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Development of Conversion Factor from Volumetric to Weight Measurement of *Acacia crassicarpa* and *Eucalyptus* sp. Pulpwood

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ABSTRACT

The sustainability of the Indonesian pulp industry depends on the supply and demand of wood raw materials used to produce wood fiber, which requires accurate and reliable information. Wood raw material supply calculations are performed using conversion factors. However, the conversion factors currently used need to be improved to reflect current wood harvesting practices. Therefore, this study aims to develop the conversion factors for stacked cubic meter (SM, m^3 stacked) to solid cubic meter (m^3) and to wood weight (tons) that are in accordance with current practices, taking into account the log length and the trunk condition (barked or debarked), specifically for *Acacia crassicarpa* and *Eucalyptus* sp. The results of the study revealed significant variations in the conversion factors that are influenced by the species of wood and the log length, as well as the influence of time, transportation, and the condition of the trunk on the reduction of wood weight. The conversion factors from SM to solid cubic meters vary by species and the log length. For *Eucalyptus* sp. with a length of 4 m and 6 m, the conversion factors are 0.59 and 0.56, respectively. Whereas, for *A. crassicarpa* with a length of4 m and 6 m, the conversion factors are 0.48 and 0.40. The results also produce conversion factors to convert volume (m^3) to wood weight (tons). These factors fluctuate based on the type and condition of the trunk, as well as whether the trunk is barked or debarked. Generally, the volume-to-weight conversion factor for *A. crassicarpa* is 0.65. Considering the condition of the trunk, the conversion factors for barked and debarked *A. crassicarpa* are 0.63 and 0.75, respectively. For *Eucalyptus* sp., the volume-to-weight conversion factors for whole wood, barked wood, and debarked wood are 0.81, 0.80, and 0.81, respectively. These results improve the existing conversion factors and serve as a valuable reference for the Indonesian government and forestry entrepreneurs, supporting Indonesian forestry governance improvements.

1. INTRODUCTION

The pulp and paper industry in Indonesia is heavily reliant on the supply of wood raw materials sourced from plantation forests governed by the Forest Utilization Business Permit (*Perizinan Berusaha Pemanfaatan Hutan* (PBPH)) scheme. The calculation of wood volume is essential for effective forest management and the wood processing sector. Various methods are available for quantifying wood volume, such as employing mathematical formulas and conversion factors [1], weighing wood on a transport vehicle [2], utilizing xylometry [3, 4], scanning the stack on the transport vehicle [5], and applying software for digital image estimation [6].

In Indonesia, industrial raw materials are provided in cubic meters of solid wood, determined by measuring the volume of stacked cubic meters (SM) and applying the conversion factor. Before shipping raw materials, PBPH quantifies the wood volume in SM units. SM refers to the volume of a stack of raw wood that contains cavities or air, resulting in an indeterminate volume. SM volume refers to the quantity of raw material utilized in the processing industry [7]. The SM volume unit is used to quantify the volume of roundwood in stacks, as it offers greater efficiency in labor, time, and cost compared to directly measuring the solid wood volume in cubic meters (m^3). The volume of standing timber is significantly affected by tree species, age, cutting length, and diameter, which serve as the primary differentiating factors. The conversion factor from SM to cubic meters can vary and is influenced by several factors, including wood log type, log length, stacking method, moisture content, temperature, and wood stacking size [8-10].

In practice, estimating the volume of solid wood in one cubic meter from standing timber in Indonesia using conversion rates takes into account only the tree species. According to the Regulation of the Director General of Forestry Production Development Number P.05/VI-BIKPHH/2008, which addresses the List of Small Roundwood

(KBK) Conversion Rates from Stack Meter Units (SM) to Cubic Meter Units (m^3), three species groups are identified: the Acacia group, Eucalyptus group, and the Mixed wood with the factor of 0.59, 0.67, and 0.63, respectively. The utilization of tree species is solely because wood classified as KBK is exclusively employed for processed wood fiber, wood pellets, or composite wood. Additionally, it streamlines the computation of taxes owed by PBPH holders.

Updating the conversion rate from SM to m^3 is crucial, particularly when used to calculate tax liabilities. When P.05/VI-BIKPHH/2008 was drafted and enacted, the log length used to determine the conversion rate was 2.4 m, which at the time was based on the width of trucks transporting wood chips. However, current PBPH holders tend to cut wood into lengths of 4 m and 6 m. Considering the lower cost of splitting the tree trunk, the use of longer hauling equipment that allows for the transport of longer logs, and the changing dimensions of wood crushers that produce wood chips up to 6 m in size, this approach is more cost-effective. This change in the length of the wood chips certainly impacts the conversion rate, as the resulting gaps become wider, creating bias if the previous factor is still used.

This bias will affect the accuracy of the tax information paid. Tax payments by PBPH will increase, increasing the price of wood raw materials in the industry, mainly pulp, and thus reducing business viability [7]. Another error in this conversion factor relates to the availability of raw materials. Sufficient raw materials are reported, but in reality, a shortage exists. The conversion factor generated must be sensitive to the parameters measured and reported [11]. Conversion factors reported and published for widespread use will impact their application in the production of derivative technologies, such as sensor utilization and factor chain analysis of wood product distribution [11, 12].

In planning the development of plantation forests for pulp production, information on the weight of the pulp produced is crucial, as it is a key component of the basic information required for forest product regulations. This information is obtained by converting m^3 of solid wood to tons. PBPH uses Circular Letter of the Director General of Forestry Production Development Number SE.7/VI-BIKPHH/2010 concerning Conversion Factors from m^3 to tons. This regulation considers the transformation of wood species in terms of cubic meters to tons, such as mixed wood (1 ton = 1.052 m^3), pine (1 ton = 0.985 m^3), and mangrove (1 ton = 0.83 m^3). This type grouping does not consider wood species used as fiber/pulp raw materials, such as *Acac*ia and *Eucalyptus*. Using species alone is insufficient to estimate tons per cubic meter of solid wood. There are several determining factors, namely the condition of the trunk (dry/wet), the nature of the wood (hard/soft), and the condition of the trunk (barked/debarked) [7].

The application of conversion factors to estimate the weight of pulp raw materials is crucial for accurately calculating paper raw material needs. Global paper production is estimated at 185 million tons, with per capita consumption ranging from 50 to 200 kg. This paper production necessitates 692 million tons of wood [13]. Inaccurate assessments of wood volume to satisfy industrial demand may result in miscalculations regarding both wood volume and the area of established plantations. Plantations contribute to deforestation.

This study aims to develop conversion factors from SM to solid cubic meters and from solid cubic meters to tons for *A. crassicarpa* and *Eucalyptus* sp. wood types used as raw materials in the paper production process. The conversion factors are crucial for determining the tax obligations of PBPH holders, assessing the availability of raw materials, and analyzing the supply-demand balance of paper raw materials.

2. RESEARCH METHODS

2.1 Time and research location

The study was carried out between January 2023 and November 2024. The research phases encompassed the coordination of research methods, identification of data availability, and development of data collection techniques. Data collection occurred between August and October 2024 at PT Riau Andalan Pulp and Paper and PT Arara Abadi in Riau Province. The data analysis occurred between October and November 2024.

2.2 Instruments and materials

The instruments employed for data collection include wood diameter measuring tools (diameter tape/phi band), length measuring tools/meter gauges, digital scales with a 100 kg capacity, SM measuring tools (1 m × 1 m × the length of the wood), the global positioning system (GPS), stationery, and tally sheets. The materials utilized include wood logs, wood inventory data, PBPH documents related to the management of wood products, the Certificate of Legality of Wood Forest Products (Surat Keterangan Sahnya Hasil Hutan Kayu (SKSHHK)), and weighing documents from the factory or mill.

2.3 Methods

Research typically proceeds through stages of data collection and analysis, encompassing the following steps:

a. Collecting felling data. The felling data encompasses the location and area of the harvesting site, harvest time, quantity of logs, log diameter, and felling volume.
b. Gathering data on the wood stack. The wood stack data pertains to the total SM weight derived from a single unit of harvesting documentation and the corresponding weight of wood within the industry.
c. Examination of the transfiguration of the SM volume to weight units.
d. Analyzing variations in wood weight attributable to harvesting time intervals, transport distances, and alterations in transportation modes, utilizing the felling documentation as the analytical unit.
e. Examining variations in wood weight during harvesting in comparison to the weight of wood utilized in the industry.
f. Developing a conversion table that incorporates wood type, transport distance, and mode of transportation.

2.4 Data collection

The data collection methods employed include a wood logs approach, subsequently referred to as the single-tree part method, and a document approach, later designated as the full-tree method. The single-tree part method entails measuring the length, diameter, and weight of the wood logs as a unit. The full tree method entails collecting data from SM and SKSHHK documents. The SKSHHK document is an official certification issued by authorized officials to validate the legality of the transportation, control, and ownership of forest products. This document verifies that the forest products in question are sourced from a legitimate origin in compliance with statutory regulations. The SKSHHK facilitates the transportation of forest products from state forest areas, superseding earlier documents like the Round Wood Transportation Letter (Surat Angkutan Kayu Bulat (SAKB)) and the Processed Wood Transportation Letter (Surat Angkutan Kayu Olahan (SAKO)). The issuance of the SKSHHK is intended to guarantee the legality of traded or transported forest products, thereby promoting sustainable forest management and mitigating the circulation of illegal forest products. The SKSHHK also functions as the foundation for the collection of levies or taxes associated with specific forest products. The data collection is categorized into two classes based on log length: one measuring 4 meters and the other measuring 6 meters, with the trunk being either barked or debarked under the conditions specified.

This method provides data on the length, base diameter, tip diameter, and weight of wood logs, measured in SM. The measurement of the center diameter was conducted on wood logs measuring 6 meters in length. The data was collected at the Timber Shelter (Tempat Penimbunan Kayu (TPK)) and the log yard, which serve as the wood storage areas within the mill. Information regarding the duration of wood storage in the log yard and the condition of the barked or debarked trunks underpins the data at the log yard. Additionally, secondary data comprises SKSHHK documents and wood weighing records. The two datasets are primary in the analysis and are interrelated.

2.4.1 Data collection at the Tempat Penimbunan Kayu

Data collection at the TPK was performed via sampling methods. The sampling method was random and contingent upon the availability of logs. The stages of data collection at the TPK were as follows:

a. Construct an SM measuring tool with dimensions of 1 meter wide and 1 meter high. The length of the measuring tool corresponded to the length of the logs according to the PBPH wood management protocols.
b. Place the logs inside the SM measuring tool until it reaches a width of 1 m and a height of 1 m.
c. Count the quantity of logs in the SM measuring tool.
d. Measure the diameter of each log, including the base and tip diameters, in centimeters.
e. Measure the length of each log, in centimeters.
f. Weigh each log in kilograms.
g. Record measurement results on a tally sheet.
h. Measurements were performed a minimum of three times, considering criteria such as wood type, trunk condition (barked or debarked), wood stockpiling duration, and log length.

Alongside the application of the SM measuring tool, measurements of logs were performed on logging trucks carrying timber. The subsequent procedures were employed to quantify the logs on logging trucks:

a. Measure the dimensions of the logging truck bed, including length, width, and height. The measurements were subsequently converted to SM. The truck used in this study consisted of two stacks. The stacks measured 8 m in length and 2.4 m in width, with the height adjusted according to the volume of timber being transported. Each stack thus had dimensions of 4 m × 2.4 m × the height of the wood stack on the truck.
b. Measure the diameter of each log in the logging truck bed, including the base and tip diameters, in centimeters.
c. Measure the length of each log, in centimeters.
d. Weigh each log in kilograms.
e. Count the quantity of logs in the logging truck bed.
f. Record the measurement results in a tally sheet.
g. Measurements were performed a minimum of three times, considering criteria such as wood type, trunk condition (barked or debarked), duration of wood storage, and log length.

All measurement results were documented in a tally sheet. Table 1 presents the tally sheet for the measurements of wood logs conducted at the TPK.

Table 1. Example of a tally sheet for measuring logs at Tempat Penimbunan Kayu

No. of Stack	Species	No. of Logs	Logs			
			L	D1	D2	W
1	*Acacia*	1				
1	*Acacia*	2				
1	*Acacia*	3				
etc	*Acacia*	etc				
2	*Acacia*	1				
2	*Acacia*	2				
2	*Acacia*	3				
etc	*Acacia*	Etc				

Note: L: log length (m); D1: the base diameter (cm); D2: the tip diameter (cm); W: log green weight (kg)

In the felling block, each log is measured and subsequently loaded onto a transport truck in accordance with the SM size designed by the PBPH. Transport vehicles exhibit varying dimensions, leading to discrepancies in meter stack sizes. Measurements at the felling block vary based on tree species and bark condition, specifically whether it is barked or debarked. Figure 1 illustrates the data collection conducted at the felling block.

Figure 1. Data collection at the felling block (TPK)

The *A. crassicarpa* species generally has a more curved trunk shape than the *Eucalyptus* sp. species. Harvesting in the felling block produces logs in two lengths: 4 m and 6 m, and also in two trunk conditions: barked or debarked. In field practice, only *Eucalyptus* sp. species receive the bark peeling treatment, which is adjusted to meet industry demand. Table 2 presents the number of sample wood stacks collected and categorized by species, log length, and trunk condition (barked or debarked). In contrast, Table 3 provides the total number of individual logs corresponding to these sampling categories, allowing for more precise volume estimation and operational analysis.

Table 2. Number of sample wood stacks

Tree Species and Length	Trunk		Total
	Debarked	Barked	
A. crassicarpa	19	25	44
4 m	14	18	32
6 m	5	7	12
Eucalyptus sp.	32	13	45
4 m	18	8	26
6 m	14	5	19
Total	51	38	89

Table 3. Number of sample logs

Tree Species and Length	Trunk		Total
	Debarked	Barked	
A. crassicarpa		978	978
4 m		506	506
6 m		472	472
Eucalyptus sp.	918	943	1861
4 m	451	457	908
6 m	467	486	953
Total	918	1921	2839

2.4.2 Data collection at the log yard

Data collection at the log yard was performed using purposive sampling methods. Sampling at the log yard was performed purposefully. The parameters considered were wood type, storage duration, trunk conditions (debarked or barked), and log length. The parameters were subsequently designed as treatments. Each treatment was replicated at least three times. The duration of wood storage was modified according to data provided by field officers and log entry/exit registration records at the log yard. It is anticipated that data will be available for newly arrived wood from the TPK (fresh cut), wood stacked for less than one week, and wood stacked for more than one week.

The stages of data collection at the log yard are outlined as follows:

a. Construct an SM measuring tool with dimensions of 1 meter wide and 1 meter high. The length of the measuring tool corresponded to the length of the logs according to the PBPH wood management protocols.
b. Place the logs inside the SM measuring tool until it reaches a width of 1 m and a height of 1 m.
c. Count the quantity of logs in the SM measuring tool.
d. Measure the diameter of each log, including the base and tip diameters, in centimeters.
e. Measure the length of each log, in centimeters.
f. Weigh each log in kilograms and grams.
g. Record measurement results on a tally sheet.
h. Measurements were performed a minimum of three times, considering factors such as wood type, trunk condition (barked or debarked), duration of wood storage, and log length.

All measurement results are documented in a tally sheet. Table 4 presents the format of the tally sheet utilized for measuring logs in the log yard.

The measurement of each log occurred at the log yard, where logs were measured and loaded into an SM measuring tool with dimensions of 1 m × 1 m × the length of the logs (4 m and 6 m), as illustrated in Figure 2.

Field measurements exhibit variations based on tree species, trunk condition (barked or debarked), and duration of exposure in the log yard. Figure 3 illustrates the data collection process at the log yard.

Table 4. Format of the tally sheet utilized for assessing wood logs in the log yard

No. Stack	Species	No. Wood Log	Time for Storage	S	Logs			
					L	D1	D2	W
1	*Acacia*	1						
1	*Acacia*	2						
1	*Acacia*	3						
etc	*Acacia*	etc						
2	*Acacia*	1						
2	*Acacia*	2						
2	*Acacia*	3						
etc	*Acacia*	etc						

Note: L: length of logs (m); D1: the base diameter (cm); D2: the tip diameter (cm); W: log green weight (kg); S: trunk condition (barked/debarked)

(a) SM measuring tool

(b) Logs loading process into the tool

Figure 2. The logs measurement using the SM measuring tool at the log yard

Table 5. Logs sample data at the log yard

Tree Species and Bark	Duration Time at the Log Yard (Weeks)			Total
	1	2	*Fresh*	
A. crassicarpa	382	173	1330	1885
Debarked	117		431	548
Barked	265	173	899	1337
Eucalyptus sp.	1004	0	2128	3132
Debarked	760		1412	2172
Barked	244		716	960
Total	1386	173	3458	5017

This variation was quantified using a log scale. Three parameters were analyzed: wood type, trunk condition (barked or debarked), and the duration between felling and storage in the log yard. The time interval was categorized into three groups: freshly received logs from the log yard (TPK), referred to as fresh cut; logs aged up to one week; and logs aged up to two weeks. Table 5 presents a summary of the data.

(a) The measurement of logs weight

(b) The measurement of the diameter of the logs

Figure 3. Data collection for the logs' weight and diameter at the log yard

2.4.3 Data collection for Surat Keterangan Sahnya Hasil Hutan Kayu documents and wood weighing documents

The collected documents encompassed data regarding the management of PBPH timber products, specifically the SKSHHK (Sub-Property Certificate) and weighing documents from the mill. The SKSHHK document served as a transportation record for timber forest products, encompassing essential data such as the SKSHHK number, details of the sender and recipient, transportation method, origin location, timber type, and volume measured in SM and m^3. The weighing document at the mill included comprehensive data concerning the SKSHHK number, transportation method, arrival date, and time of the timber, as well as the weight of both the transport equipment and the wood itself.

The SKSHHK document was established using data gathered sequentially over at least three years, or through a representative snapshot of each month within that three-year time frame. Five documents were issued monthly. The objective of data collection from these documents was to acquire pertinent data and information, thereby illustrating the correlation between timber volume in SM and m^3 from the upstream industry, the weight of timber upon arrival at the mill, and the length of timber transportation.

Data collection using the whole tree method was conducted, employing an SM volume and weight calculation approach at the transportation unit scale, in accordance with the SKSHHK document. The SKSHHK documents catalogued encompass records from the past three years, accounting for seasonal variations, specifically the dry and rainy seasons, to reflect annual conditions. Data derived from the SKSHHK document is summarized in Table 6.

Table 6. Number of SKSHHK data (documents)

Tree Species and Length of Logs	Trunk		Total
	Debarked	Barked	
A. crassicarpa	34927	620	35547
4 m	34918	554	35472
6 m	9	66	75
Eucalyptus sp.	25649	21985	47634
4 m	25649	21985	47634
6 m	0	0	0
Total	60576	22605	83181

2.5 Data analysis

The analysis was conducted on the collected data, encompassing both field measurements and documentary sources.

2.5.1 Data analysis of field measurements

Calculation of the volume was performed for each log. The volume of each log was calculated using field inventory data, which included the base diameter, tip diameter, and length of each log. The calculation of the volume of logs was conducted utilizing the Brereton formula method (Eq. (1)), as shown below:

$$V = 0.25\,\pi \left(\frac{(dp+du)}{2}\right)^2 \times L \quad (1)$$

where,

V: volume (cm^3)

π: 22/7 or 3.14

dp: base diameter (cm)

du: top diameter (cm)

L: length (cm)

The Brereton formula provides a robust estimate of solid wood volume under bark, accounting for log taper by using the mean of base and tip diameters.

To convert the volume of logs from cm³ to m³, apply Eq. (2) as follows:

$$Vs = \frac{V}{1{,}000{,}000} \quad (2)$$

where,

Vs: volume in cubic meters (m^3)

V: volume in cubic centimeter (cm^3)

Calculation of the ratio between the volume of the log and the weight of each log was carried out. This ratio was derived by comparing the volume of the log to the weight of each log. This ratio facilitated the transformation of tonnage to cubic meters. This proportion is expressed as Eq. (3), below:

$$Proportion\left(\frac{m^3}{ton}\right) = \frac{log\ volume(m^3)}{log\ green\ weight\ (ton)} \quad (3)$$

Calculation of log volume in cubic meters was performed. The log volume in one standard meter (k) is the aggregate of all logs that occupy one standard meter or SM volume, expressed as follows (Eq. (4)):

$$SM = \sum_{k=1}^{n} \mathrm{Vk} \quad (4)$$

where,

SM: Stacked cubic meter (m^3 (st))

Vk: volume of the k-th wood cut (m^3)

n: number of logs in a stack

Calculation of the conversion factor from SM to solid cubic meters was performed. The conversion factor from SM to solid cubic meters was determined by comparing the volume of the logs constituting one SM with the volume of the SM itself. The volume of SM was calculated based on the length of the logs; specifically, a log with a length of 4 m corresponds to a SM volume of 4 m³, while a log with a length of 6 m results in a SM volume of 6 m³. The log conversion factor was formulated based on the SM volume as follows (Eq. (5)):

$$CF = \frac{\sum_{k=1}^{n}(Vk)}{SM} \quad (5)$$

where,

CF: conversion factor

SM: stacked cubic meter (m³ (st))

Vk: logs volume

2.5.2 Data analysis of the log documents

Calculation of the ratio between the log volume specified in the document and the net wood weight obtained from the mill for each log category was carried out. This ratio was derived by analyzing the total volume of logs in relation to the total weight of logs in each document. This ratio was utilized to convert tonnage into cubic meters of logs. This proportion is expressed as follows (Eq. (6)):

$$Proportion\ by\ doc\left(\frac{m^3}{ton}\right) = \frac{Total\ volume\ in\ a\ doc\ (m^3)}{Wet\ weight\ in\ a\ doc(ton)} \quad (6)$$

Conversion factors of logs from volume (m³) to weight (tons) were performed. These factors were derived from the subsequent analytical steps:

a. Data were gathered from monthly and annual summaries within the Company's Wood Administration Department.
b. The chosen data encompassed various seasonal conditions, including dry and rainy seasons, resulting in a considerable range of differences associated with transportation seasons.
c. The chosen data facilitated the calculation of log conversion factors by comparing the total log volume in an individual document with the total log weight in that same document.

2.5.3 Calculation of conversion factor

The confidence interval for each conversion factor at the 95%, 90%, and 80% level was calculated using the formula (Eq. (7)):

$$\bar{x} \pm t_{\alpha/2,n-1}.SE \quad (7)$$

where,

$\bar{x}$: the average of the conversion factor

t: t-table factor

SE: standard errors

2.5.4 Factors influencing the conversion rate from cubic meters to tons

Conversion factors were established to facilitate the equitable and objective measurement of potential wood yield, employing various units of measurement, including volume and weight. These factors enhanced the effectiveness of wood management processes, including:

a. Production planning. Companies could enhance the accuracy of pulp or paper production planning by assessing the available wood volume in the forest.
b. Evaluation of efficiency conversion factors served as a metric for assessing the efficiency of the wood processing process, encompassing activities from felling to final production.
c. Cost calculation conversion factors played a crucial role in determining production costs, as they affect the quantity of wood needed for the manufacture of a specific product.
d. Sustainable forest management. Understanding conversion factors enabled companies to manage plantations sustainably, ensuring that wood utilization remains within the forest's regeneration capacity.

Several factors, including tree species, age, health, and processing methods, influenced conversion factors. Additional factors encompassed the diverse biophysical and topographical characteristics of forests, the precision of wood volume assessments, and developments in wood processing technology.

Analysis of factors influencing the conversion factor magnitude from SM to m³ or tonnage using RStudio R 4.3.1 with the Agricolae packages was performed. ANOVA was used to analyze normality by wood species, log length, and trunk conditions. Further, the Agricolae package was utilized for the Duncan Multiple Range Test (DMRT) with a significance level of 5%.

The calculation of the error rate if one of the variables, such as type (sp), log condition (tc), stacking time (t), and log length (l), is not included in estimating the conversion of weight to cubic meters. We performed bootstrapping on the regression. Bootstrapping simulations were performed on sp, tc, t, and l. The error rate was calculated using the formula (Eq. (8)):

$$e_i = \sum \frac{\mu_i - \mu}{\mu} \times 100 \quad (8)$$

where,

e_i: Error factor if not considering the independent variable i;

μ_i: The mean factor of the weight estimation model if the independent variable i is not considered in the model;

μ: The mean factor of the complete regression model.

The complete regression model is (Eq. (9)):

$$w = \alpha + sp + tc + t + l + \varepsilon \quad (9)$$

3. RESULTS AND DISCUSSION

3.1 The conversion factor of the SM to solid cubic meter (m³)

The conversion factors used in this study were derived from two log lengths: 4 m and 6 m. Table 7 presents the calculated conversion figures for wood volume from SM to m³ for 4-meter-long logs.

For logs 4 meters long, the conversion factor for *Eucalyptus* sp. exceeded that of *A. crassicarpa* (Table 7). Specifically, the conversion factor for *A. crassicarpa* ranged from 0.48 m³ ± 0.02 m³, while for *Eucalyptus* sp. ranged from 0.59 m³ ± 0.02 m³ (Table 7). The conversion factor was determined using an SM measuring one square meter (1 m × 1 m × length). For logs 6 meters long, the conversion factor was lower than 4 meter 4-

meter-long logs. The conversion factor of wood volume from SM to m^3 for 6-meter-long logs is shown in Table 8.

Table 7. Conversion factor of SM to m^3 for 4-meter-long logs

Tree Species and Trunk Condition	Sum	Average	Standard Deviation	Standard Error
A. crassicarpa	**32**	**0.48**	**0.10**	**0.02**
Debarked	14	0.54	0.07	0.02
Barked	18	0.43	0.09	0.02
Eucalyptus sp.	**26**	**0.59**	**0.09**	**0.02**
Debarked	18	0.59	0.08	0.02
Barked	8	0.58	0.12	0.04

Table 8. Conversion factor of the SM to m^3 6-meter-long logs

Tree Species and Trunk Condition	Sum	Average	Standard Deviation	Standard Error
A. crassicarpa	**12**	**0.40**	**0.12**	**0.04**
Debarked	5	0.52	0.11	0.05
Barked	7	0.32	0.02	0.01
Eucalyptus sp.	**18**	**0.56**	**0.10**	**0.02**
Debarked	13	0.57	0.10	0.03
Barked	5	0.53	0.08	0.03

The conversion factor calculation for a 6-meter-long log object yielded a factor of 1 SM, corresponding to a wood volume of 0.40 $m^3 \pm 0.04$ for *A. crassicarpa* and 0.56 $m^3 \pm 0.02$ for *Eucalyptus* sp. (Table 8). The conversion factor of *Eucalyptus* sp. exceeded that of *A. crassicarpa*. The analysis of variance results indicated that the species significantly affected the magnitude of the conversion factor, with F-factor $_{(7,80)} = 10.59$ and P-factor < 0.05. The shape of the *Eucalyptus* sp. logs was characterized by a straighter and rounder form, which, when arranged in an SM, results in a denser configuration with fewer cavities. Additionally, the curvature of the *A. crassicarpa* logs resulted in increased voids when organized within an SM. Eucalyptus species typically exhibit straighter trunks in comparison to *A. crassicarpa*. Numerous *Eucalyptus* species exhibit rapid growth, straight trunks, multiple crown branches, favourable wood properties, extensive adaptability to various soils and climates, resilience to biotic stress, and straightforward propagation via cuttings, seeds, or clonal cuttings [14, 15]. The characteristic of Eucalyptus enhances its suitability for specific applications, including timber and pulp production, where straightness is a factord trait. Research indicates that *Eucalyptus* species, including *Eucalyptus globulus* and *Eucalyptus camaldulensis*, exhibit more uniform and straight trunks in comparison to Acacia species [14, 16-18]. This linearity may result in enhanced processing efficiency and superior final products. In contrast, Acacia species, such as *A. crassicarpa*, typically exhibit more irregular and less straight trunks, complicating processing and diminishing the overall efficiency and quality of the resulting products [14, 18, 19].

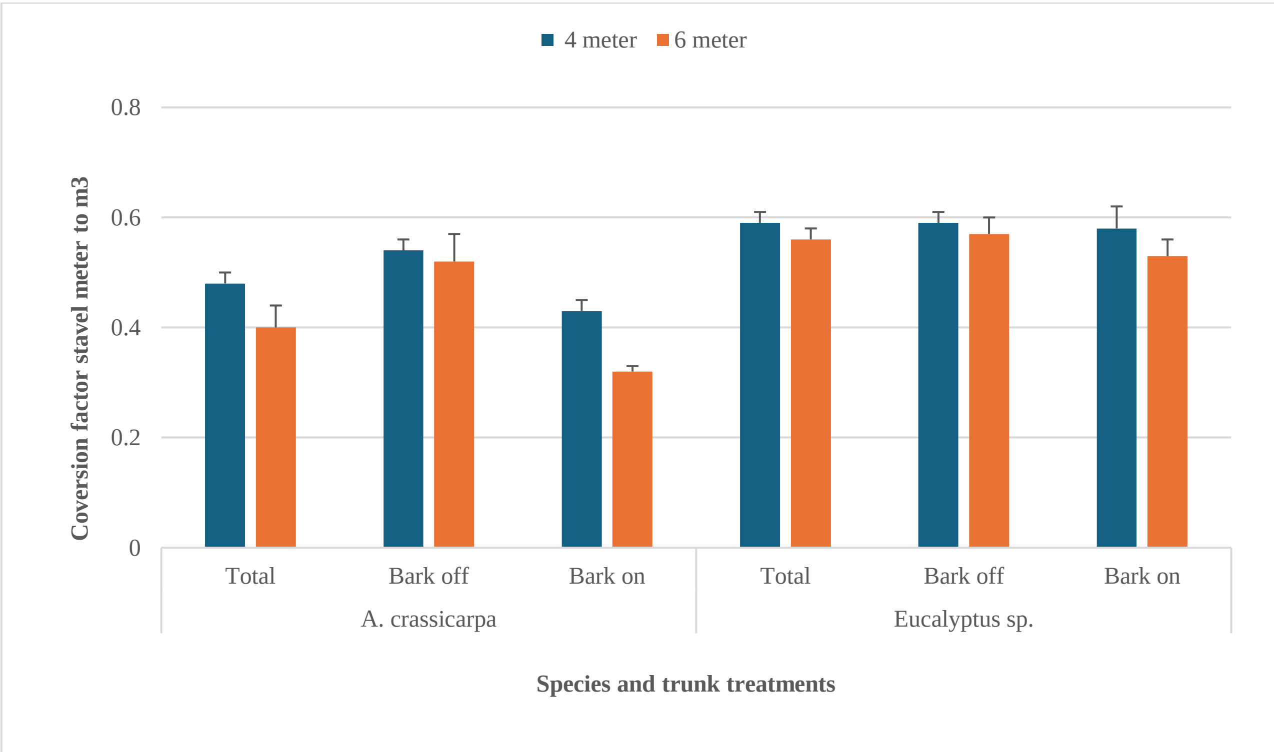

Figure 4. Proportion of conversion factor of the SM to m^3

The length of the logs influenced the magnitude of the conversion factor. The analysis results indicated that an increase in log length corresponded to a decrease in the conversion factor from SM to m^3. Shorter logs would occupy the SM more densely, resulting in a higher conversion factor. The conversion factor diminishes as log length increases. This applies uniformly to both pulpwood and firewood species. For example, measurements were conducted on coniferous and broadleaf timber with log lengths varying from 1 to 3 meters, resulting in the conversion factor diminishing from 0.72 to 0.61 for logs measuring 3 meters in length [20]. Under these situations, the conversion factor must consider both species and the length of the wood assortment [21]. Figure 4 illustrates the conversion ratios of wood volume from SM to m^3 for the species *A. crassicarpa* and *Eucalyptus* sp.

The analysis indicated that tree species, length of logs, and trunk condition affected the conversion factor. The conversion factors from SM to solid cubic meters employed by PBPHs in their business operations were determined by the Regulation of the Director General of Forestry Production Development Number P.05/VI-BIKPHH/2008, which specified 0.59 for *Acacia* species and 0.67 for *Eucalyptus* species, while this study presented divergent findings. This study presented a comparison of the wood volume conversion factor from SM to m^3 as outlined in the Regulation of the Director General of Forestry Production Development Number P.05/VI-BIKPHH/2008, detailed in Table 9.

Table 9. The comparison of wood volume conversion factors from SM units to m^3 between the Regulation of the Director General of Forestry Production Development Number P.05/VI-BIKPHH/2008 and the results of this research

Species	Current Regulation	Study	
		4 m	6 m
A. crassicarpa	0.59	0.48 ± 0.02*	0.40 ± 0.04*
Eucalyptus sp.	0.67	0.59 ± 0.02*	0.56 ± 0.02*

Note: Confidence interval was determined with the average factor (mean) ± standard error.

In practical implementation, the determination of the conversion factor cannot rely solely on the average factor. The determination of the conversion factor should take into account the standard error and the confidence interval. The confidence interval allowed for the inclusion of measurement inaccuracies associated with SM readings. This study simulated confidence intervals at three points: 95%, 90%, and 80%, while considering log lengths of 4 m and 6 m (Table 10). The conversion factor for *A. crassicarpa* at the three confidence intervals with a log length of 4 m was 0.52, 0.51, and 0.51, respectively. For a log length of 6 m, the factors were 0.48, 0.47, and 0.45. For the *Eucalyptus* sp., the conversion factors at a log length of 4 m were 0.63, 0.62, and 0.62, respectively, while for a log length of 6 m, they were 0.6, 0.59, and 0.59.

Table 10. The conversion factor simulation at different levels of significance

Conversion	Species	Conversion Factor at Confidence Interval		
		95%	90%	80%
SM units to m^3		*A. crassicarpa*		
	4 m	0.52	0.51	0.51
	6 m	0.48	0.47	0.45
		Eucalyptus sp.		
	4 m	0.63	0.62	0.62
	6 m	0.60	0.59	0.59
m^3 to ton	*A. crassicarpa*	1.5594	1.5561	1.5522
	Eucalyptus sp.	1.2508	1.2492	1.2431

The conversion factor employed by PBPHs was based on log lengths of 2.4 m, rendering it unsuitable for current conditions in which PBPHs harvest wood with log lengths of 4 m and 6 m. The alteration in log length resulted in a modification of the conversion factor from SM to m^3. Consequently, the conversion factor in the Regulation of the Director General of Forestry Production Development Number P.05/VI-BIKPHH/2008 requires adjustment.

The measurement of fresh wood weight at the harvesting site and at the mill revealed discrepancies, as illustrated in Table 11. The weight of the wood typically decreased upon arrival at the mill, with a variation of -2.03% ± 1.96%.

Table 11. The green weight at TPK and the log yard

Species	Trunk Form	Green Weight at TPK (ton)	Green Weight at Log Yard (ton)	Difference (%)
A. crassicarpa	Barked	27.04	27.06	0.07
Eucalyptus sp.	Debarked	25.70	24.76	-3.81
Eucalyptus sp.	Barked	26.68	26.06	-2.36
Average				-2.03
Deviation				1.96

The species of tree was a factor that affected the estimation of solid mass transformation from trunk wood to cubic meters. *A. crassicarpa* exhibited curved or crooked logs, whereas *Eucalyptus* sp. typically possessed straight logs. The variation in conversion factors for *A. crassicarpa* was evident, with a 4 m length of logs yielding factors of 0.43–0.54, and a 6 m length of logs producing factors of 0.32–0.52. A distinct trend was observed for *Eucalyptus* sp. at a 4-meter length, exhibiting uniformity between 0.58–0.59, and between 0.53–0.57 for a 6-meter length of logs.

Estimating the transformation of SM to m^3 solid cubic meter required consideration of the length of the logs. A longer log correlated with a lower conversion factor. The results of this study showed that the average conversion factors for *A. crassicarpa* and *Eucalyptus* sp. at a length of 4 m were 0.48 and 0.59, respectively. For a log length of 6 m, the conversion factors were 0.40 and 0.56, respectively. This study aligned with existing research indicating that tree species and length significantly influenced the diversity of SM to m^3 solid cubic meter [22]. The conversion factor of SM to solid cubic meter varied depending on whether the wood was in a barked or debarked state. The diameter of the log was another parameter. The volume of the logs was contingent upon the dimensions of the base and tip diameters, as well as the length of the logs [23].

The conversion factor in this study was lower than the conversion factor established by the Regulation of the Director General of Forestry Production Development Number P.05/VI-BIKPHH/2008. The conversion factor observed in this study aligned with findings from other research efforts. de Andrade Sandim et al. [24] indicated that for *Eucalyptus* sp. with a log length of 1 m across various clones and specific diameter classes in Brazil, the conversion factor ranged from 0.50 to 0.62. The factor in this study remains lower than the currently applicable conversion factor in Indonesia.

3.2 The conversion factor of m^3 to ton

The conversion factor of solid cubic meters to tons used by PBPHs, as a weight measure, adheres to the relevant regulations outlined in Circular Letter No. SE. 7/VI-BIKPHH/2010, issued by the Director General of Forestry Production Development. This document specified that *Acaci*a and *Eucalyptus* shared an identical conversion factor of 1.052 (0.95), categorizing both species within the Mixed Wood type group. The factor indicates that one ton of wood corresponds to a volume of 1.052 solid cubic meters, or conversely, one cubic meter of wood equals 0.95 tons.

The study revealed that *A. crassicarpa* and *Eucalyptus* sp. had different conversion factors, which contradicted the current practice of using a single conversion factor for both species [SE.7/VI-BIKPHH/2010]. The typical conversion factor from solid cubic meters to tons for *A. crassicarpa* was 0.65, whereas for *Eucalyptus* sp. it was 0.81 (Table 12). The conversion factor for barked *A. crassicarpa* was 0.63, while for the debarked *A. crassicarpa* it was 0.75. For barked *Eucalyptus* sp., the conversion factor was 0.8, and for debarked *Eucalyptus* sp., it was 0.81. What needed to be considered was that the wood had been debarked and adjusted for moisture content, as these factors significantly affected its weight. Optimizing the moisture content for better utilization [25].

Table 12. Conversion metrics from solid cubic meter to ton for *A. crassicarpa* and *Eucalyptus* sp.

Species	Condition	Average of Conversion Factors (ton.m^{-3})
A. crassicarpa	Current Regulation	0.95
	All	0.65
	Debarked	0.75
	Barked	0.63
Eucalyptus sp.	Current Regulation	0.95
	All	0.81
	Debarked	0.81
	Barked	0.80

The results of the significant difference test for conversion factors between *A. crassicarpa* and *Eucalyptus* sp. under varying bark conditions are displayed in Table 13. This suggests that the existing regulations employed by PBPHs for converting wood volume from solid cubic meters to weight in tons require improvements. Different tree species, such as *A. crassicarpa* and *Eucalyptus* sp., should not use the same conversion factor.

Table 13. The results of the real difference test for conversion factors between *A. crassicarpa* and *Eucalyptus* sp. under varying trunk conditions at a significance level of 5%

Species and Bark Condition	Proportion	Groups*
A. crassicarpa (barked)	0.63	a
A. crassicarpa (debarked)	0.75	b
Eucalyptus sp. (barked)	0.80	c
Eucalyptus sp. (debarked)	0.81	d

*Note: The average factor (mean) indicated by identical letter codes suggests no significant difference.

Table 14. Factors influencing the conversion factor from a solid cubic meter to a ton

Factors	Rate Impact (%)
Species	13.40
Logs length	0.15
Duration between harvesting and wood processing	26.01
Total	39.56

This research identified multiple factors that affect variations in conversion factors. Table 14 outlined the factors affecting the conversion factor from a solid cubic meter to ton. The findings emphasized that the time between harvesting and processing, species type, and log length significantly impacted the conversion factor from solid cubic meters to tons.

Table 14 above shows that the total possible error in determining the conversion factor from solid cubic meters to tons reaches 39.56%. The influence of differences in tree species, log length, and the length of time between harvesting and processing the wood into pulp is very significant on the valid conversion factor. The time between harvesting and processing had a substantial impact (26.01%) on the conversion factor, emphasizing the dynamic nature of wood weight due to moisture loss. The time between harvest and processing was related to the moisture content of the wood. Acuna et al. [26] stated that wood was approximately 50–55% water by weight when freshly felled. Furthermore, *A. crassicarpa* and *Eucalyptus* sp., with and without bark, also have different conversion factors, indicating varying moisture-holding capacities and densities.

Wood species had a 13.40% influence on the conversion factor. The relationship between wood species and wood density was significant. Wood density represented a parameter that posed challenges in comprehension. Wood density was influenced by the wood type, measurement position along the trunk, age, and additional factors, including growth location [27]. Wood density was quantified in terms of weight. When weighing a log of wood, it is essential to determine whether it is barked or debarked, as the presence of bark influences the overall weight of the wood [28]. The development of conversion factors should encompass various parameters, particularly those reflecting differences in growth locations.

Previously, these influencing factors were not taken into account in the conversion figures, resulting in identical outcomes. Consequently, the current practice among PBPHs in converting solid cubic meters into tons of wood, using the conversion figures as stated in the Circular Letter of the Director General of Forestry Production Development No. SE.7/VI-BIKPHH/2010, needed to be improved. This improvement sought to address variations in wood weight measurements.

Ignoring species, time between harvesting and processing, and log length resulted in a 39% error in the conversion factor. The weight of wood was directly related to its water content. The longer the time, the lower the water content, and thus the lower the weight. The water content of the tree at harvest time was the primary factor. Trees harvested in spring typically had higher water content than those harvested in winter [29]. Certain environmental conditions could impact weight loss, including temperature, humidity, and airflow. Higher temperatures increased the rate of evaporation. Lower humidity meant the air could hold more moisture, thereby accelerating the drying process. Airflow carried away moisture that evaporated from the wood surface, thereby speeding up the drying process.

These findings emphasized that understanding the spatial and temporal variation was critical for developing holistic management and better targeting of research efforts [30].

4. CONCLUSION

The research findings indicated that conversion factors were used to convert SM to solid wood volume, which were currently used for estimating harvest yields. Conversion factors required examination of the species, log length, and trunk condition, particularly whether it was barked or debarked. While converting solid cubic meters to weight required consideration of tree species, the condition of the barked or debarked, and the time elapsed from felling to processing. Ignoring these factors could result in potential conversion errors of up to 39.56%.

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AUTHOR CONTRIBUTION

Lutfy Abdullah led the conceptualization, data analysis, visualization, and contributed to all parts of the manuscript. Dony Wicaksono, Mira Yulianti, Antun Puspanti, and Sarah Andini contributed to conceptualization, data collection, and manuscript drafting and review. Soenarno, Ika Heriansyah, Fajar Lestari, Andika Silva Yunianto, and Agung Wahyu Nugroho were involved in writing and reviewing. Agustinus Panusunan Tampubolon and Fatahul Azwar contributed to data collection and manuscript writing. Muhammad Abdul Qirom contributed extensively to conceptualization, data collection and analysis, visualization, and editorial refinement.

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