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ORIGINAL

Logging Waste Dynamics and Efficiency under Reduced Impact Logging in Tropical Natural Forests

Dinámica y eficiencia de los residuos forestales en la tala de impacto reducido en bosques tropicales naturales

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ABSTRACT

Introduction: to promote sustainable forest management in the natural forests of West Papua, Indonesia, selective logging systems that incorporate low-impact harvesting techniques such as Reduced Impact Logging (RIL) are being adopted.
Objective: to analyze the volume, characteristics, and contributing factors of logging waste generated through RIL-based timber harvesting in two forest concessions.
Method: logging waste was quantified at both felling sites and landing points, with data collected from two concessions.
Results: the average estimated logging waste was 0,849 ± 0,095 m^3 $tree^{-1}$ (equivalent to 9,339 m^3 ha^{-1}), with 79,82 % (0,684 ± 0,070 m^3 $tree^{-1}$) produced at the felling site and 20,18 % (0,166 ± 0,058 m^3 $tree^{-1}$) at the landing point. Logging waste volume varied between concessions: PT WA generated 0,708 ± 0,053 m^3 $tree^{-1}$ (7,788 m^3 ha^{-1}), while PT KH recorded 0,989 ± 0,137 m^3 $tree^{-1}$ (11,868 m^3 ha^{-1}). At the felling site, the predominant waste components were stumps (29,74 %) and buttresses (21,40 %), while base ends constituted 15,1 % of waste at the landing point. The average logging waste was composed of good-quality wood (4,092 m^3 ha^{-1}; 42,79 %), defective wood (3,320 m^3 ha^{-1}; 33,32 %), and damaged wood (2,465 m^3 ha^{-1}; 24,26 %). Timber harvesting Logging efficiency averaged 85,52 ± 0,01 %, with a felling index of 88,54 ± 0,70 % and a skidding grading index of 96,59 ± 1,30 %.
Conclusions: the adoption of RIL improved overall harvesting recovery by 14,4 %, compared to an average of 80,6 % under conventional logging practices.

Keywords: Reduced Impact Logging (RIL); Logging Waste; Timber Efficiency; Wood Recovery; Tropical Natural Forests; Sustainable Forest Management.

RESUMEN

Introducción: para promover la gestión forestal sostenible en los bosques naturales de Papúa Occidental, Indonesia, se están adoptando sistemas de tala selectiva que incorporan técnicas de cosecha de bajo impacto, como la tala de impacto reducido (RIL).
Objetivo: analizar el volumen, las características y los factores contribuyentes de los residuos de tala generados a través del aprovechamiento de madera basado en RIL en dos concesiones forestales.

Método: los residuos forestales se cuantificaron tanto en los lugares de tala como en los puntos de desembarque, con datos recopilados de dos concesiones.
Resultados: el promedio estimado de residuos de tala fue de 0,849 ± 0,095 m^3 por árbol (equivalente a 9,339 m^3 por hectárea), con un 79,82 % (0,684 ± 0,070 m^3 $árbol^{-1}$) producidos en el lugar de la tala y el 20,18 % (0,166 ± 0,058 m^3 $árbol^{-1}$) en el punto de desembarque. El volumen de residuos de la tala varió entre las concesiones: PT WA generó 0,708 ± 0,053 m^3 por árbol (7,788 m^3 por hectárea), mientras que PT KH registró 0,989 ± 0,137 m^3 por árbol (11,868 m^3 por hectárea). En el lugar de la tala, los componentes predominantes de los residuos fueron los tocones (29,74 %) y los contrafuertes (21,40 %), mientras que los extremos de la base constituyeron el 15,1 % de los residuos en el punto de descarga. Los residuos forestales medios se componían de madera de buena calidad (4,092 m^3 ha^{-1}; 42,79 %), madera defectuosa (3,320 m^3 ha^{-1}; 33,32 %) y madera dañada (2,465 m^3 ha^{-1}; 24,26 %). Poda de madera La eficiencia de la tala fue de un promedio de 85,52 ± 0,01 %, con un índice de tala de 88,54 ± 0,70 % y un índice de clasificación de arrastre de 96,59 ± 1,30 %.
Conclusiones: la adopción del RIL mejoró la recuperación general de la tala en un 14,4 %, en comparación con una media del 80,6 % con las prácticas de tala convencionales.

Palabras clave: Tala de Impacto Reducido (TIR); Residuos de Tala; Eficiencia de la Madera; Recuperación de Madera; Bosques naturales Tropicales; Manejo Forestal Sostenible.

INTRODUCTION

Natural production forests in West Papua are a major source of raw materials and play an important role in the sustainability of the timber industry. There are 9,5 million hectares of natural forest in West Papua, of which ±5,5 million hectares are production forests, producing an average of 639 019 cubic meters of logs per year over the last five years (2017-2023), mostly in the Meranti species group.(1) A portion of the logs comes from timber harvesting activities in natural forests managed by selective logging systems using Reduced Impact Logging (RIL) technology. However, logs production has not been optimal due to the large amount of wood waste generated during timber harvesting operations. The amount of wood waste is a key indicator of wood utilization, and directly determining the timber harvesting efisiency.(2,3,4,5,6) Wood wastes in natural forest timber harvesting operations can attain to 45 % of the total timber potential, with the majority originating from clear bole,(7) depending on logging intensity.(8)

Achieving sustainable logging practices in West Papua requires a comprehensive understanding of logging waste and their impact on timber harvesting efficiency. Timber harvesting efficiency includes variables that affect the harvesting and side-cutting process, such as topography, tree diameter, tree height, and logging intensity. These factors directly affect the amount of wood utilization, logging waste generated, and ultimately the long-term sustainability of the forest. From a technical perspective, timber harvesting efficiency (He) is a multiplying factor to determine the annual allowable cut (AAC) set by the Ministry of Environment and Forestry to forest concessionaires.(9) Economically, the exploitation factor is crucial for estimating non-tax state revenues from the forestry sector.(10,11) Ministerial Regulation of the Ministry of Environment and Forestry No. 8 of 2021 mandates the implementation of RIL technology during timber harvesting.(12)

Timber harvesting activities in West Papua are adopting RIL technology, thereby increasing utilization. In order to perform accurate calculations, data and information on the timber potential of the harvesting stems, the utilized timber and the characteristics of the harvested waste timber are needed. Logging wood waste can be used for wood processing products.(13) Logging waste varies in composition and quantity depending on factors such as tree species, harvesting methods, terrain conditions, and operational efficiency. Inefficient timber harvesting not only leads to economic losses but also contributes to unnecessary deforestation and carbon emissions due to unutilized biomass decomposition. Identifying key factors influencing logging waste generation and assessing harvesting efficiency can provide valuable insights into waste reduction strategies, resource recovery, and sustainable forest management practices.

The aims of the current study is to analyze the volume, characteristics, and contributing factors of logging waste generated through RIL-based timber harvesting in two forest concessions in West Papua. This study has been carried out in PT Wukirasari (PT WA) and PT Kaltim Hutama (PT KH), West Papua Province.

METHOD

Research area

The study was conducted across two natural forest concessions in West Papua Province: PT Wukirasari (PT WA) and PT Kaltim Hutama (PT KH). PT WA encompasses a concession area of approximately 161 670 hectares, while PT KH spans 116 320 hectares. Geographically, PT WA is located at 134°00′21,68″ E and 02°54′15,31″ S, whereas PT KH lies at 134°52'7,31" E and 03°29'06" S.

Administratively, PT WA operates within both Teluk Bintuni and Kaimana Regencies, while PT KH is located solely within the Kaimana Regency. The topographic conditions of PT WA range from flat terrain (0-8 %) to moderately sloping land (15–25 %), in contrast to PT KH, which is characterized by more challenging terrain, varying from moderately sloping (15–25 %) to steep slopes (25–40 %). Both concessions reported that their chainsaw and skidding tractor operators had not received formal training in Reduced Impact Logging (RIL) techniques, which is a crucial component for improving harvesting efficiency and reducing logging waste.

In terms of harvesting potential, PT WA had an Annual Allowable Cut (AAC) of 3,298 hectares per year, with an estimated annual timber volume of 143 825,14 m^3. PT KH reported a higher AAC of 4,534 hectares per year, yielding an estimated timber volume of 231 374,50 m^3 annually.

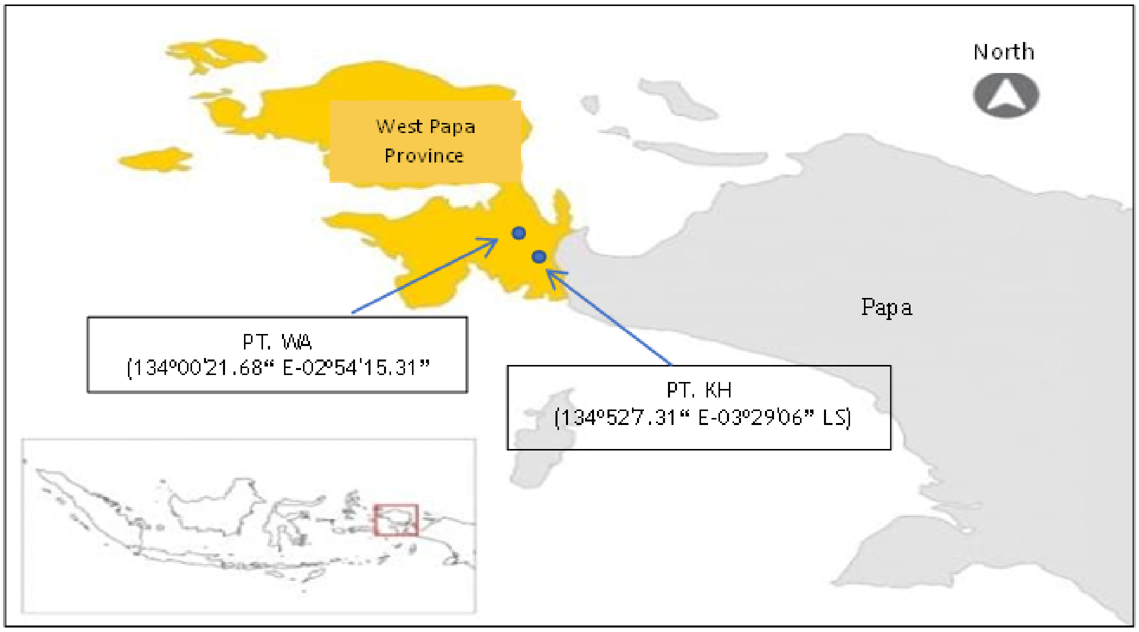

Figure 1. Research locations in natural forest areas in West Papua Province, Indonesia

This study utilized various materials and equipment. These included paint, markers, fuel, lubricants, and tally sheets for data recording. Measurement instruments comprised a phi-band, tape measure, clinometer, compass, and digital camera. Logging operations were carried out using a STIHL chainsaw (6,5 HP engine, 70 cm blade), while skidding was performed with a Caterpillar G7 tractor (175 HP engine, track wheels).

Collected data

Various data sources were used to obtain the study results that best fit the RIL method. The data can be divided into two groups:

- Primary data collected directly in the field through observation and measurement, including: potential volume of clear boles, volume of wood utilization, and felling waste in the felling site,and skidding waste a long the skidding road, and grading and scalling waste in the landing point.
- Secondary data includes general information about the forest concession, such as forest toporaphic conditions, wage system, experience of chainsaw and tractor sarad operators, and Annual Allowable Cut (AAC).

Definition

Definition of clear bole timber, utilized timber and logging wastes

- Clear Bole wood: the potential volume of clear bole timber represents the estimated amount of usable wood from a tree, calculated based on its height up to the first branch. This potential volume is used to determine the Annual Allowable Cut.(14)
- Wood utilization: the volume of utilized timber includes both the clear bole after bucking in the felling site and the timber remaining after grading and scaling at the landing point.
- Logging Wastes: all wood waste left in the forest both in felling site and landing point.

This study focuses on logging waste generated during felling, bucking, skidding, and grading scalling process.(11) Stump waste is the difference between the stump height and the allowable felling height, which is 30 cm.(15)

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Research procedures

The research procedure began with the selection of representative felling sites within natural forest concessions. Following this, fixed-area sample plots were established to facilitate systematic data collection. An inventory of standing trees was conducted within each plot, focusing on individuals with a diameter at breast height (DBH) of 20 cm or greater to assess commercial harvesting potential.

Subsequently, tree felling operations were monitored to record data on the potential clear bole, logging waste, and the volume of harvested (utilized) wood. This stage enabled the calculation of the felling index, which reflects the efficiency of wood utilization during the felling phase.

The next phase involved tracking the log skidding process, particularly examining wood losses occurring along the skid trails. This allowed for the computation of the skidding index, an indicator of transport-related inefficiencies and waste.

Finally, logs were subjected to a grading and scaling process at the landing site, where volumes of skidded logs and grading-related waste were recorded. The cumulative data from the felling and skidding phases were integrated to determine the overall logging waste efficiency, providing a comprehensive metric of timber harvesting performance in natural forest operations.

Data processing

The calculation of the volumes of utilized timber and logging wastes employs the Brereton formula[16] as follows:

$WV=1/4\ \pi \times ((Db-De)/2)^2 \times WL$

Where:
WV = Wood Volume (m3)
Db = Diameter at the base (m)
De = Diameter at the end (m)
WL = Wood Length (m)
π = Constanta (3,14)

To calculate the Timber harvesting efficiency (He), the following formula is used:[2]

He = felling index x skidding index

Where:

Felling index = (Clear bole potential-felling waste in the fellig site)/(Clear bole potential) x 100%
Skidding index =(Skidded wood-skidding and grading scalling waste)/(Skidded wood in the landing point) x 100%

Data analysis

A multiple correlation analysis was conducted to assess relationships between logging waste and influencing factors such as tree diameter, buttress height, and felling intensity.

RESULTS

Wood utilization, type and quality of logging waste

Wood utilization

The measured volumes of wood utilization and logging waste across the two forest concessions. At PT WA, wood utilization ranged from 3,792 to 4,748 m^3tree^{-1}, with an average of 4,138 ± 0,530 m^3tree^{-1} (equivalent to 45,518 m^3ha^{-1}). In PT KH, values ranged from 5,188 to 6,767 m^3tree^{-1}, averaging 5,978 ± 0,795 m^3tree^{-1} (75,360 m^3ha^{-1}) (table 1). The average volume of logging waste across both sites was 0,849 ± 0,095 m^3tree^{-1} (9,833 m^3ha^{-1}), comprising 0,708 ± 0,053 m^3tree^{-1} (7,788 m^3ha^{-1}) in PT WA and 0,989 ± 0,137 m^3tree^{-1} (11,873 m^3ha^{-1}) in PT KH. Spatially, the majority of logging waste (79,82 %) was generated at the felling site, while the remaining 20,18 % occurred as skidding waste at the landing point.

To assess the relationship between logging waste and logging factors, a multiple correlation analysis was conducted. The results revealed a statistically significant positive correlation between logging waste and tree diameter ($p < 0,01$; $r = 0,516$), indicating that approximately 51,6 % of the variation in logging waste volume is influenced by tree size. No significant correlations were found with buttress height or logging intensity. However, tree diameter was positively correlated with buttress height ($r = 0,191$), suggesting that larger trees are more likely to develop prominent buttresses, which may complicate efficient felling.

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Table 1. Usable wood volume

Forest concessions	Plots (@2 ha)	Logging intensity (trees ha^{-1})	Clear bole potency (m^{3}tree^{-1})	Felling waste (m^{3}tree^{-1})	Skidding waste (m^{3}tree^{-1})	Total logging waste (m^{3}tree^{-1})	Total logging waste (m^{3}ha^{-1})	Total wood utilization (m^{3}tree^{-1})
PT. WA	1	13	4,606	0,515	0,217	0,733	9,519	3,873
	2	12	4,44	0,513	0,135	0,648	7,773	3,792
	3	9	5,492	0,620	0,124	0,744	6,697	4,748
Averages		11	4,731±0,70	0,549±0,061	0,159±0,051	0,708±0,053	7,788 ±1,424	4,138±0,530
PT. KH	1	11	7,222	0,754	0,101	0,855	9,405	6,367
	2	11	7,898	0,905	0,226	1,131	12,436	6,767
	3	14	6,172	0,794	0,190	0,984	13,777	5,188
Average		24	7,097±0,870	0,818±0,078	0,172±0,064	0,989±0,137	11,873 ±2,240	6,107±0,821
Grand average		18	5,914±0,47	0,684±0,070	0,684±0,07	0,684±0,070	9,833 ±1,842	5,202±0,665
(%)				79,82	20,18	100,00		

This aligns with previous research showing that larger diameters typically result in higher volumes of merchantable wood and reduced relative waste. No significant correlations were found between wood utilization and either buttress height (r = 0,145, p = 0,091) or felling intensity (r = 0,099, p = 0,247), though the positive trends suggest these variables may have secondary influence under certain conditions. The weak correlation with felling intensity suggests that higher harvesting rates do not necessarily translate to better efficiency and may instead lead to greater losses due to shortcuts in operational practices.[21] A moderate but significant correlation was observed between tree diameter and buttress height (r = 0,191, p < 0,05), consistent with ecological observations that larger trees often develop more prominent buttresses, particularly in topographically complex or nutrient-poor environments.[23] Field observations further suggest that buttress height is also species-dependent and influenced by terrain.

Types of logging wastes

Logging waste is typically categorized into stump remnants, buttresses, and discarded sections from both the base and end of the trunk, as summarized in table 2. At the felling site, buttress waste was the dominant component, averaging 0,252 m^3·tree^{-1} (29,74 %), followed by stump waste at 0,184 m^3·tree^{-1} (21,40 %), end waste at 0,153 m^3·tree^{-1} (17,86 %), and base waste at 0,093 m^3·tree^{-1} (10,83 %). In contrast, at the landing site, skidding waste was primarily composed of base waste (0,129 m^3·tree^{-1} or 15,51 %) and end waste (0,038 m^3·tree^{-1} or 4,67 %).

Table 2. Types of logging wastes

Forest concessions	Plot Number	Types of felling wastes (at Felling site)				Types of skidding wastes (at Landing point)		Total logging waste (m^{3}tree^{-1})
		Buttress (m^{3}tree^{-1})	Stump (m^{3}tree^{-1})	Base waste (m^{3}tree^{-1})	End waste (m^{3}tree^{-1})	Base waste (m^{3}tree^{-1})	End waste (m^{3}tree^{-1})	
PT. WA	1	0,183	0,233	0,143	0,196	0,147	0,07	0,972
	2	0,414	0,250	0,099	0,141	0,132	0,003	1,039
	3	0,273	0,203	0,104	0,213	0,107	0,017	0,917
	Average	0,290	0,229	0,115	0,183	0,129	0,03	0,976
	(%)	29,71	23,46	11,78	18,75	13,22	3,07	100
PT. KH	1	0,224	0,145	0,053	0,093	0,071	0,03	0,616
	2	0,169	0,122	0,076	0,146	0,178	0,048	0,739
	3	0,258	0,154	0,082	0,126	0,139	0,051	0,81
	Average	0,214	0,139	0,071	0,122	0,128	0,045	0,719
	(%)	29,76	19,33	9,87	16,97	17,80	6,26	100
Grand Average (m^{3}tree^{-1})		0,252	0,184	0,093	0,153	0,129	0,038	0,848
Grand average (%)		29,74	21,40	10,83	17,86	15,51	4,67	100
		79,82 %				20,18 %		

Across concessions, PT WA reported an average buttress waste of 29,71 %, closely mirrored by PT KH at 29,76 %. Stump waste accounted for 23,46 % at PT WA and 19,33 % at PT KH. Skidding-related waste from the trunk base was 13,22 % at PT WA and 17,80 % at PT KH. These values reflect higher stump waste levels compared to previous studies conducted in Central Kalimantan (18,17 %) and East Kalimantan (6,97 %), suggesting site-specific differences in felling technique, terrain, and operator performance.(2,11)

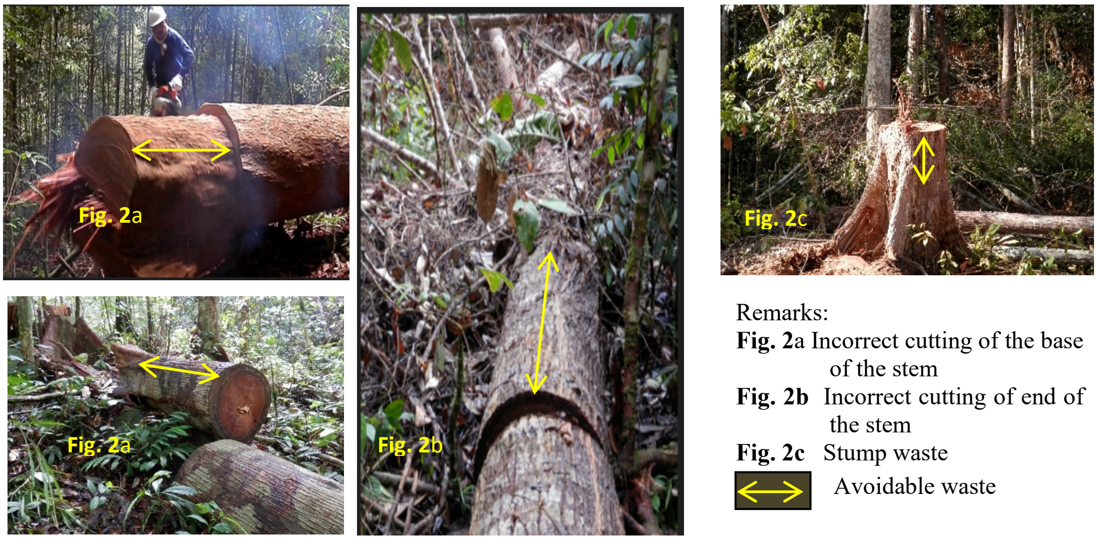

Figure 2. Common mistakes in tree felling activities

Quality of logging wastes

Detailed observations on the quality and composition of logging waste. On average, 42,79 % of the waste equivalent to 0,355 $m^3 \cdot tree^{-1}$ or 4,092 $m^3 \cdot ha^{-1}$was still in good condition and potentially recyclable. The average usable volume of logging waste was 3,773 $m^3 \cdot ha^{-1}$ at PT WA and 4,410 $m^3 \cdot ha^{-1}$ at PT KH. Defective waste, characterized by characteristics such as holes, basal rot, and excessive knots, reached 33,32 % or 0,286 $m^3 \cdot tree^{-1}$ (3,321 $m^3 \cdot ha^{-1}$). Broken or damaged waste reached 24,26 %, with an average of 0,211 $m^3 \cdot tree^{-1}$ or 2,465 $m^3 \cdot ha^{-1}$ (table 3).

Table 3. Quality distribution of logging wastes

Forest concessions	Plot Number	Quality of logging wastes							
		Good		Defect		Broken		Total	
		(m^3tree^{-1})	(m^3ha^{-1})	(m^3tree^{-1})	(m^3ha^{-1})	(m^3tree^{-1})	(m^3 ha^{-1})	(m^3tree^{-1})	(m^3.ha^{-1})
PT. WA	1	0,304	3,951	0,380	4,943	0,048	0,624	0,732	9,519
	2	0,300	3,603	0,109	1,308	0,238	2,861	0,648	7,773
	3	0,425	3,823	0,173	1,558	0,146	1,316	0,744	6,697
	Average	0,343	3,773	0,221	2,429	0,144	1,587	0,708	7,788
	(%)	48,45		31,18		20,37		100,00	
PT KH	1	0,408	4,488	0,238	2,621	0,209	2,296	0,855	9,405
	2	0,357	3,931	0,391	4,305	0,382	4,199	1,131	12,436
	3	0,315	4,415	0,424	5,929	0,245	3,433	0,984	13,777
	Average	0,368	4,410	0,351	4,213	0,279	3,343	0,990	11,873
	(%)	37,13		35,47		28,14		100,00	
Grand average		0,355	4,092	0,286	3,321	0,211	2,465	0,849	9,833
(%)		42,79		33,32		24,26		100,00	

Logging efficiency

Felling index

Table 4 summarizes the felling index across the two forest concessions. In PT WA, the felling index ranged from 88,45 % to 88,82 %, with an average of 88,66 % ± 0,19. In PT KH, it ranged from 88,55 % to 89,56 %, averaging 88,42 % ± 1,21. These values are higher than those reported in previous studies, such as Central

Kalimantan and West Sumatra 76–77 %, in East Kalimantan (86 %) and more recent findings in five Central Kalimantan concessions, which reported an average of 84 %.[2] A higher felling index indicates more efficient timber recovery within the felling plot, whereas lower values suggest greater inefficiencies and higher volumes of logging waste.

Table 4. Clear bole potency and felling index

No.	Forest concessions	Plots (topography)	Logging intensity (Trees ha^{-1})	Tree diameters (cm)	Clear bole potency (m^{3}tree^{-1})	Felling wastes (m^{3}tree^{-1})	Felling index
1	PT. WA	1 (Flat)	13	52,4	4,606	0,515	88,82
		2 (Sloping)	12	48,3	4,44	0,513	88,45
		3 (Rather steep)	9	51,7	5,492	0,62	88,71
		Averages	11	50,8±7,9	4,731±0,70	0,549±0,30	88,66±0,19
2	PT. KH	1 (Sloping)	11	62,8	7,222	0,754	89,56
		2 (Rather steep)	11	61,5	7,898	0,904	88,55
		3 (Steep)	14	61,6	6,172	0,793	87,15
		Averages	12	62,0±**12.**	7,097±0,87	0,818±0,48	88,42±1,21
Grand average			11		5,914±0,78	0,683±0,395	88,54±0,70

Skidding index

Table 5 summarizes the measurement results for wood waste, scrap volume, and the skidding index following the grading and scaling process at the landing site. Despite these procedures, skidding waste remains, averaging 0,159 ± 0,051 m^3·tree^{-1} at PT WA and 0,172 ± 0,064 m^3·tree^{-1} at PT KH. Average wood utilization was recorded at 5,970 ± 0,809 m^3·tree^{-1} in PT WA and 4,978 ± 0,659 m^3·tree^{-1} in PT KH. The skidding index, which reflects the efficiency of log transport to the landing point, averaged 0,97 ± 0,02 for PT WA and 0,96 ± 0,02 for PT KH.

Table 5. Recapitulation of skidding index calculations

Forest Concessions	Plot Number	Skidded wood (m^{3}tree^{-1})	Grading and scaling wastes (m^{3}tree^{-1})	Wood Utilization at Landing point (m^{3}tree^{-1})	Skidding index (%)
PT WA	1	4,091	0,101	3,990	96,52
	2	3,701	0,226	3,475	98,03
	3	4,682	0,190	4,492	97,64
	Average	4,158±0,494	0,172±0,064	3,986±0,509	97,40±0,78
PT.KH	1	6,251	0,217	6,033	97,52
	2	6,881	0,135	6,745	93,89
	3	5,255	0,124	5,131	95,95
	Average	6,129±0,820	0,159±0,051	5,970±0,809	95,79±1,82
Grand average		5,143±0,657	0,166±0,058	4,978±0,659	96,59±1,30

DISCUSSION

Wood utilization, type and quality of logging waste

Wood utilization

The Annual Allowable Cut (AAC) of 3298 ha·year^{-1} for PT WA and 4534 ha·year^{-1} for PT KH, the potential logging waste generated annually is considerable estimated at approximately 25 685 m^3 for PT WA and 53 810 m^3 for PT KH. Indonesia remains among the highest global contributors of logging waste in tropical forest operations,[17] largely due to poor implementation of Reduced Impact Logging (RIL) practices and inadequate operator training.

Field measurements indicate excessive felling heights at both concessions, with PT WA averaging 99,3 cm and PT KH averaging 95,3 cm above ground far exceeding RIL standards of 30 cm for RIL-C[17] and 50 cm for RIL.[18] Such inefficiencies highlight the need for improved technical execution and on-site supervision. Proper RIL felling involves cutting buttresses or using a 45° undercut to allow for safer and lower felling positions.[19] Recommended working positions include squatting, kneeling, or a bent-forward stance, which offer better control and accuracy during cutting.[2,20]

Beyond technical limitations, economic incentives also influence logging waste generation. The prevailing piece-rate wage system encourages chainsaw operators to prioritize volume over precision, potentially compromising adherence to RIL guidelines. Compensation is based on volume felled (IDR/m^3), with bonuses tied to performance targets, which may discourage waste-minimizing practices.

Previous studies have reported varied wood utilization volumes across regions. In Central Kalimantan, values ranged from 3,078 to 7,667 $m^3 \cdot tree^{-1}$ depending on logging intensity and forest type.(2,21,22,23) In Papua, reported that utilization volumes between 8,020 and 13,040 $m^3 \cdot tree^{-1}$, influenced by tree morphology.(21) Improvements in felling and bucking practices have been shown to significantly enhance utilization efficiency by 4,18 % through improved bucking 5 and up to 9,74 % through the application of RIL techniques,(24,25,26) similarly emphasize the role of felling precision in optimizing timber volume and quality.

These findings reinforce the conclusion that wood utilization in selective logging systems depends more on operational practices than on extraction intensity. Sustainable utilization can be improved through targeted interventions such as pre-harvest tree selection, directional felling, and precision bucking, all of which minimize stem damage and maximize recoverable volume.(5) Future studies incorporating species-specific wood traits, decay resistance, and product yield would offer deeper insights into improving utilization outcomes in tropical forests.

Types of logging wastes

Improper felling practices, particularly those that exceed the stump height limits prescribed by RIL-C guidelines, are a major contributor to stump waste. These issues typically result from cutting trees in a standing position without first removing buttresses, making it difficult to achieve low felling heights. This method compromises the accuracy of the undercut, back cut, and scarf notch critical components of directional felling. High buttresses further complicate accurate cutting, often resulting in deviations from the intended felling direction.(27)

Significant avoidable waste also arises from poor bucking practices. Ideally, bucking should be performed as close as possible to the first branch (approximately 10 cm from the branch collar), assuming the trunk is free from defects. Field observations reveal considerable base and end waste, often attributable to operators prioritizing speed over precision. This is largely driven by the piece-rate wage system, which incentivizes volume over efficiency. As a result, proper RIL bucking techniques are frequently neglected, particularly at the base and top sections of the stem.(28,29)

To date, neither PT WA nor PT KH have utilized the substantial potential of logging waste, primarily due to logistical, economic, and policy-related challenges. First, the scattered distribution and heterogeneity of logging residues in the field complicate collection and transportation to landing sites. Second, high transportation costs render recovery efforts economically unviable. Third, limited market demand and the lack of suitable wood processing industries constrain the commercial use of such residues. Lastly, existing government policies, which impose non-tax state revenue levies on logging waste based on small roundwood rates, are considered impractical and economically disproportionate. The efficiency of logging waste can be achieved through 3 principles namely Reduce, Reuse and Recycle. Reduce principle can be applied by reducing the number of trees cut down through good forest planning techniques and the use of sustainably sourced wood. Reuse principle can be applied by reusing logged timber for other purposes before being thrown away, such as for building materials or furniture. Recycle principle can be achieved through unused wood waste can be recycled into new products, such as by processing it into plywood or wood pellets for energy.

Quality of logging wastes

Technically, reducing high-quality logging waste can be achieved through improved felling and bucking techniques. Based on the estimated recoverable volumes of good-quality waste 3,773 $m^3 \cdot ha^{-1}$ in PT WA and 4,410 $m^3 ha^{-1}$ in PT KH and their respective Annual Allowable Cuts (3298 $ha \cdot year^{-1}$ and 4534 $ha \cdot year^{-1}$), potential increases in roundwood production are estimated at 12 443 $m^3 year^{-1}$ for PT WA and 19 995 $m^3 \cdot year^{-1}$ for PT KH. This enhanced yield would increase company revenues and government non-tax state income, supporting the economic viability of sustainable logging.(29,30)

According to (31) reforestation levies for large logs (>49 cm diameter) are valued at USD 14,50$\cdot m^{-3}$, with forest resource royalties set at 10 % of the benchmark log price. According to (31) given the 2024 average large-log market price in West Papua of USD 105,26$\cdot m^{-3}$ the estimated additional net revenue from recovered timber could reach USD 1,073 million$\cdot year^{-1}$ for PT WA and USD 1,724 million $year^{-1}$ for PT KH. In turn, this could generate approximately USD 617 000 $year^{-1}$ in additional provincial non-tax revenue from both concessions.

From a social perspective, implementing Reduced Impact Logging (RIL) techniques requires a substantial local workforce for stand inventory, operational planning, and felling. A typical RIL team includes a minimum of 11 individuals for pre-harvest inventory and six for felling operations, including chainsaw and skidder operators, assistants, and supervisors. Most personnel are recruited from nearby communities, providing local

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employment and reducing the risk of illegal logging. Workers are trained in RIL procedures to ensure compliance and operational safety.

Logging efficiency

Felling index

Field observations indicate that external factors such as company policies on log specifications, the piece-rate wage system, and log-splitting practices contribute to variations in the felling index. For example, both concessions apply a minimum scion diameter of 38 cm for log production. However, inconsistencies between this policy and actual stand conditions, combined with piece-rate wages based on production output, often lead operators to prioritize ease of cutting over optimal recovery, resulting in significant unutilized wood waste (figure 2).

Internal factors, including tree diameter, buttress height, felling intensity, and topography, are also assumed to influence felling efficiency. An F-test was conducted to assess the effect of these variables on the felling index. None of the independent variables tested forest concession, diameter, buttress height, or topography showed statistically significant influence at the 5 % level. Buttress height had the strongest, albeit non-significant, association (F = 2,391, p = 0,135). Diameter and topography, while expected to impact efficiency due to processing complexity and terrain difficulty, respectively, also showed no significant effects (diameter: F = 1,369, p = 0,371; topography: F = 1,371, p = 0,323). These results differ from previous studies, such as those in South Australia, where terrain and stem characteristics were significant predictors of harvesting performance.[32,33,34]

The lack of statistical differences between concessions (F = 0,618, p = 0,462) may reflect consistent implementation of Reduced Impact Logging (RIL) techniques across the study areas, contributing to operational uniformity.

Skidding index

The skidding index across various locations in Indonesia is relatively similar. These values are consistent with previous studies in East and Central Kalimantan, which reported skidding indices between 0,96 and 0,97.[2,11]

Optimizing the skidding index requires selecting appropriate skidding methods and tractor types tailored to timber dimensions and site conditions. Skidding waste at the landing point is often attributed to poor cutting angles at the base and top of the logs, as well as physical defects such as breakage, cracks, holes, heart rot, and excessive knots.

Logging efficiency

Based on data from table 1 and table 5, timber logging efficiency at PT WA ranged from 85,73 % to 86,71 %, averaging 86,35 %, while PT KH ranged from 83,14 % to 87,34 %, with an average of 84,70 %. These values are higher than those reported for Central Kalimantan (82 %) and East Kalimantan (83 %),[2,11] and notably above results from studies using conventional logging methods, which averaged 80,6 %.[19] Compared to earlier findings by,[34,35] which reported efficiencies of 74–75 % and 79–80 %, respectively, the current results indicate significant improvement attributed to the implementation of Reduced Impact Logging (RIL) techniques.

The application of RIL has increased average logging efficiency at PT WA and PT KH to 85,52 %, which exceeds the Ministry of Environment and Forestry (MoEF) minimum efficiency standard of 70 %[12] by 15,52 %. This improvement demonstrates the effectiveness of RIL in reducing logging waste and enhancing resource utilization. Such efficiency targets aim not only to optimize forest resource use but also to reduce the ecological impacts of timber harvesting. Enhanced efficiency also supports economic outcomes by lowering operational costs and increasing the yield of high quality logs.

While logging efficiency was high, a multiple correlation analysis showed that tree diameter, buttress height, and felling intensity were not significantly correlated with harvesting efficiency (p > 0,05). Pearson correlation coefficients were low: 0,055 for tree diameter, –0,051 for buttress height, and 0,086 for felling intensity. These values suggest weak, non-significant relationships, with tree diameter and felling intensity showing slight positive trends, while increased buttress height appeared to marginally reduce efficiency.

Overall, these results reinforce the conclusion that improvements in timber harvesting efficiency are driven more by operational practices particularly the application of RIL than by tree morphology or site conditions. In doing so, RIL supports both economic performance and environmental sustainability in natural forest management.

CONCLUSIONS

This study confirms that logging waste production is largely concentrated at logging sites. Logging waste consists mainly of buttresses, stumps, and base-end remnants. The adoption of RIL has been quite effective in reducing logging waste and increasing the volume of timber utilization, with an overall harvesting recovery by

14,4 %, compared to an average of 80,6 % under conventional logging practices.

The correlation analysis emphasizes that operational techniques, particularly those related to felling and bucking, influence efficiency more than tree morphology or terrain.

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