Use of lignocellulosic corn and rice wastes as substrates for oyster mushroom (*Pleurotus ostreatus* Jacq.) cultivation

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Abstract

The accumulation of agronomic wastes has caused several environmental problems, such as air and soil contamination, and insect and pathogen proliferation, among others. To mitigate this, studies have evaluated the use of these wastes as substrates for the cultivation of *Pleurotus* mushrooms, a low-cost/nutritionally important crop. This study aimed to evaluate the use of corn stubble and rice straw as substrates for the in vitro production of oyster mushrooms (*Pleurotus ostreatus* Jacq.) and the productive characterization (biological efficiency, production rate, earliness, daily productive capacity) of four isolated strains. The strains PO/A01, PO/A02, PO/A03, and PO/A04 were grown in Potato-Dextrose-Agar medium until complete colonization. The experiment was evaluated under a completely randomized design with 6 replications. Subsequently, the corn stubble and rice straw were disinfected, inoculated, bagged, incubated, and subjected to induction-fructification. The productive period ended after three harvests. At this stage, the experiment was conducted under a completely randomized design with a 4 × 2 factorial arrangement with 8 replications. The *P. ostreatus* strains inoculated in the corn stubble, compared to rice straw, showed 93.93% biological efficiency and a 2.07% production rate, representing increases of 30% and 50%, respectively. The strains PO/A03 and PO/A04 showed higher biological efficiency and organic matter loss. The PO/A02 strain showed greater earliness, with approximately 10 days to harvest. This study concluded that the isolated strains of *P. ostreatus* allow for the efficient use of corn stubble and rice straw, and can contribute to the management of agronomic wastes.

Novelty statement: In developing countries, production of edible mushrooms of the genus *Pleurotus* can be an efficient tool for alternative and eco-friendly agronomic waste management, allowing for highly nutritious food to be provided to the population through the bioconversion of lignocellulosic compounds. This system has a low production cost and the postharvest substrate, Spent Mushroom Substrate (SMS), can be used as organic fertilizer or animal feed. The aim of this experiment was to contribute to the technical and scientific information on the productive characterization of four *Pleurotus ostreatus* (Jacq.) strains occurring in the Peruvian region.

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Graphic abstract

Keywords Agronomic waste recycling · Biological efficiency · Production rate · Earliness

1 Introduction

Edible mushrooms of the genus *Pleurotus* comprise several species, such as *P. ostreatus*, *P. eryngii*, *P. djamor*, *P. citrinopileatus*, and *P. pulmonarius*, all of which are recognized for the importance of their nutritional, therapeutic, and pharmacological composition [1]. These species are considered excellent lignocellulosic decomposers because of their high rate of mycelial growth and enzymatic capacity. Such characteristics favor their cultivation because they can quickly colonize various agronomic wastes, such as rice straw, corn, barley, wheat, coconut husks, and banana leaves, transforming them into protein [2–6]. Some species of the genus *Pleurotus* can grow and develop at temperatures between 10 and 28 °C, with substrate humidity between 50 and 75%. In addition, they are resistant to xenobiotics [7–10].

Pleurotus ostreatus (Jacq.), known as oyster mushroom, is one of the most produced edible mushroom species in the world and represents 19% of world production, surpassed only by *Lentinula edodes* (Shiitake), with 22% [11]. *P. ostreatus* provides a food with a high nutritional content, as well as antioxidant, antimutagenic, and hepatoprotective properties [1]. Furthermore, it can be produced with low-cost technology and presents high economic profitability [12, 13].

Agricultural activity produces large amounts of agronomic waste annually, most of which is represented by

lignocellulosic biomass [14]. The improper disposal of these wastes can lead to serious environmental problems that contribute to the release of greenhouse gases, the proliferation of pests, and N immobilization in the soil [15–17]. However, studies show that proper agronomic waste management contributes to increased microbial activity, carbon sequestration, and reduced soil erosion [18–20].

According to Cherubin et al. [21], based on reporting by the United Nations Food and Agriculture Organization (FAO), the production of agronomic wastes increased by 50% in the world, reaching 5,011 million megagrams between 2003 and 2013 alone. Therefore, alternatives that aim to adequately manage these wastes are necessary. One of the pertinent alternatives for the reuse of wastes from agriculture has been to use them as raw material for the cultivation of mushrooms of the genus *Pleurotus* for human consumption [12, 22, 23]. Through their ecological bioconversion of lignocellulosic wastes, after the productive period, they can be used as organic fertilizer, for bioremediation of the soil, and in the production of biofuels [13, 24, 25].

Due to the high corn and rice consumption in Latin America and Asia, corn stubble and rice straw make up more than 40% of the agronomic wastes generated in the world [21]. In Peru, for example, according to the Ministry of Agriculture and Irrigation [26], rice consumption is one of the highest on the continent (54 kg year⁻¹). This

promotes an increase in its cultivation area, and consequently, an increase in the dry waste from the crop. It is good to highlight that this situation is not different for corn cultivation. Agronomic wastes from rice and corn are important lignocellulosic sources of C and N, with a C/N ratio greater than 30. This allows these materials to be used as substrates in the cultivation of *P. ostreatus*, owing to its specialization in the decomposition of substrates [9, 27]. This study aimed to provide evidence that the most abundant substrates in Peru, corn stubble and rice straw, can also be used in the production of the edible mushroom *P. ostreatus*, which can provide a valuable food while contributing to the management and recycling of agro-nomic wastes.

2 Material and methods

2.1 Experimental area

The experiment was conducted in the edible mushroom production module of the Faculty of Agronomy of the National Agrarian University La Molina (UNALM), Lima-Peru.

2.2 Biological material

Four strains of *Pleurotus ostreatus* (Jacq.), PO/A01, PO/A02, PO/A03, and PO/A04, isolated from the regions of Lima and Cusco, Peru, were used. The strains were identified, isolated, preserved, and registered at the Phytopathology Laboratory of UNALM.

2.3 Cultivation of strains

The purified colonies of strains isolated from *P. ostreatus* were cultured in Potato-Dextrose-Agar (PDA) medium for one week at 25 ± 2 °C under in vitro conditions. The culture medium was prepared with 500 mL L⁻¹ of an infusion of 250 g of potato, 6.5 g L⁻¹ of agar, and 18 g L⁻¹ of dextrose with the pH adjustment at 6.5. It was sterilized in an autoclave for 20 min at 121 °C and 103 kPa. In this step, the mycelial growth of the strains was evaluated until the complete colonization of the nutrient medium.

2.4 Spawn preparation

The spawn preparation was carried out according to [12] with modifications. The primary inoculum was prepared by transferring colonies of *P. ostreatus*, grown in vitro, to wheat grains until total colonization. The secondary inoculum (spawn) was prepared by transferring the primary inoculum to wheat grains. The amount of secondary inoculum was calculated considering a 5% rate of inoculation of the moistened substrate. The inoculum was incubated at 25 ± 2 °C in total darkness for one week. The wheat grains were pre-cooked and mixed with 3 g kg⁻¹ CaCO₃ and 13 g kg⁻¹ CaSO₄·2H₂O. Then they were sterilized in an autoclave at 121 °C and 103 kPa for 20 min before being used to prepare the inoculum.

2.5 Preparation of substrates

The substrates of corn stubble and rice straw were obtained from farms near the city of Lima, Peru. The substrates were chopped into 3–5 cm pieces and subsequently treated by immersion in hot water at 75 ± 5 °C for 1 h. The substrates were left to drain until 1–3 drops were released after squeezing them by hand [30]. Before inoculation, the carbon content, nitrogen content, and pH of the substrate dry samples were determined according to [28] (Table 1) in the Laboratory of Analysis of Soils, Plants, Waters, and Fertilizers of UNALM.

2.6 Mushroom production

The disinfected substrates were inoculated at a 5% inoculation rate and distributed in polypropylene bags (14 cm × 20 cm × 2 mm), containing the equivalent of 1 kg of dry mass, without nitrogen supplementation. The bags were incubated in total darkness for two weeks at a temperature of 22 ± 1 °C and $81 \pm 3\%$ RH (relative humidity). After total mycelial colonization of the substrate, the bags were transferred to a fructification room at 20 ± 2 °C and $85 \pm 5\%$ RH. In this room, vertical cuts of 2 cm were made on the surface of the bags to induce the mushrooms to grow. The primordia reached the collection point between the third and sixth day after inoculation (Fig. 1). The induction-fructification-harvesting process was repeated in three periods, separated by 12 ± 3 days,

Table 1 Chemical composition of corn stubble and rice straw used as substrates in the production of *P. ostreatus* mushrooms

Substrates	C (mg g ⁻¹)	N (mg g ⁻¹)	C/N	pH	Moisture ¹ (%)
Corn stubble (<i>Zea mays</i>)	315.45	4.70	67.12	7.21	70.20
Rice straw (<i>Oriza sativa</i>)	500.81	6.97	71.85	7.16	68.73

¹ Moisture (%) = (wet substrate – dry substrate)/wet substrate × 100

Fig. 1 Stages of the production of edible mushrooms. **A** mycelium growth in inoculated and incubated substrate; **B** Primordia growth after two days of induction; **C** young fruiting body in development; and **D** mature fruiting body for harvesting

totaling 60 ± 4 days of the productive period. At the end of the harvest, the dry mass of the Spent Mushroom Substrate (SMS) was recorded.

2.7 Experimental design

Under in vitro conditions, the experiment was conducted under a completely randomized design (CRD) with 6 replicates for each strain of *P. ostreatus*. The experimental unit was a Petri dish with PDA medium that was inoculated with a 0.5 cm^2 segment of mycelium. Under productive conditions, the experiment was conducted under a CRD,

with a 4×2 factorial design using 4 strains of *P. ostreatus* and 2 substrates (corn stubble and rice straw), with 8 replicates. The experimental unit was a $14 \text{ cm} \times 20 \text{ cm} \times 2 \text{ mm}$ polypropylene bag with an equivalent of 1 kg of dry substrate inoculated with *P. ostreatus*.

2.8 Variables analyzed

The variables analyzed were: A) the mycelial growth in vitro (mm day^{-1}), determined by the ratio of the radius of a Petri dish (40 mm) and the days it took the *P. ostreatus* mycelium to colonize the PDA medium; B) the mycelial growth in the

substrate (cm day^{-1}), determined by the ratio of the radius of each experimental unit (bag), and the incubation time that the *P. ostreatus* mycelium took to complete the vegetative state, colonizing the entire substrate, i.e., turning to a white color. This variable corresponds to a mathematical arrangement proposed by the authors to assess mycelial growth and reduce the handling of packages in the incubation phase. To do so, the bag radius (R) was estimated by the mathematical similarity of the cylindrical volume of the bags ($v = \pi \times a \times b \times h$) and the volume of a sphere ($v = 4/3 \times \pi \times R^3$). The radius measurement was calculated by:

$$R = \sqrt[3]{\frac{3}{4} \times a \times b \times h} \quad (1)$$

where R is the radius (cm), a is the major radius (semi-major axis) of the base (cm), b is the minor radius (semi-minor axis) of the base (cm), and h is the height (cm) of the mushroom grow bag, respectively.

We also evaluated, C) the biological efficiency (%), relating the conversion of the inoculated substrate into fresh mushrooms [12], established by:

$$\text{BE (\%)} = \frac{\text{Total fresh biomass of mushroom (g)}}{\text{Initial dry mass of substrate (g)}} \times 100 \quad (2)$$

D) The production rate (%), relating the biological efficiency of *P. ostreatus* strains and the days required to complete the production period [29]; E) the earliness (days), determined by the average time to obtain a harvest after induction (adapted from [30]); F) the daily productive capacity (kg day^{-1}) (adapted from [31]), through the ratio of the total biomass of fresh mushrooms harvested with the earliness and the number of harvests in the production system for 100 productive units, established by:

$$\text{PC (kg day}^{-1}\text{)} = \frac{\text{Total fresh biomass of mushroom (kg)}}{\text{Number of harvests} \times \text{Earliness (days)}} \times 100 \quad (3)$$

Finally, G) the organic matter loss (%), which represents the decomposition of the substrate by the fungus [5], determined by:

$$\text{OML (\%)} = \frac{\text{Initial substrate dry mass (g)} - \text{residual (g)}}{\text{Initial substrate dry mass (g)}} \times 100 \quad (4)$$

where the residual is the dry biodegraded substrate mass at the end of the production period, known as SMS (Spent Mushroom Substrate).

2.9 Statistical analysis

All statistical analyses were performed using R software version 3.6.3 [32], with the help of the Expdes [33] and

Fig. 2 Mycelial growth of *P. ostreatus* strains under in vitro conditions. Different letters represent significant differences according to the Tukey test at a 5% ($P < 0.05$). Mean $\pm$ SE, $n = 6$

agricolae [34] packages. The data obtained were submitted to the Kolmogorov–Smirnov test and Bartlett test to confirm the normality and homoscedasticity of residuals, both at a significance level of 5% ($P > 0.05$). Analysis of variance (ANOVA) was performed to determine the significant differences between treatments and the main effects of the factors and, when significant, they were subjected to the Tukey means test at a 5% significance level ($P < 0.05$). Additionally, Pearson's correlations between variables were calculated.

3 Results

Under in vitro conditions, the four strains isolated from *P. ostreatus* showed significant differences among them for mycelial growth (Fig. 2). The PO/A02 strain showed the lowest average growth value of 3.48 mm day^{-1} . While strains PO/A04 and PO/A03 showed greater growth with 4.08 mm day^{-1} and 3.91 mm day^{-1} , respectively.

The direct influence of the characteristics of lignocellulosic substrates on the biological efficiency variable, production rate, and earliness of the isolated strains of *P. ostreatus* are shown in Table 2. In addition, we observed that the variables of mycelial growth in the substrate, daily productive capacity, organic matter loss of the isolated strains of *P. ostreatus*, and the types of substrates (corn stubble and rice straw), were independent of each other as they did not show significance in the interaction.

The *P. ostreatus* strains showed a 29.78% increase in biological efficiency in corn stubble (93.83%) (Fig. 3A) in comparison to growth in rice straw (72.37%). The PO/A02 strain showed the lowest values of biological efficiency in corn stubble (84.63%) and rice straw (66.69%). These results were 18% and 9% lower than the PO/A03 strain, which was more efficient on both substrates, respectively.

Table 2 Mean squares of the analysis of variance of the variables evaluated in the productivity stage

Factors	Degree of freedom	Mycelial growth in substrate (cm day ⁻¹)	Biological efficiency (%)	Production rate (% day ⁻¹)	Earliness (days)	Daily productive capacity (kg day ⁻¹)	Organic matter loss (%)
Strains	3	0.3420***	461.90***	0.1726***	15.838***	0.4681***	318.13***
Substrates	1	0.5389***	7365.90***	8.4013***	35.006***	13.0779***	956.66***
Strains × Substrates	3	0.0024n.s	153.80**	0.0548*	3.216*	0.1141n.s	14.35n.s
Error	56	0.0136	31.60	0.0189	1.037	0.0507	12.81
Average		1.08	83.10	1.71	11.92	2.37	41.16
C.V. (%)		10.81	6.76	8.06	8.54	9.49	8.69

* $P < 0.05$; ** $P < 0.01$; *** $P < 0.001$ significant according to test F. Not significant (n.s.)

Fig. 3 Biological efficiency (A), Production rate (B) and earliness (C) of the *P. ostreatus* strains cultivated in corn stubble and rice straw on the production stage. Different letters, lower case for *P. ostrea-*

tus strains and upper case for substrates, indicate significant differences according to the Tukey test at a 5% ($P < 0.05$). Mean $\pm$ SE, $n = 8$

The production rate (Fig. 3B) increased by 53.33% in corn stubble (2.07%) compared to when grown in rice straw (1.35%). The PO/A01 strain had the lowest production rate (1.88%) in relation to the PO/A03 strain, which increased its production rate by 20% when grown in corn stubble.

The earliness (since induction) was significantly influenced by the type of substrate (Fig. 3C). Corn stubble reduced the number of days to harvest by 12%. The PO/A02 strain behaved as earlier in both substrates, reaching 10 days in corn stubble and 12 days in rice straw. On the other hand, the strain PO/A01, took 12 days to obtain a

Table 3 Mean values of variables mycelial growth in substrate (cm), daily productive capacity (kg day⁻¹), and organic matter loss (%) for analysis of Main effects of *P. ostreatus* strains and types of substrates when not significant in the factorial interaction

Factors	Mycelial growth in substrate (cm day ⁻¹)	Daily productive capacity (kg day ⁻¹)	Organic matter loss (%)
<i>P. ostreatus</i> strains			
PO/A01	1.18 ± 0.04 a	2.13 ± 0.10 b	39.39 ± 1.27 b
PO/A02	1.22 ± 0.03 a	2.40 ± 0.14 a	36.47 ± 0.99 c
PO/A03	0.99 ± 0.05 b	2.53 ± 0.14 a	41.77 ± 1.34 b
PO/A04	0.92 ± 0.03 b	2.43 ± 0.13 a	47.00 ± 1.67 a
Substrates			
Corn stubble	1.17 ± 0.03 a	2.82 ± 0.06 a	45.03 ± 1.00 a
Rice straw	0.99 ± 0.03 b	1.92 ± 0.04 b	37.29 ± 0.85 b

Different letters indicate significant differences ($P < 0.05$) according to the Tukey test. Mean ± SE, $n = 8$

Table 4 Pearson's correlation for the variables evaluated in the production stage of edible mushrooms

	BE	OML	PR	ES
OML	0.78***			
PR	0.89***	0.61***		
ES	-0.20n.s	0.00n.s	-0.61***	
DPC	0.82***	0.54***	0.99***	-0.72***

BE = Biological efficiency; PR = Production rate; OML = Organic matter loss; ES = Earliness; DPC = Daily productive capacity

*($P < 0.05$), ** ($P < 0.01$) and *** ($P < 0.001$). Not significant (n.s.)

harvest after induction in corn stubble and 14 days in rice straw, standing out as the slowest strain.

In Table 3, the main effects of the variables that did not present significant differences in the interaction of the study factors (types of substrates × isolated strains of *P. ostreatus*) were grouped and analyzed. It was found that strains PO/A01 and PO/A02 showed 26% faster mycelial growth than strains PO/A03 and PO/A04, which showed less than 1 cm of mycelial growth per day. We also observed that the isolated strains PO/A02, PO/A03, and PO/A04 were 15% more productive, compared to PO/A01, which reached only 2.13 kg day⁻¹. Regarding the organic matter loss, the isolated strain PO/A04 decomposed by approximately 47% of the original mass of the initial substrate, exceeding the isolated strains by 16% for PO/A01 and by 29% for PO/A03. The isolated strain PO/A02 caused lower organic matter loss in the substrates.

By analyzing the main effects of the substrates under study, we verified that the corn stubble increased by 18% the mycelial growth in the substrate (cm day⁻¹), 47% the daily productive capacity (kg day⁻¹), and 21% the organic matter loss (%), in comparison with the rice straw (Table 3).

The Pearson's correlations (Table 4) show a high positive correlation (above 80%) between the variables of biological efficiency, production rate, and daily productive capacity. We observed a moderate positive correlation between

organic matter loss and biological efficiency ($r = 0.78$, $P < 0.001$) and the production rate ($r = 0.61$, $P < 0.001$). In addition, a total absence of correlation between earliness and biological efficiency, and organic matter loss was observed.

4 Discussion

Rapid mycelial colonization is known to decrease contamination losses significantly, reducing the incubation time and productive period in an edible mushroom production system [35]. Under in vitro conditions, by controlling the temperature, humidity, and nutrient medium, the mycelial growth allows the evaluation of the vigor and growth speed of isolated strains. The different stages of mycelial growth can be identified because the soluble sugars are consumed during the stages of absorption, cell division, and mycelial growth, resulting in mycelial growth from 4 to 10 mm day⁻¹ in substrate, and from 13 to 30 mm day⁻¹ in culture medium [36]. However, as observed in our results, which demonstrated mycelial growth of less than 5 mm day⁻¹, these responses may vary according to the evaluation methodology used, nutrient medium, and biological material.

From the inoculation of the substrates, the mycelial growth can be influenced by the chemical composition, plant structure, origin, and particle size of the agronomic wastes used as substrate. Such characteristics, when added to the domain of control of environmental conditions and substrate treatment, will determine the productive performance of mushrooms [5, 37].

The biological efficiency and the production rate are variables that relate significantly to the biotransformation of the lignocellulosic wastes into fresh basidiocarps during the production period. Therefore, the variation in both will always be influenced by the type and chemical composition of the substrates used. According to Belletini et al. [38], among the most important factors are the

substrates used, the carbon–nitrogen ratio (C/N) (which should be within the range of 25–100/1), pH, particle size, and quantity of inoculum. The balance between the C/N ratio in the substrate is important to promote the proper mycelial development of the mushrooms because the total carbon is composed of recalcitrant cellulose and hemicellulose [27]. In a study by Li et al. [39], for example, it was observed that the low C/N ratio (excess of nitrogen) in stems of perilla slows the formation of basidiocarps. In a study by Yang et al. [40] that used cotton bark with a high C/N ratio (nitrogen deficiency), mycelial growth was inhibited and caused a slower colonization rate of *P. ostreatus*.

This evidence may explain why there is greater mycelial growth and greater biological efficiency in corn stubble than in rice straw (Table 1; Fig. 2). In addition, the particle size of the substrate may have influenced the responses of the mentioned variables because although both substrates had similar granulometry (between 3 and 5 cm), the corn stubble showed a greater contact surface compared to rice straw. However, we observed that this effect did not limit the aeration of the fungi; otherwise, the biological efficiency would have been negatively affected [41].

The corn stubble and rice straw reached biological efficiencies greater than 60%. These results are also observed in studies that used other types of agronomic wastes, such as tomato tuff, banana leaves, rice straw, perilla stalks, wheat straw, sawdust, and cotton seeds that presented a C/N ratio between 30 and 50 [5, 37, 39, 42, 43]. Similarly, we verified that the intrinsic characteristics of the substrate type have a direct influence on biological efficiency.

Similarly, the chemical composition of the substrates influences mycelial growth, and the physical structure (size and density) can also favor mycelial colonization, reducing the harvesting time (in days) (Fig. 3C). According to results presented by Al-Momany and Ananbeh [42], when tomato tuff was used for the cultivation of *P. ostreatus*, it was found that the average time between induction and harvest was only 8 days, which is 3 days less than that recorded for corn stubble and 5 days at less for rice straw.

In this study, the method of evaluating mycelial growth in substrates was unprecedented, since we considered the calculation of the bag radius based on the measurement of its dimensions (see Eq. 1). This method allowed us to reduce the number of evaluations by reducing the excessive handling of bags. Because the radius value (cm) was known, it was necessary to record only the total number of days of incubation to determine mycelial growth (cm day^{-1}). Other methodologies for evaluating mycelial growth in the substrate were carried out by Bernardi et al. [37], marking equidistant lines in the length of the flask with substrates. Alternatively, Thongklang [44] measured the linear length of the mycelium in bottles, while Mkhize et al. [35] monitored growth in four equally spaced

areas around the substrate bag. The disadvantage of our method, compared to other research, is that it would not be recommended to identify the stages of mycelial growth.

The daily productive capacity allowed us to verify how the quantities of mushrooms produced can be influenced by the effectiveness of the harvest number. This is associated with the earliness of the biological material, whose variation was positively correlated with the organic matter loss and at the same time showed a positive correlation with biological efficiency and production rate. These results allow for inferring the efficacy in the transformation of the lignocellulosic wastes of corn stubble and rice straw into fresh basidiocarps due to the decomposition caused by *P. ostreatus*. However, this relationship is not always evident when we compare different structures of the same plant or make comparisons among different varieties of a crop [5]. For greater certainty, chemical analysis of SMS is recommended after the end of the production period to verify how much of the initial compounds were used [13].

The results obtained highlight the behavior of the isolated strain PO/A02, even with lower biological efficiency. It reached high values of production at a rate similar to the strains that presented higher values of biological efficiency (Fig. 3). The behavior of strain PO/A02 is explained by its rapid mycelial growth in substrate and earliness, which shorten the productive period and increase the production rate. This was also observed in studies conducted by Vega and Franco [6], and Bernardi et al. [37], who productively characterized other species of the genus *Pleurotus*, on different substrates from agricultural activities such as corn cob, corn stubble, rice straw, cane bagasse, and the waste from castor oil plants.

In the present study, the chemical characteristics of the nutritive content of the mushrooms provided by the two types of substrates were not analyzed. However, at the production level, we found that the isolated strains PO/A03 and PO/A04 produced greater biological efficiency and greater organic matter loss of the substrate. According to Grimm and Wösten [45], an SMS with more organic matter loss can return to the environment with less recalcitrant compounds and be used as organic fertilizer, animal feed, or input in energy production (bioethanol) under a circular economy. On the other hand, if more productive cycles per year and a higher production rate are sought, the PO/A02 strain must be considered.

It is worth mentioning that different strains present distinct behaviors regarding mycelial growth, biological efficiency, loss of organic matter, and earliness due to their unique genetic and phenotypic characteristics [8]. Curvetto et al. [46] compared the mycelial growth, primordia initiation, time to second flush, mushroom production, and biological efficiency of five strains of *P. ostreatus*

cultivated on sunflower seed hulls and supplemented with NH_4^+ and/or Mn(II) . Different basal values were observed for each strain, and they argued that it is important to select the most productive *P. ostreatus* strains according to the substrate.

In addition to productivity parameters, there are studies regarding enzyme production among different *P. ostreatus* strains. Díaz et al. [47] evaluated the growth and laccase activity of five *P. ostreatus* strains and observed differences among all strains. Furthermore, the authors found that adding copper enhanced laccase production by some strains, thus enabling the selection of copper-sensitive strains for commercial enzyme production.

As the lignocellulolytic capacity of this species is related to its enzyme production [9], it is recommended that further studies be conducted, especially regarding the molecular biology of the strains, such as the production of laccase, manganese peroxidase, and lignin peroxidase enzymes, as well as their gene expression.

5 Conclusions

The agronomic wastes of corn stubble and rice straw are both recommended for the cultivation of *P. ostreatus*. However, compared to rice straw, corn stubble promotes greater mycelial growth and biological efficiency, reduces harvest periods, favors increased earliness, and positively influences the production and the daily productive capacity of strains isolated from *P. ostreatus*. Strains PO/A03 and PO/A04 showed higher biological efficiency, production rate, and daily productive capacity. Furthermore, they can increase the organic matter loss in the substrates. The PO/A02 strain produces mushrooms earlier, with more productive periods per year and an increasing production rate under in vitro conditions. In comparing their behavior in the substrate, the strains presented different mycelial growth; thus, even if a strain showed slower growth in PDA medium, it is still possible that it may colonize other substrates efficiently.

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Author's Contribution JRZS conceived of the presented idea, designed, and directed the project, carried out the experiment, analyzed the data, and wrote the article. MNS discussed the main idea of this project with JRZS, revised the results, and supervised the writing of the manuscript. ENMC contributed to the design and implementation of the research and supervised the findings of this work. OGM

reviewed the manuscript with JRZS and contributed to improve the results, discussion and conclusions. AAPH helped supervise every step of the project. All authors discussed the results and contributed to the final manuscript.

Compliance with ethical standards

Conflicts of interest On behalf of all authors, the corresponding author states that there is no conflict of interest.

References

1. Patel Y, Naraian R, Singh V (2012) Medicinal properties of *Pleurotus* species (*Oyster mushroom*): a review. *World J Fungal Plant Biol* 3:1–12. <https://doi.org/10.5829/idosi.wjfpb.2012.3.1.303>
2. Dawoud MEA, Eweis M (2006) Phytochemical control of edible mushrooms pathogenic bacteria. *J Food Agric Environ* 4:321
3. Vetayasupom S (2007) Lignocellulosic materials as a possible substrate for *Pleurotus ostreatus* (Fr.) kummer cultivation. *J Agron* 6:167–170
4. Sánchez C (2010) Cultivation of *Pleurotus ostreatus* and other edible mushrooms. *Appl Microbiol Biotechnol* 85:1321–1337. <https://doi.org/10.1007/s00253-009-2343-7>
5. de Carvalho CSM, de Aguiar LVB, Sales-Campos C, de Minhoni MTA, de Andrade MCN (2012) Applicability of the use of waste from different banana cultivars for the cultivation of the oyster mushroom. *Braz J Microbiol* 43:819–826. <https://doi.org/10.1590/S1517-83822012000200048>
6. Vega A, Franco H (2013) Productividad y calidad de los cuerpos fructíferos de los hongos comestibles *Pleurotus pulmonarius* RN2 y *P. djamor* RN81 y RN82 cultivados sobre sustratos lignocelulósicos. *Inf tecnológica* 24:69–78. <https://doi.org/10.4067/S0718-07642013000100009>
7. Bano Z, Rajarathnam S, Steinkraus KH (1988) *Pleurotus* mushrooms. Part II. Chemical composition, nutritional value, post-harvest physiology, preservation, and role as human food. *Crit Rev Food Sci Nutr* 27:87–158. <https://doi.org/10.1080/10408398809527480>
8. Chang ST, Miles PG (2004) Mushrooms. Cultivation, nutritional value, medicinal effect, and environmental impact. CRC Press, Boca Raton
9. Mata G, Salmones D, Savoie JM (2017) Las enzimas lignocelulolíticas de *Pleurotus* spp. In: Royse DJ, Sánchez JE (eds) *La Biol el Cultiv y las propiedades Nutr. y Med. las setas Pleurotus* spp. ECOSUR, Chiapas, México DF, pp. 63–82
10. Sekan AS, Myronycheva OS, Karlsson O, Gryganskyi AP, Blume YB (2019) Green potential of *Pleurotus* spp. in biotechnology. *PeerJ* 7:1–27. <https://doi.org/10.7717/peerj.6664>
11. Royse DJ, Sánchez JE (2017) Producción mundial de setas *Pleurotus* spp. con énfasis en países Iberoamericanos. In: Royse DJ, Sánchez JE (eds) *La Biol. el Cultiv. y las propiedades Nutr. y Med. las setas Pleurotus* spp. ECOSUR, Chiapas, México DF, pp. 17–24
12. Estrada AER, Pecchia J (2017) Cultivation of *Pleurotus ostreatus*. In: *Edible Med. Mushrooms*. John Wiley & Sons, Ltd, pp. 339–360
13. Owaid MN, Abed IA, Al-Saeedi SSS (2017) Applicable properties of the bio-fertilizer spent mushroom substrate in organic systems as a byproduct from the cultivation of *Pleurotus* spp. *Inf Process Agric* 4:78–82. <https://doi.org/10.1016/j.inpa.2017.01.001>
14. Kuhad RC, Singh A, Eriksson K-EL (1997) Microorganisms and enzymes involved in the degradation of plant fiber cell walls. In: Eriksson K-EL, Babel W, Blanch HW, Cooney CHL, Enfors S-O, Eriksson K-EL, Fiechter A, Klivanov AM, Mattiasson B, Primrose

- SB, Rehm HJ, Rogers PL, Sahm H, Schügerl K, Tsao GT, Venkat K, Villadsen J, von Stockar U, Wandrey C (eds) *Biotechnology in the Pulp and Paper Industry*. Springer, Berlin, Heidelberg, pp 45–125
15. Dinardo-Miranda LL, Fracasso JV (2013) Sugarcane straw and the populations of pests and nematodes. *Sci Agric* 70:305–310. <https://doi.org/10.1590/S0103-90162013000500012>
 16. Jin VL, Baker JM, Johnson JM-F et al (2014) Soil greenhouse gas emissions in response to corn stover removal and tillage management across the US corn belt. *BioEnergy Res* 7:517–527. <https://doi.org/10.1007/s12155-014-9421-0>
 17. Ferreira DA, Franco HCJ, Otto R, Vitti AC, Fortes C, Faroni CE, Garside AL, Trivelin PCO (2016) Contribution of N from green harvest residues for sugarcane nutrition in Brazil. *Gcb Bioenergy* 8:859–866. <https://doi.org/10.1111/gcbb.12292>
 18. Franzluebbers AJ (2015) Farming strategies to fuel bioenergy demands and facilitate essential soil services. *Geoderma* 259:251–258. <https://doi.org/10.1016/j.geoderma.2015.06.007>
 19. Junior FPP, Portilho IIR, Mercante FM (2015) Microbiological attributes of the soil under cultivation of sugar cane with and without burning straw. *Semin Ciências Agrárias* 36:151–164
 20. Poeplau C, Don A (2015) Carbon sequestration in agricultural soils via cultivation of cover crops—a meta-analysis. *Agric Ecosyst Environ* 200:33–41. <https://doi.org/10.1016/j.agee.2014.10.024>
 21. Cherubin MR, Márcio D, Oliveira S et al (2017) Crop residue harvest for bioenergy production and its implications on soil. *Sci Agric* 75:255–272. <https://doi.org/10.1590/1678-992x-2016-0459>
 22. Rani P, Kalyani N, Prathiba K (2008) Evaluation of lignocellulosic wastes for production of edible mushrooms. *Appl Biochem Biotechnol* 151:151–159. <https://doi.org/10.1007/s12010-008-8162-y>
 23. Sözbir GD, Bektaş I, Zülkadir A (2015) Lignocellulosic wastes used for the cultivation of *Pleurotus ostreatus* mushrooms: effects on productivity. *BioResources* 10:4686–4693
 24. Herrero-Hernández E, Andrades MS, Marín-Benito JM, Sánchez-Martín MJ, Rodríguez-Cruz MS (2011) Field-scale dissipation of tebuconazole in a vineyard soil amended with spent mushroom substrate and its potential environmental impact. *Ecotoxicol Environ Saf* 74:1480–1488. <https://doi.org/10.1016/j.ecoenv.2011.04.023>
 25. Fang W, Ye J, Zhang P, Zhu X, Zhou S (2017) Solid-state anaerobic fermentation of spent mushroom compost for volatile fatty acids production by pH regulation. *Int J Hydrogen Energy* 42:295–300. <https://doi.org/10.1016/j.ijhydene.2017.04.148>
 26. MINSA (2017) Ministerio de Agricultura y Riego del Perú: Informe del Arroz. In: Dir. Gen. Políticas Agrar. Dir. Estud. Económicos e Inf. Agrar. Gob. la Repub. del Perú., MINSA. DGPA, Lima, pp. 1–9
 27. Ryu J-S, Kim MK, Im CH, Shin P-G (2015) Development of cultivation media for extending the shelf-life and improving yield of king oyster mushrooms (*Pleurotus eryngii*). *Sci Hortic* 193:121–126. <https://doi.org/10.1016/j.scienta.2015.07.005>
 28. da Silva FC (2009) *Manual de Análises Químicas de Solos, Plantas, Fertilizantes*, 2nd edn. Embrapa Comunicação para Transferência de Tecnologia, Brasília
 29. Avendaño-Hernández RJ, Sánchez JE (2013) Self-pasteurised substrate for growing oyster mushrooms (*Pleurotus* spp.). *African J Microbiol Res* 7:220–226. <https://doi.org/10.5897/AJMR12.1832>
 30. Bermúdez RC, García N, Gross P, Serrano M (2001) Cultivation of *Pleurotus* on agricultural substrates in Cuba. *Micol Apl Int* 13:25–29
 31. Ardón-Lopez C (2007) *La producción de los hongos comestibles*. Dissertation, Universidad de San Carlos de Guatemala
 32. R Core Team (2019) R: A Language and Environment for Statistical Computing
 33. Ferreira EB, Cavalcanti PP, Nogueira DA (2018) Experimental Designs package
 34. Mendiburu F (2019) agricolae: Statistical Procedures for Agricultural Research
 35. Mkhize SS, Zharare GE, Basson AK, Mthembu MS, Cloete J (2017) Performance of *Pleurotus pulmonarius* mushroom grown on maize stalk residues supplemented with various levels of maize flour and wheat bran. *Food Sci Technol* 37:570–577. <https://doi.org/10.1590/1678-457x.27216>
 36. Martínez DA, Buglione MB, Filippi MV, del Carmen RL, Rodríguez GE, Agüero MS (2015) Mycelial growth evaluation of *Pleurotus ostreatus* and *Agrocybe aegerita* on pear pomaces. *An Biol* 37:1–10. <https://doi.org/10.6018/analesbio.37.1>
 37. Bernardi E, do Minotto E, Nascimento JS (2013) Evaluation of growth and production of *Pleurotus* sp. in sterilized substrates. *Arq Inst Biol (Sao Paulo)* 80:318–324. <https://doi.org/10.1590/S1808-16572013000300009>
 38. Bellettini MB, Fiorda FA, Maievas HA, Teixeira GL, Ávila S, Hornung PS, Júnior AM, Ribani RH (2019) Factors affecting mushroom *Pleurotus* spp. *Saudi J Biol Sci* 26:633–646. <https://doi.org/10.1016/j.sjbs.2016.12.005>
 39. Li H, Zhang Z, Li M, Li X, Sun Z (2017) Yield, size, nutritional value, and antioxidant activity of oyster mushrooms grown on perilla stalks. *Saudi J Biol Sci* 24:347–354. <https://doi.org/10.1016/j.sjbs.2015.10.001>
 40. Yang WJ, Guo FL, Wan ZJ (2013) Yield and size of oyster mushroom grown on rice/wheat straw basal substrate supplemented with cotton seed hull. *Saudi J Biol Sci* 20:333–338. <https://doi.org/10.1016/j.sjbs.2013.02.006>
 41. Zhang R, Li X, Fadel JG (2002) Oyster mushroom cultivation with rice and wheat straw. *Bioresour Technol* 82:277–284. [https://doi.org/10.1016/S0960-8524\(01\)00188-2](https://doi.org/10.1016/S0960-8524(01)00188-2)
 42. Al-momany A, Ananbeh K (2010) Conversion of agricultural wastes into value added product with high protein content by growing *Pleurotus ostreatus*. *Surviv Sustain*. https://doi.org/10.1007/978-3-540-95991-5_139
 43. Girmay Z, Gorems W, Birhanu G, Zewdie S (2016) Growth and yield performance of *Pleurotus ostreatus* (Jacq. Fr.) Kumm (oyster mushroom) on different substrates. *AMB Express* 6:1–7. <https://doi.org/10.1186/s13568-016-0265-1>
 44. Thongklang N (2016) Testing agricultural wastes for the production of *Pleurotus ostreatus*. *Mycosphere* 7:766–772. <https://doi.org/10.5943/mycosphere/7/6/6>
 45. Grimm D, Wösten HAB (2018) Mushroom cultivation in the circular economy. *Appl Microbiol Biotechnol* 102:7795–7803. <https://doi.org/10.1007/s00253-018-9226-8>
 46. Curvetto NR, Figlas D, Devalis R, Delmastro S (2002) Growth and productivity of different *Pleurotus ostreatus* strains on sunflower seed hulls supplemented with N-NH₄ and/or Mn. *Bioresour Technol* 84:171–176. [https://doi.org/10.1016/S0960-8524\(02\)00013-5](https://doi.org/10.1016/S0960-8524(02)00013-5)
 47. Díaz R, Alonso S, Sánchez C, Tomasini A, Bibbins-Martínez M, Díaz-Godínez G (2011) Characterization of the growth and lactase activity of strains of *Pleurotus ostreatus* in submerged fermentation. *BioResources* 6:282–290

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