Waste and Biomass Valorization
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ORIGINAL PAPER

Sustainable Reuse of Coconut Husk and *Arundo donax* Biomass for Oyster Mushroom (*Pleurotus ostreatus*) Cultivation

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Abstract

The sustainable reuse of organic residues is a key strategy for reducing the ecological footprint of mushroom cultivation and promoting a circular bioeconomy. Green coconut husks and biomass from the invasive grass *Arundo donax* were evaluated as alternative lignocellulosic substrates for the cultivation of the oyster mushroom *Pleurotus ostreatus*. Five substrate formulations combining different proportions of coconut husk and shredded *A. donax* biomass were tested and compared with a conventional eucalyptus sawdust control. Mycelial colonization time, onset and duration of fruiting, cumulative fresh yield, fresh and dry mass, and carbon, nitrogen, and protein concentrations of the fruiting bodies were assessed. Substrates enriched with *A. donax*, particularly the 75:25 mixture (*A. donax*: coconut husk), reduced colonization time by up to 10 days and achieved the longest production period and highest fresh yield (308g). The coconut-only substrate produced mushrooms with higher dry matter content (27.1% vs. 15.2% in the control), whereas the 100% *A. donax* substrate enhanced nitrogen and protein concentrations. Overall, both residues proved suitable for oyster mushroom cultivation, providing a functional outlet for challenging-to-manage lignocellulosic wastes by converting them into productive substrates that yield nutritious food while contributing to environmental mitigation and the promotion of a circular bioeconomy.

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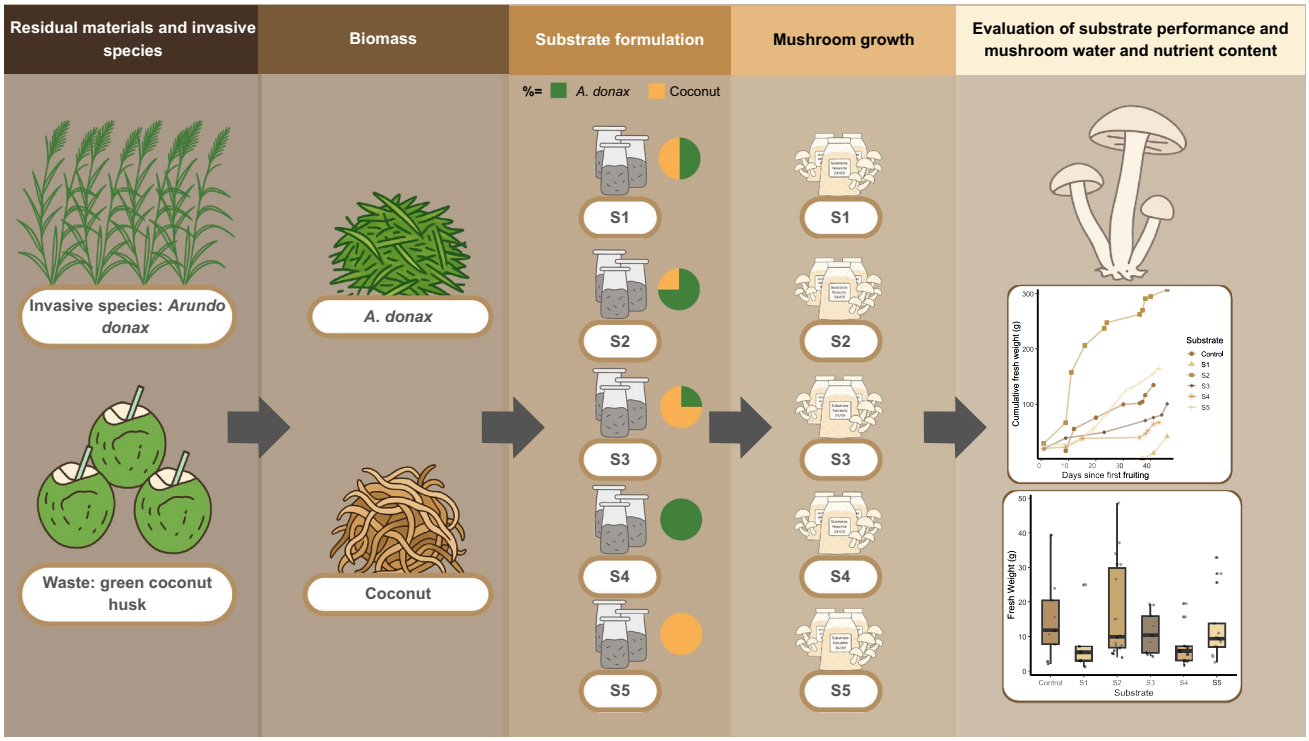
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Graphic abstract



Experimental workflow illustrating the use of *Arundo donax* and green coconut husk as biomass sources for formulating alternative substrates (S1–S5) for mushroom cultivation, followed by the evaluation of substrate performance and mushroom water and nutrient content, showing that S2 achieved the highest yield and the longest fruiting period, whereas the coconut-only substrate (S5) produced mushrooms with the highest dry matter content.

Keywords *Pleurotus ostreatus* · Organic residues · Waste valorization · Circular economy · Sustainable agriculture

Introduction

Edible mushrooms are widely recognized for their high nutritional value, characterized by elevated levels of proteins, essential amino acids, vitamins, and minerals [1, 2]. In addition, many mushrooms produce bioactive secondary metabolites, such as antioxidant compounds, which further enhance their potential as functional foods [3–6]. This combination of nutritional and functional attributes, coupled with the growing consumer demand for healthier diets and environmentally responsible eating practices, has driven the expansion of the global mushroom market [7, 8]. This growth has been accompanied by increased commercial production and international trade, underscoring the sector's significant economic potential [9–11]. Global mushroom production has increased sharply in recent decades. Output rose approximately 13.8-fold between 1990 and 2020, reaching about 42.8 million tonnes, driven by rising demand and advances in cultivation technologies [12–15]. This upward trend is expected to continue as production systems become more efficient and demand for sustainable foods increases worldwide [16]. Among the most economically relevant species, the oyster mushroom (*Pleurotus* spp.) stands out for its ease of cultivation, rapid growth, and remarkable adaptability to nutrient-poor substrates [17]. These characteristics make *Pleurotus* spp. cultivation a viable source of income for small-scale farmers and agricultural enterprises [18]. As global production intensifies, there is an increasing need to identify sustainable cultivation practices that minimize environmental impacts and allow the reuse of vegetable waste as substrate.

One of the most widely used methods in commercial mushroom production, including *Pleurotus* spp., is solid-state cultivation under controlled conditions [8, 19–21]. This approach enables the efficient use of a variety of organic materials, such as sugarcane bagasse, rice straw, sawdust, corn cobs, and numerous other plant-based residues derived from agriculture and industry [8, 19–24]. Many of these substrates are by-products of industrial, agricultural, and domestic activities that, when improperly disposed of,

can cause environmental impacts and pose risks to human and animal health [25–27]. The reuse of these residues as substrate for mushroom cultivation represents a sustainable and high-value-added alternative, capable of transforming discarded materials into human food [28–32]. This practice is considered one of the most effective strategies for reusing lignocellulosic biomass in a sustainable manner [27–29, 33].

In this context, two lignocellulosic residues with significant potential for mushroom cultivation in Brazil stand out: green coconut husks and biomass of the invasive grass *Arundo donax* L (Poaceae). Green coconut is widely consumed fresh, but improper disposal of the shells can cause environmental problems due to the large volume sent to landfills and their slow decomposition. In addition to these environmental impacts, this waste also poses a public health risk, as it can serve as a breeding ground for the larvae of *Aedes aegypti*, a vector of dengue fever [34]. This important arboviral disease affects millions of people worldwide, particularly in tropical countries, and is responsible for thousands of deaths every year [35]. Despite these challenges, coconut shells are rich in lignin and cellulose [36], making them a promising substrate for the cultivation of mushrooms such as *Pleurotus* spp. Studies indicate that lignocellulosic materials, including coconut fiber, are efficient for mycelium development and mushroom production [17, 37, 38]. Another biomass with significant potential is that of the invasive grass *Arundo donax*, whose rapid spread threatens native biodiversity [39, 40]. This worldwide invasive species exhibits high growth rates and can form dense populations, competing with native species for resources and space and altering the dynamics of the ecosystems where it establishes itself [41, 42]. This flammable species has the potential to modify fire regimes in invaded areas and demands costly, long-term management efforts [43]. Although mechanical control strategies have been adopted to limit its spread, these are often ineffective, as regeneration readily occurs from stem fragments and rhizomes [40, 44]. However, due to its high concentration of cellulose, hemicellulose, and other nutrients [45–47], *A. donax* can be a viable alternative for mushroom substrate formulation [48].

Given the need to reduce the ecological footprint, defined as a metric that assesses the impact of human activities on natural resources, this study aims to evaluate the potential of green coconut residue and shredded biomass of *Arundo donax* as alternative substrates for the cultivation of oyster mushrooms (*Pleurotus ostreatus*). The proposal is based on an integrated and sustainable approach to organic waste management, seeking to transform environmental liabilities into high-value and resource-efficient food products. Although lignocellulosic residues are widely recognized as suitable substrates for mushroom cultivation, comparative studies explicitly evaluating invasive grass biomass and urban green coconut waste, while simultaneously addressing cultivation performance and nutritional quality, remain limited. Based on the chemical characteristics of the tested biomasses, we hypothesized that substrates enriched with *A. donax* biomass would promote faster mycelial colonization and longer production periods due to their grass-derived lignocellulosic structure and higher nitrogen content. Also, we further expected that nitrogen-rich substrates would result in mushrooms with higher nitrogen and protein concentrations. By testing these hypotheses, this study demonstrates how waste coconut husks and *A. donax* biomass can contribute to reducing waste management costs and ecological impacts, while generating knowledge relevant to public policies, collaborative environmental management, and income generation.

Materials and Methods

Obtaining the Isolate, Cultivation, and Storage Conditions

The fungal isolate was obtained from a commercially purchased oyster mushroom (*P. ostreatus*) from a supermarket chain in the Federal District, Brazil. For isolation, the basidioma was initially subjected to a surface disinfection protocol adapted from Dos Reis et al. [49]. In summary, a mature fruiting body with the pileus removed was selected and submerged in 70% ethanol for 2 min. It was then immersed in 4% sodium hypochlorite (NaClO) for 5 min and rinsed five times with sterile distilled water. To verify the effectiveness of the disinfection process, an aliquot from the final rinse water was plated onto potato dextrose agar (PDA). For tissue isolation, ~ 5 mm fragments were excised from the inner region of the stipe and transferred to PDA plates. The plates were incubated at 25 °C for 7 days. The resulting fungal colonies were subcultured onto fresh PDA under the same incubation conditions. Subsequently, the isolates were deposited in the Mycological Collection of the University of Brasília (CCUB) using the Castellani method and preserved in 10% glycerol, under accession number CCUB 6218.

Substrate Preparation

Green coconut husks were collected from Parque Olhos D'Água, located in Asa Norte, Brasília, Federal District, Brazil (15.74387°S, 47.88472°W). Individuals of the invasive species *A. donax* were collected at different phenological stages in Cerrado fragments at the Darcy Ribeiro Campus of the University of Brasília (15.7658°S, 47.8722°W). After collection, both green coconut husks and *A. donax* biomass were processed separately in a plant waste shredder. The shredded biomass was arranged on benches and stored in a greenhouse under ambient temperature (~ 25 °C)

and natural ventilation for outdoor air drying for 14 days (Fig. 1a–c).

After the drying process, green coconut husk and *Arundo donax* biomass were used to formulate substrates for mushroom cultivation. Five experimental substrates were prepared by combining different proportions of these lignocellulosic materials, in addition to a control substrate composed exclusively of eucalyptus sawdust (Table 1). Eucalyptus was selected because it is a substrate commonly used for the cultivation of *Pleurotus* spp. [50] and represents one of the main materials employed for mushroom production in the Federal District region of Brazil. The experimental formulations consisted of the following ratios (% *A. donax*: % coconut husk): S1, 50:50; S2, 75:25; S3, 25:75; S4, 100:0; and S5, 0:100. All substrates, including the control, received the same supplementation per kilogram of dry base substrate, consisting of cornmeal (200g), yeast extract (10g), calcium carbonate ($CaCO_3$, 10 g), and calcium sulfate ($CaSO_4$, 10 g). Cornmeal and yeast extract were added as nutritional supplements to enhance mycelial growth, while $CaCO_3$ and $CaSO_4$ were included to stabilize pH and improve substrate structure. This supplementation protocol was adapted from standard mushroom cultivation methods described by Urben (2017) [51]. For each treatment, 1 kg of the supplemented dry substrate was placed into autoclavable polyethylene bags (20 × 40 cm; 0.06 mm thickness), and the moisture content was adjusted to approximately 65% [20]. The bags were sterilized by double autoclaving at 121 °C for 20 min, with a 6-h interval between cycles, and then kept under ambient conditions for 48 h prior to fungal inoculation.

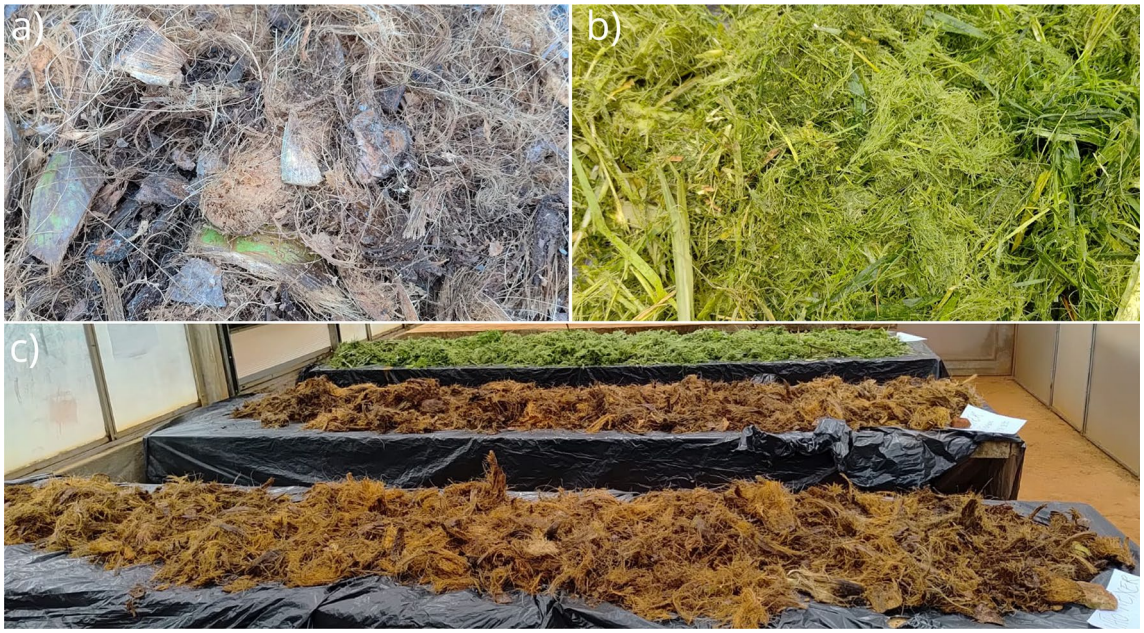


Fig. 1 Processing of green coconut husk and *Arundo donax* L. (Poaceae) biomass. Biomass resulting from the grinding process: **a** green coconut husk and **b** *A. donax*. **c** Drying of biomass on greenhouse benches, at room temperature (~ 25 °C) and natural ventilation

Table 1 Composition of substrates used in the experimental cultivation of *Pleurotus ostreatus*

Materials	S1	S2	S3	S4	S5	Control
Arundo donax (%)	50	75	25	100	–	–
Coconut husk (%)	50	25	75	–	100	–
Sawdust (%)	–	–	–	–	–	100
Cornmeal (g/kg)[1]	200	200	200	200	200	200
Yeast extract(g/kg)[1]	10	10	10	10	10	10
$CaCO_3$ (g/kg)[1]	10	10	10	10	10	10
$CaSO_4$ (g/kg)[1]	10	10	10	10	10	10

[1] Supplements were added per kilogram of dry base substrate. S1–S5: experimental substrates combining different proportions of *A. donax* and coconut husk. Control: 100% eucalyptus sawdust. "–" indicates absence of the component

Mycelial Inoculation and Mushroom Cultivation

The *P. ostreatus* strain was cultivated on PDA for 14 days at 24 °C in darkness. Following this incubation period, ten ~ 5 mm mycelial plugs were transferred into each sterilized cultivation bag containing the experimental substrates. The bags were then placed in a growth chamber constructed from PVC pipes and transparent polyethylene film and maintained in darkness at room temperature (~ 25 ± 5 °C) to promote substrate colonization. To mitigate the risk of contamination by saprophytic fungi, such as *Aspergillus* spp. and *Trichoderma* spp. [52, 53], each treatment was carried out with nine replicates. During incubation, the substrates were monitored daily. To maintain adequate humidity during this phase, a humidifier was operated every two days in 12-h cycles. Once full colonization was achieved (Fig. 2a–c) and primordia had formed (Fig. 2d–g), small incisions were made in the plastic bags to initiate fruiting. From that point onward, the humidifier was activated daily for 12 h to maintain relative humidity between 80 and 90%, under continuous artificial lighting (24h/day). Fruiting bodies were considered mature and ready for harvest when the gills were fully developed and exposed (Fig. 2h) [54].

Growth, Production, and Chemical Composition of Substrates and Mushrooms

Six variables were selected to evaluate the efficiency of the proposed substrates for mushroom cultivation: (1) time required for mycelial colonization; (2) time until the onset of mushroom production; (3) total production duration and accumulated fresh mushroom weight; (4) fresh weight of the harvested mushrooms; (5) water content and dry matter content; and (6) nutrient composition of the mushrooms (carbon, nitrogen, and total protein content).

The experiment was initiated on April 3, 2025, with the inoculation of the *P. ostreatus* strain into the substrates and was conducted until July 17, 2025, lasting a total of 106 days. Substrate colonization by *P. ostreatus* mycelium was monitored daily after inoculation. The time required for complete colonization was recorded in days and was defined as the point at which mycelial growth visibly covered the entire surface of the substrate within the culture bags [54, 56]. Following colonization, daily monitoring was continued to determine the number of days until the appearance of mature fruiting bodies (Fig. 2j). Total production duration was calculated from the day the substrate produced its first mushroom until the end of the experiment, while accumulated fresh weight was defined as the total sum of mushroom weights produced by each substrate throughout the entire production period. The fresh weight of mushrooms was determined immediately after harvest using an analytical balance. To determine dry weight and water content, the protocol described by Owaid et al. [57] was adopted, with minor adaptations. Five mushrooms were randomly harvested from each substrate, weighed fresh, and then dried in an oven at 65 °C for three hours. After drying, the samples were weighed again. Dry weight (%) was calculated as (dry weight/fresh weight) × 100, and moisture content (%) was calculated as ((fresh weight – dry weight)/fresh weight) × 100.

Carbon (C) and nitrogen (N) concentrations in the substrates (coconut and *A. donax*) and in mushroom samples were determined using the total combustion method on a CN628 analyzer (LECO Corporation, St. Joseph, MI, USA). For each analysis, 100 mg of freeze-dried and finely ground material was used and further dried at 60 °C for 6 h to remove residual moisture. Combustion was carried out at 950 °C using helium ($H_2O < 3$ ppm; $O_2 < 2$ ppm) as the carrier gas under a pressure of 669 mmHg. The instrument was calibrated with certified C and N standards (LECO 502-055-44). Total protein content was estimated from the nitrogen concentration using a conversion factor of 6.25, which was selected because it has been previously applied in studies involving *Pleurotus* spp. [20], allowing direct comparison with published data. The C/N ratio was calculated individually for each replicate by dividing the total carbon concentration (%) by the total nitrogen concentration (%) [20].

Statistical Analysis

All statistical analyses were performed in the RStudio environment (version 4.4.0). To assess significant differences in substrate colonization time, emergence of the first basidioma, and nutrient and water contents of the mushrooms, the data were initially inspected. Means and standard deviations were calculated for each variable and substrate using the *dplyr* package (version 1.1.4). To evaluate the efficiency of the proposed substrates for mushroom cultivation, generalized and linear mixed-effects models (GLMMs) were fitted for each response variable using the *glmmTMB* (version 1.1.11) and *nlme* packages (version 3.1.168) in R. The selection of error distributions (families) for the fitted models was based on the intrinsic nature of each response variable and on diagnostic evaluation of model residuals. The *fitdistplus* package (version 1.2.4) was used to identify the probability distribution that best fit the data. Separate models were developed for each of the four response variables of interest: (i) accumulated fresh mushroom weight (g), (ii) fresh weight (g), (iii) final dry weight percentage (%), and (iv) water content (%). In each model, treatments (S1–S5 and control) were included as fixed effects to test for differences among substrates. To account for variation among replicates nested within treatments, a hierarchical structure was included in the random-effects



Fig. 2 Cultivation process and developmental stages of *Pleurotus ostreatus* basidioma. **a**–**c** Substrate bag showing complete colonization by fungal mycelium. **d**–**g** Primordia formation at different stages of development inside the cultivation bags. **h** Mature basidiomata with well-developed and exposed gills (indicated by white arrows). The images were acquired using the protocol MSFP [55]

component of the models. The validity of the final models was assessed using the *DHARMa* package (version 0.4.7) by checking model assumptions, and evaluating Akaike Information Criterion (AIC) values, with and without random effects. For nutrient composition, linear models were fitted for protein, nitrogen, and carbon contents using the *lm* function in R. The C/N ratio was analyzed using the Kruskal–Wallis test followed by a post hoc multiple comparison test.

Results

Carbon and Nitrogen Content in *Arundo donax* and Coconut

Differences in chemical composition were observed between the two substrates with respect to carbon and nitrogen content. For carbon (%C), a mean value of 43.79 ± 0.10% was recorded for coconut fiber, whereas a higher mean of 45.71 ± 0.54% was observed for *A. donax*. Nitrogen (%N) also differed between substrates, with coconut fiber presenting a mean of 0.77% ± 0.08% and *A. donax* showing a mean of 2.40 ± 0.12%. The C/N ratio differed significantly between substrates, with coconut fiber showing a higher value (57.3 ± 6.51) than *A. donax* (19.1 ± 1.30). The Kruskal–Wallis test indicated a significant effect of substrate type on the C/N ratio ($\chi^2 = 3.86$, $p = 0.0495$).

Colonization of the Substrate and Monitoring of Fruiting of *Pleurotus ostreatus*

The time required for complete mycelial colonization differed among substrates (Fig. 3a–b). The control and S1 showed the slowest colonization, whereas substrates

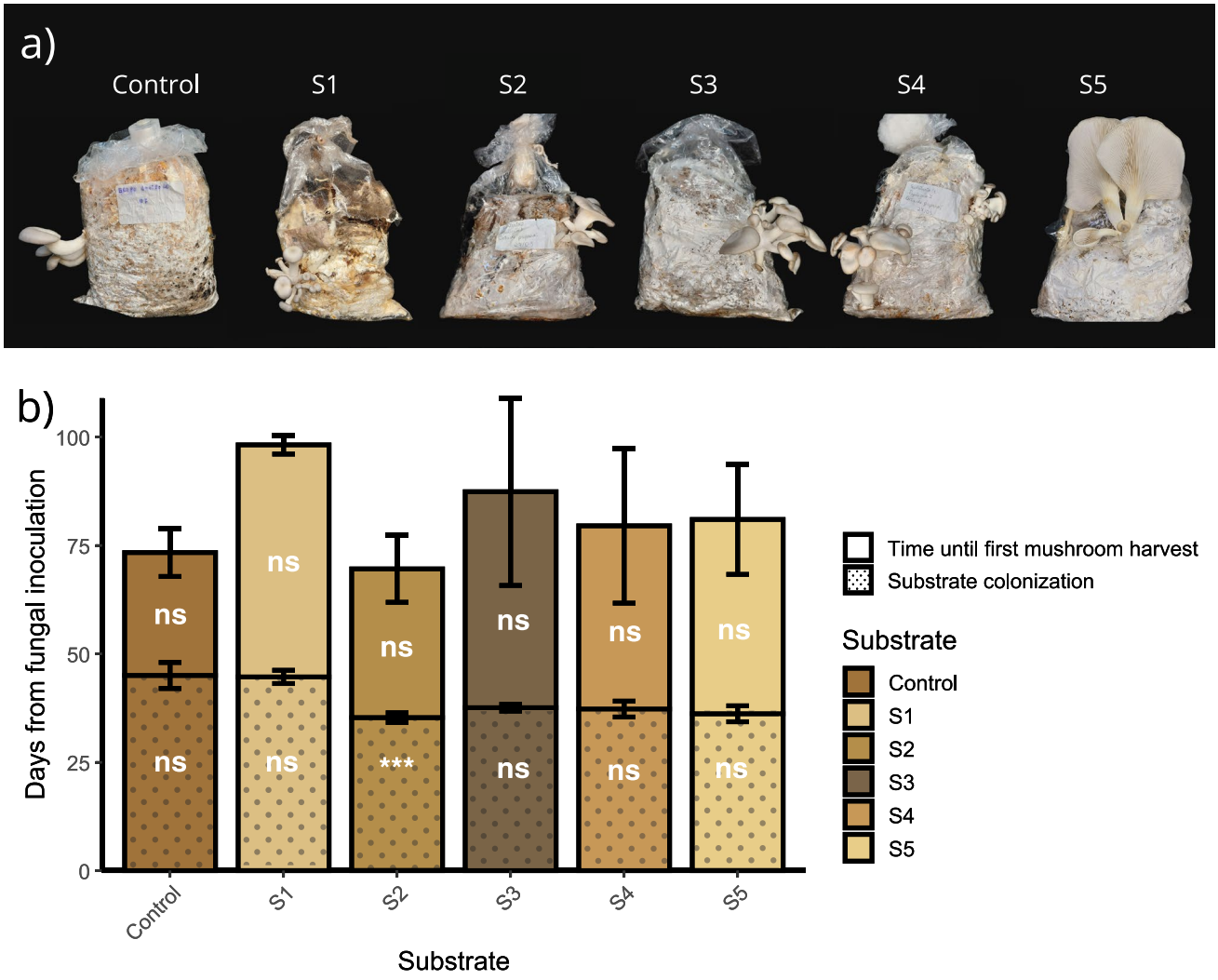


Fig. 3 Substrate colonization and time to fruiting of oyster mushrooms (*Pleurotus ostreatus*) cultivated on different substrates. **a** Photographs of the control and alternative substrates (S1–S5) at the onset of fruiting body formation. **b** Mean total time (in days) from fungal inoculation to the first mushroom harvest, partitioned into the period required for complete substrate colonization (patterned bars) and the subsequent period until the emergence of the first fruiting bodies (solid bars). Substrate composition ratios (% *Arundo donax* biomass: % coconut husk) were as follows: S1, 50:50; S2, 75:25; S3, 25:75; S4, 100% *A. donax* biomass and S5, 100% coconut husk. Error bars represent the standard deviation for each phase. Asterisks (***) indicate statistically significant differences ($p < 0.001$); ns: not statistically significant. Control (n = 5), S1 (n = 5), S2 (n = 5), S3 (n = 6), S4 (n = 5), and S5 (n = 5)

containing higher proportions of *A. donax* and/or coconut husk (S2–S5) promoted faster mycelial growth. Among these, S2 showed the shortest colonization time. The linear mixed-effects model confirmed a significant effect of substrate type on colonization time ($p < 0.0001$), with S2, S3, S4, and S5 reducing colonization time by approximately 7–10 days compared to the control, while S1 did not differ significantly. Some replicates were lost due to contamination by saprophytic fungi (mainly *Aspergillus* spp. and *Trichoderma* spp.), occurring predominantly before full colonization. However, contamination did not differ systematically among treatments and did not affect the overall trends observed. In contrast to colonization time, the time to first harvest did not differ significantly among substrates ($p > 0.05$). Although the control showed a relatively rapid transition from colonization to fruiting, this did not compensate for its slower initial colonization. When considering the entire cultivation cycle, from inoculation to first harvest, substrate S2 resulted in the shortest overall production time.

Production Performance and Fresh Biomass of Mushrooms

The duration and intensity of mushroom production differed among substrates (Fig. 4a–b). Substrate S2 showed the longest production period (46 days) and the highest cumulative fresh weight (308g), indicating sustained and productive fruiting. Substrates S3, S4, and S5 also exhibited relatively long production periods (43–46 days), but with lower cumulative yields (100g, 66.8g, and 165 g, respectively). The control substrate had a shorter production period (33 days), but yielded 134 g of fresh biomass concentrated over only 8 productive days, suggesting a more intense but less sustained production pattern. In contrast, substrate S1 showed the poorest performance, with a short production window (10 days), only 3 fruiting days, and the lowest total yield (41.5g). The generalized linear mixed model (gamma family) showed no significant differences in fresh biomass compared to the control ($p > 0.05$; Fig. 4a). However, substrate S4 tended to produce less biomass, with an average reduction of 7.52g relative to the control, representing a marginal effect ($z = -1.84$, $p = 0.065$). The estimated mean fresh weight for the control was 14.94g.

Dry Mass and Water Percentage of Mushrooms

A GLMM was used to analyze mushroom water content, which showed a significant effect of substrate type (Fig. 5a). Treatment S5 resulted in a significantly lower water content compared to the control ($z = -3.29$, $p = 0.001$), while Treatment S4 showed a marginal tendency toward higher water content ($z = 1.76$, $p = 0.078$). No significant differences were observed for Treatments S1, S2, and S3 ($p > 0.24$). The estimated mean water content was $84.8 \pm 2.93\%$ for the control, while substrates S1, S2, S3, S4, and S5 showed mean values of $88.2 \pm 4.21\%$, $84.0 \pm 3.26\%$, $86.6 \pm 8.49\%$,

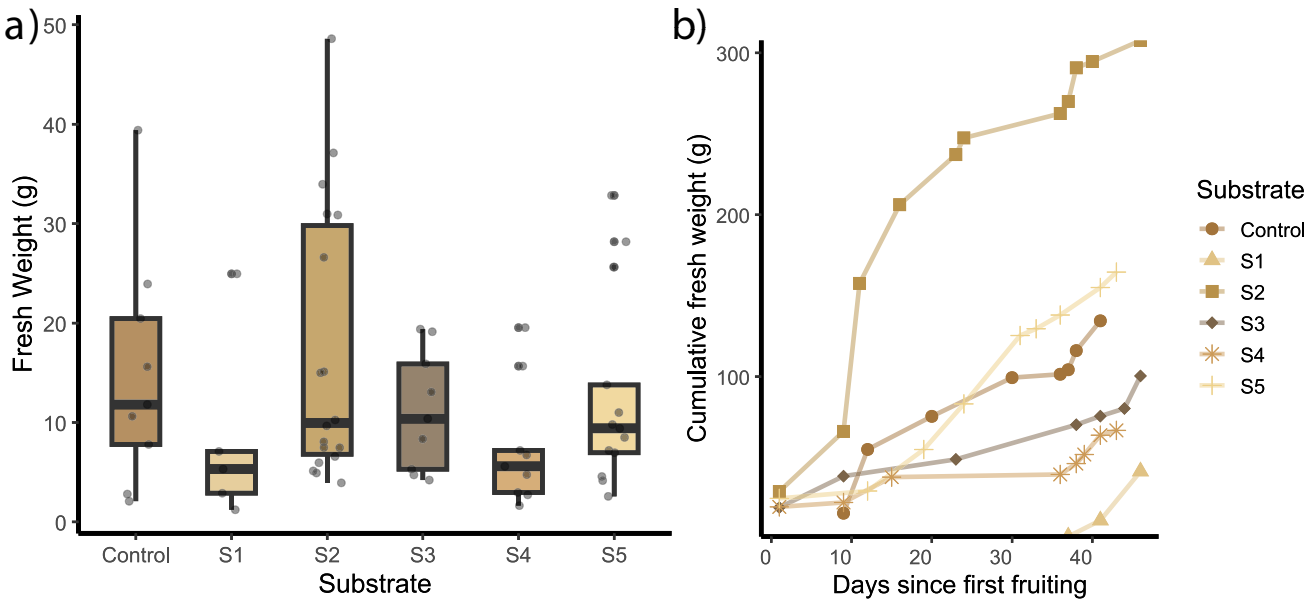


Fig. 4 Fresh weight of oyster mushrooms (*Pleurotus ostreatus*) cultivated on different substrates. **a** Variation in the fresh weight (g) of basidiomata collected per substrate. **b** Cumulative fresh weight of oyster mushrooms over time for each substrate. The graph shows the cumulative fresh biomass (g) from the first day of fruiting (day 1) up to the last recorded harvest day. Substrate composition ratios (% *Arundo donax* biomass: % coconut husk): S1, 50:50; S2, 75:25; S3, 25:75; S4, 100% *A. donax* biomass and S5, 100% coconut husk. Control (n = 5), S1 (n = 5), S2 (n = 5), S3 (n = 6), S4 (n = 5), and S5 (n = 5)

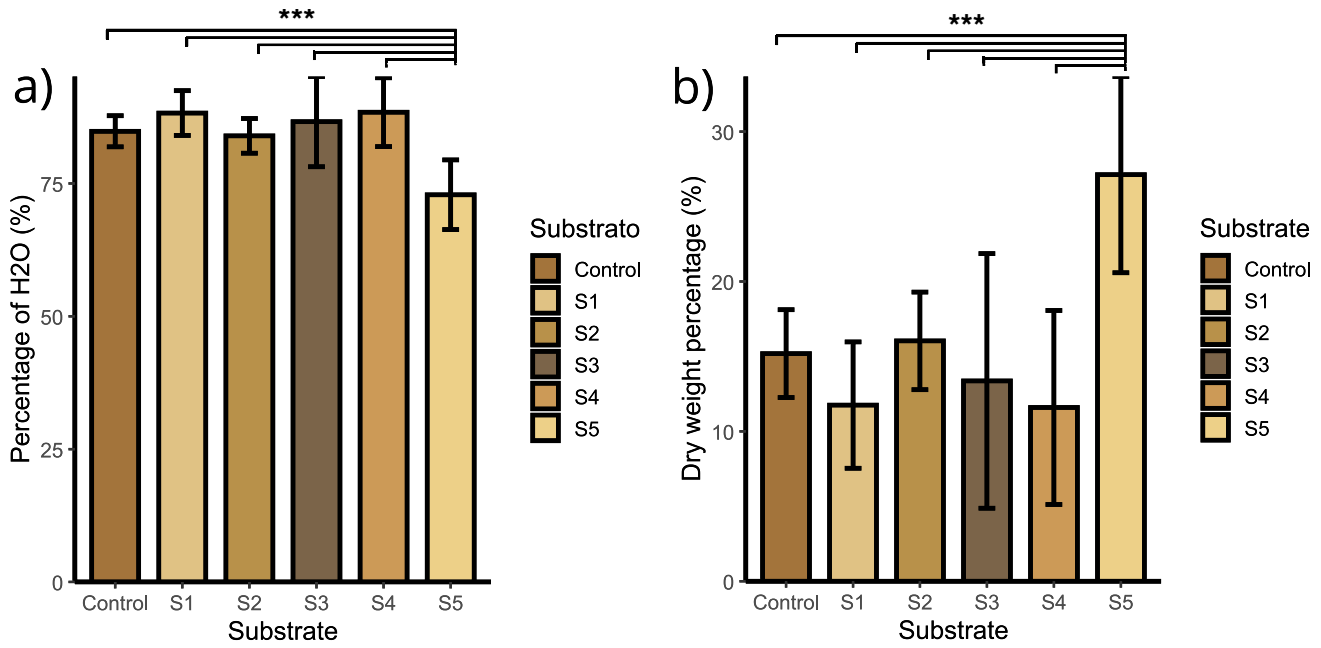


Fig. 5 Water content and dry weight percentage of oyster mushrooms (*Pleurotus ostreatus*) grown on different substrates. Panel **a** shows the average water content (%), while panel **b** shows the percentage of dry mass (%). Error bars represent standard deviations. Asterisks (***) indicate statistically significant differences ($p < 0.001$). Substrate composition ratios (% *Arundo donax* biomass: % coconut husk): S1, 50:50; S2, 75:25; S3, 25:75; S4, 100% *A. donax* biomass and S5, 100% coconut husk. Control (n = 5), S1 (n = 5), S2 (n = 5), S3 (n = 6), S4 (n = 5), and S5 (n = 5)

88.4 ± 6.47%, and 72.9 ± 6.55%, respectively. An opposite pattern was observed for dry matter content (Fig. 5b). Treatment S5 significantly increased dry matter content ($z = 3.29$, $p = 0.001$), raising the estimated mean from 15.2 ± 2.93% in the control to 27.1 ± 6.55%. Treatment S4 again showed a marginal trend, this time toward reduced dry matter content ($z = -1.76$, $p = 0.078$). The estimated mean dry matter percentages for substrates S1, S2, S3, S4, and S5 were 11.8 ± 4.21%, 16.0 ± 3.26%, 13.4 ± 8.49%, 11.6 ± 6.47%, and 27.1 ± 6.55%, respectively.

Carbon and Nitrogen Content in Mushrooms

The chemical composition differed among the substrates for the three variables analyzed (Fig. 6). Carbon content showed moderate variation among treatments ($F(5,6) = 14.67$, $p = 0.003$, adjusted $R^2 = 0.861$), with the control showing a mean value of 43.61%. Substrates S2, S3, and S5 exhibited significantly lower carbon content compared to the Control, whereas S1 and S4 did not differ significantly. Nitrogen content showed more pronounced variation among substrates, with S2, S3, S4, and S5 presenting significantly higher nitrogen levels than the Control, while S1 did not differ significantly. Protein content also differed significantly among treatments ($F(5,6) = 64.53$, $p < 0.001$, adjusted $R^2 = 0.967$), with S2, S3, S4, and S5 showing higher protein content compared to the Control, whereas S1 again showed no significant difference. Overall, S4 (composed of 100% *A. donax*) consistently exhibited the highest nitrogen and protein levels, while S2, S3, and S5 showed slightly reduced carbon content, highlighting marked differences in chemical composition among the substrates. The C/N ratio ranged from 8.33 to 10.3 across substrates, with mean values of 10.3 ± 0.13 (Control), 10.2 ± 0.14 (S1), 8.95 ± 0.15 (S2), 9.21 ± 0.15 (S3), 8.33 ± 0.11 (S4), and 8.91 ± 0.04 (S5). No significant differences were detected among treatments according to the Kruskal–Wallis test ($p > 0.05$).

Discussion

These results underscore the potential for valorizing urban lignocellulosic residues, specifically green coconut husk, an agro-industrial by-product, and *A. donax* biomass harvested from invasive species control. While both materials proved effective substrates for *P. ostreatus* cultivation, *A. donax* biomass yielded slightly higher productivity. By redirecting these residues from disposal streams into mushroom production, this study reinforces the capacity of *Pleurotus* spp. to convert diverse wastes into edible biomass [14, 58]. Furthermore, this approach aligns with circular bioeconomy strategies, offering a sustainable income-generating model for small-scale urban and peri-urban producers [33]. However,

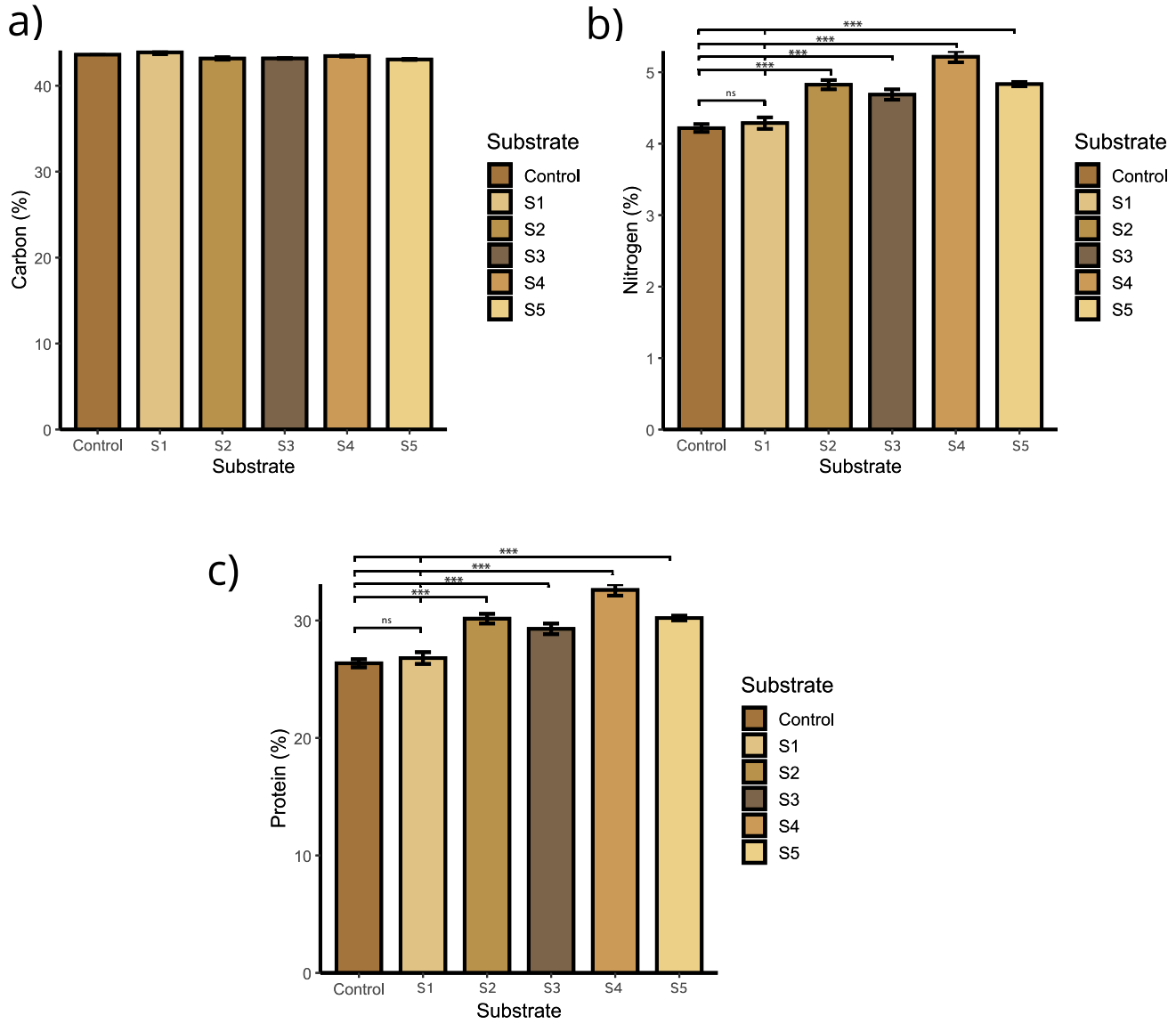


Fig. 6 Carbon, nitrogen, and protein content of oyster mushroom (*Pleurotus ostreatus*) fruiting bodies cultivated on different substrates. **a** Mean carbon concentration (%) across treatments. **b** Mean nitrogen concentration (%) across treatments. c) Mean protein concentration (%) across treatments. Bars represent the mean values ± standard deviation (SD) for each substrate. Asterisks above the bars indicate significant differences among substrates according to statistical testing ($p < 0.05$, $p < 0.01$, $p < 0.001$); ns: no significant difference. Substrate composition ratios (% *Arundo donax* biomass: % coconut husk): S1, 50:50; S2, 75:25; S3, 25:75; S4, 100% *A. donax* biomass and S5, 100% coconut husk. The error bars indicate standard deviation. Control (n = 5), S1 (n = 5), S2 (n = 5), S3 (n = 6), S4 (n = 5), and S5 (n = 5)

the practical implementation of such systems will depend on the integration of technical, economic, and logistical factors.

The mushrooms grew successfully on all tested substrates, composed of different proportions of green coconut and *A. donax* biomass. This outcome highlights a practical and productive application for these specific waste materials. From a physiological perspective, this result suggests that *Pleurotus* spp. can efficiently exploit substrates with contrasting structural and chemical properties, indicating a high degree of metabolic flexibility [8, 19–21]. This capacity is largely attributed to their lignocellulolytic enzymatic system, which enables the degradation of structurally complex plant polymers such as lignin, cellulose, and hemicellulose [19–24, 37, 38]. Its relevance becomes even more pronounced in the context of the escalating waste management crises facing urban centers. In Brazil's Federal District, for example, the disposal of green coconut husks is a subject of intense public debate [59]. Improper management of this waste has contributed to landfill overflow and health risks, prompting recent legislative actions to regulate its selective

collection and reuse [60, 61]. Similarly, for over a decade, local authorities have struggled to control *A. donax*, a species listed among the world's 100 worst invasive plants threatening the Cerrado [62]. Our findings indicate that both residues hold great potential for fungiculture and could be incorporated into public policies aimed at promoting circular economy practices and biodiversity conservation [33, 63].

The variation observed in substrate colonization time and onset of fruiting among treatments reflects the decisive influence of substrate physicochemical properties on fungal development (Fig. 3b), as previously reported for *Pleurotus* spp. [20, 64, 65]. Substrates enriched with *A. donax*, particularly S2 (75% *A. donax*), exhibited accelerated colonization compared to the eucalyptus control. This response may be associated with the lower C/N ratio of *A. donax* biomass relative to coconut fiber, which increases nitrogen availability for fungal metabolism and may enhance the synthesis of lignocellulolytic enzymes involved in substrate degradation [20, 68, 69, 70–73, 74]. Moderate C/N ratios are known to optimize lignocellulolytic enzyme activity and favor efficient mycelial expansion in basidiomycetes [20, 48, 64–67]. In contrast, substrates with elevated C/N ratios, such as coconut-dominated formulations, may require increased metabolic investment in nitrogen acquisition, potentially delaying early colonization [20]. Although the statistical comparison with the control did not reveal significant differences in some performance parameters, the consistent reduction in colonization time observed for S2 suggests a biologically relevant advantage. This outcome partially supports our initial hypothesis that nitrogen-enriched substrates would promote faster mycelial establishment and improved cultivation efficiency. Importantly, the superior performance of S2 indicates that optimal productivity does not depend solely on maximal nitrogen concentration, but rather on a balanced interaction between structural lignocellulosic support and nutrient availability. Similar patterns have been reported for grass-derived substrates, including *A. donax*, which often outperform wood-based materials in colonization dynamics and yield stability [48, 68, 69, 70–73]. This advantage is likely related to the lower recalcitrance and greater accessibility of carbohydrates in grass-derived biomass, which can facilitate faster mycelial growth.

Although no statistically significant differences in fresh weight were detected among treatments and the control (Fig. 4a), substrate S2 consistently accumulated the highest total biomass throughout the production cycle. This pattern reinforces its biological relevance and practical potential for cultivation. In contrast, S1 (50% coconut fiber and 50% *A. donax*) showed reduced productivity and longer cultivation time, suggesting that intermediate proportions of these residues may not provide optimal structural or nutritional balance under the tested conditions. Such differences highlight that substrate performance depends not only on nutrient availability but also on the interaction between lignocellulosic composition, moisture retention capacity, and metabolic accessibility [20, 48, 64–67, 75–78]. These results indicate that the success of alternative substrates relies on formulation balance rather than solely on the substitution of conventional materials.

The chemical composition of the mushrooms varied according to the substrate used. The S4 treatment, composed exclusively of *A. donax*, yielded fruiting bodies with the highest nitrogen and protein contents.This result is consistent with the inherently higher nitrogen concentration found in *A. donax* biomass compared with green coconut residue, indicating that substrate composition can directly influence nitrogen incorporation into fruiting bodies and, consequently, their nutritional quality. As highlighted for other variables in this study, the substrate type directly influences mycelial colonization, mushroom yield, and the nutritional profile of the fruiting bodies, particularly their protein content [20, 66, 67, 79]. The fact that the *A. donax*-based substrate produced mushrooms with higher nitrogen and protein contents highlights the potential of this material as a low-cost substrate for enhancing the nutritional value of the crop. Furthermore, the other substrates tested produced mushrooms with nitrogen and protein contents similar to those observed in the control treatment, which used the conventional substrate. Collectively, the evidence indicates that the chemical composition of the substrate can directly affect the nutritional quality of oyster mushrooms, especially their protein levels. The use of regionally available lignocellulosic residues can lower mushroom production costs and support more sustainable cultivation practices [68, 70–73]. Moreover, spent mushroom substrates help reduce soil-borne fungi, bacterial wilt, and nematode reproduction by improving the rhizosphere microbiota and increasing chitinase and glucanase activities [80–83].

Despite the promising performance of the tested substrates, some limitations should be acknowledged particularly regarding the extrapolation of these results to large-scale production systems. Incubation was subject to natural environmental fluctuations, which introduced a degree of stochasticity that may have influenced colonization rates and overall yield. Furthermore, sporadic contamination events reduced the final number of replicates. Although sufficient sample sizes were maintained for robust statistical analysis, these losses likely increased intra-treatment variance. Future research conducted under strictly controlled climatic conditions would minimize experimental noise and allow for a more granular assessment of substrate performance. From an economic and logistical perspective, the use of *A. donax* and coconut residues presents both opportunities and challenges. While these materials are abundant and low-cost in many regions, preprocessing steps such as drying, size reduction, and sterilization represent additional

operational costs that may influence large-scale feasibility. These steps may demand significant initial investment in infrastructure and energy, particularly in mechanization and thermal treatment processes, which can limit adoption by small-scale producers. In particular, the mechanical fragmentation of the fibrous *A. donax* culms and the moisture stabilization of coconut husks add operational complexity. Moreover, cost–benefit analyses and life cycle assessments are still needed to determine whether the environmental advantages of these substrates outweigh the economic and energetic inputs required for their processing. Nevertheless, when sourced locally, these residues offer a viable alternative to conventional lignocellulosic inputs, potentially reducing the carbon footprint associated with transportation and advancing circular bioeconomy frameworks. Future studies integrating technical performance with economic feasibility and supply chain logistics will be essential to support their large-scale implementation.

Conclusions

Our findings demonstrate that both *A. donax* biomass and green coconut husk are viable alternative substrates for the cultivation of edible mushrooms, specifically *Pleurotus ostreatus.* These residues supported mycelial growth and basidiome production, indicating their suitability for sustainable mushroom cultivation. Among the tested formulations, substrate S2 (75% *A. donax* and 25% coconut husk) is the most recommended, as it combines faster mycelial colonization, sustained production over time, and the highest cumulative fresh biomass. Given their local availability and low cost, these materials could be strategically implemented in small-scale agricultural systems, particularly in regions where waste management and invasive species pose environmental challenges. By transforming these burdens into a high-value food source, this study provides a foundational framework for public policies centered on circular economy principles and ecological restoration.

Future steps should include pilot projects with smallholder farmers to assess the practicality, productivity, and economic viability of these substrates under real-world conditions. In addition, detailed cost–benefit analyses and supply chain assessments will be essential to evaluate scalability and long-term feasibility. Such initiatives may not only contribute to local income generation, but also promote circular economy practices and ecological restoration through the reuse of organic waste and control of invasive plant species.

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Data availability The authors declare that the data regarding substrate composition are provided in the Materials and Methods section. Should the raw datasets containing information on colonization time, production period, and substrate characteristics be required, they are available from the corresponding author upon reasonable request.

Declarations

Conflict of interest The authors have no relevant financial or non-financial interests to disclose.

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References

1. Heleno, S.A., Barros, L., Sousa, M.J., Martins, A., Ferreira, I.C.: Tocopherols composition of Portuguese wild mushrooms with antioxidant capacity. Food Chem. **119**, 1443–1450 (2010). https://doi.org/10.1016/j.foodchem.2009.09.025
2. Reis, F.S., Barros, L., Martins, A., Ferreira, I.C.: Chemical composition and nutritional value of the most widely appreciated cultivated mushrooms: an inter-species comparative study. Food Chem. Toxicol. **50**, 191–197 (2012)
3. Venditti, A., Frezza, C., Sciubba, F., Serafini, M., Bianco, A.: Primary and secondary metabolites of an European edible mushroom

and its nutraceutical value: *Suillus bellinii* (Inzenga) Kuntze. Nat. Prod. Res. **31**, 1910–1919 (2017)
4. Hess, J., Wang, Q., Gould, T., Slavin, J.: Impact of *Agaricus bisporus* mushroom consumption on gut health markers in healthy adults. Nutrients **10**, 1402 (2018). https://doi.org/10.3390/nu10101402
5. Fukushima-Sakuno, E.: Bioactive small secondary metabolites from the mushrooms *Lentinula edodes* and *Flammulina velutipes*. J. Antibiot. **73**, 687–696 (2020). https://doi.org/10.1038/s41429-020-0354-x
6. You, S.W., Hoskin, R.T., Komarnytsky, S., Moncada, M.: Mushrooms as functional and nutritious food ingredients for multiple applications. ACS Food Sci. Technol. **2**, 1184–1195 (2022)
7. Bell, V., Silva, C.R.P.G., Guina, J., Fernandes, T.H.: Mushrooms as future generation healthy foods. Front. Nutr. **9**, 1050099 (2022). https://doi.org/10.3389/fnut.2022.1050099
8. Suwannarach, N., Kumla, J., Zhao, Y., Kakumyan, P.: Impact of cultivation substrate and microbial community on improving mushroom productivity: a review. Biology **11**, 569 (2022). https://doi.org/10.3390/biology11040569
9. Dias, E.S.: Mushroom cultivation in Brazil: challenges and potential for growth. Cienc. Agrotecnol. **34**, 795–803 (2010). https://doi.org/10.1590/S1413-70542010000400001
10. Thakur, M.P., Singh, H.K.: Advances in the cultivation technology of tropical mushrooms in India. JNKVV Res. J. **48**, 120–135 (2014)
11. Chong, J.L., Chew, K.W., Peter, A.P., Ting, H.Y., Show, P.L.: Internet of things (IoT)-based environmental monitoring and control system for home-based mushroom cultivation. Biosensors **13**, 98 (2023). https://doi.org/10.3390/bios13010098
12. Bijla, S.: Status of mushroom production: global and national scenario. Mushroom Res. (2023). https://doi.org/10.36036/mr.32.2.2023.146647
13. Royse, D.J., Baars, J., Tan, Q.: Current overview of mushroom production in the world. In: Zied, D.C., Pardo-Giminez, A. (eds.) Edible and Medicinal Mushrooms: Technology and Applications, pp. 5–13. John Wiley & Sons LtD, Hoboken (2017)
14. Grimm, D., Wösten, H.A.B.: Mushroom cultivation in the circular economy. Appl. Microbiol. Biotechnol. **102**, 7795–7803 (2018). https://doi.org/10.1007/s00253-018-9226-8
15. Okuda, Y.: Sustainability perspectives for future continuity of mushroom production: the bright and dark sides. Front. Sustain. Food Syst. **6**, 1026508 (2022). https://doi.org/10.3389/fsufs.2022.1026508
16. Badoni, P., Siddiqui, S.A.: Metamorphosis of mushroom production from tradition to automation. Discov. Appl. Sci. **7**, 974 (2025). https://doi.org/10.1007/s42452-025-07517-w
17. Raman, J., Jang, K.Y., Oh, Y.L., Oh, M., Im, J.H., Lakshmanan, H., Sabaratnam, V.: Cultivation and nutritional value of prominent *Pleurotus* spp.: an overview. Mycobiology **49**, 1–14 (2021)
18. Cunha Zied, D., Sánchez, J.E., Noble, R., Pardo-Giménez, A.: Use of spent mushroom substrate in new mushroom crops to promote the transition towards a circular economy. Agronomy **10**, 1239 (2020). https://doi.org/10.3390/agronomy10091239
19. Vetayasuporn, S.: Oyster mushroom cultivation on different cellulosic substrates. Res. J. Agric. Biol. Sci. **2**, 548–551 (2006)
20. Hoa, H.T., Wang, C.L., Wang, C.H.: The effects of different substrates on the growth, yield, and nutritional composition of two oyster mushrooms (*Pleurotus ostreatus* and *Pleurotus cystidiosus*). Mycobiology **43**, 423–434 (2015). https://doi.org/10.5941/MYCO.2015.43.4.423
21. Girmay, Z., Gorems, W., Birhanu, G., et al.: Growth and yield performance of *Pleurotus ostreatus*. In: Jacq. Fr. Kumm. on different substrates. AMB Express 6, 87 (2016). https://doi.org/10.1186/s13568-016-0265-1
22. Siwulski, M., Rzymski, P., Budka, A., et al.: The effect of different substrates on the growth of six cultivated mushroom species and composition of macro and trace elements in their fruiting bodies. Eur. Food Res. Technol. **245**, 419–431 (2019). https://doi.org/10.1007/s00217-018-3174-5
23. Zakil, F.A., Hassan, K.M., Sueb, M.M., Isha, R.: Growth and yield of *Pleurotus ostreatus* using sugarcane bagasse as an alternative substrate in Malaysia. IOP Conf. Ser. Mater. Sci. Eng. **736**, 022021 (2020)
24. Di Piazza, S., Benvenuti, M., Damonte, G., Cecchi, G., Mariotti, M.G., Zotti, M.: Fungi and circular economy: *Pleurotus ostreatus* grown on a substrate with agricultural waste of lavender, and its promising biochemical profile. Recycling **6**, 40 (2021). https://doi.org/10.3390/recycling6020040
25. Chang, S., Wasser, S.: The cultivation and environmental impact of mushrooms. Oxford Research Encyclopedia of Environmental Science (2017). Available at: /https://oxfordre.com/environmentalscience/view/10.1093acrefore/9780199389414.001.0001/acrefore-9780199389414-e-231. Accessed: 25 Feb 2025
26. Ab Rahman, S.M.S., Naher, L., Siddiquee, S.: Mushroom quality related with various substrates' bioaccumulation and translocation of heavy metals. J. Fungi **8**, 42 (2021). https://doi.org/10.3390/jof8010042
27. Zotti, M., Cecchi, G., Canonica, L., Di Piazza, S.: A review of nature-based solutions for valorizing aromatic plants' lignocellulosic waste through oyster mushroom cultivation. Sustainability **17**, 4410 (2025). https://doi.org/10.3390/su17104410
28. Zhang, R., Li, X., Fadel, J.G.: Oyster mushroom cultivation with rice and wheat straw. Bioresour. Technol. **82**, 277–284 (2002)
29. Baysal, E., Peker, H., Yalinkiliç, M.K., Temiz, A.: Cultivation of oyster mushroom on waste paper with some added supplementary materials. Bioresour. Technol. **89**, 95–97 (2003). https://doi.org/10.1016/s0960-8524(03)00028-2
30. Martín, C., Zervakis, G.I., Xiong, S., Koutrotsios, G., Strætkvern, K.O.: Spent substrate from mushroom cultivation: exploitation potential toward various applications and value-added products. Bioengineered **14**, 2252138 (2023). https://doi.org/10.1080/21655979.2023.2252138
31. Llanaj, X., Törős, G., Hajdú, P., Abdalla, N., El-Ramady, H., Kiss, A., Solberg, S.Ø., Prokisch, J.: Biotechnological applications of mushrooms under the water-energy-food nexus: crucial aspects and prospects from farm to pharmacy. Foods **12**, 2671 (2023). https://doi.org/10.3390/foods12142671
32. Khan, A., Murad, W., Salahuddin, Ali, S., Shah, S.S., Halim, S.A., Khalid, A., Kashtoh, H., Khan, A., Al-Harrasi, A.: Contribution of mushroom farming to mitigating food scarcity: current status, challenges and potential future prospects in Pakistan. Heliyon 10, e40362 (2024). https://doi.org/10.1016/j.heliyon.2024.e40362
33. Mohini, Mishra, S., Sundaramurthy, S. et al.: Circular economy approach to municipal cellulosic waste valorization: novel substrate development for commercial *Pleurotus ostreatus* production. Waste Biomass Valor. (2025). https://doi.org/10.1007/s12649-025-03116-3.
34. Chatterjee, S., Chakraborty, A., Sinha, S.K.: Spatial distribution and physicochemical characterization of the breeding habitats of *Aedes aegypti* in and around Kolkata, West Bengal, India. Indian J. Med. Res. **142**(1), S79–S86 (2015). https://doi.org/10.4103/0971-5916.176631
35. Ilic, I., Ilic, M.: Global patterns of trends in incidence and mortality of dengue, 1990–2019: an analysis based on the global burden of disease study. Medicina **60**(3), 425 (2024)
36. Mazumder, S., Zhang, N.: Cellulose–hemicellulose–lignin interaction in the secondary cell wall of coconut endocarp. Biomimetics **8**, 188 (2023). https://doi.org/10.3390/biomimetics8020188

37. Rambey, R., Matondang, G.P.N., Siregar, E.B.M.: Growth and productivity of oyster mushroom (*Pleurotus ostreatus*) on mixed planting media of cocopeat with sawdust. IOP Conf. Ser. Earth Environ. Sci. **209**, 012035 (2018)
38. Taskirawati, I., Sari, W., Lebang, G.K., Nurharis, M., Abadi, E.I.: The composition of coconut fibers and tofu pulp as a growing media of oyster mushrooms (*Pleurotus ostreatus*). IOP Conf. Ser. Earth Environ. Sci. **830**, 012060 (2021)
39. Simões, K.C.C., Hay, J.D.V., de Andrade, C.O., de Carvalho, O.A., Gomes, R.A.T.: Distribuição de cana-do-reino (*Arundo donax* L.) no Distrito Federal, Brasil. Biodivers. Bras. **3**, 97–105 (2013)
40. Calazans, E., Lopes, A., Girotto, L., de Paula, A.L.O., Franco, A.C., Ferreira, C.S.: Mechanical control inadvertently increases risk of alien plant invasion: influence of stem fragmentation and inundation regimes on *Arundo donax* regeneration in Neotropical savanna. Aust. J. Bot. **71**, 223–230 (2023). https://doi.org/10.1071/BT22139
41. Guthrie, G.: Impacts of the invasive reed *Arundo donax* on biodiversity at the community-ecosystem level. Doctoral dissertation, University of the Western Cape (2007)
42. Mascia, F., Fenu, G., Angus, R., Bacchetta, G.: *Arundo micrantha*, a new reed species for Italy, threatened in the freshwater habitat by the congeneric invasive *A. donax*. Plant Biosyst. **147**, 717–729 (2013). https://doi.org/10.1080/11263504.2012.761289
43. Velez-Gavilan, J.: *Arundo donax* (giant reed). CABI Compendium, 1–22 (2024). https://doi.org/10.1079/cabicompendium.1940
44. Boose, A.B., Holt, J.S.: Environmental effects on asexual reproduction in *Arundo donax*. Weed Res. **39**, 117–127 (1999). https://doi.org/10.1046/j.1365-3180.1999.00129.x
45. Di Nasso, N.N., Roncucci, N., Triana, F., Tozzini, C., Bonari, E.: Seasonal nutrient dynamics and biomass quality of giant reed (*Arundo donax* L.) and miscanthus (*Miscanthus* × *giganteus* Greef et Deuter) as energy crops. Ital. J. Agron. **6**, e24 (2011). https://doi.org/10.4081/ija.2011.e24
46. Galal, T.M., Shehata, H.S.: Growth and nutrient accumulation potentials of giant reed (*Arundo donax* L.) in different habitats in Egypt. Int. J. Phytoremediat. **18**, 1221–1230 (2016). https://doi.org/10.1080/15226514.2016.1193470
47. Cano-Ruiz, J., Sanz, M., Curt, M.D., Plaza, A., Lobo, M.C., Mauri, P.V.: Fertigation of *Arundo donax* L. with different nitrogen rates for biomass production. Biomass Bioenergy **133**, 105451 (2020). https://doi.org/10.1016/j.biombioe.2019.105451
48. Claude, I., Aimable, N., Mediatrice, H., Zhou, H., Lin, D., Liu, P., Lin, Z.: Evaluation of the influence of varied Juncao grass substrates on physiological and enzymatic reactions of *Pleurotus ostreatus*. Curr. Issues Mol. Biol. **46**, 9493–9502 (2024). https://doi.org/10.3390/cimb46090563
49. dos Reis, J.B.A., Lorenzi, A.S., do Vale, H.M.M.: Methods used for the study of endophytic fungi: a review on methodologies and challenges, and associated tips. Arch. Microbiol. **204**, 675 (2022). https://doi.org/10.1007/s00203-022-03283-0
50. Viriato, V., Mäkelä, M.R., Kowalczyk, J.E., Ballarin, C.S., Loiola, P.P., Andrade, M.C.: Organic residues from agricultural and forest companies in Brazil as useful substrates for cultivation of the edible mushroom *Pleurotus ostreatus*. Lett. Appl. Microbiol. **74**(1), 44–52 (2022)
51. Urben, A.F. Produção de cogumelos por meio de tecnologia chinesa modificada: biotecnologia e aplicações na agricultura e na saúde. Editora técnica. 3. ed. rev. e ampl. – Brasília, DF :Embrapa (2017)
52. Lu, N., Yuan, W.D., Wu, Y.L., et al.: Identification of contaminants as members of the *Bacillus pumilus* group and analysis of contamination sources in the cultivation of *Pleurotus geesteranus* mushrooms. J. Plant Pathol. **103**, 105–115 (2021). https://doi.org/10.1007/s42161-020-00669-1
53. Ajis, A.H., Tan, Y.S., Chai, L.C.: Green mould contamination of *Pleurotus pulmonarius* cultivation in Malaysia: Unravelling causal agents and water source as critical factors. Fungal Biol. **128**, 2197–2206 (2024). https://doi.org/10.1016/j.funbio.2024.09.005
54. Fufa, B.K., Tadesse, B.A., Tulu, M.M.: Cultivation of *Pleurotus ostreatus* on agricultural wastes and their combination. Int. J. Agron. **2021**, 1465597 (2021). https://doi.org/10.1155/2021/1465597
55. dos Reis, J.B.A., Schirmer, S.C., Lauriola, C.T., dos Santos, G.B., Rodrigues, A.J.P., Januário, G.M., do Vale, H.M.M., Pinho, D.B.: Microbes, smile for the picture: protocol and guide for capturing images and processing of microbial cultures with smartphones. Int. Microbiol. (2025). https://doi.org/10.1007/s10123-025-00701-3
56. Akyüz, M., Kırbağ, S.: Cultivation of king eryngii (*Pleurotus eryngii* (DC. ex Fr.) Quel.) isolates on various local agro-residues. Biomass Convers. Bioref. **14**, 12197–12205 (2024). https://doi.org/10.1007/s13399-022-03051-6
57. Owaid, M.N., Abed, I.A., Al-Saeedi, S.S.S.: Nutraceutical value of four oyster mushroom species, higher Basidiomycetes. Hacet. J. Biol. Chem. **45**, 117–123 (2017). https://doi.org/10.15671/HJBC.2017.143
58. Sánchez, C.: Cultivation of Pleurotus ostreatus and other edible mushrooms. Appl. Microbiol. Biotechnol. **85**(5), 1321–1337 (2010). https://doi.org/10.1007/s00253-009-2343-7
59. G1: Projeto de lei prevê coleta seletiva para o coco verde. G1 Distrito Federal (2024). Available at: https://g1.globo.com/df/distrito-federal/df2/video/projeto-de-lei-preve-coleta-seletiva-para-o-coco-verde-12599245.ghtml. Accessed: 23 Jul 2025
60. Câmara dos Deputados: Proposta determina coleta seletiva e logística reversa para o coco verde. Comunicação—Meio ambiente e energia. 9 abr. 2024. Available at: https://www.camara.leg.br/noticias/1048680-proposta-determina-coleta-seletiva-e-logistica-reversa-para-o-coco-verde/. Accessed on: Aug 8, 2025.
61. Martins, A.P., Sanches, R.A., da Silva, P.L.R., Borelli, C., Watanabe, T., Marcicano, J.P.P.: The post-consumption problem of green coconut in Brazil:: Alternatives and sustainability. Sustainability Debate **7**(1), 44–57 (2016). https://doi.org/10.18472/SustDeb.v7n1.2016.16566
62. Instituto Chico Mendes de Conservação da Biodiversidade (ICMBio): ICMBio promove debate sobre plantas invasoras no Distrito Federal. Brasília (2013). Disponível em: https://www.gov.br/icmbio/pt-br/assuntos/noticias/ultimas-noticias/icmbio-promove-debate-sobre-plantas-invasoras-no-distrito-federal. Accessed: 25 jul. 2025
63. Vieira, F., Santana, H.E., Jesus, M., Santos, J., Pires, P., Vaz-Velho, M., Ruzene, D.S.: Coconut waste: discovering sustainable approaches to advance a circular economy. Sustainability **16**, 3066 (2024). https://doi.org/10.3390/su16073066
64. Kinge, T.R., Adi, E.M., Mih, A.M., Ache, N.A., Nji, T.M.: Effect of substrate on the growth, nutritional and bioactive components of *Pleurotus ostreatus* and *Pleurotus florida*. Afr. J. Biotechnol. **15**, 1476–1486 (2016). https://doi.org/10.5897/AJB2015.15130
65. Kinge, T.R., Djidjou, T.A.M., Nji, T.M., Ache, N.A., Mih, A.M.: Effect of local substrates on the growth and yield of *Pleurotus ostreatus* K. in the North West Region, Cameroon. Curr. Res. Environ. Appl. Mycol. **6**, 11–19 (2016). https://doi.org/10.5943/cream/6/1/2
66. Maheswari, S., Rajarajan, P., Pandian, P.M., Sheeba, E., Bayineni, V.K.: Influence of different substrates on growth and yield of *Pleurotus ostreatus*. J. Appl. Hortic. **22**, 215–219 (2020). https://doi.org/10.37855/jah.2020.v22i03.38

67. Muswati, C., Simango, K., Tapfumaneyi, L., Mutetwa, M., Ngezimana, W.: The effects of different substrate combinations on growth and yield of oyster mushroom (*Pleurotus ostreatus*). Int. J. Agron. **2021**, 9962285 (2021). https://doi.org/10.1155/2021/9962285
68. de Ita, V., Angeles, M., Antonio, C., Dolores, M., Lara, H.: Wild reed (*Arundo donax*) as an alternative substrate in the production of *Pleurotus ostreatus*. Sci. Fungorum **48**, 15–22 (2018)
69. Islam, M.Z., Rahman, M.H., Hafiz, F.: Cultivation of oyster mushroom (*Pleurotus flabellatus*) on different substrates. Int. J. Sustain. Crop Prod. **4**, 45–48 (2009)
70. Royse, D.J., Rhodes, T.W., Ohga, S., Sanchez, J.E.: Yield, mushroom size and time to production of *Pleurotus cornucopiae* grown on switch grass substrate spawned and supplemented at various rates. Bioresour. Technol. **91**, 85–91 (2004). https://doi.org/10.1016/S0960-8524(03)00151-2
71. Vieira, F.R., de Andrade, M.C.N.: Optimization of substrate preparation for oyster mushroom (*Pleurotus ostreatus*) cultivation by studying different raw materials and substrate preparation conditions (composting: phases I and II). World J. Microbiol. Biotechnol. **32**, 190 (2016). https://doi.org/10.1007/s11274-016-2152-y
72. Masevhe, M.R., Taylor, N.J., Soundy, P.: Alternative substrates for cultivating oyster mushrooms (*Pleurotus ostreatus*). S. Afr. J. Plant Soil **33**, 97–103 (2016). https://doi.org/10.1080/02571862.2015.1079932
73. Wu, N., Tian, F., Moodley, O., Song, B., Jia, C., Ye, J., Li, C.: Optimization of agro-residues as substrates for *Pleurotus pulmonarius* production. AMB Express **9**, 184 (2019). https://doi.org/10.1186/s13568-019-0907-1
74. Besufekad, Y., Mekonnen, A., Girma, B., Daniel, R., Tassema, G., Melkamu, J., Denboba, L.: Selection of appropriate substrate for production of oyster mushroom (*Pleurotus ostreatus*). J. Yeast Fungal Res. **11**, 15–25 (2020). https://doi.org/10.5897/JYFR2019.0187
75. Ashraf, J., Ali, M.A., Ahmad, W., Ayyub, C.M., Shafi, J.: Effect of different substrate supplements on oyster mushroom (*Pleurotus* spp.) production. Food Science and Technology **1**, 44–51 (2013). https://doi.org/10.13189/fst.2013.010302
76. Ashrafi, R., Mian, M.H., Rahman, M.M., Jahiruddin, M.: Reuse of spent mushroom substrate as casing material for the production of milky white mushroom. J. Bangladesh Agric. Univ. **15**, 239–247 (2017). https://doi.org/10.3329/jbau.v15i2.35069
77. Aghajani, H., Bari, E., Bahmani, M., Humar, M., Ghanbary, M.A.T., Nicholas, D.D., Zahedian, E.: Influence of relative humidity and temperature on cultivation of *Pleurotus species*. Maderas Cienc. Tecnol. **20**, 571–578 (2018). https://doi.org/10.4067/S0718-221X2018005004501
78. Wiesnerová, L., Hřebečková, T., Jablonský, I., Koudela, M.: Effect of different water contents in the substrate on cultivation of *Pleurotus ostreatus* Jacq. P. Kumm. Folia Hortic. **35**, 25–31 (2023). https://doi.org/10.2478/fhort-2023-0002
79. Garuba, T., Abdukkareem, K.A., Ibrahim, I.A., Oyebamiji, O.I., Shoyooye, O.A., Ajibade, T.D.: Influence of substrates on the nutritional quality of *Pleurotus pulmonarius* and *Pleurotus ostreatus*. Ceylon J. Sci. (2017). https://doi.org/10.4038/cjs.v46i1.7419
80. Chen, J.-T., Huang, J.: Antimicrobial activity of edible mushroom culture filtrates on plant pathogens. Plant Pathol. Bull. **19**, 261–270 (2010)
81. Wang, H.W., Xu, M., Cai, X.Y., Feng, T., Xu, W.L.: Application of spent mushroom substrate suppresses *Fusarium* wilt in cucumber and alters the composition of the microbial community of the cucumber rhizosphere. Eur. J. Soil Biol. **101**, 103245 (2020). https://doi.org/10.1016/j.ejsobi.2020.103245
82. Hahn, M.H., Mazaro, S.M., Rodrigues, F.Á., et al.: Using mushroom substrate as a strategy for the control of *Meloidogyne javanica* on tomato roots. Trop. Plant Pathol. **50**, 7 (2025). https://doi.org/10.1007/s40858-025-00702-7
83. Hahn, M.H., Silva, M.C.C., Rocha, M.G.C.D., Quadros, L.P., Rodrigues, F.Á., May De Mio, L.L., Duarte, H.D.S.S.: Defense responses of tomato plants grown in substrate amended with mushrooms for the control of *Meloidogyne javanica*. Bragantia **84**, e20240287 (2025). https://doi.org/10.1590/1678-4499.20240287

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