JARQ 60 (4), 389-397 (2026) https://www.jircas.go.jp

Harvest Decision Rules for Processing Use of Elongated Moso Bamboo Shoots: Defining the Harvest Limit Based on an Internode Hardness Threshold and Utilizable Biomass

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Abstract

Because bamboo shoots elongate and harden rapidly, harvest delays under an aging workforce and labor shortages reduce commercial value and can increase culm density, complicating bamboo forest management. Some elongated shoots that miss the fresh market can still be processed before extensive lignification, but operational decision rules are scarce. We propose a decision-making framework for labor-efficient harvesting that integrates a rapid, non-destructive field indicator (internode hardness) with processing suitability (edibility after processing) and utilizable biomass (edible weight after processing). Elongated Moso bamboo shoots (*Phyllostachys edulis*) collected from managed stands in Yamagata Prefecture, Japan, were assessed; processing suitability was evaluated under a boil–dry procedure used for Japanese menma. Regression analysis identified 4.5 kg/cm^2 as an operational hardness threshold based on an 80% edibility criterion. Using this threshold, edible weight increased with shoot length and was highest at 200 cm-250 cm, while shoots ≥ 250 cm showed diminishing returns. Edible portions were concentrated in upper sections, whereas basal sections were largely inedible. These findings provide operational decision rules by combining a hardness threshold, a management-based harvest length, and selective harvesting of upper portions, thereby reducing unnecessary transport of inedible biomass and improve labor efficiency and resource use.

Discipline: Forestry
Additional key words: cell wall, lignification, non-wood forest products

Introduction

Bamboo is a fast-growing forest resource that is widely distributed from tropical to temperate regions worldwide and has diverse uses and high economic value (Zhang et al. 2021, FAO 2025). In Japan, Moso bamboo (*Phyllostachys edulis*), introduced from China approximately 300 years ago, is the predominant large bamboo species cultivated throughout the country (Shibata 2003, Torii & Okuda 2010). Its young shoots are widely used as resources for agriculture, forestry, and tourism (MAFF 2024). However, recent studies have reported that bamboo shoot harvesting has become increasingly difficult because of an aging workforce and labor shortages (Furusawa & Nakamura 2021, Sun et al. 2021, Nonaka 2002). This situation is not unique to Japan; similar challenges have been reported in other bamboo-dominated regions in Asia, where bamboo expansion and management abandonment associated with workforce aging and labor shortages have been documented (Zheng et al. 2021, Sun et al. 2020).

Because bamboo shoots grow rapidly and vascular bundle hardening progresses early, edible shoots lose nearly all commercial value if harvesting is delayed by only a few days, and the resulting production of elongated shoots increases culm density (Miwa et al. 1993). Poorly managed bamboo forests with increased culm density can create new problems, such as encroachment into adjacent areas (Furusawa & Nakamura 2021, Sun et al. 2021). Therefore, utilization of shoots before they become woody has attracted attention as a strategy to suppress over-densification while improving resource-use efficiency, and processing into preserved food products is one such option. Although delayed harvest increases the

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Received 9 January 2026; accepted 6 March 2026; J-STAGE Advanced Epub 30 July 2026.
https://doi.org/10.6090/jarq.25J18

proportion of elongated shoots unsuitable for the fresh market, a subset can still be utilized for processing before extensive lignification. Identifying the harvest limit compatible with processing is therefore essential for labor-efficient management. Because processing suitability depends strongly on lignification, harvest decisions must be made within a narrow period and often under severe labor constraints; accordingly, decision-support tools that balance resource-use efficiency, processing suitability, and labor input are critically important for sustainable bamboo forest management in regions facing population decline and labor shortages. In Japan, one example of such processing use is the growing production of "Japanese menma" (RCA 2021), and in this study processing suitability was evaluated under a boil–dry procedure used in Japanese menma production (RCA 2021). The current Japanese menma production manual recommends harvesting elongated shoots at a length of 150 cm-200 cm based on practical experience (RCA 2021). However, this recommendation has not been sufficiently quantitatively validated through rigorous scientific examination, and its effectiveness under labor-limited conditions remains unclear. Moreover, scientific studies that examine harvesting criteria for elongated shoots from a management and decision-making perspective remain scarce.

Therefore, we position this study as a decision-making framework for the effective and labor-saving utilization of rapidly lignifying bamboo shoots. By using internode hardness as a rapid, non-destructive indicator of early lignification and integrating it with evaluations of processing suitability (i.e., edibility after processing) and utilizable biomass, we propose a framework to support practical harvesting decisions under conditions of declining labor availability. Although the framework is demonstrated using elongated Moso bamboo shoots in the context of Japanese menma production, the approach proposed here is broadly applicable to bamboo-dominated regions, particularly in Asia, that share challenges such as labor shortages and increasing culm density.

Materials and methods

1. Materials

Elongated Moso bamboo shoots used in this study were collected from managed Moso bamboo forests in Yamagata Prefecture, Japan, over a three-year period from 2021 to 2023 (Fig. 1), and bamboo shoots were randomly selected from the available elongated shoots at each site. Shoots were collected 7-10 d after shoot emergence, and detailed information on the collection period and number of samples for each year is provided in Table 1. The collected shoots ranged in length from approximately 100 to 300 cm, covering the 150 cm-200 cm range commonly recommended in the Japanese menma production manual (RCA 2021).

2. Operational hardness threshold between elongated bamboo shoot nodes

After collection, before processing, total shoot length and internode hardness were measured on fresh shoots. Since elongated bamboo shoots exhibit non-uniform hardness within a single internode, tissues that remain edible after processing and those that become inedible may coexist within the same internode. Therefore, hardness was measured at three or five points per internode, depending on internode length (Fig. 2), using a fruit hardness tester (KM-type; Fujiwara Scientific, Japan) equipped with a hemispherical plunger (12 mm in diameter, 10 mm in height). Measurements were conducted within 3 h after collection to minimize post-harvest changes. Each measurement point was treated as an independent observation to capture within-internode heterogeneity, and values were not averaged within an internode. Because hardness was evaluated on fresh, unprocessed tissues, no correction was applied for differences in moisture content at the time of measurement.

Subsequently, to evaluate edibility after processing, shoots were processed using a boiling and drying procedure based on industrial practices obtained through interviews with a menma manufacturing company (Micro Corporation, Japan). After hardness measurement, shoots were longitudinally split in half and cut into sections containing two to four internodes (approximately 30 cm). These sections were subjected to primary boiling (30 min) followed by drying at 60°C for 24 h and then stored in sealable polyethylene bags with silica gel. For secondary processing, the dried specimens were boiled in an autoclave at 90°C for 24 h, after which the water was replaced and maintained at 90°C for 3 h. The water was then replaced again, and the samples were soaked for 24 h.

After processing, edibility was evaluated through a sensory test involving mastication to simulate actual consumption conditions. All samples were evaluated by a single assessor to minimize inter-evaluator variability. Samples were classified on a three-point scale based on chewing discomfort: (1) unchewable, (2) somewhat difficult to chew, and (3) chewable. Only samples scored as 3 were categorized as edible. The relationship between internode hardness and the proportion of edible samples

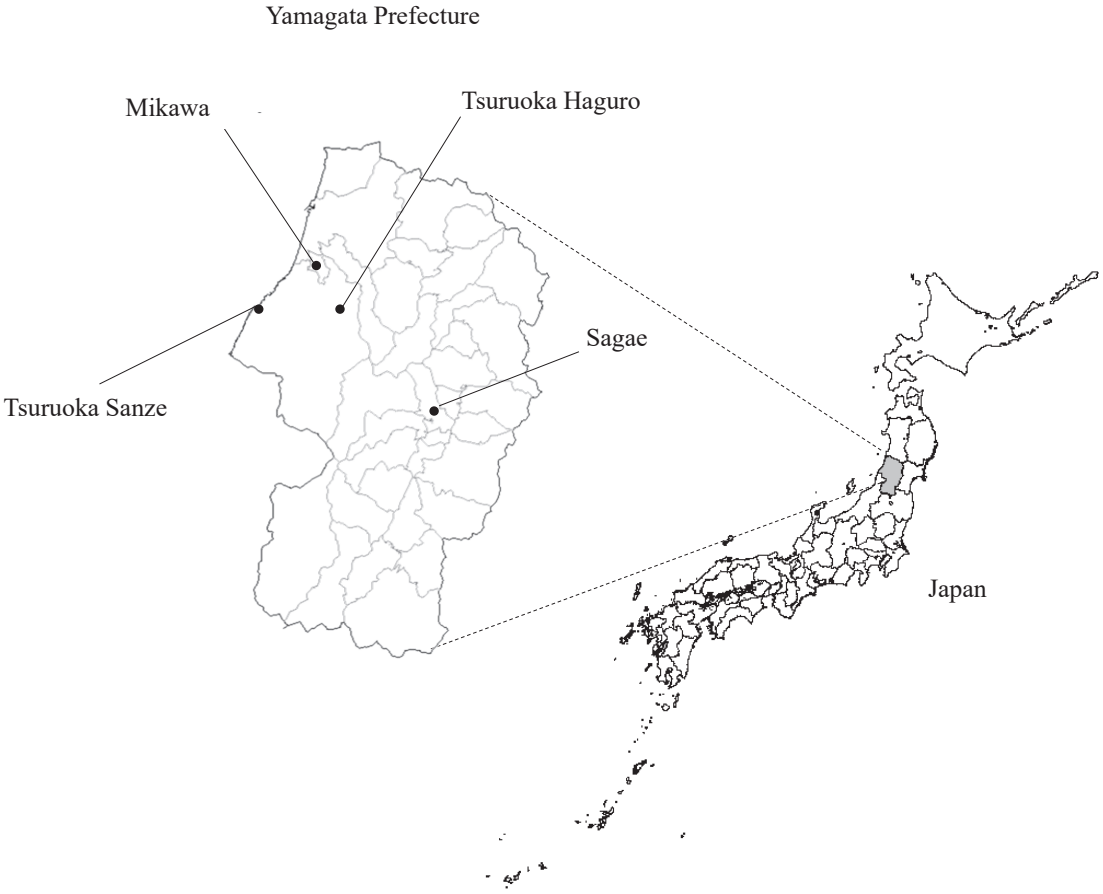


Fig. 1. Geographic locations of the sample collection sites
The map shows the four sampling sites in Yamagata Prefecture, Japan: Sanze and Haguro districts in Tsuruoka City, Mikawa Town, and Sagae City.

Table 1. Details of sample collection

Collection site	Collection period			Number of samples
Tsuruoka Sanze	2021	14-May	– 21-May	13
	2022	13-May	– 19-May	59
	2023	8-May	– 12-May	16
Tsuruoka Haguro	2021	24-May	– 4-Jun	37
	2022	24-May	– 1-Jun	19
	2023	22-May	– 1-Jun	71
Mikawa	2021	18-May	– 19-May	10
	2022	16-May		3
	2023	18-May		5
Sagae	2021			0
	2022	13-May		2
	2023	18-May	– 22-May	3

was analyzed to determine an operational hardness threshold. Because partial removal of inedible tissue is feasible in this processing system, the operational hardness threshold was defined as the hardness value at which more than 80% of samples were judged edible, balancing resource utilization and industrial sorting efficiency. This threshold was estimated using second- to fourth-order polynomial regression models in R (version 4.5.0) based on data from 45 elongated bamboo shoots. Polynomial regression was employed as an empirical approach to capture the non-linear relationship between internode hardness and edibility, and the optimal model was selected based on adjusted R^2 and Akaike information criterion.

3. Relationship between internode hardness and major cell wall constituent composition

To identify cell wall components associated with internode hardness and processing suitability (edibility after processing), the main cell wall constituents were analyzed in samples representing different hardness levels. Samples were obtained from portions of elongated bamboo shoots with hardness values ranging from 4.1 to 4.9 kg/cm^2. The samples were oven-dried, ground into powder, and analyzed following the Manual of Wood Quality Experiments (JWRS 2000). All analyses were performed in triplicate for each hardness level. Extractives were removed by Soxhlet extraction using an ethanol–benzene mixture (1:2, v/v). Holocellulose content was determined using Wise's method, and hemicellulose content was calculated as the difference between holocellulose and α-cellulose. Lignin content was determined using the Klason method, and acid-soluble lignin was quantified by measuring absorbance at 205 nm-210 nm with a UV–visible spectrophotometer (UV-2700; Shimadzu Corporation, Japan).

4. Elongated bamboo shoot length and edible weight

To evaluate the effect of elongated bamboo shoot length on utilizable biomass, 95 elongated bamboo shoots collected in 2023 were analyzed. Total shoot length and internode hardness were measured, and edible portions were defined as internodes with hardness values ≤ 4.5 kg/cm^2 based on the operational hardness threshold empirically derived in this study (see Section 2 and Results). Edible weight was measured for each shoot, and

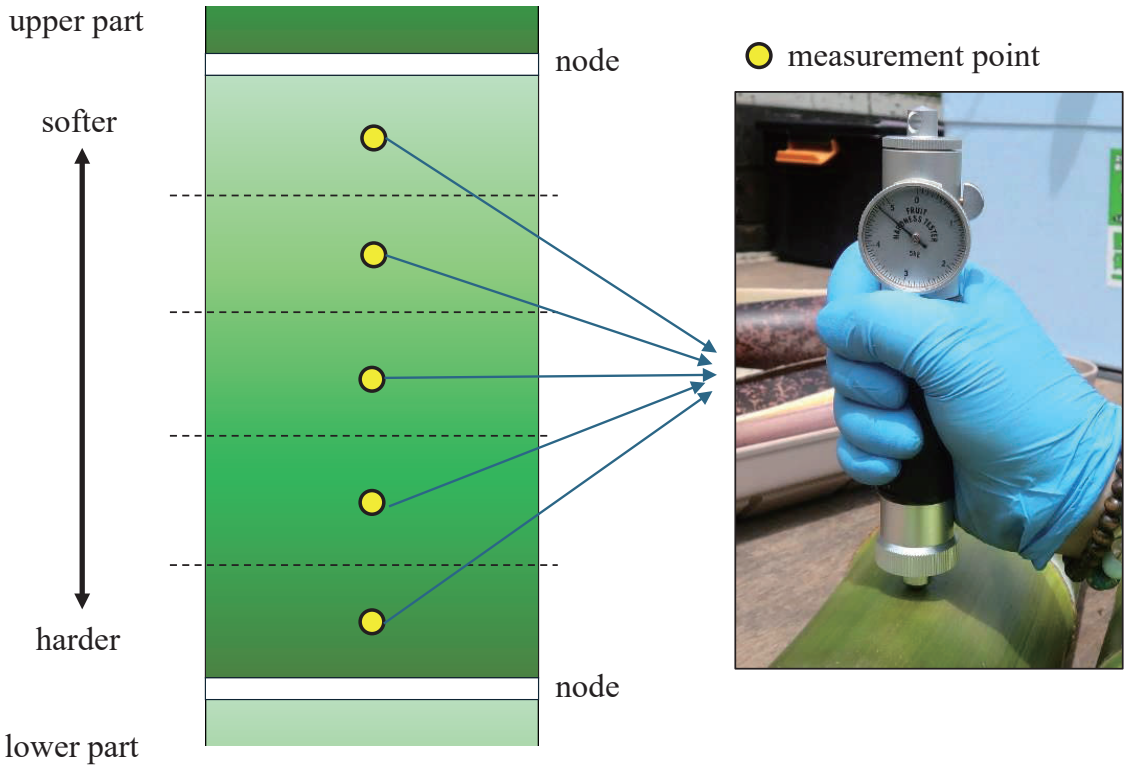


Fig. 2. Method for measuring hardness within an internode
The schematic (left) shows the measurement points used to capture variation in hardness along the internode, and the photograph (right) shows handheld measurement using a fruit hardness tester. Three to five points were measured per internode depending on internode length.

samples were classified into four length categories: 100 cm-150 cm, 150 cm-200 cm, 200 cm-250 cm, and ≥ 250 cm. These categories were defined with reference to the length range commonly used in practice (150 cm-200 cm; RCA 2021). Differences in edible weight among the four length categories were analyzed using the Kruskal–Wallis test, followed by multiple comparisons using the Steel–Dwass method when significant differences were detected. Statistical analyses were performed using Excel Statistics (version 4.07; Social Survey Research Information Co., Ltd.).

In addition, the vertical distribution of edible portions within shoots was examined. This four-section scheme was adopted to provide an operationally simple assessment that can be readily applied in harvesting and processing settings, consistent with the decision-support aim of the study. Each shoot was divided into four sections according to its harvest length: basal (A), lower middle (B), upper middle (C), and tip (D) sections (Fig. 3). The edible percentage in each section was calculated as the proportion of internodes with internode hardness values ≤ 4.5 kg/cm^2. For this analysis, 141 elongated bamboo shoots collected in 2021 and 2022 were used.

Results

1. Operational hardness threshold at the time of elongated bamboo shoot collection

The relationship between internode hardness at collection and edibility is shown in Figure 4. All 399 samples with an internode hardness of 5.0 kg/cm^2 were judged inedible. Based on the proportion of edible samples at each hardness level, second- to fourth-order polynomial regression models were fitted, and the fourth-order model showed the best fit, with the highest adjusted R^2 (0.982) and the lowest AIC (66.62). The model is expressed as:

$$Y = 111.83 - 19.13X + 8.81X^2 - 1.66X^3 + 0.085X^4$$

where Y is the predicted percentage of edible samples (%) and X is the internode hardness (kg/cm^2). According to this model, the predicted proportion of edible samples was 92.14% at 4.4 kg/cm^2, 82.76% at 4.5 kg/cm^2, and 67.08% at 4.6 kg/cm^2. Because 4.5 kg/cm^2 met the predefined 80% criterion, the operational hardness threshold at the time of bamboo shoot collection was determined to be 4.5 kg/cm^2.

2. Internode hardness and main cell wall constituent composition

Table 2 summarizes the main cell wall constituent composition of samples at different internode hardness levels. α-Cellulose content was 20.09%-25.90% at hardness levels of 4.7-4.9 kg/cm^2 and ranged from 13.57% to 23.58% at 4.1-4.6 kg/cm^2. Hemicellulose content was approximately 25% at 4.7-4.9 kg/cm^2 (24.89%-26.12%) and decreased at lower hardness levels, ranging from 12.26% to 18.04% at 4.1-4.5 kg/cm^2. Klason lignin increased with hardness, showing a marked rise between 4.4 and 4.5 kg/cm^2 (from 1.35 ± 0.83% to 3.08 ± 0.10%) and reaching 12.55 ± 0.28% at 4.9 kg/cm^2. In contrast, acid-soluble lignin was higher at lower hardness levels (18.14%-19.50% at 4.1-4.4 kg/cm^2) and decreased at higher hardness levels, reaching 5.66 ± 0.17% at 4.9 kg/cm^2.

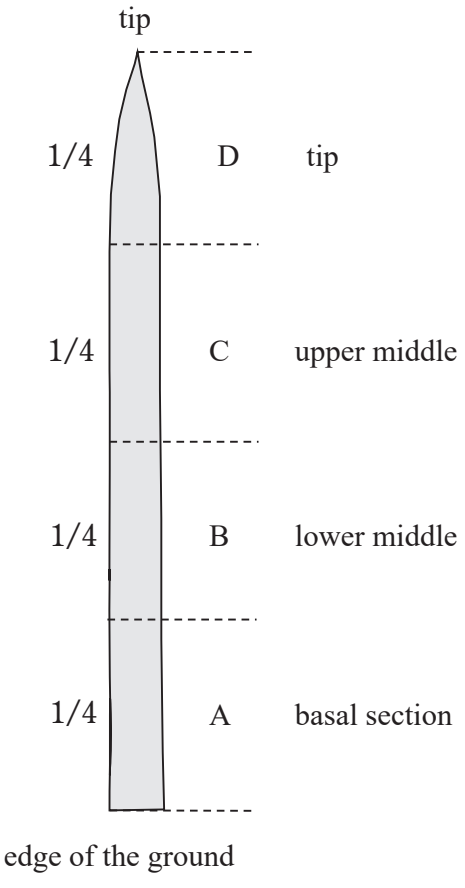


Fig. 3. Schematic diagram of an elongated bamboo shoot divided into four sections
The shoot was divided from the base to the tip into four parts (labeled A-D) to evaluate the vertical distribution of edible portions. Sections were defined as follows: (A) basal, (B) lower middle, (C) upper middle, and (D) tip.

3. Elongated bamboo shoot length, edible weight, and vertical distribution of edible portions

Figure 5 shows the relationship between bamboo shoot length and edible weight. Mean edible weight increased with shoot length and was highest in the 200 cm-250 cm group (1346.8 ± 93.5 g), followed by a slight decrease in shoots ≥ 250 cm. A Kruskal–Wallis test detected significant differences in edible weight among the four length groups (χ^2 = 9.140, df = 3, p = 0.0275). Steel–Dwass multiple comparisons showed that the 200 cm-250 cm group had a significantly higher edible weight than the 100 cm-150 cm group (p = 0.0204), whereas no other pairwise comparisons were significant.

Figure 6 shows the distribution of edible tissue

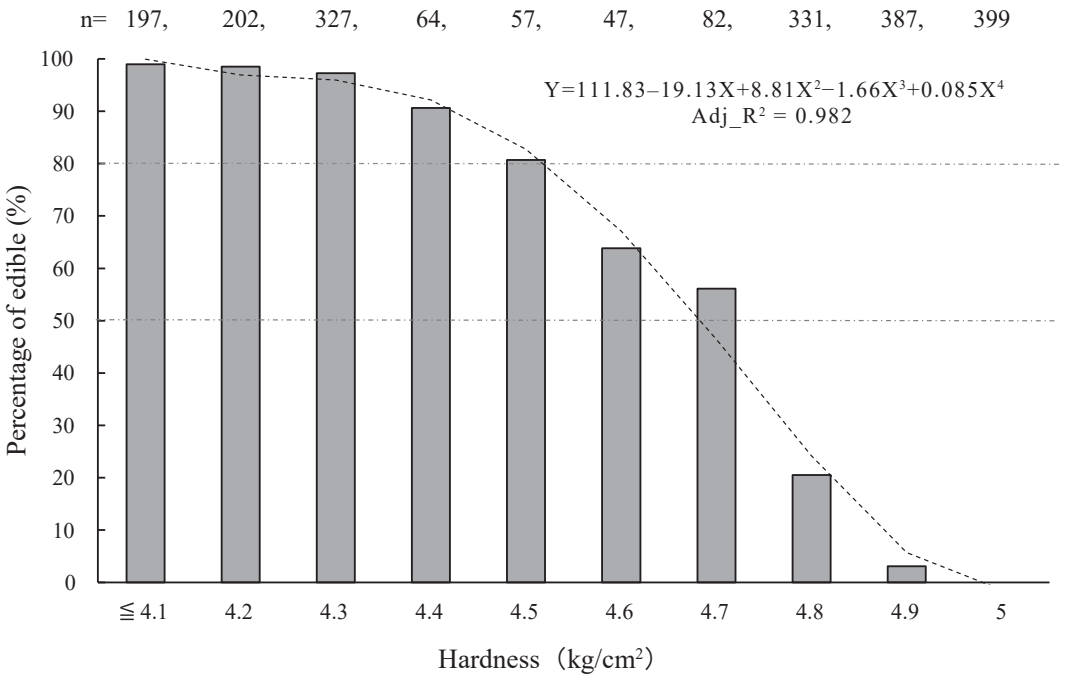


Fig. 4. Relationship between internode hardness and percentage of edible samples
Bars indicate the observed percentage of samples judged edible at each hardness level; sample sizes (n) are shown above the bars. The dashed line indicates the fitted regression curve, and horizontal dash-dotted lines indicate the 80% and 50% criteria. The 80% criterion represents an operational hardness threshold: rather than requiring a hardness level at which all tissues are utilizable (100%), it assumes routine sorting and partial trimming of inedible tissue to define the practical hardness limit for utilization.

Table 2. Cell wall constituent composition at different internode hardness level

Hardness value (kg/cm²)	α-cellulose (%)	Hemicellulose (%)	Klason lignin (%)	Acid-soluble lignin (%)
4.9	25.90 ± 0.87	24.89 ± 0.43	12.55 ± 0.28	5.66 ± 0.17
4.8	22.64 ± 0.29	26.12 ± 0.33	10.51 ± 0.52	9.24 ± 0.06
4.7	20.09 ± 0.31	25.57 ± 0.45	6.70 ± 0.11	12.27 ± 0.25
4.6	15.60 ± 0.82	15.57 ± 0.70	3.89 ± 0.24	15.91 ± 0.36
4.5	19.33 ± 1.87	18.04 ± 1.86	3.08 ± 0.10	15.81 ± 0.34
4.4	23.58 ± 3.28	16.51 ± 3.25	1.35 ± 0.83	19.01 ± 0.25
4.3	13.57 ± 0.41	17.29 ± 0.25	0.06 ± 0.03	19.33 ± 0.12
4.2	13.80 ± 0.83	15.10 ± 0.93	1.68 ± 0.84	18.14 ± 0.16
4.1	17.03 ± 1.06	12.26 ± 0.92	0.06 ± 0.06	19.50 ± 0.63

Values are presented as mean ± standard error (n= 3).

across the four vertical sections (A-D) in Figure 3. The basal section (A) was almost entirely inedible, whereas the edible proportion increased in the lower middle section (B; 31%). In contrast, most of the upper middle section (C; 81%) and nearly all of the tip section (D; 99%) were edible.

Discussion

This study elucidates the relationship between internode hardness, processing suitability (i.e., edibility after processing), and cell wall composition in elongated Moso bamboo shoots. Consistent with the study aim stated in the Introduction section, we interpret these relationships as an evidence-based decision-making framework to support labor-efficient harvest decisions for processing use by integrating a rapid, non-destructive indicator (internode hardness) with processing suitability and utilizable biomass (edible weight after processing). Within this framework, an internode hardness of approximately 4.5 kg/cm^2 serves as an operational hardness threshold that delineates tissues likely to remain processable from those that have already become difficult to utilize. The correspondence between this threshold and lignin-related compositional change supports the physiological basis of the hardness-based criterion.

In Moso bamboo, cell wall formation proceeds sequentially: cellulose microfibrils are deposited first, followed by hemicellulose, and lignin is then deposited and polymerized within this matrix, progressively rigidifying the wall (Fukazawa 1997, Tobimatsu 2017). During culm development, lignification intensifies at later stages, accompanied by an increase in high-molecular-weight (Klason) lignin and a decrease in acid-soluble lignin (Kiryu et al. 2017, Furusawa & Ashitani 2021). The compositional transition observed

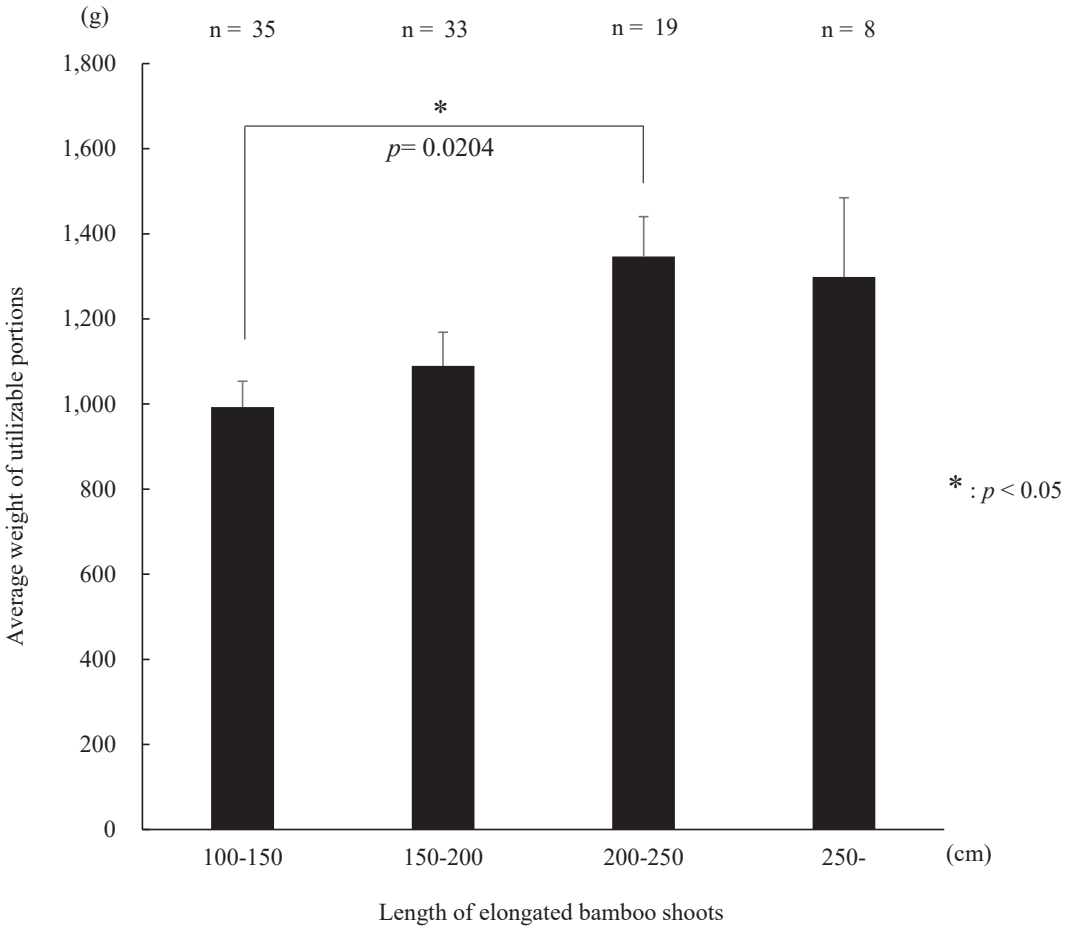


Fig. 5. Average edible weight by shoot length
Bars show mean ± SE, and sample sizes (n) are shown above the bars. Differences among groups were tested using the Kruskal–Wallis test, followed by the Steel–Dwass multiple comparisons. The asterisk indicates a significant difference between the 100 cm-150 cm and 200 cm-250 cm groups (*$p < 0.05$).

around the operational hardness threshold suggests that approximately 4.5 kg/cm^2 corresponds to the onset of substantial lignin accumulation and polymerization, marking a shift in processing suitability. This supports internode hardness as a practical proxy for early lignification and thus as an operational decision rule for determining the harvest limit compatible with processing use. In addition, feruloyl arabinoxylan is deposited at the onset of secondary wall (S2) formation (Munekata et al. 2022), and lignin deposition initially occurs on the epidermal side of bamboo shoots (Kiryu et al. 2018); together, these findings suggest that early lignification in epidermal-side tissues may strongly influence chewability and edibility.

Next, we examined the relationship between harvest length and utilizable biomass (edible weight after processing). As shoots continue to elongate, lignification at the base appears to outpace the addition of newly formed processable tissue at the tip, resulting in diminishing returns in utilizable biomass; this interpretation is consistent with known gradients in cell wall maturation and cellulose crystallinity along the shoot axis (Nomura 1980, Toba et al. 2015). The management-based harvest length (200 cm-250 cm) exceeds the empirically recommended length of 150 cm-200 cm in a current industry manual for Japanese menma (RCA 2021), suggesting that evidence-based decision rules may improve labor efficiency and usable yield under labor-limited conditions. Because current practices often involve transporting whole shoots including substantial inedible portions, selectively harvesting upper portions and leaving basal residues on-site can reduce avoidable handling and transport of unutilizable biomass. Depending on production needs and biennial yield fluctuations (Ueda 1963, Nonaka 2010), flexible strategies such as collecting a defined upper fraction of the shoot may also be effective.

Overall, this study operationalizes an evidence-based decision-making framework for the labor-efficient utilization of rapidly lignifying bamboo shoots by linking a physiological proxy (internode hardness) to processing suitability and utilizable biomass. Although demonstrated using elongated Moso bamboo shoots in the context of Japanese menma production, the framework can be adapted to other bamboo-dominated regions, particularly in Asia, where similar labor constraints and management challenges have been reported (Zheng et al. 2021, Sun et al. 2020). Because the hardness threshold is intended as an operational decision rule, broader application requires confirming that the hardness–suitability relationship

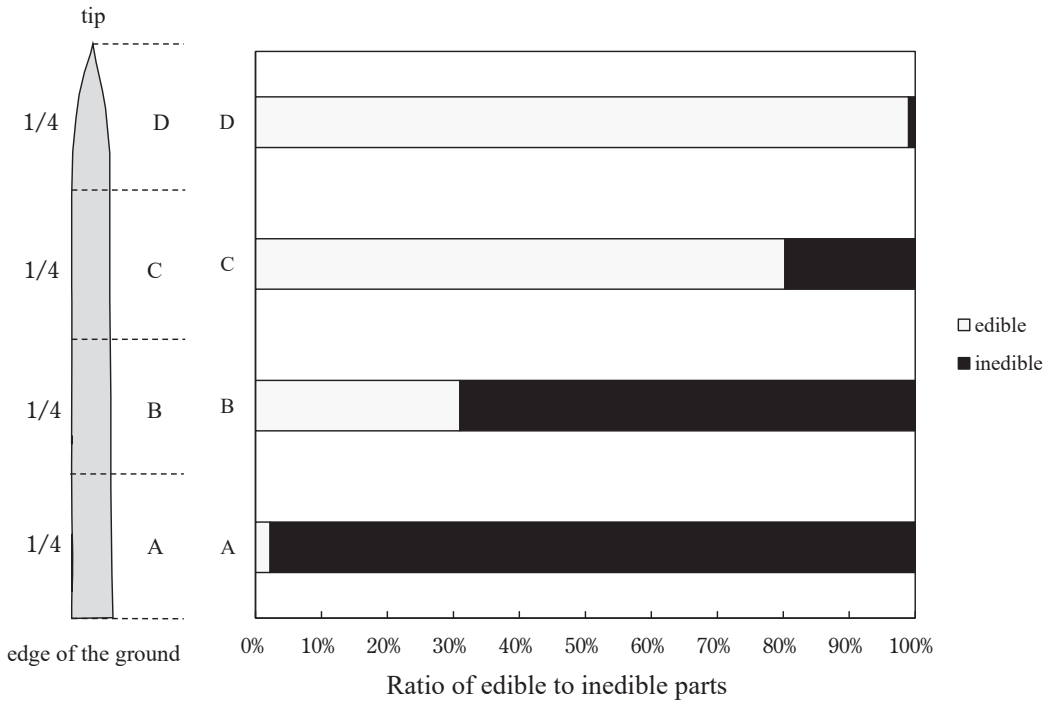


Fig. 6. Percentage of edible portions in each vertical section of elongated bamboo shoots
Shoots were divided into four sections (A-D) as defined in Figure 3. Edible portions were defined as internodes with hardness values ≤ 4.5 kg/cm^2. The stacked bars indicate the proportion ratio of edible (white) and inedible (black) internodes in each section.

holds across different sites and processing conditions. Future studies should therefore test the framework under contrasting climatic/edaphic settings and processing regimes and, if needed, adjust the operational hardness threshold to match local quality requirements.

Acknowledgements

We extend our gratitude to the inhabitants of the Sanze area of Tsuruoka City, Mikawa Town, and Yamagata Prefecture for their cooperation in the collection of materials for this study. We would also like to express our deepest gratitude to Micro Corporation for their advice on menma processing. We thank Editage (www.editage.com) for their support in English language editing of this manuscript.

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