



Unveiling the biochemical composition of selected paddy straw cultivars: A step toward sustainable waste utilization

A Arundathi^{1*}, D Amirtham¹, T T Dhivyaprabha²

¹ Department of Plant Biotechnology, Centre for Plant Molecular Biology & Biotechnology, Tamil Nadu Agricultural University, Coimbatore, Tamil Nadu, India

² Department of Plant Molecular Biology & Bioinformatics, Tamil Nadu Agricultural University, Coimbatore, Tamil Nadu, India

Corresponding Author: A Arundathi

Abstract

Paddy straw is a significant agricultural residue generated in huge quantities which have various industrial applications which include bioethanol, biochar production, mushroom cultivation, compost, and silica extraction. This research aims to assess the biochemical composition of three different durations of paddy straw varieties including CO54 (short duration), CO50 (medium duration), and CR1009 (long duration). The findings highlight substantial variations in biochemical composition between the three duration-based varieties. Among the three varieties, the long-duration variety (CR1009) shows a higher lignocellulosic composition when compared to the short (CO 54) and medium-duration (CO 50) varieties, making it a better option for industrial applications requiring robust structural biomass. Compared to the other two varieties, the short-duration (CO 54) has better digestibility because of its easy digestibility, which makes it a suitable substrate for effective bioethanol production. The medium-duration variety CO50 with an intermediate composition and the high lignocellulosic content of CR1009 can be efficiently used for a wide range of industrial applications which includes bioethanol, biochar production, compost, mushroom cultivation, and silica extraction with suitable pre-treatment approaches. This study promotes resource-efficient and sustainable industrial practices by providing insightful information about the best way for utilization of paddy straw based on its biochemical characteristics.

Keywords: Cellulose, hemicellulose, lignin, paddy straw, silica, substrate

Introduction

Rice is one of the most significant crops, and it ranks third in production after wheat and maize [1]. Around 800 million metric tons of rice are produced annually worldwide, equivalent to a significant amount of paddy straw [2]. In addition to the grains, the rice crop produces at least 50% non-edible biomass in the form of straw, which includes the stem, leaf blades, leaf sheaths, and panicle post-harvest remnants [3]. After the grains were harvested, the paddy straw was traditionally used for field ploughing, composting, animal feed, flooring for cattle houses, straw crafts, field covering, and burning [4]. Increasing population leads to food demand, which consequently generates excess paddy residues, which may cause severe environmental and socioeconomic issues if not managed sustainably [5]. While burning 1 kg of dry paddy straw, nearly 0.7–4.1 g of methane, 0.019–0.057 g of N₂O released, and other gaseous pollutants such as CO₂, SO₂, NO_x, HCl, carcinogenic PHA (polycyclic aromatic hydrocarbons), dioxins, and furans are also produced [6]. Approximately 85–90% of paddy straw is burned in the field during the rabi season [7]. States like Uttar Pradesh, Punjab, Haryana, and Maharashtra burned the greatest amount of crop residues [8]. Continuously burning leads to many health hazards to both animals and humans [9].

There is a critical requirement to find a solution for economical and environment friendly approaches for the utilization of paddy straw. Because of its high cellulose, hemicellulose, and lignin content, it is an excellent substrate material for the generation of bioethanol, biodiesel, biochar,

and biogas [3, 10]. Using the solid-state fermentation technique, a variety of different products can be produced from rice straw [11]. Moreover, various biomaterials that are primarily employed in tissue engineering, such as hydrogels, bio-nanocomposites, bio-aerogels, and biofilms, can be made from cellulosic polymers derived from industrial and agricultural wastes [12].

Material and methods

Collection of samples

Paddy straw samples of different duration varieties were collected from Paddy Breeding Station (PBS), Tamil Nadu Agricultural University, Coimbatore which includes CO 54 (short duration), CO 50 (medium duration) and CR1009 (long duration). Collected paddy straw samples were shade dried for few days. For biochemical analysis shade dried straw samples were oven dried and ground into powder samples.

EC, pH and moisture content

The pH and electrolyte conductivity (EC) were measured using the Cavins *et al.* method [13]. Moisture content was estimated by oven dry method [14, 15].

Estimation of cellulose

Cellulose content was estimated by using Updegraff method [16]. Powdered straw samples of 0.5 g was mixed with 3 ml of acetic: nitric acid reagent using a vortex mixer. The mixture was heated in a water bath at 100°C for 3 minutes, cooled, and centrifuged for 15–20 minutes. The

supernatant was discarded, and the residue was washed with water. Subsequently, 10 ml of 67% H₂SO₄ was added to the residue, and the mixture was left for 1 hour. A 1 ml aliquot of this solution was diluted to 100 ml. From this diluted solution, 1 ml was taken, mixed with 10 ml of anthrone reagent, and thoroughly blended. The tubes were heated in a boiling water bath for 10 minutes, cooled, and the absorbance was measured at 630 nm. A blank was prepared using anthrone reagent and water. A standard curve was generated using 0.4–2 ml of a standard cellulose solution (equivalent to 40–200 µg of cellulose), adjusting the volume, and following the same procedure from the washing step to develop the colour. The cellulose content in the sample was calculated using the standard graph.

Estimation of hemicellulose

Hemicellulose content was determined by Van Soest method [17]

1. Percentage of neutral detergent fibre content

First, weighed the empty crucible then the paddy straw powdered samples of 1 g were taken in the crucible and added 100 ml of neutral detergent solution at room temperature into crucible with 0.5 g of sodium sulphite and some drops of n-octanol. Then heated to boiling and reflux 60 minutes from onset of boiling. Filtered and washed it for 3 times with boiling water, then twice with cold acetone. Dried it for 8 hours at 105 °C and then cooled in a desiccator. Noted the final weight and calculated the percentage of neutral detergent fibre content.

$$\text{NDF \%} = (\text{weight of crucible} + \text{weight of residue}) - \text{weight of crucible} / \text{weight of sample} \times 100.$$

2. Percentage of acid detergent fibre content

First, weighed the empty crucible then the paddy straw powdered samples of 1 g were taken in the crucible and added 100 ml of acid detergent solution at room temperature into crucible and some drops of n-octanol. Then heated to boiling and reflux 60 minutes from onset of boiling. Filtered and washed it for 3 times with boiling water, then twice with cold acetone. Dried it for 8 hours at 105 °C and then cooled in a desiccator. Noted the final weight and calculate the percentage of acid detergent fibre content.

$$\text{ADF \%} = (\text{weight of crucible} + \text{weight of residue}) - \text{weight of crucible} / \text{weight of sample} \times 100.$$

$$\text{Hemicellulose} = \text{Neutral Detergent Fibre (NDF\%)} - \text{Acid Detergent Fibre (ADF\%)}$$

Estimation of lignin

Lignin content was determined by Stafford method [18]. 0.5 g of dried sample was ground with ether and centrifuged at 2000g for 5min, discarded the supernatant. Then washed the sediment with water, recentrifuged and discarded the supernatant. Repeated washings twice and added 2ml of NaOH to the residue and extract obtained at 70–80°C for 12–16hours. Then cooled for some time, added 0.45ml of 2N HCl and adjusted the pH to 7 or 8 with NaOH. The volume was made to 3ml with water. Finally centrifuged at 2000g for 5min. and collected the supernatant. To 0.8ml of extract, added 0.8ml of 0.1M sodium phosphate buffer, pH 7.0. To another aliquot of 0.8ml extract, added 0.8ml of 0.1N NaOH (pH 12.3). Measured the absorbance at 245 and 350nm. Calculated the lignin concentration from the difference between A₂₄₅ and A₃₅₀ (E₃₅₀) on pH 7.0 and 12.3 samples with buffer and NaOH, respectively. Used a

conversion factor, 32 to calculate the lignin content (32 x mg phenol = mg lignin, calculated from bagasse sample).

Estimation of silica

Using spectrophotometry, the silica concentration of paddy straw was estimated by Elliot and Snyder method [19]. Silica extract was prepared by taking 100 mg straw sample from each variety in a 50 mL poly propylene tube then it was dried at 60°C in a hot air oven. The tubes were then vortexed and autoclaved for 20 minutes at 121°C after 3 mL of a 50% NaOH solution was added. After that extracted solution was transferred to 50mL volumetric flask and make up the volume with distilled water. From this volumetric flask containing extracted solution, 1.0mL aliquot was taken and transferred to another 50mL volumetric flask. Following that, 10 mL of ammonium molybdate solution (54 g/L, pH 7.0) and 30 mL of 20% acetic acid were added solution was then thoroughly mixed. Afterwards 5mL of 20% tartaric acid and 1mL reducing agent added. In this reducing agent was prepared by mixing solution A with 2g Na₂SO₃, 0.4g 1-amino-2-naphthalene-4-sulphanilic acid in 50mL distilled water; solution B with 25g NaHSO₃ in 200mL distilled water finally diluted it into 250mL. Following the addition of all reagents volume make up to 50mL and measured the absorbance at 650nm after 30 minutes. Standard silica solution was made with pure SiO₂ heated with Na₂SO₃ and prepared stock solution of 100ppm. From that working standard (0, 0.5, 1.0, 1.5, 2.0, 2.5, 3.0, 3.5, 4.0 mL) were prepared in 50mL volumetric flask and colour development obtained by following previously mentioned steps.

Total carbon, total nitrogen and C/N ratio

Total carbon was estimated by using Walkey and Black method [20]. Taken 0.5g of powdered paddy straw samples of each variety in conical flask. Then 10mL of 1N K₂Cr₂O₇ and 20mL of concentrated H₂SO₄ added to it. Mixed them thoroughly and allowed to stand for 30 minutes. Afterwards 200mL of distilled water and 10mL of orthophosphoric acid added to it. Finally, diphenylamine indicator added and titrated them against with 0.5N FAS. Dull green colour obtained as end point and calculated the total carbon content. Total nitrogen content was estimated by using Kjeldahl method [21, 22]. First powdered paddy straw samples were subjected to acid digestion and after digestion cooled them at room temperature. Titration and distillation were carried out using a Kelplus Ecotitrator and obtained total nitrogen content. Using the total carbon and total nitrogen content C/N ratio were calculated.

FTIR analysis

The functional groups in the aqueous sample of the selected ground paddy straw cultivars were determined by recording its Fourier Transform Infrared (FTIR) spectra with a Shimadzu MIRacle 10(ZnSe) ATR with a wave number of range 4000–400 cm⁻¹ and a resolution of 4 cm⁻¹.

Statistical analysis

Using descriptive statistics, the biochemical characteristics of paddy straw were statistically examined. The same datasets were further utilized to prepare interactive plot, heat map and dendrogram. R Studio (version 4.4.2) was used for data analysis in order to generate descriptive statistics and graphical representations.

Results

Biochemical parameters were estimated to characterize the variations among the different duration paddy straw varieties. For each variety, each parameter was replicated three times. Parameters including moisture content, pH, and

EC for these three varieties ranged from 10.0 - 10.6%, 6.85 - 7.26 and 1.043 - 1.045 dS/m (Table 1). The cellulose, hemicellulose, lignin and silica content ranged from 34.4 - 46.7%, 17.8 - 24.0%, 5.61 - 14.17%, and 8.24 - 15.77% with a mean of 40.84%, 21.1%, 9.65%, and 11.74% (Table 1).

Table 1: Descriptive statistics of biochemical characterization of three different duration paddy straw varieties

Paddy straw variety	Moisture (%)	EC	pH	Cellulose (%)	Hemi cellulose (%)	Lignin (%)	Silica (%)	Total carbon (%)	Total nitrogen (%)	C/N ratio
Short duration CO 54	10.33 ± 0.17	1.045 ± 0.0003	7.24 ± 0.008	34.53 ± 0.07	18.33 ± 0.44	5.61 ± 0.00	8.25 ± 0.003	23.56 ± 0.06	0.47 ± 0.0008	50.48 ± 0.10
Medium duration CO 50	10.20 ± 0.20	1.043±0.0003	6.86 ± 0.003	41.37 ± 0.07	21.13 ± 0.85	11.24 ± 0.006	11.24 ± 0.006	24.18 ± 0.02	0.39 ± 0.0008	62.44 ± 0.14
Long duration CR 1009	10.16 ± 0.17	1.043±0.0003	6.93 ± 0.003	46.63 ± 0.03	23.83 ± 0.16	15.76 ± 0.006	15.76 ± 0.006	25.14 ± 0.008	0.31 ± 0.0005	80.57 ± 0.13
Range	(10.0 - 10.6)	(1.043 - 1.045)	(6.85 - 7.26)	(34.4 - 46.7)	(17.8 - 24.0)	(5.61 - 14.17)	(8.24 - 15.77)	(23.45 - 25.15)	(0.311 - 0.468)	(50.32 - 80.77)
Min	10	1.043	6.85	34.4	17.8	5.61	8.24	23.45	0.311	50.32
Max	10.6	1.045	7.26	46.7	24	14.17	15.77	25.15	0.468	80.77

These results were similar to Bhattacharya *et al.* experiment [3], it was observed that the range of cellulose, hemicelluloses, lignin, and Silicon varied from 28.5-41%,

15.3-25.9%, 6.2-12.6%, and 5-8%. Using Heatmap, variations among these varieties in lignocellulosic composition was visualized (Fig. 1).

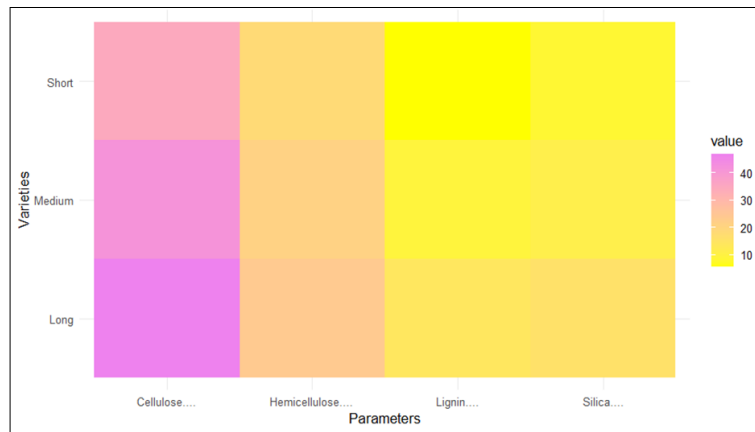


Fig 1: Heat map of biochemical characteristics of selected three cultivars of rice straw (Long duration variety CR1009; Medium duration variety CO 50 and S- Short duration variety CO 54)

The results showed that long duration paddy straw variety (CR1009) have high lignocellulosic composition compared to medium (CO50) and short duration (CO54) paddy straw varieties was depicted (Fig.2). Other parameters which

include total carbon, total nitrogen and C/N ratio for these three varieties ranged from 23.45-25.15%,0.311-0.468%, and 50.3:1 - 80.7:1.

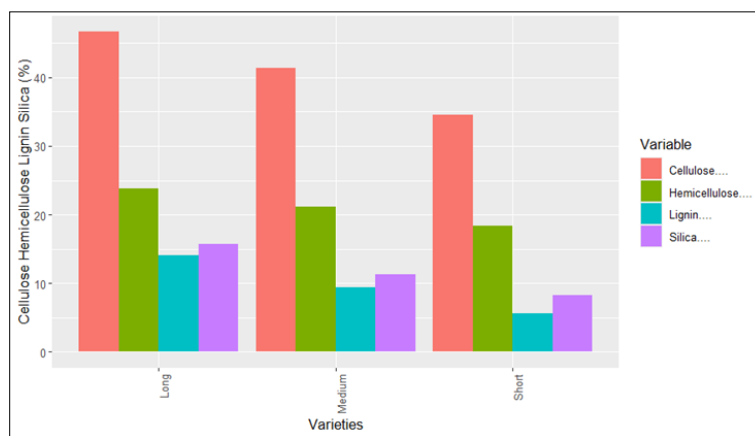


Fig 2: Biochemical characterization of substrate potential of selected rice straw cultivars (Long duration variety CR1009; Medium duration variety CO 50 and S- Short duration variety CO 54)

These paddy straw varieties were categorized into high, medium, and low ranges for these biochemical parameters using descriptive statistics (Table 1). The relatedness of paddy

straw varieties was investigated using a dendrogram based on their biochemical parameters, mainly lignocellulosic composition (Fig.3).

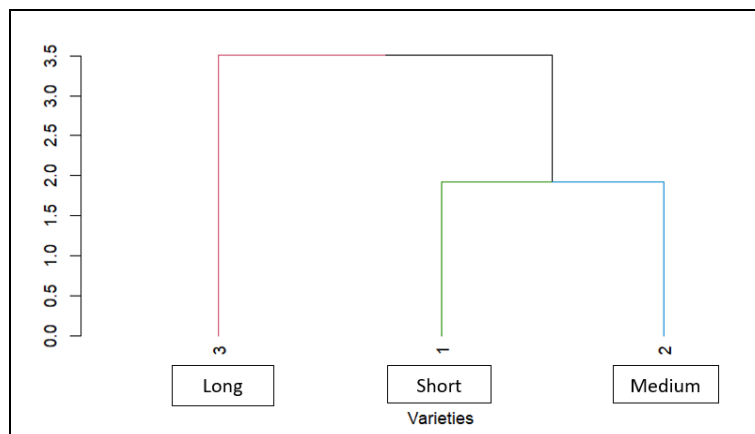


Fig 3: Dendrogram using Average Linkage (Between Groups) derived from Hierarchical cluster analysis (Long duration variety CR1009; Medium duration variety CO 50 and S- Short duration variety CO 54)

The presence of functional groups in the lignocellulosic materials of these three different paddy straw varieties was confirmed by the FTIR analysis. (Table 2).

Table 2: Analysis of peaks corresponding to different functional groups present in rice straw by FTIR analysis

Major components	Wave number (cm ⁻¹)	FTIR reading	Functional group	References
Cellulose	3300-3500	3348.42, 3348.42, 3320.13	OH- bond	[3, 10]
Hemicellulose	1750-1510	1635.64, 1643.35, 1643.35	C=O stretching vibrations in acetyl fragments	[23]
Lignin	1650-1515	1635.64, 1643.35, 1643.35	Aromatic	[3, 10].
	600-900	601.79, 601.79, 601.76, 686.66, 678.94, 686.66	CH out-of-plane bending vibrations	[24]

CR1009, CO 50, and CO 54 showed the peak values such as 3302.33 cm⁻¹, 3348.42 cm⁻¹, and 3348.42 cm⁻¹, which proved the presence of cellulose. Then, for the peak values for lignin include 1643.35 cm⁻¹, 1643.35 cm⁻¹, and

1635.64 cm⁻¹. Peak values for hemicelluloses comprise of 1635.64 cm⁻¹, 1643.35 cm⁻¹, 1643.35cm⁻¹(Fig. 4a,4b,4c). These results were similar to the findings of Bhattacharyya *et al.* and Malik *et al.* experiments [3, 10].

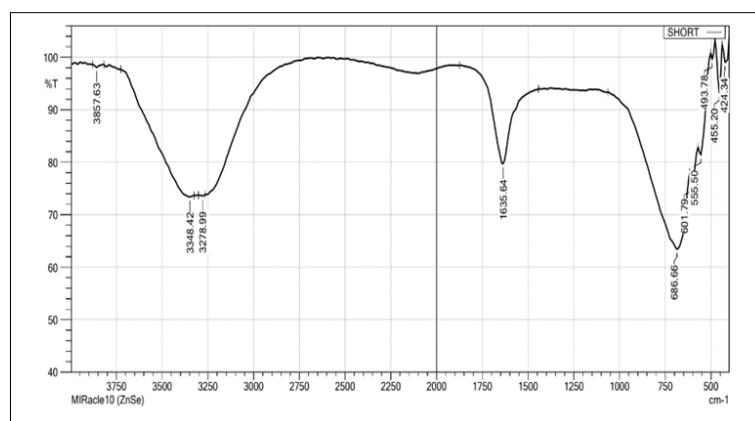


Fig 4a: FTIR analysis of short duration variety CO 54

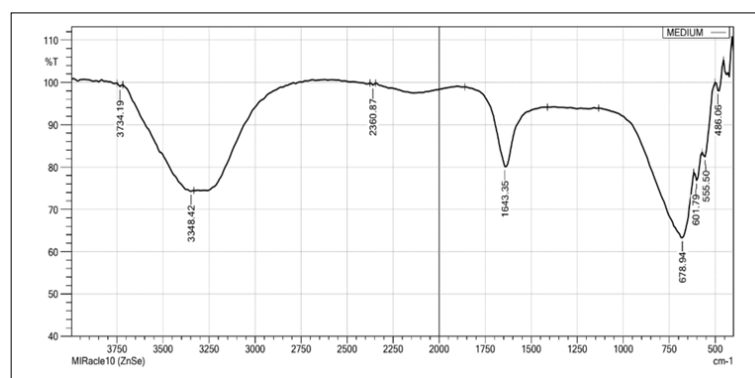


Fig 4b: FTIR analysis of medium duration variety CO 50

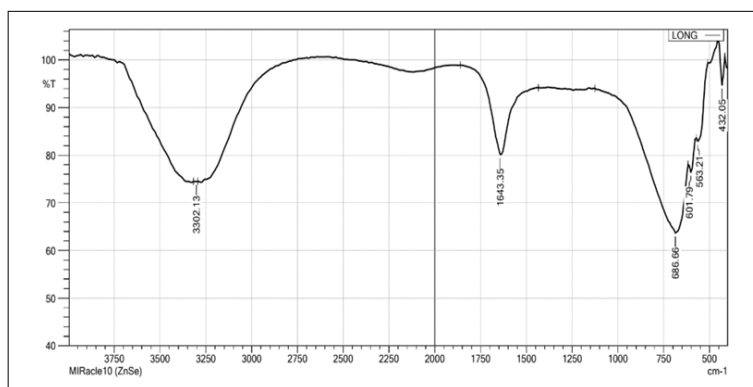


Fig 4c: FTIR analysis of long duration variety CR1009

Discussion

The main constituents of rice straw are cellulose, hemicellulose, and lignin which are the essential building blocks of plant cell walls [25]. In-field techniques such as open-field burning or soil incorporation can be used to manage rice straw, while off-field uses include use in manufacturing (acoustic materials, 3D objects, composites, cement bricks, and handmade paper), energy production (thermal power, combustion, bioethanol, biogas, and biochar), and agriculture (bedding, compost, and mushroom cultivation) [26].

The most abundant biomass feedstock is rice straw, which can yield 205 billion litres of bioethanol per year (5% of total consumption). It is high in cellulose (32–47%), hemicellulose (19–27%), and lignin (5–24%), with glucose, xylose, and arabinose as its main carbohydrates [27, 28, 29]. In order to produce biofuels and other valuable products, these lignin and carbohydrate complexes must be broken and the polysaccharides hydrolyzed into their subsequent monomers [30]. Paddy straw is a viable resource for the generation of ethanol due to its abundance of hexose (C6) and pentose (C5) sugars, which can be degraded into simple sugars and then fermented [31].

The purpose of pre-treatment is to enhance cellulose accessibility to cellulases by reducing cellulosic crystallinity, reducing structural barriers produced by hemicelluloses, and separating lignin from cellulose [32, 33]. When compared to raw straw, which had a cellulose content of 32.6%, steam pretreatment and biological treatment raised it to 39.5% and 37.6%, respectively. *T. hirsuta* selectively broke down lignin, increasing the concentration of cellulose, an essential characteristic for effective biomass utilization [34, 35]. Likewise, alkali-pretreated paddy straw containing *T. reesei* and *S. cerevisiae* is preferred because it has reduced enzyme loading, a shorter reaction time, and a higher ethanol yield [36, 37]. High levels of cellulose and hemicelluloses of paddy straw, which hydrolyze easily to produce fermentable sugars [1, 38]

Rice straw is rich in silica, which prevents ethanol production and enzymatic hydrolysis. The lignin and silica in paddy straw are broken down by various pretreatment techniques, such as physical, chemical, biological, and physiochemical methods [39]. After pretreatment with organosolv, which removes most of the lignin content, and sodium carbonate helps in eliminating more than 91% of silica content, the ethanol yields boosted significantly from 39.3% to 78.7% [40]. The most environmentally friendly method is the green solvent-based pretreatment, which

makes use of bio-based solvents like ethyl lactate, which are non-toxic, biodegradable, and improve enzymatic digestibility [41]. Low silica and lignin content with medium to high cellulose content is suitable for bioethanol production. Short duration variety CO54 with low lignin and silica content can be easily digested than CO50 and CR1009, so it can be better utilized for bioethanol production. With proper pretreatment CO50 and CR1009 paddy straw are also utilized for bioethanol production.

Biochar, or biomass-derived charcoal, is the highly aromatic material that remains when biomass is thermally broken down while oxygen is either completely or partially excluded [42]. Paddy straw contains lignocellulosic components, which include cellulose (32–47%), hemicellulose (19–28%), and lignin (5–24%), have been shown to produce good yields of biochar when rice straw (RS) is pyrolyzed [43, 44, 45, 46]. Various thermochemical conversion techniques for biochar derived from paddy straw include pyrolysis [47], torrefaction or carbonization [48], hydrothermal liquefaction [49], and gasification [50]. A potential approach to improve soil fertility, increase carbon storage, and reduce greenhouse gas emissions, pyrolysis of rice straw is the best way to produce biochar for soil amendment [51]. A low-cost, environmentally friendly adsorbent for treating wastewater, rice straw-derived biochar (RSB), is enhanced through pyrolysis and modification techniques [52]. Xiao *et al* [53] investigated how silicon (Si) and carbon (C) in rice straw-derived biochar change when subjected to different pyrolysis temperatures (150–700°C). The pyrolysis occurs at specific temperature ranges: (i) cellulose (semi-crystalline) decomposes at 305–375°C, (ii) hemicellulose (branched polymer) at 200–350°C, and (iii) lignin (phenolic) at 250–500° [54, 55, 56]. The decomposition of biomass takes place in a wide temperature range when the lignin content is high. Biochar derived from feedstock rich in lignin releases less dissolved organic matter through leaching and provides greater stability [57]. Higher lignin content promotes biochar production, resulting in a higher yield of biochar [58]. Medium to high lignin content is suitable for biochar production. Medium (CO50) and long (CR1009) varieties are matched this criterion makes better biochar for good yield.

Silica (SiO₂) is a very significant inorganic material that has been widely used in a variety of applications, including electric and thermal insulators, absorbents, optical fibers, glasses, food additives, and pharmaceutical products [59, 60]. An effective way for turning agricultural waste into useful materials was demonstrated by Nandiyanto *et al* [61]. who

created a simple extraction process to create silica particles from rice straw waste. Using base dissolution and acid precipitation, amorphous silica with a 90.8% yield was recovered from rice straw ash [62]. According to Jyani *et al* [63], silica was effectively extracted from paddy straw by a green solvent-based pretreatment employing ethyl lactate, yielding 1.57 g per 2.5 g PSA with 62.8% recovery.

After pre-treating the biomass of paddy straw with dilute sulphuric acid to eliminate polysaccharides and other impurities and delignified the biomass using an alkaline mixture to extract nano-silica of uniform shape with an average size of ~17 nm was successfully separated at a 9.26% yield with simultaneous extraction of lignin from paddy straw [64]. Using rice straw, an effective zinc complex with lignin, silica, and fatty acid natural materials was produced, which was successfully utilized as an activator and antioxidant in the fabrication of rubber composites [65]. High-lignin paddy straw can be used in the production of adhesives, coatings, and bio-based polymers, reducing dependency on petrochemical products [66]. Due to high silica and lignin content in long duration variety (CR1009), silica extraction better option for the production of nanoparticles and lignin-based composites, which can be utilized for various industrial applications.

Agricultural residue (rice straw, rice bran, sawdust, molasses) is an excellent source for mushroom cultivation [67]. Rice straw is a good substrate for mushroom growth, as evidenced by the 10% higher oyster mushroom yield in paddy straw compared to wheat straw [68]. The commercial cultivation of *Calocybe indica* can be done with rice straw as a substrate which yields nutritional mushrooms within 15 days [69]. *P. florida* fungal hyphae deeply enter rice straw, breaking down lignin and improving digestibility [70]. According to Li *et al* [71], lignin was significantly degraded during the primordia formation period and spawn running, and its degradation slowed down following the primordia stages in *P. ostreatus* cultivation. The cultivation of mushrooms requires carbon (cellulose, hemicellulose, and lignin), nitrogen, and inorganic elements. The high silica content of rice straw creates a barrier to mushroom growth, which makes it difficult to extract nutrients [72, 73]. Kaur *et al* [74], investigated the dual use of paddy straw, the first cultivation of *P. florida* mushrooms in paddy straw, which yields 53.1%, and the synthesis of SiO₂ nanoparticles from spent straw, which was extracted 32.5%. Lignin content in paddy straw plays a crucial role, and it is converted into a nitrogen-rich lignin-humus complex which offers a source of protein for mushroom mycelium growth [75, 76, 77]. *Volvariella volvacea* produces a range of cellulase enzymes for the breakdown of cellulose which requires the substrate with high cellulose content [78]. High cellulose, hemicellulose in CR1009 are suitable for mushroom cultivation with proper pre-treatment to remove silica content. Short (CO54) and medium (CO50) duration varieties are also utilized for mushroom cultivation, though it has low silica content with low to moderate cellulose and hemicellulose content.

Rice straw is a difficult target because of its high lignin content and broader C/N ratio [79]. Rice straw decomposes slowly due to its high C:N ratio. It breaks down more quickly and improves nutrient availability when combined with low C: N materials, such as cattle manure, and inoculated with bacteria that break down lignocellulose [80]. Poultry droppings were added to paddy straw in 8:1 ratio to

reduce its C:N ratio and accelerate the composting process [81]. Sharma *et al* [82], explored the quick paddy straw composting with the help of an efficient microorganism consortium which includes *Lactobacillus spp.*, *Phanerochaete chrysosporium*, *Streptomyces globisporous*, *Candida tropicalis* and an enriched photosynthetic bacterial inoculum. Based on this short duration variety CO54, which has comparatively narrow C:N ratio compared with the other two varieties. CO54 can be easily decomposed than CO50 and CR1009. With appropriate co-composting approaches, which can narrow down the C:N ratio of CR1009 and CO50 paddy straw for making them suitable for composting.

Conclusion

In present study, the different-duration paddy straw varieties, including short (CO54), medium (CO50), and long (CR1009) duration varieties, were biochemically characterized. The results showed significant variations in their biochemical composition, which might influence their industrial applications. Short-duration variety (CO54) with low silica and lignin content showed higher digestibility, making them suitable for bioethanol production and composting, whereas long-duration variety (CR1009), with higher lignin content and silica, is better suited for biochar production and silica extraction. With a balanced lignocellulosic composition, the medium duration variety (CO50) offers better adaptability in industrial applications especially as a suitable substrate for mushroom cultivation. CR1009 paddy straw can be utilized for many industrial applications because of its high ligno cellulosic composition, by following economic and resource-efficient pre-treatment approaches. With better pretreatment approaches towards paddy straw based on their biochemical characterization, it can be fully utilized with many applications. A better understanding of their biochemical composition will be very useful for identifying their suitability in industrial applications. The transformation of agricultural wastes, particularly paddy straw into usable products not only reduces environmental pollution caused by open-field burning but also promotes eco-friendly alternatives in agriculture and industry. Future research should focus on process optimization and techno-economic analysis to scale up its use in real-world applications.

Acknowledgments

We duly thank the laboratory facilities by Tamil Nadu Agricultural University, Coimbatore and Bharat Ratna Prof. C.N.R. Rao Research Centre, Avinashilingam Institute for Home Science and Higher Education for Women, Coimbatore.

Reference

1. Binod P, Sindhu R, Singhanian RR, Vikram S, Devi L, Nagalakshmi S, *et al.*, Bioethanol production from rice straw: an overview. *Bioresour Technol*,2010;101:4767. <https://doi.org/10.1016/j.biortech.2009.10.079>
2. Wati L, Kumari S, Kundu BS, Paddy straw as substrate for ethanol production. *Indian J Microbiol*,2007;47:26. <https://doi.org/10.1007/s12088-007-0005-y>
3. Bhattacharyya P, Bhaduri D, Adak T, Munda S, Satapathy BS, Dash PK, *et al.*, Characterization of rice straw from major cultivars for best alternative industrial

- uses to cutoff the menace of straw burning. *Ind Crops Prod*,2020;143:111919.
<https://doi.org/10.1016/j.indcrop.2019.111919>
4. Matsumura Y, Minowa T, Yamamoto H, Amount, availability and potential use of rice straw (agricultural residue) biomass as an energy resource in Japan. *Biomass Bioenerg*,2005;29:347.
<https://doi.org/10.1016/j.biombioe.2004.06.015>
 5. Sharma S, Pappu A, Asolekar SR, Sustainable recycling of paddy straw through development of short-fiber-reinforced composites: exploring gainful utilization of agricultural waste. *Clean Technol Environ Policy*,2024;26:109. <https://doi.org/10.1007/s10098-023-02607-y>
 6. Oanh NTK, Ly BT, Tipayarom D, Manandhar BR, Prapat P, Simpson CD, *et al.*, Characterization of particulate matter emission from open burning of rice straw. *Atmos Environ*,2011;45:493.
<https://doi.org/10.1016/j.atmosenv.2010.09.023>
 7. Singh JM, Singh J, Kumar H, Singh S, Sachdeva J, Kaur B, *et al.*, Management of paddy straw in Punjab: an economic analysis of different techniques. *Indian J Agric Econ*,2019;74:301.
<http://dx.doi.org/10.22004/ag.econ.343444>
 8. Jain N, Bhatia A, Pathak H, Emission of air pollutants from crop residue burning in India. *Aerosol Air Qual Res*,2014;14:422.
<https://doi.org/10.4209/aaqr.2013.01.0031>
 9. Lohan SK, Jat HS, Yadav AK, Sidhu HS, Jat ML, Choudhary M, *et al.*, Burning issues of paddy residue management in north-west states of India. *Renew Sustain Energy Rev*,2018;81:693.
<https://doi.org/10.1016/j.rser.2017.08.057>
 10. Malik K, Sharma A, Harikarthik D, Rani V, Arya N, Malik A, *et al.*, Deciphering the biochemical and functional characterization of rice straw cultivars for industrial applications. *Heliyon*,2023;9:e16339.
<https://doi.org/10.1016/j.heliyon.2023.e16339>
 11. Gunjan, Singh R, Pradhan S, Valorization of byproducts produced during extraction and purification of biodiesel: a promising biofuel. In: *Biofuel Extraction Techniques*,2023:333.
<https://doi.org/10.1002/9781119829522.ch12>
 12. Soorbaghi FP, Isanejad M, Salatin S, Ghorbani M, Jafari S, Derakhshankhah H, Bioaerogels: synthesis approaches, cellular uptake, and biomedical applications. *Biomed Pharmacother*,2019;111:964.
<https://doi.org/10.1016/j.biopha.2019.01.014>
 13. Cavins TJ, Whipker BE, Fonteno WC, Harden B, McCall I, Gibson JL, Monitoring and managing pH and EC using the PourThru extraction method. *Hortic Info Leafl*,2000:590:1.
 14. Hoa HT, Wang CL, Wang CH, The effects of different substrates on the growth, yield, and nutritional composition of two oyster mushrooms (*Pleurotus ostreatus* and *Pleurotus cystidiosus*). *Mycobiology*,2015;43:423.
<https://doi.org/10.5941/MYCO.2015.43.4.423>
 15. Jittabut P, Physical and thermal properties of briquette fuels from rice straw and sugarcane leaves by mixing molasses. *Energy Procedia*,2015;79:2.
<https://doi.org/10.1016/j.egypro.2015.11.452>
 16. Updegraff DM, Estimation of cellulose by anthrone reagent. *Anal Chem*,1969;32:420.
 17. Van Soest PV, Robertson JB, Lewis BA, Methods for dietary fiber, neutral detergent fibre, and non-starch polysaccharides in relation to animal nutrition. *J Dairy Sci*,1991;74:3583. [https://doi.org/10.3168/jds.S0022-0302\(91\)78551-2](https://doi.org/10.3168/jds.S0022-0302(91)78551-2)
 18. Stafford HA, Differences between lignin-like polymers formed by peroxidation of eugenol and ferulic acid in leaf sections of *Phleum*. *Plant Physiol*,1960;35:108.
<https://doi.org/10.1104/pp.35.1.108>
 19. Elliott CL, Snyder GH, Autoclave-induced digestion for the colorimetric determination of silicon in rice straw. *J Agric Food Chem*,1991;39:1118.
<https://doi.org/10.1021/jf00006a024>
 20. Walkley A, Black IA, Method of total organic carbon determination in soil samples. *Soil Sci*,1934;37:29.
<http://dx.doi.org/10.13140/RG.2.2.22043.00807>
 21. Kirk PL, Kjeldahl method for total nitrogen. *Anal Chem*,1950;22:354.
<https://doi.org/10.1021/ac60038a038>
 22. Bremner JM, Determination of nitrogen in soil by the Kjeldahl method. *J Agric Sci*,1960;55:11.
<https://doi.org/10.1017/S0021859600021572>
 23. Kostyukov SG, Matyakubov HB, Masterova YY, Kozlov AS, Pryanichnikova MK, Pynenkov AA, *et al.*, Determination of lignin, cellulose, and hemicellulose in plant materials by FTIR spectroscopy. *J Anal Chem*,2023;78:718.
<https://doi.org/10.1134/S1061934823040093>
 24. Movasaghi Z, Rehman S, ur Rehman DI, Fourier transform infrared (FTIR) spectroscopy of biological tissues. *Appl Spectrosc Rev*,2008;43:134.
<https://doi.org/10.1080/05704920701829043>
 25. Sarnklong C, Cone JW, Pellikaan W, Hendriks WH, Utilization of rice straw and different treatments to improve its feed value for ruminants: a review. *Asian-Australas J Anim Sci*,2010;23:680.
<https://doi.org/10.5713/ajas.2010.80619>
 26. Singh L, Brar BS, A review on rice straw management strategies. *Nat Environ Pollut Technol*,2021;20:1485.
<https://doi.org/10.46488/NEPT.2021.v20i04.010>
 27. Maiorella BL, Ethanol. In: Young M (Ed.), *Compr Biotechnol*, Pergamon Press, Oxford, 1985, 861.
 28. Roberto IC, Mussatto SI, Rodrigues RC, Dilute-acid hydrolysis for optimization of xylose recovery from rice straw in a semi-pilot reactor. *Ind Crops Prod*, 2003, 17:171. [https://doi.org/10.1016/S0926-6690\(02\)00095-X](https://doi.org/10.1016/S0926-6690(02)00095-X)
 29. Yoswathana N, Phuriphapat P, Treyawutthiwat P, Eshtiaghi MN, Bioethanol production from rice straw. *Energy Res J*,2010;1:26.
<https://doi.org/10.3844/erjsp.2010.26.31>
 30. Chaturvedi V, Verma P, An overview of key pretreatment processes employed for bioconversion of lignocellulosic biomass into biofuels and value-added products. *3 Biotech*,2013;3:415.
<https://doi.org/10.1007/s13205-013-0167-8>
 31. Hans M, Kumar S, Chandel AK, Polikarpov I, A review on bioprocessing of paddy straw to ethanol using simultaneous saccharification and fermentation. *Process Biochem*,2019;85:125.
<https://doi.org/10.1016/j.procbio.2019.06.019>
 32. Cheng JJ, Stomp AM, Growing duckweed to recover nutrients from wastewaters and for production of fuel ethanol and animal feed. *Clean Soil Air*

- Water,2009:37:17.
<https://doi.org/10.1002/clen.200800210>
33. Kumar P, Barrett DM, Delwiche MJ, Stroeve P, Methods for pretreatment of lignocellulosic biomass for efficient hydrolysis and biofuel production. *Ind Eng Chem Res*,2009:48:3713.
<https://doi.org/10.1021/ie801542g>
 34. Shi J, Sharma-Shivappa RR, Chinn M, Howell N, Effect of microbial pretreatment on enzymatic hydrolysis and fermentation of cotton stalks for ethanol production. *Biomass Bioenerg*,2009:33:88.
<https://doi.org/10.1016/j.biombioe.2008.04.016>
 35. Arora A, Priya S, Sharma P, Sharma S, Nain L, Evaluating biological pretreatment as a feasible methodology for ethanol production from paddy straw. *Biocatal Agric Biotechnol*,2016:8:66.
<https://doi.org/10.1016/j.bcab.2016.08.006>
 36. Chadha BS, Kanwar SS, Garcha HS, Simultaneous saccharification and fermentation of rice straw into ethanol. *Acta Microbiol Immunol Hung*,1995:42:71.
 37. Zhu S, Wu Y, Yu Z, Wang C, Yu F, Jin S, *et al.*, Comparison of three microwave/chemical pretreatment processes for enzymatic hydrolysis of rice straw. *Biosyst Eng*,2006:93:279.
<https://doi.org/10.1016/j.biosystemseng.2005.11.013>
 38. Sarif NN, Jumali SS, Biotransformation methods of paddy straw into bioethanol. *IOP Conf Ser Earth Environ Sci*,2021:757:012085.
<https://doi.org/10.1088/1755-1315/757/1/012085>
 39. Hendriks ATWM, Zeeman G, Pretreatments to enhance the digestibility of lignocellulosic biomass. *Bioresour Technol*,2009:100:10.
<https://doi.org/10.1016/j.biortech.2008.05.027>
 40. Khaleghian H, Molaverdi M, Karimi K, Silica removal from rice straw to improve its hydrolysis and ethanol production. *Ind Eng Chem Res*,2017:56:9793.
<https://doi.org/10.1021/acs.iecr.7b02830>
 41. Pereira CS, Silva VM, Rodrigues AE, Ethyl lactate as a solvent: properties, applications and production processes – a review. *Green Chem*,2011:13:2658.
<https://doi.org/10.1039/C1GC15523G>
 42. Antal MJ, Grønli M, The art, science, and technology of charcoal production. *Ind Eng Chem Res*,2003:42:1619. <https://doi.org/10.1021/ie0207919>
 43. Zamora R, Sánchez Crispín JA, Producción de un extracto ácido de paja de arroz. *Acta Cient Venez*,1995:46:135.
 44. Kadam KL, Forrest LH, Jacobson WA, Rice straw as a lignocellulosic resource: collection, processing, transportation, and environmental aspects. *Biomass Bioenerg*,2000:18:369. [https://doi.org/10.1016/S0961-9534\(00\)00005-2](https://doi.org/10.1016/S0961-9534(00)00005-2)
 45. Guan R, Li X, Wachemo AC, Yuan H, Liu Y, Zou D, *et al.*, Enhancing anaerobic digestion performance and degradation of lignocellulosic components of rice straw by combined biological and chemical pretreatment. *Sci Total Environ*,2018:637:9.
<https://doi.org/10.1016/j.scitotenv.2018.04.366>
 46. Griffin GJ, Ward LP, Madapusi S, Shah KV, Parthasarathy R, A study of chemical pre-treatment and pyrolysis operating conditions to enhance biochar production from rice straw. *J Anal Appl Pyrolysis*,2022:163:105455.
<https://doi.org/10.1016/j.jaap.2022.105455>
 47. Zong Y, Xiao Q, Lu S, Biochar derived from cadmium-contaminated rice straw at various pyrolysis temperatures: cadmium immobilization mechanisms and environmental implication. *Bioresour Technol*,2021:321:124459.
<https://doi.org/10.1016/j.biortech.2020.124459>
 48. Tan M, Li H, Huang Z, Wang Z, Xiong R, Jiang S, *et al.*, Comparison of atmospheric and gas-pressurized oxidative torrefaction of heavy-metal-polluted rice straw. *J Clean Prod*,2021:283:124636.
<https://doi.org/10.1016/j.jclepro.2020.124636>
 49. Harisankar S, Prashanth PF, Nallasivam J, Mohan RV, Vinu R, Effects of aqueous phase recirculation on product yields and quality from hydrothermal liquefaction of rice straw. *Bioresour Technol*,2021:342:125951.
 50. Pei H, Jin B, Huang Y, Quantitative analysis of mass and energy flow in rice straw gasification based on mass and carbon balance. *Renew Energy*,2020:161:846.
<https://doi.org/10.1016/j.renene.2020.08.014>
 51. Wu W, Yang M, Feng Q, McGrouther K, Wang H, Lu H, *et al.*, Chemical characterization of rice straw-derived biochar for soil amendment. *Biomass Bioenerg*,2012:47:268.
<https://doi.org/10.1016/j.biombioe.2012.09.034>
 52. Foong SY, Chan YH, Chin BLF, Lock SSM, Yee CY, Yiin CL, *et al.*, Production of biochar from rice straw and its application for wastewater remediation – An overview. *Bioresour Technol*,2022:360:127588.
<https://doi.org/10.1016/j.biortech.2022.127588>
 53. Xiao X, Chen B, Zhu L, Transformation, morphology, and dissolution of silicon and carbon in rice straw-derived biochars under different pyrolytic temperatures. *Environ Sci Technol*,2014:48:3411.
<https://doi.org/10.1021/es405676h>
 54. Hassan M, Liu Y, Naidu R, Parikh SJ, Du J, Qi F, *et al.*, Influences of feedstock sources and pyrolysis temperature on the properties of biochar and functionality as adsorbents: a meta-analysis. *Sci Total Environ*, 2020, 744:140714.
<https://doi.org/10.1016/j.scitotenv.2020.140714>
 55. Wei Y, Chen W, Liu C, Wang H, Facial synthesis of adsorbent from hemicelluloses for Cr(VI) adsorption. *Molecules*,2021:26:1443.
<https://doi.org/10.3390/molecules26051443>
 56. Yaashikaa PR, Kumar PS, Varjani S, Saravanan A, A critical review on the biochar production techniques, characterization, stability, and applications for circular bioeconomy. *Biotechnol Rep*,2020:28:e00570.
<https://doi.org/10.1016/j.btre.2020.e0057>
 57. Kim HB, Kim JG, Kim T, Alessi DS, Baek K, Mobility of arsenic in soil amended with biochar derived from biomass with different lignin contents: relationships between lignin content and dissolved organic matter leaching. *Chem Eng J*,2020:393:124687.
<https://doi.org/10.1016/j.cej.2020.124687>
 58. Rangabhashiyam S, Balasubramanian P, The potential of lignocellulosic biomass precursors for biochar production: performance, mechanism and wastewater application – a review. *Ind Crops Prod*,2019:128:405.
<https://doi.org/10.1016/j.indcrop.2018.11.041>
 59. Bansal V, Ahmad A, Sastry M, Fungus-mediated biotransformation of amorphous silica in rice husk to nanocrystalline silica. *J Am Chem*

- Soc,2006:128:14059.
<https://doi.org/10.1021/ja062113+>
60. Liou TH, Preparation and characterization of nano-structured silica from rice husk. *Mater Sci Eng A*,2004:364:313.
<https://doi.org/10.1016/j.msea.2003.08.045>
 61. Nandiyanto ABD, Rahman T, Fadhlulloh MA, Abdullah AG, Hamidah I, Mulyanti B, Synthesis of silica particles from rice straw waste using a simple extraction method. *IOP Conf Ser Mater Sci Eng*,2016:128:012040. <https://doi.org/10.1088/1757-899X/128/1/012040>
 62. Lu P, Hsieh YL, Highly pure amorphous silica nanodisks from rice straw. *Powder Technol*, 2012:225:149.
<https://doi.org/10.1016/j.powtec.2012.04.002>
 63. Jyani M, Palanisamy K, Phutela UG, Characterization and extraction of silica particles from green solvent pretreated paddy straw. *Bull Mater Sci*,2024:47:154.
<https://doi.org/10.1007/s12034-024-03266-5>
 64. Kauldhar BS, Yadav S, Turning waste to wealth: A direct process for recovery of nano-silica and lignin from paddy straw agro-waste. *J Clean Prod*,2018:194:158.
<https://doi.org/10.1016/j.jclepro.2018.05.136>
 65. Abdel Zaher KS, El-Sabbagh SH, Abdelrazek FM, Nawwar GAM, Utility of zinc (lignin/silica/fatty acids) complex derived from rice straw as antioxidant and activator in rubber composites. *Polym Eng Sci*,2019:59(s2):E196.
<https://doi.org/10.1002/pen.25029>
 66. Ragauskas AJ, Beckham GT, Bidy MJ, Chandra R, Chen F, Davis MF, *et al.*, Lignin valorization: improving lignin processing in the biorefinery. *Science*,2014:344:1246843.
<https://doi.org/10.1126/science.1246843>
 67. Kamthan R, Tiwari I, Agricultural wastes – potential substrates for mushroom cultivation. *Eur J Exp Biol*, 2017, 7:31. <https://doi.org/10.21767/2248-9215.100031>
 68. Zhang R, Li X, Fadel JG, Oyster mushroom cultivation with rice and wheat straw. *Bioresour Technol*,2002:82(3):277.
[https://doi.org/10.1016/S0960-8524\(01\)00188-2](https://doi.org/10.1016/S0960-8524(01)00188-2)
 69. Chelladurai G, Yadav TK, Pathak RK, Chemical composition and nutritional value of paddy straw milky mushroom (*Calocybe indica*). *Nature Environ Pollut Technol*,2021:20(3):1157.
 70. Kaur K, Phutela UG, Morphological and structural changes in paddy straw influenced by alkali and microbial pretreatment. *Detritus*,2018:3:30.
 71. Li X, Pang Y, Zhang R, Compositional changes of cottonseed hull substrate during *P. ostreatus* growth and the effects on the feeding value of the spent substrate. *Bioresour Technol*,2001:80:157.
[https://doi.org/10.1016/S0960-8524\(00\)00170-X](https://doi.org/10.1016/S0960-8524(00)00170-X)
 72. Chang ST, Miles PG, *Edible mushrooms and their cultivation*. (CRC Press, USA), 1989.
 73. Baysal E, Peker H, Yalinkiliç MK, Temiz A, Cultivation of oyster mushroom on waste paper with some added supplementary materials. *Bioresour Technol*,2003:89(1):95. [https://doi.org/10.1016/S0960-8524\(03\)00028-2](https://doi.org/10.1016/S0960-8524(03)00028-2)
 74. Kaur D, Pandey OP, Reddy MS, Production of silica nanoparticles from rice husk and rice straw by fungal-mediated biotransformation using *Pleurotus florida*. *Biomass Convers Biorefin*,2025:15:803.
<https://doi.org/10.1007/s13399-023-05155-z>
 75. Porselvi A, Vijayakumar R, Evaluation of paddy straw varieties on the cultivation and nutritional value of two oyster mushroom species. *Int J Res Advent Technol*,2019:7(5):556.
<https://doi.org/10.32622/ijrat.752019339>
 76. Scrase R, Cultivating mushrooms: Making composted and non-composted substrates. *Mycologist*,1996:10(2):52.
[https://doi.org/10.1016/S0269-915X\(96\)80095-4](https://doi.org/10.1016/S0269-915X(96)80095-4)
 77. Arundathi A, Amirtham D, Thiribhuvanamala G, Rajagopal B, Bharathi N, Praveen T, *et al.*, Assessing the potential of various lignocellulosic waste as substrate for mushroom cultivation. *Ann Phytomed*,2024:13(2):298.
<http://dx.doi.org/10.54085/ap.2024.13.2.29>
 78. Yella VK, Chadrapati A, Kuri A, Miglani I, Andrews AA, Singh S, Cultivation technology and spawn production of *Volvariella volvacea*: Paddy straw mushroom. *Pharm Innov J*,2021:10(5):1184.
 79. Zhu N, Effect of low initial C/N ratio on aerobic composting of swine manure with rice straw. *Bioresour Technol*, 2007:98(1):9.
<https://doi.org/10.1016/j.biortech.2005.12.003>
 80. Tuomela M, Vikman M, Hatakka A, Itävaara M, Biodegradation of lignin in a compost environment: a review. *Bioresour Technol*,2000:72(2):169.
[https://doi.org/10.1016/S0960-8524\(99\)00104-2](https://doi.org/10.1016/S0960-8524(99)00104-2)
 81. Pandey AK, Gaiind S, Ali A, Nain L, Effect of bioaugmentation and nitrogen supplementation on composting of paddy straw. *Biodegradation*,2009:20:293.
<https://doi.org/10.1007/s10532-008-9221-3>
 82. Sharma A, Sharma R, Arora A, Shah R, Singh A, Pranaw K, *et al.*, Insights into rapid composting of paddy straw augmented with efficient microorganism consortium. *Int J Recycl Org Waste Agric*,2014:3:1.
<https://doi.org/10.1007/s40093-014-0054-2>