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# Fuel and material utilization of a waste shiitake (*Lentinula edodes*) mushroom bed derived from hardwood chips I: characteristics of calorific value in terms of elemental composition and ash content

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## Abstract

To understand the fuel characteristics of a waste shiitake mushroom bed derived from hardwood chips, the moisture content at the time of disposal and after 1 month, as well as its calorific value, ash content, and elemental composition, were investigated. The moisture content on a wet basis ( $MC_w$ ) was 78% at the time of disposal and was as high as 63% even 1 month after disposal. It is considered that the slow drying process is caused by the low moisture permeability of the skin of mushroom bed, and therefore, it is preferable to crush the waste mushroom bed before drying. Comparing the gross calorific value on a dry basis of the waste mushroom bed with that of the cultivation bed wood chips, the value inside of the waste mushroom bed was similar, while that of its skin was significantly lower (by 11%). The reason for this lies in the significantly higher ash content and nitrogen content compared to those of wood. When analyzed from the combustion heat of the contained elements, it was found that both the cultivation bed wood chips and the waste mushroom bed had almost no hydrogen contributing to combustion due to their high oxygen content, and they were dependent on the heat generation of carbon. As a result of finding the relationship between the net calorific value that can be used as a boiler fuel and  $MC_w$ , for example, the value at an  $MC_w$  of 50% was calculated to be 7.6 MJ/kg, which was almost the same as that of sugi (*Cryptomeria Japonica*) sapwood and bark. The ash content of the waste mushroom bed was about 7%, which is close to that of bark and about ten times that of the wood used for the cultivation bed. When the waste mushroom bed is used as boiler fuel, appropriate ash treatment is required as in the case of using bark.

**Keywords:** Waste mushroom bed, Hardwood chips, Moisture content, Gross calorific value, Net calorific value, Ash content, Elemental composition

## Introduction

Mushroom production in each country is on the rise due to the recent boom in health foods. According to FAO statistics (Food and Agricultural Organization of the United Nations, 2017 results) [1], there are 30 countries

that produce more than 10,000 tons per year, with a total of 10.18 million tons. There are 43 countries with less than 10,000 tons, but because their production in total is tens of thousands of tons, the total production of the world is approximately 10.2 million tons. The growth in mushroom production is supported by the conversion from raw wood cultivation to mushroom bed cultivation, and the effective utilization of mushroom beds after harvesting (hereinafter referred to as waste mushroom beds)

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has become an issue from the view point of a resource recycling society. For example, in China, which has the highest mushroom production in the world, efforts are being made to produce wood pellets from waste mushroom beds and convert the heat source for district heating from coal to wood pellets [2].

According to Japanese government statistics [3], the total production of mushrooms in Japan is 456,000 tons (2018 results). Among several kinds of mushrooms, shiitake mushrooms are the largest on a production value basis, and the number of large-scale shiitake mushroom bed cultivation farms is increasing. Figure 1 shows the production process at the shiitake farm in the Kuji area of the Iwate prefecture, Japan. At this shiitake farm, hardwood logs collected from a nearby area are chipped to form a cultivation bed, which is disposed of after about 11 months through six times of harvesting. Traditionally, the treatment of waste mushroom beds was to provide fertilizer to local farmers, but as the number of waste mushroom beds has increased (currently more than 1 million per year), their effective use has become a serious problem. Therefore, recently, the use of waste mushroom beds as fuel has commenced by mixing these beds with the bark fuel of a woody biomass boiler that produces steam used for sterilization of the cultivation bed, as well as for providing hot water used for heating the cultivation

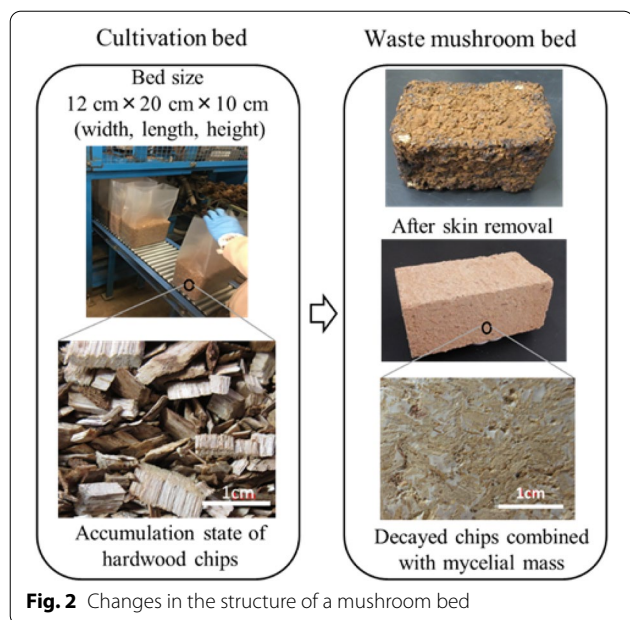
house in winter. However, there are many things to be clarified, such as the characteristics of the waste mushroom bed as a fuel, which are namely the moisture content, ash content, calorific value, and so on. Conversely, it may be used as a material by taking advantage of the morphological characteristics of the waste mushroom bed. Figure 2 compares the state of accumulation of wood chips between at the time of cultivation bed preparation and at the time of disposal. When the waste mushroom bed is dried, the mycelia play a role of an adhesive and the decaying chips are bonded to each other, resulting in a structure similar to a lightweight particleboard or an insulation fiberboard, and after removing the skin, a rectangular block-shaped material can be obtained.

The purpose of this series of studies is to collect basic data for fuel and material utilization of the waste mushroom bed shown in Fig. 2 (right). As for material utilization, we will report the mechanical properties and thermal insulation properties of the blocks obtained by drying the waste mushroom beds in the 2nd and 3rd reports, respectively.

In the present 1st report, the moisture content of waste mushroom beds at the time of disposal and after 1 month, as well as the ash content, elemental composition, and calorific value, are shown as basic properties for fuel utilization. In particular, the calorific value of the



**Fig. 1** Production process of shiitake mushroom using hardwood chip cultivation beds



**Fig. 2** Changes in the structure of a mushroom bed

waste mushroom bed is discussed in comparison with that of undecayed wood and the mycelium itself. Then, differences in the calorific values among these materials are also discussed from the viewpoint of their elemental composition. Furthermore, the substance flow from mushroom bed preparation to disposal is discussed through the results of elemental analysis and an ash content test.

## Materials and methods

### Details of the cultivation bed

It is necessary to know the details of the cultivation beds, because the fuel or material properties of the waste mushroom beds are dependent on them. Therefore, the tree species and density of the raw wood, the size of the pieces after chipping, and the weight of the cultivation bed were investigated at the shiitake cultivation farm shown in Fig. 1. More than 90% of the hardwood logs were mizunara (*Quercus crispula*). A total of 20 mizunara disks with a diameter of 8–20 cm and a thickness of 2 cm were collected from a log stockyard, dried to an air-dried state (13% of the moisture content on a dry basis,  $MC_d$ ), and their density was measured. In addition, 50 pieces of wood chip samples were randomly extracted from a chip stockyard, dried to an air-dry state, and the dimensions were measured. Furthermore, 30 cultivation bed samples were randomly extracted in each of Step 3 and 5 shown in Fig. 1 and they were then weighed.

The results of the above measurements are listed in Table 1. The average dimensions of wood chips were 10.1 mm in width, 1.9 mm in thickness, and 7.7 mm in

**Table 1** Details of the cultivation bed (mean  $\pm$  std)

Raw material density (Air-dried, kg/m <sup>3</sup> )	Chip dimensions (Air-dried, mm)	Weight per bed including forming bag* (g)	
		Before sterilization	After fungus inoculation
N = 20 780 $\pm$ 66	N = 50 R: 10.1 $\pm$ 1.0 T: 1.9 $\pm$ 0.2 L: 7.7 $\pm$ 0.8	N = 30 2888 $\pm$ 47	N = 30 2852 $\pm$ 39

N the number of samples, R, T, L; radial, tangential, and longitudinal directions, respectively

\*The weight of plastic forming bag (13 g)

length, which are much smaller than those dimensions of the wood chips used in the paper industry. In Step 2 of Fig. 1, nutrients and water are added to the wood chips, and the moisture content on a wet basis,  $MC_w$ , is adjusted to about 60%. Nutrients (details will be described later) make up about 10% of the total weight of the cultivation bed. The average weight of the cultivation bed including a plastic forming bag was 2888 g before steam sterilization. The average weight after steam sterilization decreased by 36 g to 2852 g although about 10–13 g of inoculative fungus was added. The dimensions of the cultivation bed were about 12 cm in width, 20 cm in length, and 10 cm in height.

As shown in Fig. 1, it takes about 4 months before fungus spread fully into the cultivation bed after fungus inoculation, and then shiitake harvesting is repeated six times with an interval of 1 month. The total yield of shiitake mushroom from one cultivation bed was 913 g (2017 results), and the cultivation beds become waste mushroom beds about 11 months after preparation.

### Moisture content tests

Within 3 days of the last harvest, 100 waste mushroom bed samples were randomly extracted from a cultivation house, taken out of the plastic forming bag, and weighed. A histogram of the weight was created with a class of 50 g, and then about 1/3 of the samples were extracted from each class and their  $MC_w$  were obtained by the oven-drying method ( $N=36$ ).

Another moisture content test was performed on the waste mushroom beds that had been left for 1 month to examine their drying properties. After the last harvest, they were transferred from a cultivation house to a well-ventilated greenhouse with a concrete soil for a waste yard. Although the temperature in the greenhouse was unknown, the average temperature in the region during this period was 19 °C according to the local meteorological data. The same testing procedure as the sampling within 3 d after disposal was applied to these

waste mushroom beds and their  $MC_w$  were determined ( $N=39$ ).

**Preparation of powder samples**

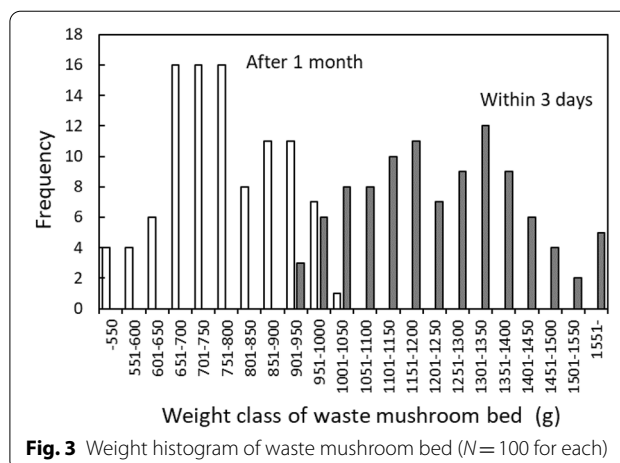
Powder samples were used in the tests of elemental analysis, ash content, and calorific value, which are described below. There are four types of samples: the skin of the waste mushroom bed, the inside of the waste mushroom bed, the mycelium, and the wood chips used for the cultivation bed. About 100 g of chip samples were prepared for both the skin and the inside from several waste mushroom beds within 3 d after disposal. The skin chips were collected by scraping the surface of the waste mushroom bed with a knife. The chip samples of mycelium were prepared from the stem part of the shiitake fruiting body, because it was difficult to take out only the mycelium from the inside of the waste mushroom bed. First, these four chip samples in an air-dry condition were powdered using a Willey mill. Then, they were classified by a three-stage sieve, and the following three kinds of fractions were prepared: F1: 0.5–2 mm; F2: 0.15–0.5 mm; F3: less than 0.15 mm (an F3 sample is used for the experiments in the third report of this study).

**Elemental analysis and ash content tests**

Carbon (C), hydrogen (H), and nitrogen (N) were quantified using a fully automatic elemental analyzer (Yanoko CHN Corder MT-6). F2 powder of each sample was used and the samples were left for 5 d in an air-conditioned laboratory where the device was placed to prevent moisture absorption/desorption during analysis. Approximately, 2 mg of each sample was used for each analysis and weighed to within an accuracy of 1 µg. Three replicate analyses were conducted, and the ash content was also measured automatically through the analysis. To calculate the oven-dry weight of the samples, the moisture content on a dry basis,  $MC_d$ , during the analysis was determined by an oven-drying method using about 2 g of the remaining sample.

After the analysis, however, three types of samples other than the mycelium showed a small amount of detected nitrogen, hence other highly accurate tests were necessary. Therefore, nitrogen was quantified for these samples using another analyzer (SUMIGRAPH NC-22A). About 100 mg of oven dry F2 sample was used for each analysis and weighed with an accuracy of 10 µg. Three replicate analyses were performed.

Among ash measurements obtained through the elemental analysis, the wood chips did not meet the precision required for analysis due to the lack of a detected amount of ash. Therefore, an ash content test by the usual determination method [4] was added. About 1 g of oven dry F1 sample was weighed in a melting pot with an



**Table 2 Weight and moisture content of waste mushroom bed (mean ± std)**

	Within 3 days	After 1 month
Wet weight (g) (COV, N)	1235 ± 173 (0.140, 100)	772 ± 122 (0.158, 100)
Oven dry weight (g) (COV, N)	249.1 ± 21.5 (0.086, 36)	275.0 ± 43.0 (0.157, 39)
$MC_w$ (%) (COV, N)	78.2 ± 4.5 (0.057, 36)	63.4 ± 6.5 (0.105, 39)

COV coefficient of variation, N the number of samples,  $MC_w$  moisture content on a wet basis

accuracy of 0.1 mg. This was heated at 600 °C for 8 h to obtain ash, and then the ash weight was measured with the same accuracy. The ratio of the dry ash weight to the oven dry sample weight was defined as the ash content (%). Five replicate tests were performed for the three types of samples other than the mycelium.

**Calorific value tests**

In accordance with JIS M8814 [5], a gross calorific value ( $H_h$ ) was determined for the four types of samples using an automatic bomb calorimeter (Shimadzu CA-4P). Approximately 1 g of F1 sample was weighed per test with an accuracy of 0.1 mg, and three replicate tests were performed. Furthermore, the moisture content at the time of the test,  $MC_w$ , was measured by an oven-drying method using 2–3 g of the sample. The  $MC_w$  was used to calculate gross calorific values on a dry basis.

**Results and discussion**

**Moisture contents of waste mushroom beds**

Figure 3 shows two weight histograms of a waste mushroom bed. One is within 3 days after disposal and the other is 1 month later. Statistical data for the wet weight of 100 samples and on an oven dry weight of the extracted samples are listed in Table 2. First, focusing on

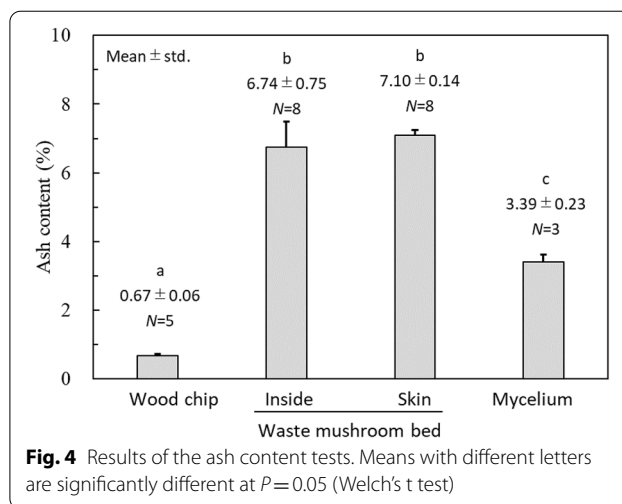
within 3 days after disposal, the wet weight was 1235 g on average and had a coefficient of variation (COV) of 14%. The variation on the wet weight is affected not only by the amount of moisture that is included but also by the weight of the substance because the oven dry weight was not constant and had a COV of about 9%. Their  $MC_w$  was about 78% on average and had a COV of about 6%.

Second, focusing on 1 month after disposal, the wet weight was 772 g on average and had a COV of 16%. As discussed above, this variation is affected not only by the amount of moisture included but also by the weight of substance because the oven dry weight was not constant and had a COV of about 16%. Their  $MC_w$  was about 63% on average with a COV of about 11%. The average  $MC_w$  decreased from 78 to 63% after being left for about 1 month. The moisture content on a dry basis is easier to intuitively understand the drying properties from, so when converted, its  $MC_d$  decreases from 379 to 181%. This indicates that the amount of moisture was about 3.8 times the substance weight within 3 d after disposal, and 1.8 times after being left for 1 month. This also suggests that a one-month natural drying process is not long enough to obtain a good woody biomass fuel. The slow drying is presumed to be due to the low moisture permeability of the skin of the mushroom bed. As will be described later, the skin is browned due to the deposition of melanin pigment. It is speculated that this browning results in the low moisture permeability. Therefore, when the waste mushroom bed is used as a boiler fuel, it is preferable to expose the inside through a crushing process followed by drying.

Focusing on the oven dry weights shown in Table 2 again, they had a COV of about 9% and 16% for the samples within 3 days and on 1 month after disposal, respectively. Although the reason for the difference of COV between the two sample groups is not clear, these variations means that the degree of wood decay varies to some extent from sample to sample. This suggests that there will be a concern of density variation when using as a block material shown in Fig. 2, while it is not a big problem when using as boiler fuel.

#### Ash contents and elemental composition

Figure 4 shows the results of the ash content tests. The wood chips showed a value of about 0.7%, which is close to the values reported [6] for live oak (0.6%) and black oak (0.5%). Conversely, the ash content of waste mushroom bed was about 7%, which is 10 times the value of wood chips. There was no significant difference in ash contents between the inside and the skin, and the average ash content became 6.78% when the law of mixing was applied assuming a weight ratio of inside to skin of 10:1. The waste mushroom bed is a mixture of decayed



**Fig. 4** Results of the ash content tests. Means with different letters are significantly different at  $P = 0.05$  (Welch's t test)

wood chip residues and mycelium. The ash content of the mycelium itself was 3.4%, while that of the waste mushroom bed was about double. The reason for this is considered to result from the nutrients added to the wood chips during the cultivation bed preparation. The ash content of nutritional supplements is as high as 4–8% (details will be described later). During shiitake cultivation, the elements that make up the ash move to some extent in the fruit bodies that are repeatedly harvested, and they are lost in small amounts by elution into supplemental water. Except for these two systems, the ash constituent elements remain in the mushroom bed, and it is considered that the ash content is concentrated due to the decrease in the overall weight due to biodegradation. The high ash contents of the waste mushroom bed measured in this study are comparable to those of hardwood bark. For example, Kofujita [7] reported that the ash contents of mizunara (*Quercus crispula*) bark and buna (*Fagus crenata*) bark were 5.7% and 7.3%, respectively. The disadvantage of using bark as a boiler fuel is the high ash content compared to wood chips [8]. When using the waste mushroom bed as fuel, the treatment of ash will be necessary, as with bark.

Table 3 lists the results of the elemental analysis. The air-dry base contents of C, H, and N of each sample are shown together with their  $MC_d$  values. These values were converted to oven-dry base values using the formulas shown below the table. Here, a simple moisture correction was done for C and N (only for mycelium), and in addition to this, bound water was deducted for H. Furthermore, the content of O was obtained by subtracting the sum of these three elements and ash from the entire system. The values for the whole waste mushroom bed in Table 3 were calculated from the law of mixing, assuming a weight ratio of inside to skin of 10:1. The carbon,

**Table 3 Results of the elemental analysis**

	Air-dry base content (%)				Oven-dry base content (%)*			
	MC <sub>d</sub>	C	H	N	C	H	N	O
Wood chip	9.2	44.68 (0.33)	5.96 (0.02)	–	48.79 (0.36)	5.49 (0.02)	0.16 (0.02)	44.89 (0.38)
Waste bed								
Inside	9.4	40.98 (0.46)	5.62 (0.06)	–	44.84 (0.50)	5.10 (0.06)	0.53 (0.02)	42.79 (0.55)
Skin	13.6	40.70 (0.28)	5.30 (0.01)	–	46.24 (0.31)	4.51 (0.01)	1.57 (0.01)	40.59 (0.32)
Whole	–	–	–	–	44.94	5.05	0.62	42.60
Mycelium	9.7	41.41 (0.06)	6.39 (0.03)	2.07 (0.09)	45.41 (0.07)	5.93 (0.03)	2.27 (0.09)	42.99 (0.20)

Data are shown as a mean of three replicate tests; values in parenthesis show standard deviations

Samples for nitrogen contents other than the mycelium were tested at an oven dry state

\* Oven-dry-base C (%) = C' (%) × (100 + MC<sub>d</sub>)/100

H (%) = H' (%) × (100 + MC<sub>d</sub>)/100 – MC<sub>d</sub> × 2/18;

N (%) = N' (%) × (100 + MC<sub>d</sub>)/100

where, C' (%), H' (%), and N' (%) are the air-dry-base carbon, hydrogen and nitrogen percentages, respectively. MC<sub>d</sub>: dry-base moisture content

O (%) = 100 – (C (%) + H (%) + N (%) + Ash content (%))

hydrogen, and oxygen contents of the waste mushroom bed (whole) were slightly lower than those of the wood chips. This is thought to be due to the higher ash content than that of wood chips as discussed above. Conversely, the nitrogen content was about four times greater in the waste mushroom bed. This is because the nitrogen content of the skin is about ten times that of wood, in addition to the high nitrogen content inside of the waste mushroom bed. It is considered that the high nitrogen content of the skin is due to the inclusion of a dark brown melanin pigment. The formation of the melanin pigment is believed to occur, because mycelium protects its territory from other bacteria and prevents water loss [9].

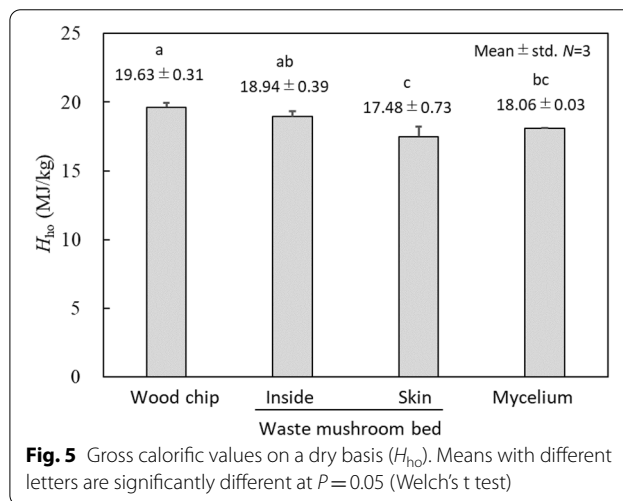
These elemental composition data will be used later in the discussion of calorific value and in the calculation of the substance flow during shiitake mushroom bed cultivation.

**Calorific values**

The results of calorific value tests are as follows:  $H_h$  (mean ± std.) and MC<sub>w</sub> for the wood chips were 18.08 ± 0.28 MJ/kg and 7.9%, respectively; 17.55 ± 0.36 MJ/kg and 7.3% for the inside of the waste mushroom bed, respectively; 15.54 ± 0.65 MJ/kg and 11.1% for the skin of the waste mushroom bed, respectively; and 16.40 ± 0.02 MJ/kg and 9.2% for the mycelium, respectively. To compare the gross calorific values on a dry basis ( $H_{ho}$ ) among the samples, these  $H_h$  values were converted to  $H_{ho}$  using the following equation:

$$H_{ho} = H_h \times 100 / (100 - MC_w). \tag{1}$$

Figure 5 compares the  $H_{ho}$  values among the samples. The  $H_{ho}$  value of oak wood [10] was reported to be



18.4 to 22.1 MJ/kg, therefore the  $H_{ho}$  value of the wood chips (19.63 MJ/kg) obtained in this study is reasonable. Although the  $H_{ho}$  value of the inside of the waste mushroom bed was not significantly reduced compared to the wood chips, that of the skin was about 11% lower than that of the wood chips. Assuming a weight ratio of the inside to skin of 10:1, the  $H_{ho}$  value for the whole waste mushroom bed is calculated to be 18.81 MJ/kg from the law of mixing, which was 4–5% lower compared to the wood chips. Focusing on the  $H_{ho}$  value of the mycelium (18.06 MJ/kg), this value was 8% lower compared to the wood chips and had no significant difference compared to both the inside and the skin of the waste bed. This result suggests that the presence of mycelia is not the main factor that reduces the  $H_{ho}$  of the waste mushroom bed.

Generally, the calorific value of a woody biomass fuel is affected by the amount of ash. Also, nitrogen in fuel does not contribute to heat generation. Therefore, the correction values ( $H_{ho'}$ ) of the  $H_{ho}$  values excluding ash and nitrogen were calculated using the following equation:

$$H_{ho'} = H_{ho} \times 100 / (100 - \text{Ash content} (\%) - N (\%)). \quad (2)$$

Substituting the ash content (%) shown in Fig. 4 and  $N$  (%) shown in Table 3 into the Eq. (2), the values of  $H_{ho'}$  for the wood chips, inside of the waste mushroom bed, skin of the waste mushroom bed, and mycelium were determined to be 19.79 MJ/kg (100%), 20.42 MJ/kg (103%), 19.14 MJ/kg (97%), and 19.15 MJ/kg (97%), respectively. Here, the value in parentheses is the ratio to the value of the wood chips. Compared to the differences among the samples shown in Fig. 5, the differences in the correction values were smaller. From this analysis, it was found that the differences in  $H_{ho}$  among the samples were due to the amounts of ash and nitrogen.

The calorific value of a fuel is the sum of the combustion heat values of the combustible components, and the  $H_{ho}$  value of wood and bark can be estimated by Eq. (3) in general [11].

$$H_{ho} = 33.94C + 142.5(H - O/8) \text{ (MJ/kg)}. \quad (3)$$

Here,  $C$ ,  $H$ , and  $O$  are the weights (kg) of carbon, hydrogen, and oxygen contained in 1 kg of oven dry fuel, respectively. The variable  $(H - O/8)$  of the second term is called the "effective hydrogen" of the system. The oxygen contained in the fuel is not used as oxygen for combustion, and usually a portion of the hydrogen is combined with this oxygen to form bound water. Therefore, the amount of hydrogen contained in the bound water ( $H_2O = 2:16 = 1:8$ ), that is,  $O/8$ , is subtracted from the amount of contained hydrogen. The values of  $H - O/8$  using the results shown in Table 3 for the wood chips, the inside of the waste mushroom bed, the skin, and the mycelium were  $-0.0015$  kg,  $-0.0025$  kg,  $-0.0056$  kg, and  $0.0056$  kg, respectively. From these results, it was found that there was no effective hydrogen other than the mycelium and that the heat generated by the effective hydrogen in the mycelium was only 0.8 MJ/kg. In other words, the mycelium can be expected to generate a small amount of heat from hydrogen, while the other three are all from carbon. The calculated values of  $H_{ho}$  according to Eq. (3) are 16.56 MJ/kg (84%), 15.22 MJ/kg (80%), 15.69 MJ/kg (90%), and 16.21 MJ/kg (90%) for the wood chips, the inside of the waste mushroom bed, the skin, and the mycelium, respectively. Here, the values in parentheses are the ratios to the measured values shown in Fig. 5. The values calculated by Eq. (3) were underestimated by up to 16% of the actual measured value. A

similar underestimation was observed when applying Eq. (3) to coniferous bark and wood [8]. Although Eq. (3) underestimates the measurements, it can clarify the properties of woody biomass fuels in which the presence of oxygen reduces the available hydrogen for combustion.

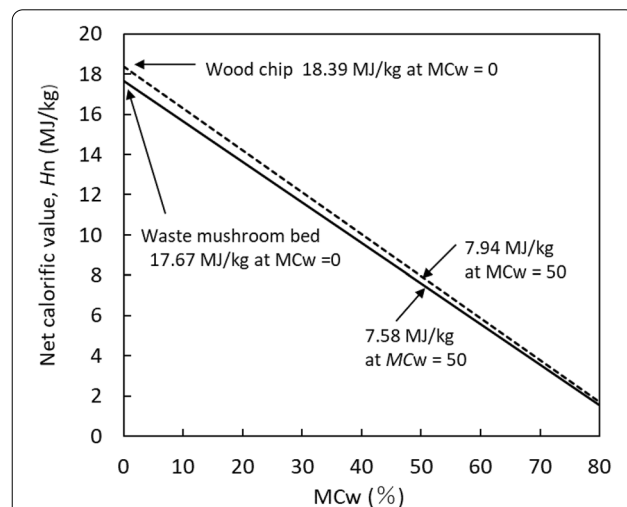
The gross calorific values obtained on a dry basis,  $H_{ho}$ , which have been discussed so far, are a basic indicator of calorific value. The gross calorific value at a moisture content of  $MC_w$  (%) is shown using Eq. (4), which is a modification of Eq. (1). These calorific values include the latent heat of condensation ( $H_s$ ) of water vapor because the water vapor generated by combustion cannot escape outside of the bomb calorimeter. Usually, in boiler combustion, water vapor in exhaust gas is diffused into the atmosphere without being condensed. Therefore, the amount of heat that can be used is called the net calorific value ( $H_n$ ), and this is the value obtained by subtracting  $H_s$  from  $H_h$  (Eq. (6)). The value of  $H_s$  can be calculated from Eq. (5) [8, 11]. Here,  $h$  is the weight ratio of hydrogen in the fuel. For example, from Table 3, the value of  $h$  in the waste mushroom bed (whole) is 5.05% at an  $MC_w$  of 0% and 2.53% at an  $MC_w$  of 50%.

$$H_h = H_{ho}(100 - MC_w)100 \quad (4)$$

$$H_s = 2.512(9 \times h + MC_w)100 \text{ [MJ/kg]} \quad (5)$$

$$H_n = H_h - H_s \text{ [MJ/kg]} \quad (6)$$

Figure 6 shows the relationship between  $H_n$  and  $MC_w$ . It was found that the  $H_n$  of the waste mushroom beds was 4–5% lower than that of the original wood chips in



**Fig. 6** Relationships between moisture content on a wet basis ( $MC_w$ ) and the net calorific value for both the waste bed (whole) and the original wood chips

any moisture content range. The waste mushroom beds will generate an  $H_n$  of 7.6 MJ/kg when they are dried up to about an  $MC_w$  of 50%. This value is almost the same as the  $H_n$  of general woody biomass fuel. For example,  $H_n$  values at an  $MC_w$  of 50% have been reported to be 7.5 MJ/kg and 8.0 MJ/kg for sapwood and bark of sugi (*Cryptomeria Japonica*), respectively [8].

**Substance flow during shiitake mushroom bed cultivation**

In this section, we discuss the substance flow during the shiitake cultivation by comparing the weight composition of the cultivation bed at the time of preparation and at the time of disposal.

First, the weight composition of one cultivation bed was determined using the following procedure (the results are shown in Table 4). In Step 2 of Fig. 1, wood chips with a volume of 6 m<sup>3</sup> and 310 kg of nutrients (90 kg of rice bran and 220 kg of wheat bran) are placed into the mixer, and water is added to adjust the  $MC_w$  to 60%. From this batch, 1080 cultivation beds are made. Therefore, the weight of one batch in the mixer become 3105 kg, because the average weight of one cultivation bed is 2875 g when the forming bag is deducted (see Table 1). Because the  $MC_w$  is 60%, the moisture

weight is 1863 kg, and thus, the total oven dry weight of the chips and nutrients is 1242 kg. To divide this oven dry weight into wood chips and nutrients, the oven dry weight of the nutrients is calculated via the following calculation. If the  $MC_w$  values of rice bran and wheat bran are 10.3% [12] and 13.4% [13], respectively, the oven dry weights are calculated to be 80.7 kg and 190.5 kg, respectively. Therefore, the oven dry weight of the wood chips is 970.8 kg. When these values are divided by the number of cultivation beds (1080), the weight composition per cultivation bed is obtained as follows: moisture: 1725 g; wood chip oven dry weight: 898.9 g; rice bran oven dry weight: 74.8 g; and wheat bran oven dry weight: 176.4 g. Also, because the average weight of the inoculum is 11.5 g, if the  $MC_w$  of the inoculum is equivalent to that of the shiitake fruiting body (90.3%) [12], the oven dry weight of the inoculum becomes 1.12 g. Summing these values together, the oven dry weight of the cultivation bed becomes 1151.2 g.

Next, the weights of the four elements (C, H, N, and O) and ash constituting one cultivation bed in an oven dry state (1151.2 g) were determined by the following procedure. First, the composition ratios of C, H, N, O, and ash for wood chips, rice bran, wheat bran, and inoculum used in the calculation are shown in the upper half of Table 5. Here, the values for the wood chips and inoculum are the same as those shown in Table 3 and Fig. 4, and the values of the rice bran and wheat bran were obtained from literature [14, 15]. Second, the weights of the four elements and the ash in each component are calculated by multiplying their oven dry weight by the composition ratio, and then the total weights of each element and ash are calculated (see the lower half of Table 5). This calculation revealed that the ratio of elements to the oven dry weight of the

**Table 4 Weight composition of the cultivation bed**

Components	Weight per mixer batch (kg)	Weight per bed (g)
Water	1863	1725
The values below are oven-dry weight		
Wood chip	970.8	898.9
Rice bran	80.7	74.8
Wheat bran	190.5	176.4
Inoculum	–	1.12 (Total: 1151.2)

**Table 5 Elemental weight composition of an oven-dry cultivation bed**

Components	C	H	N	O	Ash	Total
Ratios used for the calculation (%)						
Wood chip	48.79	5.49	0.16	44.89	0.67	100.0
Rice bran	48.10	6.98	2.63	34.39	7.90	100.0
Wheat bran	46.30	5.98	2.26	41.16	4.30	100.0
Inoculum	45.41	5.93	2.27	42.99	3.39	100.0
Weight (g)						
Wood chip	438.6	49.3	1.4	403.5	6.1	898.9
Rice bran	36.0	5.2	2.0	25.7	5.9	74.8
Wheat bran	81.7	10.5	4.0	72.6	7.6	176.4
Inoculum	0.50	0.07	0.03	0.48	0.04	1.12
Total*	556.8 (48.4%)	65.1 (5.7%)	7.4 (0.6%)	502.3 (43.6%)	19.6 (1.7%)	1151.2 (100%)

\* Values in parentheses are a percentage of the total weight



cultivation bed was 48.4% for carbon, 5.7% for hydrogen, 0.6% for nitrogen, 43.6% for oxygen, and 1.7% for ash.

Next, the weights of the four elements (C, H, N, O) and ash in one waste mushroom bed are determined. They were calculated by multiplying the average oven dry weight (249.1 g; within 3 days after disposal, see Table 2) by their composition ratio (whole bed) shown in Table 3 and an ash content of 6.78%. Table 6 compares the calculation results with the values of the cultivation bed. Table 6 also shows the values calculated from the total yield of the fruiting bodies. Because the yield of shiitake mushrooms per bed is 913 g, if its  $MC_w$  is 90.3% [12], the oven dry weight will be 88.6 g. The weights of the four elements (C, H, N, and O) and ash in this dry weight were calculated from the ratios of the inoculum shown in Table 5.

From Table 6, the following can be observed regarding the substance flow in shiitake mushroom bed cultivation. First, there was a weight loss of about 78% from a cultivation bed weight of 1151 g to a waste mushroom bed weight of 249 g. This loss is mainly due to mycelium respiration and proliferation, fruiting body formation, and repeated fruiting body harvesting. In addition, it is considered that some of the amino acids were leached out and moved to wastewater due to the watering operation during cultivation. Second, the weight losses of the four elements C, H, N, and O were in the range of 79–81% and were close to each other. One of the reasons for this is considered to be that shiitake mushrooms are white-rot fungi and they attack all of the chemical constituents of the cell wall [16]. In other words, because lignin has a higher carbon content than cellulose and hemicellulose [8], it is considered that the carbon residual rate increases when lignin cannot be decomposed. To discuss the changes in these four elements in detail, it will be necessary to examine the changes in the major chemical components of wood before and after decay. Third, the weight loss of ash was about 14%, which was significantly lower than that of the four elements. As already mentioned in the section pertaining to the ash results, the ash was concentrated throughout a cultivation from 1.7% ash in

the cultivation bed (see Table 5) to 6.8% ash in the waste mushroom bed. The fourth is the movement of nitrogen. Of the 7.4 g of nitrogen contained in the cultivation bed, 1.5 g remained in the waste mushroom bed and 2.0 g was transferred to the fruiting bodies. Therefore, it is considered that a difference of 3.9 g was leached as various amino acids into supplemental water during cultivation. Finally, we focus on the C/N ratio of the waste mushroom bed. Itoh [13] reported that the yield was maximized when the C/N ratio of the shiitake cultivation bed was 70–80. When the C/N ratio was calculated using the values shown in Table 6, it was about 75 for both the cultivation bed and waste mushroom bed. This result suggests the possibility that the waste mushroom bed can be mixed with the cultivation bed and reused.

## Conclusions

The findings obtained from this work are summarized as follows:

- (1) The shiitake mushroom bed at the time of disposal contained about 3.8 times the oven dry weight of moisture, and even after 1 month of natural drying, it contained about 1.8 times the oven dry weight of moisture. The slow drying is presumed to be due to the low moisture permeability of the skin of the mushroom bed. Therefore, it is necessary to crush the waste mushroom bed and then dry it before using it as a boiler fuel.
- (2) The ash content of the waste mushroom bed was about 7%, which was close to that of bark and about ten times that of the wood used for the cultivation bed. When the waste mushroom bed is used as a boiler fuel, appropriate ash treatment is required as in the case of using bark.
- (3) The gross calorific value on a dry basis ( $H_{ho}$ ) inside of the waste mushroom bed was 18.9 MJ/kg, which was not significantly lower than that of cultivation bed wood chips. However, the  $H_{ho}$  of the skin of the waste mushroom bed was significantly lower by 11% than that of the cultivation bed wood chips

**Table 6 Comparison of the elemental weight composition between the cultivation bed and waste mushroom bed in an oven-dry base**

	C	H	N	O	Ash	Total
Cultivation bed, $W_0$ <sup>a</sup> (g)	556.8	65.1	7.4	502.3	19.6	1151.2
Waste mushroom bed, $W_1$ <sup>b</sup> (g)	112.0	12.6	1.5	106.1	16.9	249.1
Weight loss; $(1-W_1/W_0) \times 100$ (%)	79.9	80.6	79.7	78.9	13.8	78.4
Shiitake mushroom <sup>c</sup> (g)	40.2	5.3	2.0	38.1	3.0	88.6

<sup>a</sup>, <sup>b</sup> Element weight of cultivation bed and waste mushroom bed, respectively

<sup>c</sup> Sum of six repeated harvests from one cultivation bed

because of its higher ash and nitrogen contents. As a result, the  $H_{ho}$  of the whole waste mushroom bed was 18.8 MJ/kg, which was 4–5% lower than that of the cultivation bed wood chips. The  $H_{ho}$  of mycelium itself was 18.1 MJ/kg, which was significantly lower by 8% than that of the cultivation bed wood chips due to its significantly higher nitrogen and ash contents. When analyzed considering the combustion heat of the contained elements, it was found that both the cultivation bed wood chips and the waste mushroom bed had almost no hydrogen contributing to combustion due to the high oxygen content, and they were dependent on the heat generation of carbon.

- (4) The relationship between the net calorific value and moisture content on a wet basis ( $MC_w$ ) was obtained for the waste mushroom bed. The net calorific value was 4–5% lower than that of the cultivation bed wood chips at any moisture content level, and it was 7.6 MJ/kg at an  $MC_w$  of 50%, which was almost the same as that of sugi (*Cryptomeria Japonica*) sapwood and bark.
- (5) Comparing the oven dry weight of the waste mushroom bed with that obtained at the time of preparing the cultivation bed, the weight loss was about 78%. The weight losses of the four elements C, H, N, and O were in the range of 79–81% and were close to each other. Conversely, the weight loss of ash was about 14%, which was significantly lower than that of the four elements, such that the ash was concentrated through cultivation from 1.7% in the cultivation bed to 6.8% in the waste mushroom bed.

#### Abbreviations

$MC_w$ : Moisture content on a wet basis;  $MC_d$ : Moisture content on a dry basis;  $H_t$ : Gross calorific value;  $H_{ho}$ : Gross calorific value on a dry basis;  $H_n$ : Net calorific value.

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#### Authors' contributions

NS designed the study and analyzed the data, and was a major contributor in writing the manuscript. ZJ conducted calorific value tests and contributed to writing the manuscript. All authors read and approved the final manuscript.

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#### Availability of data and materials

The datasets used and/or analyzed during the current study are available from the corresponding author on reasonable request.

#### Competing interests

The authors declare that they have no competing interests.

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