduced toxicity of malachite green decolorized by laccase produced from *Ganoderma* sp. rckk-02 under solid-state fermentation. *3 Biotech* **2015**, *5*, 621–631. [CrossRef]
128. Pazarbasi, M.B.; Kocyigit, A.; Ozdemir, G.; Yasa, I.; Karaboz, I. Decolorization of various leather dyes and leather industry effluent by *Trametes trogii* TEM H2. *Fresenius Environ. Bull.* **2012**, *21*, 1410–1416.
129. Diwaniyan, S.; Kharb, D.; Raghukumar, C.; Kuhad, R.C. Decolorization of synthetic dyes and textile effluents by basidiomycetous fungi. *Water Air Soil Pollution.* **2010**, *210*, 409–419. [CrossRef]
130. Lallawmsanga, L.V.V.; Passari, A.K.; Muniraj, I.K.; Uthandi, S.; Hashem, A.; Abd Allah, E.F.; Alqarawi, A.A.; Singh, B.P. Elevated levels of laccase synthesis by *Pleurotus pulmonarius* BPSM10 and its potential as a dye decolorizing agent. *Saudi J. Biol. Sci.* **2019**, *26*, 464–468. [CrossRef]
131. Yu, G.; Wen, X.; Li, R.; Qian, Y. In vitro degradation of a reactive azo dye by crude ligninolytic enzymes from nonimmersed liquid culture of *Phanerochaete chrysosporium*. *Process Biochem.* **2006**, *41*, 1987–1993. [CrossRef]
132. Chicatto, J.A.; Rainert, K.T.; Goncalves, M.J.; Helm, C.V.; Altmajer-Vaz, D.; Tavares, L.B.B. Decolorization of textile industry wastewater in solid state fermentation with Peach-Palm (*Bactris gasipaes*) residue. *Braz. J. Biol.* **2018**, *78*, 718–727. [CrossRef]
133. Moreno, A.; Figueroa, D.; Hormaza, A. Diseño estadístico para la remoción eficiente del colorante rojo 40 sobre tuza de maíz. *Producción Limpia* **2012**, *7*, 9–19.
134. Xu, L.; Sun, K.; Wang, F.; Zhao, L.T.; Hu, J.H.; Ma, H.L.; Ding, Z.Y. Laccase production by *Trametes versicolor* in solid-state fermentation using tea residues as substrate and its application in dye decolorization. *J. Ind. Microbiol. Biot.* **2019**. Submitted.
135. Liu, H.; Zhang, Z.; Xie, S.; Xing, H. Study on transformation and degradation of bisphenol A by *Trametes versicolor* laccase and simulation of molecular docking. *Chemosphere* **2019**, *224*, 743–750.
136. Zhou, M.F.; Yuan, X.Z.; Zhong, H.; Liu, Z.F.; Li, H.; Jiang, L.L.; Zeng, G.M. Effect of biosurfactants on laccase production and phenol biodegradation in solid-state fermentation. *Appl. Biochem. Biotechnol.* **2011**, *164*, 103–114. [CrossRef]
137. Koutrotsios, G.; Larou, E.; Mountzouris, K.C.; Zervakis, G.I. Detoxification of olive mill wastewater and bioconversion of olive crop residues into high-value-added biomass by the choice edible mushroom *Hericium erinaceus*. *Appl. Biochem. Biotechnol.* **2016**, *180*, 195–209. [CrossRef]
138. Elbatal, A.I.; Elkenawy, N.M.; Yassin, A.S.; Amin, M.A. Laccase production by *Pleurotus ostreatus* and its application in synthesis of gold nanoparticles. *Biotechnol. Rep.* **2015**, *5*, 31–39. [CrossRef]