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Performance of different sawmill technologies; a case study of sawmills operating in Uganda's softwood plantations

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ABSTRACT

This study determined timber volume and timber value recovery of different plantation sawmill technologies. Data were collected from four sawmills in three forest plantation clusters. A two-way ANOVA was used to test the difference in performance between sawmill technologies and the combined effect of sawmill type and log diameter on performance. Sawmill technology significantly ($p < 0.05$) affected timber volume recovery and value recovery. The medium band sawmill had both the highest volume recovery (43%) and value recovery (209,700 UGX/m3) whereas the mobile circular sawmill had both the lowest volume recovery (26%) and value recovery (90,000 UGX/m3). The interaction effect of sawmill technology and log diameter significantly ($p < 0.05$) affected timber volume and value recovery. Mean timber volume recovery of sampled sawmills was 32% while value recovery was 123,800 UGX/m3. Studies on effect of market demands and sawyer's skills on volume, value and throughput and how they can be optimized to improve profitability and sustainability of the resource are recommended.

Key words: Plantation sawmill technologies, Timber volume recovery, Timber value recovery,Uganda

RÉSUMÉ

Cette étude a déterminé le volume de bois et la valeur de récupération du bois de différentes technologies de scieries de plantations. Les données ont été collectées auprès de quatre scieries dans trois clusters de plantations forestières. Une ANOVA à deux voies a été utilisée pour tester la différence de performance entre les technologies de scierie et l'effet combiné du type de scierie et du diamètre des grumes sur la performance. La technologie de scierie a significativement ($p < 0,05$) affecté la récupération du volume et de la valeur du bois. La scierie à bande moyenne a enregistré la plus haute récupération de volume (43%) et de valeur (209 700 UGX/m3), tandis que la scierie circulaire mobile a affiché la plus basse récupération de volume (26%) et de valeur (90 000 UGX/m3). L'effet d'interaction de la technologie de scierie et du diamètre des grumes a significativement ($p < 0,05$) affecté la récupération du volume et de la valeur du bois. La récupération moyenne du volume de bois des scieries échantillonnées était de 32%, tandis que la récupération de valeur était de 123 800 UGX/m3. Des études sur l'effet des demandes du marché et des compétences des scieurs sur le volume, la valeur et le débit, et sur la

Mots clés : Technologies de scieries de plantations, récupération du volume de bois, récupération de la valeur du bois, Ouganda

Introduction

Globally, forest cover declined from 4.48 billion hectares in 1990 to 4.06 billion hectares in 2022 (FAO, 2022). To restore forest cover, forest plantations, amongst other pathways, have been promoted and have increased from 123 million hectares in 1990 to 294 million hectares in 2020 (Yang *et al*., 2021). Uganda, whose forest cover declined from 24% of the total land area in 1990 to 13% in 2019 (Musoke, 2021), is among the countries promoting plantation forestry (SPGS, 2020). According to Brand (2022), forest plantations are intensively managed to offer a solution to the growing wood demand in order to shift wood supply pressure from natural forests thereby allowing for their conservation.

According to FAO (2018), the conversion of forest plantations into sawn timber constitutes most of the primary wood processing in the world. In Uganda, two-thirds of the commercial forest plantations were established primarily for production of sawn timber (Howard, 2022). To yield the expected benefits, these plantations have to be managed responsibly (Jacovelli, 2014). Secondly, they should be harvested at maturity, when their growth rate has reached its maximum (FAO, 2020). At maturity, it is best to harvest and re-plant so as to supply wood products whilst promoting a circular economy and generating revenues downstream the forest-based value chain. Conversion of the harvested trees into the different wood products must also be efficient with limited generation of wastes (FAO, 2022).

The higher the conversion efficiency, the smaller the plantation area harvested to meet a given demand for sawn timber. According to Taube *et al*. (2020), the often used indicator of conversion efficiency for plantation sawmills is the timber volume recovery i.e. timber volume extracted from a unit sawlog volume expressed as a percentage. While at the international level, volume recovery is benchmarked at 60%, most developing countries have a volume recovery below 40% (Ledger, 2017). This implies that more than 60% of the sawlog volumes is converted into other products of low value and this reduces the timber value recovery, another conversion effieciency indicator expressed as the monetary value of sawntimber produced from a unit volume of sawlogs (Quebec *et al*. 2015).

Timber volume recovery of sawmills operating in Uganda's forest plantations seldom exceeds 40% (Mwamakimbullah, 2020). The low volume recovery is attributed to antiquated sawmilling technologies and sawing methods, semi-skilled sawyers, and poor-quality logs. Some of the sawmills have thick blades that are inappropriate for conversion of the small diameter plantation logs (Kambugu *et al*. 2005; Turinawe and Mulimba, 2017). Even those with relatively thin blades lack decision support tools to guide sawyers in making optimal sawing decisions (Ngobi, 2019). No study has been undertaken to determine timber value recovery to the best of the authors' knowledge.

Numerous efforts to improve performance have been undertaken including extending technical and financial assistance to tree growers to ensure good quality trees (Jacovelli, 2014), research and recommendations on suitable sawmill technologies (Kambugu *et al*. 2005), training and assisting sawyers in acquiring modern sawmills (Mwamakimbullah, 2020). The objective of this study was to compare timber volume and timber value recovery of sawmills technologies used in conversion of forest plantations. This was required as a basis for determining further interventions that may be required in building a profitable, sustainable and resilient plantation sawnwood processing industry in Uganda.

Materials and Methods

Study Area. The study was conducted in three forest plantation clusters including the Central, Eastern and Albertine clusters. Particular districts were Mubende, Mayuge, and Hoima and Masindi respectively.

Sampling and Data Collection. Three clusters were purposively selected based on accessibility and potential number of sawmills. Selection of individual sawmills from the clusters was purposive to include both medium and mobile sawmills and also different sawblade types particularly circular and band sawblades. A medium sawmill was selected from the Eastern cluster, a mobile band sawmill from the Central cluster in Mubende whereas a mobile circular sawmill and a mobile band sawmill were selected from the Albertine cluster.

$$k = \frac{N_q * N_d}{N_l} \qquad [i]$$

Where: N_d= Target number of days to be spent at a sawmill i.e., 3 or 4 given resource constraints; N_q= Average number of logs sawn at a sampled sawmill per day and was obtained from production records at the mill; N_l= Number of logs to be sampled (≥ 90).

For each sampled log, the small and butt end diameters were measured using a caliper. Log length was measured using a measuring tape and the maximum deviation from the main axis was measured using a string and meter rule. The number and nominal dimension as well as the unit price for each timber size sawn were also recorded.

Table 1. Sampling intensities used

Sample sawmill	N_d	N_q	k	N_l
Medium band sawmill	3	500	14	106
Mobile band sawmill-A	4	60	2	98
Mobile band sawmill-B	4	60	2	100
Mobile circular sawmill	4	65	2	103

Data Analysis

Quality characterization of logs. Small end diameter was used to group sampled logs using cluster analysis. For each sampled log, volume was obtained using log volume tables based on small end diameter and length. Taper (t_l) and sweep (S_l) were obtained using Equations ii and iii and from Missanjo and Magodi (2015) and Monserud *et al.* (2004) respectively.

$$t_l = \frac{b - s}{l} \qquad [ii]$$

$$S_l = \frac{w}{l} \qquad [iii]$$

Where; b = butt-end log diameter (mm); s = small-end log diameter (mm); l = log length (m) and w = maximum deviation (mm) of the log from the main axis.

For each log diameter class, average taper (t_{lc}) was calculated using Equation iv.

$$t_{lc} = \frac{\sum t_l}{N_x} \qquad [iv]$$

Where: N_x = Number of logs in the log diameter class

For each sampled sawmill, average weighted taper (t_s) was calculated from Equation v.

$$t_s = \sum_r t_r * \frac{V_r}{V} \qquad [v]$$

Where: V_r = Total volume of logs (m^3) in log diameter class I, t_r = taper of log diameter class r, V = Total volume of logs (m^3) sampled at the sawmill.

The average sweep for each diameter class as well as the average weighted sweep at each sawmill were determined using a similar approach to taper above (Equations iv and v).

Timber volume recovery. Timber volume recovery of each sampled log (T_l) was calculated using Equation vi as in Kambugu et al., 2005).

$$T_l = \frac{V_t}{V_l} x\,100 \qquad [vi]$$

Where V_t = volume of timber sawn from the log.

Volume of timber (V_t) sawn from each sampled log was determined using Equation vi.

$$V_t = \frac{\sum_i n_i w_i h_i l_i}{Q} \qquad [vii]$$

Where: n_i= number of pieces of timber of size i sawn, w_i = nominal width (mm) of timber of size i sawn, h_i = nominal thickness (mm) of timber of size i sawn, l_i = length (mm) of timber of size i sawn, Q = conversion factor ($1x10^6$) from mm^3 to m^3.

The average volume recovery for each diameter class as well as the average weighted volume recovery at each sawmill were determined using a similar approach to taper above (Equations iv and v).

The difference in timber volume recovery between sawmills was tested using a two-way ANOVA at 5% significance level.

Timber value recovery. Timber value recovery of each sample log (R_l) was obtained from Equation viii.

$$R_l = \frac{r_l}{V_l} \qquad [viii]$$

Where; r_l = potential revenue (UGX) of timber sawn from sample log, V_l= Volume (m^3) of sample log. Potential revenue (r_l) of timber sawn from each sample log was obtained from Equation ix.

$$r_l = \sum_i p_i n_i \qquad [ix]$$

Where: p_i = price (UGX) of a timber piece of size i sawn, n_i = number of timber pieces of size i sawn.

The average value recovery for each diameter class as well as the average weighted value recovery at each sawmill were determined using a similar approach to taper above (Equations iv and v).

The difference in timber value recovery between sawmills was tested using a two-way ANOVA at 5% significance level.

Results

Quality characterization of logs. The mean small-end diameter, taper and sweep of logs sampled were 20cm, 7mm/m and 4mm/m respectively. Logs sawn at the medium band sawmill were relatively large with a mean diameter of 25cm whereas those sawn at the mobile circular sawmill were the smallest with a mean diameter of 18cm. Logs sawn at the mobile circular sawmill were also more tapered (7mm) whereas those sawn at the medium band sawmill were less tapered with only 4mm (Table 2).

Table 2. Characteristics of logs sawn by sampled sawmills

Sawmill	Small end diameter class (cm)				Weighted Average		
	12-16	17-20	21-24	25-32	Diameter (cm)	Taper (mm/m)	Sweep (mm)
Medium band	15	18	22	28	25	6.7	4.22
Mobile band -A	18	19	21	26	19	6.7	3.97
Mobile band -B	17	20	21	25	19	6.4	3.99
Mobile circular	14	19	22	28	18	6.8	3.82
	Average				20	6.7	4

Timber volume recovery. The medium band sawmill had the highest timber volume recovery for each log diameter class whereas the mobile circular sawmill had the lowest volume recovery for most of the diameter classes. On average, the medium band sawmill had 43% while the mobile circular sawmill had 26%. Generally, timber volume recovery increased with increasing log diameter across the sampled sawmills. (Table 3).

Table 3. Descriptive statistics on timber volume recovery

Sawmill category	Volume recovery (%) by log diameter class				
	12cm-16cm	17cm-20cm	21cm-24cm	25cm-32cm	Weighted Average
Medium band sawmill	27	31	36	46	43
Mobile band sawmill-A	27	27	33	38	31
Mobile band sawmill-B	25	25	30	27	27
Mobile circular sawmill	25	25	27	28	26

Timber volume recovery significantly ($p < 0.05$) varied between log diameter classes and was significantly ($p < 0.05$) affected by the sawmill technology (Table 4). Volume recovery significantly ($p < 0.05$) differed between the medium band sawmill and mobile band sawmill-A; medium band sawmill and mobile band sawmill-B; medium band sawmill and mobile circular sawmill; mobile band sawmill-A and mobile band sawmill-B; and mobile band sawmill-A and mobile circular sawmill. There was no significant ($p > 0.05$) difference in timber volume recovery between mobile band sawmill-B and mobile circular sawmill (Table 5).

Table 4. Analysis of variance on timber volume recovery

Source	Type III Sum of Squares	Df	Mean Square	F	p value
Corrected Model	21027	15	1401	30	0.00
Intercept	152810	1	152810	3344.	0.00
Sawmill	1714	3	571	12	0.00
Log diameter class	2427	3	809	17	0.00
Sawmill * log class	2281	9	253	5	0.00
Error	17864	391	45		
Total	439123	407			
Corrected Total	38891	406			

Table 5. Post hoc analysis on volume recovery between sawmills

Sawmill	Sawmill	Mean Difference	Std. Error	P value	95% Confidence Interval	
					Lower Bound	Upper Bound
1	2	9.23	.94	0.00	8.58	13.45
	3	15.16	.94	0.00	10.51	15.38
	4	15.92	.93	0.00	12.65	17.49
2	3	5.92	.95	0.00	-.54	4.40
	4	6.05	.95	0.00	1.59	6.51
3	4	0.12	.95	0.18	-.32	4.58

1 = Medium band sawmill, 2 = Mobile band sawmill-A, 3= Mobile band sawmill-B, 4 = Mobile circular sawmill

Post hoc tests indicated significant ($p < 0.05$) differences in timber volume recovery between log diameter classes 12-16cm and 21-24cm; 12-16cm and 25-32cm; 17-20cm and 21-20cm; 17-20cm and 25-32cm; and 21-24cm and 25-32. Timber volume recovery of log diameter class 12-16cm was not significantly ($p > 0.05$) different from that of log diameter class 17-20cm (Table 6).

Timber value recovery. Similar to timber volume recovery, the medium band sawmill and mobile circular sawmill had the highest and lowest timber value recovery rates respectively. Medium band sawmill had 209,700 UGX/m^3 whereas the mobile circular sawmill had 90,000 UGX/m^3. Value recovery increased with increasing log diameter. Large diameter logs (25-32cm) yielded highest value recovery for medium band sawmill and mobile band sawmill-A. For mobile band sawmill-B and mobile circular sawmill, medium diameter logs (21-24cm) yielded the highest timber value recovery. The mean timber value recovery of sampled sawmills was 127,100UGX/m^3 (Table 7).

Table 6. Post hoc test in timber volume recovery between log classes

					95% Confidence Interval	
(I) diameter	(J) diameter	Mean Difference (I-J)	Std. Error	P value	Lower Bound	Upper Bound
12-16	17-20	.04	.96	1.00	-2.44	2.53
	21-24	-6.1	.86	0.00	-8.43	-3.94
	25-32	-16.25	.95	0.00	-18.72	-13.79
17-20	21-24	-6.23	.97	0.00	-8.75	-3.71
	25-32	-16.30	1.05	0.00	-19.01	-13.58
21-24	25-32	-10.06	.96	0.00	-12.55	-7.57

Table 7. Descriptive statistics on timber value recovery

Sawmill category	Value recovery (UGX/m^3) by log diameter class				
	12cm-16cm	17cm-20cm	21cm-24cm	25cm-32cm	Average
Medium band sawmill	112000	150200	174800	224600	209700
Mobile band sawmill	104200	104700	130600	139300	116000
Mobile band sawmill	86300	82300	108200	90300	93000
Mobile circular sawmill	81800	80700	85900	72300	90000

The sawmill technology as well as log diameter had significant ($p < 0.05$) effect on timber value recovery. The interaction in log diameter and sawmill technology also had a significant ($p < 0.05$) effect on timber volume recovery (Table 8).

Table 8. Analysis of variance on timber value recovery

Source	Type III Sum of Squares	df	Mean Square	F	p value value
Corrected Model	1049963572000	15	69997571450	108	0.00
Intercept	2302021730000	1	2302021730000	3571	0.00
Sawmill	170432790800	3	56810930280	88	0.00
Log class	44190728680	3	14730242890	22	0.00
Sawmill * log class	50321051350	9	5591227928	8	0.00
Error	251992001200	391	644480821		
Total	7547806022000	407			
Corrected Total	1301955573000	406			

a. R Squared = .806 (Adjusted R Squared = .799)

Post hoc tests indicated significant ($p < 0.05$) differences in timber value recovery between all individual sawmills (Table 9).

Table 9. Post hoc test on timber value recovery between sawmills

sawmill	Sawmill	Mean Difference	Std. Error	P value	95% Confidence Interval Lower Bound	95% Confidence Interval Upper Bound
1	2	85600	3548	0.00	76400	94700
	3	22000	3539	0.00	98400	116700
	4	10600	3521	0.00	109100	127300
2	3	22000	3599	0.00	12700	31300
	4	32600	3581	0.00	23400	41900
3	4	10600	3572	0.02	1400	19800

1= Medium band sawmill, 2 = Mobile band sawmill-A, 3 = mobile band sawmill-B, 4 = Mobile circular sawmill.

Timber value recovery was significantly ($p < 0.05$) different between log diameter classes 12-16cm and 21-24cm; 12-16cm and 25-32cm; 17-20cm and 21-20cm; 17-20cm and 25-32cm; and 21-24cm and 25-32. There was no significant ($p > 0.05$) difference in timber value recovery between log diameter classes 12-16cm and 17-20cm (Table 10).

Table 10. Post hoc test on timber value recovery between log classes

(I) diameter	(J) diameter	Mean Difference (I-J)	Std. Error	P value	95% Confidence Interval Lower Bound	95% Confidence Interval Upper Bound
12-16	17-20	-2300	3626	0.92	-11600	70300
	21-24	-32700	3264	0.00	-41200	-24300
	25-32	-108700	3587	0.00	-118000	-99500
17-20	21-24	-30400	3663	0.00	-39900	-21000
	25-32	-106400	3953	0.00	-116600	-96200
21-24	25-32	-75900	3624	0.00	-85300	-66600

Discussion

Quality characterization of logs. Sawmills sawed small sized logs with a mean diameter of 20cm. These logs were of similar sizes to logs sampled in Ngobi (2019) but smaller than logs sawn by the sawmills in early 2000 (Kambugu *et al*., 2005). The small size of logs might be attributed to the fact that sawmills harvested thinnings, which according to Zhu *et al*. (2007), usually yield logs of small diameters. Log size sawn by the sawmills varied; on average, the medium band sawmill sawed larger logs than mobile band sawmill-A, mobile band sawmill-B and mobile circular sawmill. This is because the medium band sawmill sawed logs from third thinnings of 14 years where as the other sawmills sawed logs of 10 to 12 years.

Mean log taper was 7mm/m and can be considered as medium taper given log taper classes by Missanjo and Magodi (2015). Taper was different between log diameter classes but similar between sawmills. Generally, larger logs tapered more than small logs. The positive correlation in log diameter and taper was also reported in Bilous *et al*. (2021); and Rabidin and Jamil (2022). According to Gomat *et al*. (2011); Kohler *et al*. (2016); and Salekin *et al*. (2021), log taper of a particular tree species is a function of age, site conditions, initial density and silvicultural treatments applied. The relatively similar conditions particularly species, age, initial density and silvicultural treatments applied to the plantations might have resulted to logs of similar log taper between sawmills. Log sweep was not different between log diameter sizes. Additionally, log sweep was also not different between sawmills. The mean sweep of logs sawn was 4.00mm/m. Given the mean taper and log diameter obtained, the percent sweep deduction as calculated in Hamner *et al*. (2007) of the logs would be one percent indicating that logs are generally straight.

Timber volume recovery. Timber volume recovery was different between plantation sawmills. The medium band sawmill had the highest volume recovery of 43%, which is above the average volume recovery of 40% reported for such sawmill technologies (Ngaga, 2011; Borz *et al*., 2021). High volume recovery of the medium band sawmill can possibly be attributed to use of thin saw blade (2mm) which resulted into thinner kerf (3mm) and consequently low volume losses. Although mobile band sawmill-A and mobile band sawmill-B had similar kerf width as the medium band sawmill, they had lower timber volume recovery. This could be because the medium band sawmill sawed larger logs with an average diameter of 25cm relative to the 19cm log diameter sawn by the two mobile band sawmills. Positive correlation of log diameter and volume recovery was also reported in Kambugu *et* *al*. (2005) and Ngobi (2019). Furthermore, the medium band sawmill was equipped with some decision support tools such as the laser beams which allowed sawyers to correctly position and allocate sawing lines in ways that maximized volume. The medium band sawmill also had a variable timber length system, re-saws and edgers and recovered thinner, narrower and/or shorter pieces of timber from slabs thereby increasing the timber volume recovered.

Timber volume recovery of mobile band sawmill-A (32%) was higher than volume recovery of mobile band sawmill-B (26%). According to Kambugu *et al.* (2005) and Ngaga (2011), mobile band sawmills can yield from 33% to 46% depending on the log size. Therefore, volume recovery of mobile band sawmill-A can be considered to be closer to the anticipated volume recovery of such a technology. However, volume recovery of mobile band sawmill-B was below the expected volume recovery. This is because at mobile band sawmill-B, sawyers were less skilled with no knowledge of timber volume recovery and sawed logs with a sole objective of meeting timber demand.

The mobile circular sawmill had the lowest timber volume recovery of 25%. Low volume recovery from mobile circular sawmill was also reported in Kambugu *et al*. (2005) and Thomas and Buehlmann (2022) and is attributed to use of thicker sawblades. The mobile circular sawmill had a thicker sawblade of 5mm and a resultant wider kerf of 6mm which was double the kerf width associated with medium and mobile band sawmills. The mobile circular sawmill also lacked optimizing tools and sawed the smallest logs with an average small end diameter of 18cm.The effect of log sweep and log taper on timber volume recovery was not significant. However, the interaction effect of sawmill technology and log diameter affected timber volume recovery. Generally, volume recovery of plantation sawmills in Uganda was 31% and thus lower than that reported in countries using similar sawmill technologies, for example 33% in Tanzania (Ngaga, 2011) and 32% in Kenya (Mathu, 2011). Timber volume recovery of plantation sawmills in Uganda (29%) was also below the international benchmark volume recovery rate of 60% (Ledger, 2017). Considering the annual pine sawlog supply of 550,000m^3 (FAO, 2020), only 170,500m^3 of pine sawn timber was being produced per year while close to 379,500m^3 of sawlog volume harvested was wasted and converted to low value by-products mostly sawdust and slabs.

Timber value recovery. The medium band sawmill and mobile circular sawmill had the highest and lowest value recovery of 200,700 UGX/m^3 and 90,000 UGX/m^3 respectively. High value recovery of the medium band sawmill can be attributed to the fact that the sawmill had the highest timber volume recovery of 43% and therefore recovered more timber volume per logs milled than other sawmills. The positive effect of volume recovery and timber prices on timber value recovery was also reported in Elustondo *et al*. (2005) and Quebec *et al*. (2015).

The mobile circular sawmill had the lowest timber value recovery despite having a higher timber value per cubic meter (378,800UGX/m^3) than mobile band sawmill-B (365,200UGX/m^3). This can be attributed to the lowest timber volume recovery attained by the mobile circular. Mobile band sawmill-A had higher timber value recovery than mobile band sawmill-B and this was possibly because the former sawmill had a significantly higher timber volume recovery and higher timber value per cubic meter.

Generally, the ex-mill unit timber volume price of plantation sawmills, excluding VAT was 421,200 UGX/m^3. The mean timber value recovery of sawmills was 133,900 UGX/m^3. Although no data on milling cost was collected, mean average milling costs for sawmills operating within plantations can be estimated at 100,000 UGX/m^3 (FAO, 2020). Therefore, revenue gains of plantation sawmills are low and might be within 33,000 UGX/m^3 subject to timber handling costs.

Conclusions

Sawmill technology affected timber volume and value recovery. Timber volume recovery ranged from 26% to 43% with an average of 32% whereas timber value recovery ranged from 90,000 to 209,000 UGX/m^3 and averaged at 123,800UGX/m^3. Logs sawn were small sized, straight with medium taper. There is therefore need to study log throughput of the different sawmill technologies, the effect of market demands and sawyer's skills on volume, value and throughput, and how they can be optimized to improve profitability and sustainable plantation forest management.

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Declaration of Conflict of interest

The authors declares no conflict of interest in the paper.

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