BINDURA UNIVERSITY OF SCIENCE EDUCATION

DEPARTMENT OF NATURAL RESOURCES

Potential of Increasing Utilisable Volume from Thinnings, Harvesting Waste and Sawmill Wastes to Promote Product Diversification at Nyanga Pine, Zimbabwe

MVUDUDU ANTHONY S.

(B222719B)

A DISSERTATION SUBMITTED IN PARTIAL FULFIMENT OF THE REQUIRMENTS OF THE BACHELOR OF SCIENCE HONOURS DEGREE IN FORESTRY AND ENVIRONMENTAL MANAGEMENT

Date: 05/2025

DEDICATION

This research is dedicated to all those who believed in my ability to work towards attaining the next level of academic excellence, my family and my lecturers.

ACKNOWLEDGEMENTS

I wish to acknowledge God Almighty for his grace and favour towards the completion of my research. I also want to give thanks to my project supervisor, Dr. L. Mujuru, for the enduring patience, guidance and supervision throughout my research project. I'm thankful to the Nyanga Pine Planning team who ran around to assist in data gathering so as to ensure that critical deadlines were met. To the lecturers who took their time to share their knowledge, you are greatly appreciated. To my family, thank you for your continued encouragement along this long and difficult journey. Your love, patience and support made all this possible. Finally I extend my thanks to my colleagues also studying for a BSc in Forestry and Environmental Management, for the constant reminders and updates.

ABSTRACT

Forest product utilization has shifted from the traditional sawn timber towards engineered wood products such as plywood. This research examined the potential increase in utilizable volume through product diversification from sawn timber only to plywood and paper products at The Wattle Company's Nyanga Pine Division, Zimbabwe. The aim was to assess the potential increase in utilizable volume from utilizing first thinning, second thinning residues, harvesting waste and sawmill byproducts to produce plywood and paper products. A quasi-experimental design was used, where data were collected from *Pinus patula* and *P. taeda* compartments at 4, 12, and 20 years of age (representing first thinning, second thinning, and clear-felling stages respectively). Tree volumes were calculated from diameter and height measurements using standardized allometric formulae. Destructive sampling was used to determine bark thickness and log volume. Results showed that diversification significantly enhances utilizable volume ($p<0.05$). For plywood production, utilizable volume significantly increased from 238 m^3/ha (sawn timber only) to 252 m^3/ha (6% gain), primarily from clear-felling residues (13.05 m^3/ha). Paper showed significantly greater gains than plywood, raising utilizable volume to 271 m^3/ha which is 12 % higher than producing sawn timber alone. Combined diversification of plywood and paper maximized utilizable volume to 285 m^3/ha (73.8 % efficiency). Therefore, results suggest the significance of these product diversifications, thus rejecting the null hypothesis (H_0) that diversification has no potential to increase volume utilization. In this regard, integrating plywood and paper production into forestry operations has potential to enhance round wood utilization, economic resilience and sustainability, aligning with global trends in forest-based bio economies.

Key words: Product diversification, Utilisable volume, thinning, waste, Resource efficiency, Sustainability.

TABLE OF CONTENTS

DEDICATION i

ACKNOWLEDGEMENTS ii

ABSTRACT iii

TABLE OF CONTENTS iv

LIST OF FIGURES vi

LIST OF TABLES vii

LIST OF APPENDICES viii

LIST OF ABREVIATIONS ix

CHAPTER 1 - INTRODUCTION .... - 1 -

1.1. Background .... - 1 -

1.2. Problem Statement .... - 3 -

1.3. Justification .... - 3 -

1.4. Aim .... - 4 -

1.4.1. Research Objectives .... - 4 -

1.4.2. Research Questions .... - 4 -

CHAPTER 2 - LITERATURE REVIEW .... - 5 -

2.1. Introduction .... - 5 -

2.2. Potential of Utilising Thinnings and Harvesting Residues for Plywood Production .... - 6 -

2.3. Utilisation of Thinnings, Harvesting Residues and Sawmilling Residues for Pulp And Paper Production .... - 7 -

2.4. Potential for Thinnings and Harvesting and Sawmilling Residues in Full Diversification into Plywood and Paper Production .... - 8 -

CHAPTER 3 – MATERIALS & METHODS .... - 9 -

3.1. Description of the Study Site .... - 9 -

3.2. Research Design .... - 10 -

3.3. Sampling and Data Collection .... - 10 -

3.3.1. Quantification of Standing Volumes due for Harvesting .... - 11 -

3.3.2. Quantification of Second Thinning Standing Volumes .... - 12 -

3.3.3. Estimation of Average Bark Thickness .... - 13 -

3.3.4. Estimation of Utilisable Percentages per Product .... - 14 -

3.3.5. Quantification of First Thinning Volume .... - 15 -

3.3.6. Quantification of Sawmilling Timber and Residues .... - 16 -

3.4. Data Analysis .... - 18 -

CHAPTER 4 - RESULTS .... - 19 -

4.1. Thinnings and Harvesting Volumes with Potential to be used for Plywood Production .... - 19 -

4.2. Thinnings, Harvesting and Sawmilling Residues with Potential to be used for Pulp and Paper Production .... - 19 -

4.2.1. Thinnings and Harvesting Volumes with Potential to be used for Pulp and Paper Production .... **Error! Bookmark not defined.**

4.2.2. Sawmilling Residues with Potential to be used for Pulp and Paper Production .... **Error! Bookmark not defined.**

4.3. Thinnings, Harvesting and Sawmilling Residues with Potential to be used Through Full Diversification into Plywood, Pulp and Paper Production .... - 20 -

CHAPTER 5 – DISCUSSION .... - 22 -

5.1. Thinnings and Harvesting Volumes for Plywood Production .... - 22 -

5.2. Thinnings, Harvesting, and Sawmilling Residues for Paper Production .... - 22 -

5.3. Full Diversification into Plywood and Paper Production .... - 23 -

5.4. Synthesis and Implications .... - 23 -

CHAPTER 6 - CONCLUSION AND RECOMMENDATIONS .... - 24 -

6.1. Conclusion .... - 24 -

6.2. Recommendations .... - 24 -

REFERENCES .... - 26 -

APPENDICES .... - 26 -

LIST OF FIGURES

Figure 4.1: Volume distribution per product type against the total available volume under full product diversification ....- 21 -

LIST OF TABLES

Table 3.1: Total areas by *Pinus* species, percentages representation, sample area and number of sample trees per species at 20 years ....- 11 -
Table 3.2: Areas per *Pinus* species, percentages representation, sample area and number of sample trees per species at 12 years of age..- 12 -
Table 3.3: Areas for sampling per Pinus species at 4 years ....- 16 -
Table 4.1: Volume with potential to be utilised for plywood (Mean ± SE)..- 19 -
Table 4.2: Volume from forest resource with potential to be utilised for pulp and paper products (Mean ± SE) ....- 20 -
Table 4.3: Volume from Sawmill with potential to be utilised for pulp and paper products (Mean ± SE) ...- 20 -

LIST OF APPENDICES

Appendix I: Clear felling compartments to be sampled per Pinus species, their total areas, sample areas and number of sample trees.

Appendix II: Second thinning compartments to be sampled per Pinus species, their total areas, sample areas and number of sample trees.

Appendix III: First thinning compartments to be sampled per *Pinus* species, their total areas, sample areas and number of sample trees.

Appendix IV: Turnitin Originality Check Results.

LIST OF ABREVIATIONS

ANRC	African Natural Resources Centre
EFI	European Forest Institute
EU	European Union
FAO	Food and Agriculture Organisation
GDP	Gross Domestic Product
NWFPs	Non-wood forest products
TAFORI	Tanzanian Forest Research Institute
USA	United States of America
USDA	United States Department of Agriculture

CHAPTER 1 - INTRODUCTION

1.1. Background

Product diversification in the forestry industry has been considered a solution for sustainable forest utilisation. Hurmekoski et al. (2018) provided evidence for this, predicting that by 2030, the forestry sectors in the United States, Finland, Sweden, and Canada would have expanded their markets and produced new products. They added that, within the same time period, the forest industries' revenue streams are likely to increase annually to levels between 18 and 75 billion euros. Although the value chains in these countries differ significantly, in terms of roundwood consumption, as well as harvesting ages and operational complexity, the presumed significance of the wood-based industries in the economies is enhanced by engineered products (Ibid).

Hansen and Juslin (2018) confirmed a global increase in demand for engineered wood products, indicating a notable shift in consumer preferences from the traditional sawn timber towards engineered wood products like plywood. The demand is driven by the sustainability and versatility of engineered wood products compared to traditional sawn timber. Other notable benefits realised at a global level include; the improvement in the economic resilience of timber based communities due to a decline in vulnerability to price fluctuations in the sawn timber market (Grobbelaar and Visser, 2021), better resource utilisation, improved production efficiency and more sustainable forestry practices including the utilisation of lower-grade wood that might otherwise be wasted (Schubert et al., 2022). Diversification into engineered wood products reduces deforestation while increasing focus on sustainability and eco-friendliness as more of the annually available forest resources produce more products, giving a competitive advantage (Adhikari and Ozarska. 2018).

There is therefore need for timber companies to integrate diversification strategies into their long-term planning, focusing on research and development to innovate and improve product lines and align with sustainability goals (Hansen and Juslin, 2018). This highlights both the economic advantages and the positive environmental implications of moving from sawn timber to plywood and paper products.

The inclusion of non-timber forest products that require minimal capital investment has been the primary emphasis of product diversification in Africa (Ndoye et al., 1998; Shackleton et al., 2011; Ingram et al., 2012). However, three major African timber players, namely; South Africa, Ghana and Côte d'Ivoire, have expanded their product lines to include either or both engineered wood and paper products. This has facilitated better integration into the global timber markets, contributing 1.6%, 4%, and 2.4% respectively to national Gross Domestic Product (GDP) (Asumadu, 2004). Except for South Africa, most sub-Saharan nations are nearly entirely dependent on imported paper and engineered wood products (Uzu et al., 2022). In West Africa, both Ghana and Cote d'Ivoire trade both domestically and internationally, although they import a lot of paper and engineered wood products (ANRC, 2021).

Katsvanga and Mudyiwa (2019), showed that Zimbabwe's timber industry with three main timber companies (Border Timbers, The Wattle Company Ltd. and Allied Timbers Zimbabwe) and numerous bush (mobile) sawmills, rely on one fibre and particle board plant and a single veneer and plywood factory. However, at the time of the study, both plants were closed due to financial constraints, thus pointing to a serious lack of timber product diversity in Zimbabwe.

The maximisation of tree volume utilisation in monoculture commercial forests, which is a key characteristic of Zimbabwean commercial forestry, has become a key focus in recent research, with need to increase the wood-based product mix. For example, at Nyanga Pine Division Sawmill, harvested round wood volume delivered to the sawmill, yields an average of 45% as sawn timber and approximately 12% chips used for fueling the boiler used in the timber drying process, giving a utilisation efficiency of +/- 57%. Another +/-12% is lost as sawdust whilst +/-31% for incineration as sawmill waste (D. Sithole pers comm).

By utilising a broader range of log sizes, timber companies (e.g. The Wattle Company Pvt Ltd in Zimbabwe) can improve forest health and resilience leading to better long-term resource productivity and sustainability (Duchesne et al., 2013). In this study an approximation of the potential volume utilisation in product diversification (i.e. sawn timber, plywood and paper) was assessed relative to the total merchantable volume in sawn timber alone.

1.2. Problem Statement

Research on the usage of forests has mostly concentrated on yields (Sist et al., 2013; Boungou and N'Doua, 2024) and recovery (Mayaka et al., 2014; Ngobi, 2020). Zhang et al. (2023) investigated methods for optimising water consumption and demonstrated their impact on growth rates and timber quality. Boncina et al. (2007) showed that thinning and selective logging improved the structural integrity and aesthetic qualities of timber. Although selective logging resulted in higher recovery rates (Baral et. al., 2025), the importance of understanding the environmental influences in order to optimise timber yields and recovery becomes important (Joshi et. al., 2023).

Duncker et. al (2012) concluded that integrated forest management approaches, combining ecological and economic goals, significantly enhanced timber yields compared to conventional practices. Another study showed that adaptive management strategies can mitigate the loss in timber quality and recovery emanating from global warming and climate change (World Bank, 2024). However, in Zimbabwe, there is limited documentation on possibility of utilising sawmill and thinning wastes for other marketable products such as plywood, pulp and paper. This study therefore assesses the potential of timber product diversification using thinnings and waste from sawn timber to plywood and paper products.

1.3. Justification

The Wattle Company Private Limited and other forest based organisations will benefit from the results of this study as they provide valuable insight on wasted volume that may be turned into other goods. This information will help product range expansion strategy from pine sawn timber to plywood and paper products, improve their round wood volume utilisation and inform the strategic planning function of the organisation.

The increased product range will enable improved resilience to economic fluctuations as greater product offerings reduce over-reliance on one market segment (i.e. market expansion and more jobs created, sustainability). Results can create a foundational database for utilisable volume beyond the traditional minimum tip diameter of 13cm created with consideration of the local environmental and silvicultural challenges affecting the Zimbabwean commercial forestry sector.

1.4. Aim

To assess the potential of product diversification from sawn timber to plywood and paper products by utilising first and second thinnings, and harvesting and sawmilling waste at the Wattle Company's Nyanga Pine Division, Mutasa District of Manicaland in Zimbabwe.

1.4.1. Research Objectives

1. Determine the quantity of first, second thinning and harvesting volume that has potential to be utilised for plywood production.
2. Determine the quantity of first, second thinning and harvesting volume and sawmilling waste for potential utilisation in pulp and paper production.
3. Determine the full potential utilisable gains from thinnings and harvesting volumes and sawmilling residues, from full diversification into both plywood and paper production.

1.4.2. Research Questions

1. What is volume of first and second thinning, harvesting and sawmilling waste that can be utilisable for plywood production?
2. What is the volume of first and second thinning, harvesting and sawmilling waste that can be utilisable for paper production?
3. What is the volume of first and second thinning, harvesting and sawmilling waste that can be utilisable for full diversification into both plywood and paper production?

CHAPTER 2 - LITERATURE REVIEW

2.1. Introduction

Product diversification has become a topic of significant interest in the forestry industry. To put it simply, diversification is a scaling strategy in which a company expands the range of goods and services it provides (André and Pache, 2016). As demand for traditional sawn timber products has fluctuated, forestry companies have sought to expand their product portfolios and this has led to exploring the potential of plywood and paper products as alternative revenue streams. Wood and non-wood forest products have supported economies globally employing approximately 33 million people, most of them, in developing nations. Although the forestry sector is thought to account for only 1% of the world's GDP, this percentage is larger in nations with abundant forests (FAO, 2020). For example, wood products dominate formal GDP contributions in countries with strong timber industries like Sweden, Canada and Brazil (World Bank, 2019). Non-wood forest products (NWFPs), while often underreported in national accounts, contribute significantly to informal economies. For example, in India, NWFPs contribute over 20 % of forest-related GDP (Chopra, 2021). There is thus scope for increasing the formal wood industry's contribution to GDP.

Depending on the region, tree harvesting often accounts for 30 to 80 percent of the world's annual forest development. For example, in the year 2020, the harvest rate for USA was less than 50 %, while Finland and Sweden were 75-80%, and the EU average was about 65%. In China and Russia they had 30% or less (Hetemäki et al., 2020). Therefore, encouraging the best possible use of obtained wood is essential to the long-term viability of the forestry industry.

The rising demand for varied wood-based products, coupled with significant fluctuations in timber resources, necessitates a thorough understanding of how product diversification integrates the use of thinnings, harvesting residues, and sawmilling byproducts. This understanding is crucial for sustainable forest management and economic viability (Freer-Smith et al., 2019). The transition to a wider variety of forest products is only sustainable if it is supported by more efficient utilisation of forest resources and a reduction in waste.

The strategic integration of plywood and paper manufacturing alongside sawn timber production can foster a symbiotic relationship, wherein materials formerly relegated as waste or deemed low-value are repurposed into value-added commodities. This amplifies the economic yield from each harvested tree and fosters a more circular bioeconomy. There is a significant need for increased investment in research on these questions compared to the current situation (Hetemäki et al., 2020). The diversification of forest products into plywood and paper production in even-aged pine plantations traditionally grown for sawn timber, presents a multifaceted challenge and opportunity for optimising utilisable tree volume.

2.2. Potential of Utilising Thinnings and Harvesting Residues for Plywood Production

Globally, forest thinning and harvesting residues represent a significant potential source of raw material for plywood production. Food and Agriculture Organisation FAO (2022) established that approximately 50-60 % of harvested wood is processed into sawn boards, plywood and engineered wood globally. Approximately 30-50 % of harvested wood biomass is left as residues, which could be repurposed for plywood manufacturing if properly collected and processed (FAO, 2021).

In 2023, 5 % of the global plywood market, valued at US$84 billion, was derived from thinning and harvesting residues. In Europe, less than 20 % of thinning logs are processed into plywood due to size limitations and in Scandinavia about 15-20 % of thinning logs are used in plywood-core production (European Forest Institute, 2023). Japan utilises about 70 % of thinning logs for the production of chips and plywood cores due to its advanced processing technology (Japan Forestry Agency, 2021). David (2014) suggested that thinning logs can supply approximately 15-25 % of plywood raw material in managed forests. However, smaller diameters would mean a drop in veneer recovery rates from 70-80 % for large logs, down to 50-60 % (Dobner et al., 2013).

Forest residues are often underutilized but have been tested as supplementary material for plywood. Some studies suggest that up to 20 % bark content can be incorporated into plywood cores without significantly reducing strength, but ultimately improving resource efficiency (Kain et al., 2020; Supriyadi et al., 2025; Walkiewicz et al., 2022). Thiffault et al., (2023), added that only 30-50 % of logging residues are collected for bioenergy or wood products. In Europe, 60 % harvesting-residue usage was recorded in Scandinavia, while tropical regions recover less than 20 % (World Resources Institute, 2020). Finland and Sweden recover 10 % residues for plywood manufacturing (Metsa Group, 2023). In South East Asia, India collects less than 20 % of its residues while the rest are burnt (World Bank, 2020) and the Congo Basin utilises less than 10 % (World Resource Institute, 2022). Residue- based panels are approximately 10-15 % cheaper than those made from mainstream- production materials, although they require about 20 % more energy for drying (Bergman et al., 2014). However, the utilisation of thinnings and harvesting residues for plywood production hinges on several key factors, including the species and age of the pine, the quality and dimensions of the available wood. The recovery efficiency of the peeling process is also very key (Dobner et al., 2013).

2.3. Utilisation of Thinnings, Harvesting Residues and Sawmilling Residues for Pulp And Paper Production

First and second thinning, forest harvesting residues, and sawmill byproducts serve as feedstock for pulp and paper production around the world. The first and second thinning in managed forests yields 20–50 m^3/ha of recoverable biomass, depending on species and stand density (Telles-Antonio et al., 2022). Approximately 20-30 % becomes pulp for paper and packaging (World Bank, 2021). Harvesting residues (i.e. branches, tops, and small-diameter logs) account for 20–30 % of total harvested timber, with 10–25 % being suitable for pulp production (Enters, 2001). The FAO (2021) estimated that 1.2–1.8 billion m^3 of forest residues are generated annually worldwide, but only 35–45 % are currently utilised due to logistical and economic constraints. Sawmilling residues like sawdust, bark, and offcuts, contributes 40–50 % of log input, with 30–60 % being usable for pulp (Saal et al., 2017).

In Europe, Nordic countries recover 60–70 % of thinning residues for pulp, with Sweden and Finland leading in efficiency (Rytter et al., 2016). According to the European Forest Institute (2023), of the thinning volume in Europe, between 40-60 % is utilised for pulp or particleboard. Sawmill residues contribute 25 – 30 % of total pulp feedstock in the European Union (Forest Europe.2022). In North America, the U.S. and Canada generate 50–70 million dry tons of forest residues/year, with 40 % used in pulp mills (USDA Forest Service, 2023). North American sawmill residues supply 15-20 % of pulpwood demand (USDA Forest Service, 2022). In Asia, China and India rely on agricultural residues, but increasingly use *Eucalyptus* and *Acacia* thinning wood (Pandey, 2022). East African *Pinus* and *Eucalyptus* plantations generate 8–15 m^3/ha of thinning residues, but most are burned (TAFORI, 2018). Logging residues from tropical forests in West Africa, could supply 5–10 million m^3/year, but collection is inefficient (Uzu et al., 2022). In Southern Africa, sawmills produce 3-5 million tons/year of residues, yet only 20-30 % are used for pulp (Haile et al., 2021).

2.4. Potential for Thinnings and Harvesting and Sawmilling Residues in Full Diversification into Plywood and Paper Production

The diversification of product streams from pine sawn timber to plywood and paper products can significantly increase the overall utilisation of tree volume harvested from even-aged pine plantations (Pandey, 2022). Thus the growing demand for sawn timber, coupled with engineered wood products, combined with the requirement for sustainable forest management, has prompted research into alternate raw materials for plywood manufacture. Advancements in adhesive technology have enabled the production of plywood from a wider range of wood species and grades, potentially increasing the suitability of previously underutilised pine resources for plywood manufacturing (Islam et al., 2021). The use of thinning logs in plywood production has the potential to increase resource efficiency, reduce waste, and promote sustainable forestry practices.

By diverting thinnings, harvesting residues, and sawmilling residues to plywood and paper production, a greater proportion of the harvested biomass is converted into valuable products, reducing waste and maximising the economic value derived from the forest resource (Asamoah et al., 2020). The easiest timber residues to incorporate into product diversification are machining off-cuts and other wastes containing no substance other than wood, which can be used in the particleboard sector or to extract high value-added molecules (Ramaux et al., 2024). It is important to quantify these wastes in order to fully appreciate their impact on the utilisable wood volume.

CHAPTER 3 – MATERIALS & METHODS

3.1. Description of the Study Site

The study was conducted at Nyanga Pine Division of The Wattle Company Pvt Ltd, located between coordinates 18º32′57″S 32º39′21″E and 18º25′49″S 32º41′52″E in Mutasa Rural District, eastern highlands of Zimbabwe. The total Plantation Area is approximately 12 507 hectares. The Division is made up of two blocks of Estates namely Nyanga Estates (comprising Selborne, Inyawari, Reenen, Nyakupinga and Mutarazi estates) and Dunsinane Estates made up of Simla and Eastbourne estates. Nyanga estates are located about 65 kilometers from Mutare along Nyanga road while Dunsinane estates are 35 kilometers north of Mutare along Smallbridge Dam road. The plantations are currently managed on a 20 year rotation with an average of 450 hectares being clear felled annually to produce approximately 150 000 m^3 of pine saw logs (WACO, 2006).

The lowest altitude is 1020 meters reaching a maximum of 1945 meters above sea level. Nyanga Pine Division is characterised by rugged topography and is located in the Nyanga mountain range's Eastern escarpment. It is the source of a number of perennial rivers, including the Odzi, Duru, Nyakupinga, and Mutarazi Rivers (Mujuru et al., 2014).

Nyanga Pine Division is classified under Natural Region (NR) I in Zimbabwe's agro-ecological classification system, with average annual rainfall estimated at roughly 1,200mm. The seasonality of the region is classified as moderate, with distinct wet and dry seasons (Mujuru, 2014). Besides contributing to the lush vegetation, this makes it conducive to forestry activities. The temperatures are generally mild, with cooler conditions at higher elevation, which is typical of mountainous region. The minimum temperature may drop as low as 0 °C, while the average maximum temperature is 28 °C with a mean of 24 °C. The months of May through August have the lowest temperatures, while October through February have the warmest. The average relative humidity ranges from 58% in September to 86% in January and February. Easterly blowing winds are prevailing and dominant during the months of November to May (WATCO, 2025).

The Division is characterised by Kaolinitic soils (Zimbabwean classification), which is orthoferrallitic. In the FAO classification, this corresponds to Rhodic ferralsols (FAO, 2006).

The soils have a high level of erosion resistance and are distinguished by their good depth, permeability, and structural stability. They have very poor chemical properties, especially low weathering rates and high acidity (Mujuru et al., 2014).

Nyanga Pine Estates are well known for their rich biodiversity and unique ecosystems. The surrounding regions are home to a wide range of native plants and animals, including evergreen mountain forests dominated by Brachestergia species, even though the vegetation type within the pine plantations is primarily *Pinus* species specifically managed for sawn timber production (Food and Nutrition Council, 2022). These indigenous forests support various wildlife species and maintain the vast biodiversity.

3.2. Research Design

A randomised block design was used for data collection from harvesting compartments, and a split plot design was applied for thinnings. Sampling focused on two dominant commercial *Pinus* species: *Pinus patula* and *P. taeda*. The species constitute the main pine timber species commercially grown in Zimbabwean forest estates. Plots of pine trees were randomised into different groups based on proportional representation according to species and age. Each treatment block was replicated across the Estates, so as to account for variable growth conditions, such as soil type and moisture levels. This design enabled consideration of the utilisable volumes across the different species type while accounting for external environmental variations (Gomez and Gomez, 1984).

3.3. Sampling and Data Collection

The pine plantation was stratified by species into six strata, with focus on 4, 12 and 20 year compartments which are the years for first thinning, second thinning and clear felling respectively. The *Pinus* species cover a total of 9999 ha, with 385, 424 and 404 ha at 4, 12 and 20 years respectively. All compartments planted with *Pinus patula* and *Pinus taeda* in the selected age classes were sampled because the other species did not have some of the age classes required in this research.

Within each treatment group systematic sampling was used to ensured that the data collected is representative of the entire population. A 3% sampling intensity was applied to the areas selected for each species, at each age class to establish the sample area from which diameter at breast height and height measurements were collected and recorded.

Tree diameters were classified into 2 cm diameter classes presented as odd numbers, and any decimal were rounded down to the nearest odd number in centimeters. Tree heights were rounded down to the nearest meter so as to simplify inventory entries.

3.3.1. Quantification of Standing Volumes due for Harvesting

Harvesting data was collected from 20-year old trees due for harvesting. Twenty-eight compartments were sampled from the compartment register. The selected compartments are listed in Appendix I**.** Table 3.1 shows the number of tree samples from *P. patula* and *P. taeda*.

Table 3.1: Total areas by *Pinus* species, percentages representation, sample area and number of sample trees per species at 20 years

Species	**Total Species Area (Ha)**	**Percentage (%)**	**Sample Area (Ha)**	**No. of Sample Trees**
P. patula	273	82	8.205	3696
P. taeda	59	18	1.77	798
Totals	**332**	**100**	**9.975**	**4494**

The following steps were followed:

A systematic sampling design with a randomly selected starting point was used following Kohl and Magnussen (2016). Every twentieth line (60 m apart) was considered as the plot. Plots were laid perpendicular to the second line-thinning direction that was used historically so as to cater for variation in growth due to varying conditions resulting from line and selective tree removal. This sampling design was chosen to uniformly distribute the sample trees over the entire compartment thus accounting for terrain and environmental condition diversity. In each line every fifth tree was considered as a sample tree where height and diameter (dbh) were measured using sunnto hypsometer and diameter tape respectively following West (2004). This measurement helped in determining the volume proportion to merchantable height.

Tree volume was calculated using equation I (Oderwald and Popescu., 2003).

$$\mathbf{V = \frac{\pi}{4} \times D^2 \times H \times F} \qquad \textbf{[I]}$$

Where
V is the tree volume in cubic meters,
D is the diameter (over-bark) at breast height in meters,
H is the height in meters, and
F is a form factor that accounts for the shape of the tree.

For the purpose of this study the form factor used was **0.4** (Edwards, 1983).

3.3.2. Quantification of Second Thinning Standing Volumes

Second thinning data was collected from 12-year old trees due for the second thinning operation. Twenty-six compartments were sampled from the compartment register and are listed in Appendix II**.** The representation of the main two *Pinus* species; *P. patula* and *P. taeda* are shown in table 2. *Pinus elliottii, P. kesiya, P. Tecunumanii* and *P. maximinoi* were not included because of low representation in the overall plantation. Table 3.2 shows the number of tree samples from *P. patula* and *P. taeda*.

Table 3.2: Areas per *Pinus* species, percentages representation, sample area and number of sample trees per species at 12 years of age

Species	Total Species Area (Ha)	Percentage (%)	Sample Area (Ha)	No. of Sample Trees
P. patula	229.5	54	6.89	1670
P. taeda	99.5	23	2.99	704
Total	**329**	**77**	**9.88**	**2374**

The following steps were followed:

Systematic sampling was used after stratification by *Pinus* species following Shaw (2017). Two hundred and thirty-six trees are removed per hectare during the second thinning operation. This number was multiplied by the total sample area of 9.88 Ha, to give the sample population. The proportional representation for each species at 12 years was used to determine the number of trees per species to be included in the sample.

A random starting point was selected where a fixed area square sample plot measuring 441m^2 (i.e. 21 meters * 21 meters) was established. Trees to be removed during second thinning were marked following Rollinson (1985). Under this system, trees exhibiting undesirable qualities were targeted for removal.

All trees marked for removal during thinning were measured to cater for variation in growth within the compartment. Using a split plot design, two sample plots were located in every 3 hectares within each of the compartments being sampled. The number of samples in each compartment is shown in Appendix 2. This sampling design was chosen to uniformly distribute the sample trees over the entire compartment thus accounting for terrain and environmental condition diversity. In each plot all marked trees were measured for height and diameter (dbh) using sunnto hypsometer and diameter tape respectively. The tree volumes were calculated using equation I.

3.3.3. Estimation of Average Bark Thickness

Among the sample trees at 12 and 20 years respectively, 10 stems per species (*Pinus patula and P. taeda)* were randomly identified and numbered for destructive sampling to enable tracking through the felling and log making process for measurement of bark thickness and comparison with standing tree sampling results. These 10 sample trees were felled and cross cut into log classes categorised by over-bark diameter class and log length following FAO (1982). The tip diameter classes were as follows:

- Saw logs: Diameter – 13 cm and above, length - 2.1 m to 6.0 m.
- Plywood logs: Diameter – 11 cm, length - 1.4 m and 2.7 m.
- Pulp logs: Diameter – 7 cm – 9 cm, length - typically shorter lengths.

This classification guided the log making process during the inventory process.

Log diameters under-bark were measured at the tips and butts of each log and bark thicknesses were calculated following equation II

$$\boldsymbol{dub = dob - (bark\ thickness * 2)} \qquad \textbf{[II]}$$

Where
dob is diameter over-bark, and

dub is diameter under-bark.

An average bark thickness was derived by dividing the total bark thicknesses by the total number of measurements. Each measured diameter class was reduced by the bark percentage before volume calculations were made.

3.3.4. Estimation of Utilisable Percentages per Product

For each log used for bark thickness measurements, over-bark tip diameter, mid diameter and big-end diameter including log length were measured using diameter caliper and tape measure respectively, before entering the sawmill.

NB. Defects, branches, or other factors that limit the usable portion of the tree, affecting saw logs merchantable volume were considered for the purpose of the study, as they can still be utilised for pulp.

Each diameter was reduced by the average bark thickness.

Log volume was calculated using Newton’s formula III (Purser Tarleton Russell Ltd., 2025).

$$\boldsymbol{V = L * (D^2 + 4 * Dm^2 + d^2) * (\pi/24)} \qquad \textbf{[III]}$$

Where

V is the volume in cubic meters,
L is the length of the log in meters,
D is the large-end under-bark diameter of the log in meters,
Dm is the under-bark diameter midway along the log length in meters,
d is the small-end under-bark diameter of the log in meters.

Logs below the specified minimum diameters, were not recorded since they were not contributing to the intended product categories. The saw logs and veneer logs were then transported to the sawmill for processing while the remaining residues were put back into the compartment after taking measurements as there was no pulp plant at the time to process them.

The resultant utilisable volume down to 13 cm tip diameter was deducted from utilisable volume down to a minimum tip diameter of 11 cm and 7 cm to give the volume to be gained from the introduction of plywood and paper production respectively for the 10 trees.

The average gained utilisable volume for the 10 trees per product category was calculated as a percentage of average total tree volume using equation IV (FAO, 2020).

$$\text{Percentage of Volume Used} = \frac{Volume\ for\ Product}{Total\ Standing\ Tree\ Volume} \times 100 \qquad \textbf{[IV]}$$

Where

"Volume for product" is the volume of the specific part of the tree in cubic meters, being processed for a particular product.

"Total standing tree volume" refers to total volume of the tree before it is felled.

NB. As the 'volume for product' was derived through destructive sampling, it was assumed that the non-utilisable volume would account for sawdust, undersized lop and top and bark lost during processing.

The resultant average percentage per product and average wastage percentage was applied to the average clear felling and second thinning volume per hectare and per annum respectively for Nyanga Pine Division to get an indication of the potential proportion of standing volume that can be utilised by each product.

3.3.5. Quantification of First Thinning Volume

First thinning data was collected from 4-year old stands due for first thinning to estimate volumes that can be utilised for paper production. Twenty-two compartments were used in the sample. The chosen compartments are shown in Appendix III.

Systematic sampling was used on compartments stratified according to the two main species: *Pinus patula* and *P. taeda* to determine potential for utilisation in pulp production. Four hundred and twenty-five trees are removed per hectare during the thinning operation. This number was multiplied by the sample area of 8.43 Ha to give the sample population. The proportional representation for each species within the whole plantation was used to determine the number of trees per species to be included in the sample. Table 3.3 shows the number of tree samples from *P. patula* and *P. taeda*.

Table 3.3: Areas for sampling per Pinus species at 4 years

Species	Total Area (Ha)	Percentage (%)	Sample Area (Ha)	No. of Sample Trees
P. patula	227	59	6.81	2895
P. taeda	54	14	1.62	689
Total	281	63	8.43	3584

Trees to be removed during first thinning were marked following Rollinson (1985). Only the trees marked for removal during first thinning were measured so as to a prpoer representation of the potential yield at 4 years. A split plot design where two sample plots measuring 441m^2 (i.e. 21 meters * 21 meters) were established for every 3 hectares within each of the compartments being sampled. To achieve this, each compartment was subdivided into 3 ha sections where two plots were placed randomly. Appendix 4 shows the area for each compartment and the number of plots taken in each. This sampling design was chosen to uniformly distribute the sample trees over the entire compartment thus accounting for terrain and environmental condition diversity. In each plot every marked tree was measured for height and diameter (dbh). A measuring rod and diameter caliper were used for measuring height and diameter, respectively.

Equation I was used to estimate the volume of trees to be removed during the first thinning operation and derived by multiplying the average volume per stem by the number of stems to be removed during the operation (i.e. 425 trees).

3.3.6. Quantification of Sawmilling Timber and Residues

Sawmilling residues, made up of chips, offcuts, sawdust and trimmings constitute a significant amount of volume which can be incorporated into value added products like paper. For this study, the rough sawn timber and associated offcuts from processing of wet timber were measured and recorded. The remaining part (chips, saw dust, trimmings, etc.) was not considered for measurement as they are utilised as boiler fuel or burnt in the incinerator (Sofuoğlu and Kurtoğlu, 2012).

The weight of empty 15-tonne haulage truck(s) to be used for transporting logs was determined on a weighbridge before loading ten 15-tonne truck-loads of 20-year-old saw logs with tip diameters of 13 to 45 cm and log lengths from 2.1 m to 6.0 m. The logs were tracked through the sawmill production line. Each load (incl. trucks and saw logs) was weighed at the weighbridge as they entered the sawmill and their weights recorded. Each log was coloured on the big ends using paint, which was allowed to dry, to enable easier tracking through the production line (Dykstra et al, 2003). The weights of the empty truck(s) were deducted from the weight of the loaded truck(s) to give the weight of the logs only.

NB. Due to the mix of pine species and trimming in the sawmill during processing, species proportional representation was disregarded after sawn timber processing. Instead, only those offcuts from logs with paint marks made during loading of logs to the sawmill were considered.

All loads for the study were processed at the same time and separately from non-study production material.

The weights of all the logs were added together and equation V used to give the total delivered volume.

$$\boldsymbol{Volume}\ (\boldsymbol{m^3}) = \frac{\boldsymbol{Weight}\ (\boldsymbol{Kg})}{\boldsymbol{Density}\left({}^{\boldsymbol{kgs}}/_{\boldsymbol{m^3}}\right)} \qquad \textbf{[V]}$$

Where the average density of pine of 800kg/m^3 was used as is recommended by the Global Allometric Organisation (Chave et al., 2014).

The dimensions of the rough sawn timber produced in the sawmill were captured and computed using equation VI (FAO, 2020).

$$\boldsymbol{V} = \sum((\boldsymbol{L}(\boldsymbol{m}) * \boldsymbol{W}(\boldsymbol{mm}) * \boldsymbol{T}(\boldsymbol{mm}))/\ \mathbf{1\,000\,000}) \qquad \textbf{[VI]}$$

Where;

L is the board length in meters,
W is the board width in mm and
T is the board thickness in mm

Offcuts were collected and stacked for each load to avoid risk of mixing with material outside that marked for the study. This stacking method allowed easier loading arrangement into the pre-weighed 15-tonne trucks before being weighed on the weighbridge to determine the weight of the offcuts. The weights of the empty trucks were deducted from the weights of the loaded trucks to give the weight of the offcuts only, which were added together to get the total weight of offcuts. Equation VI was used to get the total volume of offcuts produced.

Percentage volume of offcuts generated from processing the total volume of the 10 saw-log loads was calculated and multiplied by the average annual volume delivered to the sawmill, 150 000m^3, for processing into rough sawn timber to give an indication of the offcut residues which can be converted into utilisable volume for the purpose of paper production.

NB. There was no volume of offcuts that could be used for plywood as offcuts cannot be rotary peeled.

3.4. Data Analysis

A three-way ANOVA statistical test was used to determine if there was a statistically significant difference in utilisable volume expected due to diversification into plywood and paper products. The analysis was done using ‘utilisation based on the production of sawn timber only’ as the control against which utilisation by plywood and paper products were analysed.
A p-value less than 0.05 would have resulted in rejection of H_0, as a significant effect would exist. Post-hoc tests were used to determine which product class contributed the most significant change to utilisable volume.

The statistical analysis was carried out in R using base R functions aov (analysis of variance) and lm (linear model). For second thinning and harvesting residues as well as first thinning logs the aov function was used while the lm (linear model) function was used for sawmilling residues (R Core Team, 2021).

CHAPTER 4 - RESULTS

4.1. Thinnings and Harvesting Volumes with Potential to be used for Plywood Production

Product diversification that includes plywood has significantly higher total utilisable volume per hectare (252 m^3) than sawn timber (238 m^3) as indicated by the p-values per raw material type. This volume is recovered from second thinning and clear felling only, with nothing being utilised from first thinnings. Table 4.1 shows the potential volume increase per hectare per raw material type, to be gained from diversification into plywood production.

Table 4.1: Volume with potential to be utilised for plywood (Mean ± SE)

Raw material Type	Standing Volume (m^3/Ha)	Saw logs (m^3/Ha)	Plywood logs (m^3/Ha)	p-value
First Thinning n = 3584	16.0978 ± 0.0006	-	-	0.05
Second Thinning n = 2374	43.6153 ± 0.0038	25.6718 ± 0.0022	0.7429 ± 0.0001	0.00
Clear Felling n = 4494	326.3394 ± 0.0112	212.1206 ± 0.0073	13.0536 ± 0.0004	0.00

4.2. Thinnings, Harvesting and Sawmilling Residues with Potential to be used for Pulp and Paper Production

Results for pulp and paper potential utilisable volume are split into two; (i) volume to be recovered through pulp and paper production, from the forest resource and (ii) volume to be recovered from sawmilling residues after processing of delivered saw logs.

Product diversification to include plywood has potential to significantly increase total utilisable volume per hectare to a minimum of 271 m^3, up from 238 m^3 for sawn timber production only, as indicated by the p-values per each raw material type. Utilisable volume for pulp and paper production can be recovered from all three raw material types (1st thinning, 2nd thinning and clear felling). Table 4.2 shows the potential volume increase per hectare, per raw material type, to be gained from diversification into pulp and paper production.

Table 4.2: Volume from forest resource with potential to be utilised for pulp and paper products (Mean ± SE)

Raw material Type	Standing Volume (m^3/Ha)	Saw logs (m^3/Ha)	Pulp/paper logs (m^3/Ha)	p-value
First Thinning n = 3584	16.0978 ± 0.0006	-	10.0060 ± 0.0004	0.00
Second Thinning n = 2374	43.6153 ± 0.0038	25.6717 ± 0.0022	4.5388 ± 0.0004	0.00
Clear Felling n = 4494	326.3394 ± 0.0112	212.1206 ± 0.0073	18.6357 ± 0.0006	0.00

Product diversification that includes pulp and paper products has significantly higher total utilisable volume recovery per hectare (183 m^3) at the processing plant than sawn timber (102 m^3). Table 4.3 shows the potential volume increase per hectare, per raw material type, to be gained from sawmilling residues through diversification into pulp and paper production.

Table 4.3: Volume from Sawmill with potential to be utilised for pulp and paper products (Mean ± SE)

Raw Material Type	Input Volume (m^3)	Sawn Timber Volume (m^3)	Pulp/Paper Volume (m^3)	p-value
Second Thinning n = 2374	25.6717 ± 0.0022	11.0389 ± 0.0010	8.7284 ± 0.0008	0.00
Clear Felling n = 4494	212.1206 ± 0.0073	91.2119 ± 0.0031	72.1210 ± 0.0025	0.00

4.3. Thinnings, Harvesting and Sawmilling Residues with Potential to be used Through Full Diversification into Plywood, Pulp and Paper Production

Full product diversification that includes all products namely; sawn timber, plywood, pulp and paper products has significantly higher total utilisable volume recovery per hectare (230 m^3) than sawn timber only which produces an end-product volume of 102 m^3 per hectare. Of the 230 m^3 volume achievable from full utilisation, 195 m^3, 25m^3 and 10 m^3 are derived from clear felling, second thinning and first thinning respectively. Figure 4.1 shows the volume distribution per product type achievable through full product diversification.

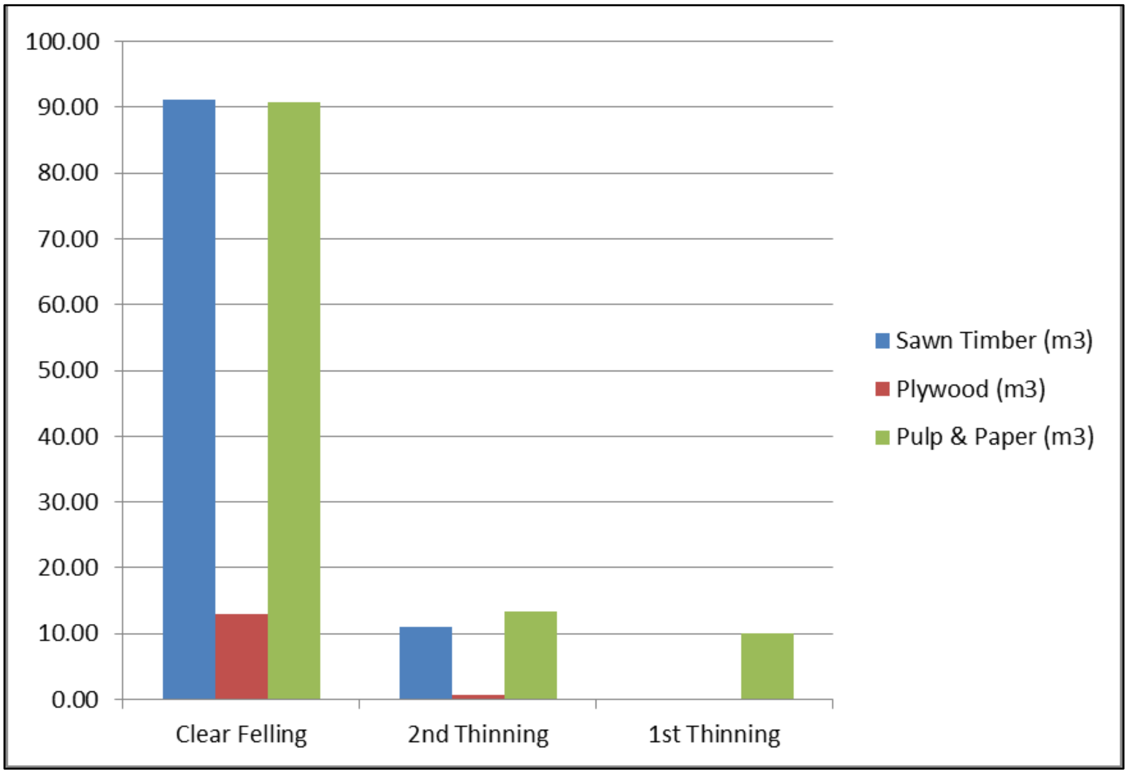

Figure 4.1: Volume distribution per product type achievable through full product diversification

CHAPTER 5 – DISCUSSION

5.1. Thinnings and Harvesting Volumes for Plywood Production

Results showed a significant utilisable volume for plywood production from second thinning residues and clear-felling residues (Table 4.1). This aligns with global trends where thinning logs contribute 15 – 25% of plywood feedstock in managed forests (David, 2014), though in this study, a lower recovery (e.g., 1.7% of clear-felling volume) reflects a narrow diameter range for plywood logs which quickly overlaps with the minimum diameter for saw logs. The European Forest Institute (2023) similarly reported that less than 20% of thinning logs in Europe are used for plywood due to size constraints, mirroring Nyanga Pine's potential. The 6% gain in utilisable volume (238 - 252 m^3/ha) highlights plywood's role in valorising residues but underscores the need for advanced processing technology (e.g., Japan's 70% utilisation) to overcome diameter-related inefficiencies (Japan Forestry Agency, 2021). First-thinning material was unsuitable for plywood due to small diameters (<11 cm), aligning with global limitations (EFI, 2023; Dobner et al., 2013).

5.2. Thinnings, Harvesting, and Sawmilling Residues for Paper Production

Diversification into paper production unlocked substantial volume: first thinning yielded 10.01 ± 0.0004 m^3/ha, second thinning residues 4.54 ± 0.0004 m^3/ha, clear-felling residues 18.64 ± 0.0006 m^3/ha, and sawmill offcuts contributed 72.12 ± 0.0025 m^3/ha (Tables 4.2 – 4.3). This resonates with FAO (2021), which estimates that 20–30 % of global thinning biomass is suitable for pulp, although in this study there was higher efficiency for first-thinning volume utilised (62.2 %). Notably, sawmill residues, often underused in Zimbabwe (Katsvanga & Mudyiwa, 2019) represented 34% of paper feedstock, aligning with global patterns where sawmill byproducts supply 30 – 60% of pulp (Saal et al., 2017). The 12% utilisable volume gain from 238 to 271 m^3/ha surpasses plywood's gains, emphasizing paper's viability for low-grade biomass utilisation. Pandey (2022) stressed that, pulp markets offer the broadest utility for residues, supported by this study where, 119,033 m^3/year supported paper potential from Nyanga Pine, a resource efficiency milestone consistent with FAO (2021) goals.

5.3. Full Diversification into Plywood and Paper Production

Full diversification maximised utilisable volume to 285 m³/ha (124,057 m³ annually), a 73.8 % efficiency rate (Table 4.4). This synergy reduced waste by repurposing 88.5% of forest biomass (vs. 57% in sawn-timber-only systems), validating Asamoah et al. (2020), who stated that integrated product streams enhance circular bioeconomies. First-thinning material, previously wasted, became viable for paper yielding 10.01 m³/ha, while plywood production utilised smaller logs (down to 11 cm tip diameter). This aligns with Hetemäki et al. (2020), who emphasised the need for "cascading use" of wood for sustainability. However, logistical barriers remain as the study assumed 100% residue recovery, whereas Thiffault et al. (2023) showed that only 30–50% of residues are typically collected globally. The 221% potential increase in utilisable volume over sawn timber alone underscores diversification's transformative potential but warrants investment in collection infrastructure.

5.4. Synthesis and Implications

The 114 m³/ha gain from paper production alone versus 13.8 m³/ha for plywood highlights paper as the highest-value diversification pathway, supporting Pandey's (2022) assertion that pulp markets optimise low-grade biomass use. However, plywood diversifies revenue streams, mitigating market risks (Hansen and Juslin, 2018). Zimbabwe's heavy reliance on sawn timber (Katsvanga & Mudyiwa, 2019) renders these findings critical for policy: as investing in residue collection could unlock 124,057 m³/year of additional volume. Future research should address economic viability, including transport costs for dispersed residues and technology adoption for small-log processing such as Japan's advanced peeling (Japan Forestry Agency, 2021).

Nyanga Pine Division can transform from a sawn-timber monoculture into a multiproduct hub, aligning with global forest bioeconomy trends (Hansen & Juslin, 2018). By adopting a "cascading use" approach (Hetemäki et al., 2020), the organisation's forestry operation can unlock 124,057 m³/year of additional value, fostering sustainability and economic resilience.

CHAPTER 6 - CONCLUSION AND RECOMMENDATIONS

6.1. Conclusion

Results suggest that product diversification into plywood and paper production can significantly enhance utilisable wood volume instead of sawmilling only. The plywood potential can be met by volumes from second thinning and clear-felling residues, thus increasing total utilisable volume by 6 % and utilising mid-sized residues.

A potential of 33.20 m^3/ha can be utilised for paper production using paper-compatible biomass; first thinnings, second-thinning residues and clear-felling residues. Of the saw logs that are delivered to the sawmill, offcuts are also suitable for incorporation into paper production.

Full diversification produces 285 m^3/ha of utilisable volume for integrated production, giving a 73.8 % efficiency and 20 % increase in volume compared to sawn timber alone. The synergy of plywood and paper increases volumes to near-total biomass utilisation. The null hypothesis (H_0), that diversification has no potential to increase volume utilisation is rejected. Results affirm that product diversification can significantly boost resource efficiency, economic resilience, and sustainability in Forestry.

Based on findings, operational shifts can enable the collection and systematic recovery of clear-felling residues (18.64 m^3/ha) and sawmill offcuts (72.12 m^3/ha) for paper production, leveraging existing infrastructure. First thinning biomass would then be redirected from waste to paper pulp, requiring minimal capital investment.

6.2. Recommendations

There is need to invest in higher efficiency equipment like Japan's core veneer systems to enhance plywood recovery from second-thinning logs, as well as to consider bark utilisation by producing bark-based panels in order to utilise 5–8% of residue volume currently incinerated. Strategic partnerships like collaborating with regional paper mills (e.g. South Africa), can enable access to the pulp market.

There is need for policy advocacy by lobbying for incentives supporting diversified wood-processing infrastructure. More research into transport/logistics costs for residue collection is needed in order to address recovery gaps. Species-specific trials are needed, that test diversification potential in minor species (e.g., *P. kesiya*, *P. maximinoii*) which were excluded from this study.

REFERENCES

Adhikari, S. and Ozarska, B. (2018). Minimizing environmental impacts of timber products through the production process "From Sawmill to final products". *Environtal Systems Research*, 7(1), 6. https://doi.org/10.1186/s40068-018-0109-x.

African Natural Resources Centre (ANRC). (2021). Intra-African trade in wood products: Case studies from Benin, Cameroon, Ghana and the Republic of Congo. African Development Bank. Abidjan, Cote d'Ivoire.

Andre, K., and Pache, A. C. (2016). From caring entrepreneur to caring enterprise: Addressing the ethical challenges of scaling up social enterprises. *Journal of Business Ethics*, 133(4):659-675. https://doi.org/10.1007/s10551-014-2445-8.

Asamoah, O., Kuittinen, S., Abrefa Danquah, J., Quartey. E.T., Bamwesigye, D., Mario Boateng, C. and Pappinen, A. (2020). 'Assessing wood waste by timber industry as a contributing factor to deforestation in Ghana.' *Forests*, 11(9):939. https://doi.org/10.3390/f11090939.

Asumadu, K. (2004). Development of wood-based industries in Sub-Saharan Africa: A report prepared for the project "Lessons learnt on sustainable forest management in Africa." Asumadu & Associates, East Brighton, Australia.

Baral, S., Neumann, M., Prasad Joshi, K. Basnyat, B. and Vacik, H. (2025). Exploring the implications of selective harvesting for forest dynamics: A longitudinal analysis of Sal dominated community forests. *Trees, Forests and People*, 20. 100832. ISSN 2666-7193. https://doi.org/10.1016/j.tfp.2025.100832.

Bergman, R., Puettmann, M. E., Taylor, A. and Skog, K. E. (2014). The carbon impacts of wood products. *Forest Products Journal*, 64(7/8):220-231. https://doi.org/10.13073/FPJ-D-14-00047.

Boungou, W. and N'Doua, B. (2024). Climate Change and Wood Production. *Journal of Forest Economics*, 39:1-38. https://doi.org/10.1561/112.00000572.

Boncina, A., Kadunc, A. and Robic, D. (2007). Effects of selective thinning on growth and development of beech (Fagus sylvatica L.) forest stands in south-eastern Slovenia. *Annals of Forest Science*, 64 (1):47-57. hal-00884056

Chave, J., Andalo, C., Brown, S., Cairns, M., Chambers, J., E. M., & & E. A. (2014). Tree allometry and improved estimation of carbon stocks and balance in tropical forests. *Oecologia*, 145(1):87-99.

Chopra, K. (2021). 'Economic contribution of non-wood forest products in India.' *Journal of Forest Economics*, 35(2):45-60.

David, C. (2014). Commercial thinning and its potential contribution to the timber supply in British Columbia's Interior forests: A look at Finnish and Swedish forest practices and their applicability in British Columbia's Interior forests. Southern Swedish Forest Research Center.

Dobner, M., Nutto, L., and Higa, A. (2013). Recovery rate and quality of rotary peeled veneer from 30-year old *Pinus taeda* logs. *Annals of Forest Science*, 70(4):429-437. https://doi.org/10.1007/s13595-013-0274-z .

Duchesne, I., Pitt, D. and Tanguay, F. (2013). Effects of precommercial thinning on the forest value chain in northwestern New Brunswick: Part 4 – Lumber production, quality and value. *The Forestry Chronicle*, 89(04):474-489. https://doi.org/10.5558/tfc2013-089.

Duncker, P., Barreiro, S., Hengeveld, G., Lind, T., Mason, W., Ambroży, S. and Spiecker, H. (2012). Classification of Forest Management Approaches: A New Conceptual Framework and Its Applicability to European Forestry. *Ecology and Society*, 17. https://doi.org/10.5751/ES-05262-170451.

Dykstra, D., Kuru, G. and Nussbaum, R.. (2003). Technologies for log tracking. *International Forestry Review*, 5(3):262-267. https://doi.org/10.1505/IFOR.5.3.262.19137.

Edwards, P. N. (1983). Timber measurement: Afield guide. Forestry Commission Booklet 49. Fourth impression. Forestry Commission, Edinburgh.

Enters, T. (2001). Tresh or Treasure? Logging and mill residues in Asia and the Pacific. Asia-Pacific Forestry Commission. FAO. Bangkok. ISBN 974-7946-12-2.

European Forest Institute (EFI) (2023). Circular Bioeconomy in the forestry sector. Joensuu: European Forest Institute.

Falk, B. (2009). Wood as a sustainable building material. Forest products journal, 59(9).

Food and Agriculture Organisation (1982). Classification and definitions of forest products. FAO Forestry Paper, No. 32. FAO, Rome. ISBN: 92-5-001209-8.

Food and Agriculture Oganisation, (2006). Fertiliser use by crop in Zimbabwe. Food and Agriculture Oganisation, Rome. https://www.fao.org/4/a0395e/a0395e00.htm.

Food and Agriculture Organisation (2020). Forest product conversion factors. Food and Agriculture Organisation of the United Nations. Available at: http://www.fao.org/forest-resources-assessment/en.

Food and Agriculture Organisation (2020). Global Forest Resources Assessment 2020. Food and Agriculture Organisation of the United Nations. Available at: http://www.fao.org/forest-resources-assessment/en.

Food and Agriculture Organisation (2020). The state of the world's forests. Rome: FAO.

Food and Agriculture Organisation (2021). Global forest sector outlook. Rome: Food and Agriculture Organisation of the United Nations.

Food and Agriculture Organisation (2022). Global forest resources assessment. Rome: Food and Agriculture Organisation of the Unitaed Nations. Available at: http://www.fao.org/forest-resources-assessment/en.

Food and Nutrition Council (2022).Mutasa D|istrict Food and Nutrition Security Profile. Government of Zimbabwe.

Forest Europe (2022). State of Europe's forests. www.foresteurope.org.

Freer-Smith, P., Muys, B., Bozzano, M., Drössler, L., Farrelly, N., Jactel, H., Korhonen, J., Minotta, G., Nijnik, M. and Orazio, C. (2019). Plantation forests in Europe: challenges and opportunities. *From Science to Policy*, 9. European Forest Institute. https://doi.org/10.36333/fs09.

Gomez, K.A. and Gomez, A.A. (1984) Statistical Procedures for Agricultural Research. 2nd Edition, John Wiley and Sons, New York, 680 p.

Grobbelaar, S. and Visser, K. (2021). An analysis of South African sawmilling competitiveness. *Southern Forests: a Journal of Forest Science*, 83(1):28-37. https://doi.org/10.2989/20702620.2020.1813646.

Haile, A., Gelebo, G. G., Gelebo, T., Tesfaye, W., Mengie, A., Mebrate, A., Abuhay, D. Y. and Limeneh, D. Y. (2021). Pulp and papermill wastes: utilisations and prospects for high value-added biomaterials. *Bioresources and Bioprocessing*, 8(35). https://doi.org/10.1186/s40643-021-00385-3.

Hansen, E. and Juslin, H. (2018). Strategic Marketing in the Global Forest Industries (Third Edition). Oregon State University.

Hetemäki, L., Palahí, M. and Nasi, R. 2020. Seeing the wood in the forests. *Knowledge to Action*, 01. European Forest Institute. https://doi.org/10.36333/k2a01.

Hurmekoski, E., Jonsson, R., Korhonen, J., Jänis, J., Mäkinen, M., Leskinen, P. and Hetemäki, L. (2018). Diversification of the forest industries: role of new wood-based products. *Canada Journal of Forest Research*, 48(12):1417-1432. https://doi.org/10.1139/cjfr-2018-0116.

Ingram, V., Ndoye, O., Ipongo, D. M., Tieguhong, J. C. and Nasi, R. (2012). Non-timber forest products:contribution to national economy and strategies for sustainable management. Publications office of the European Union.

Islam, N., Rahman, F., Kumar Das, A. and Hiziroglu, S. (2021). An overview of different types and potential of bio-based adhesives used for wood products. *International Journal of Adhesion and Adhesives*, 112(012012):102992. https://doi.org/10.1016/j.ijadhadh.2021.102992.

Japan Forestry Agency (2021). Annual report on forests and forestry. Tokyo: Government of Japan.

Joshi, R., K.C., Jibesh, Dhakal, P. and Devkota, U. (2023). Exploring the Impact of Thinning Operations on Forest Ecosystems in Tropical and Temperate Regions Worldwide: A Comprehensive Review. *Journal of Resources and Ecology*, 14:1227-1242. https://doi.org/10.5814/j.issn.1674-764x.2023.06.011.

Kain, G., Tudor, E. M. and Barbu. M. (2020). Bark thermal insulation panels: An exploration study on the effects of bark species. *Polymers*, 12:2140. https://doi.org/10.3390/polym12092140.

Kassambara, A. (2020). Ggpubr: 'ggplot2' Based Publication Ready Plots. Available at http://cran.r-project.org/web/packages/ggpubr/index.html.

Katsvanga K., and Mudyiwa S (2019). The potential for all in-inclusive public private partnerships in Zimbabwe's forest sector. AFF Report. African Forest Forum, Nairobi.

Köhl, M., Magnussen, S. (2016). Sampling in Forest Inventories. In: Pancel, L., Köhl, M. (eds) Tropical Forestry Handbook. Springer, Berlin, Heidelberg. https://doi.org/10.1007/978-3-642-54601-3_72.

Mayaka, T. B., Eba'a-Atyi, R. and Nkie, M.(2014). On volume recovery index and implications for sustainable logging in Congo Basin. *Forest Ecology and Management*, 313:292-299. ISSN 0378-1127. https://doi.org/10.1016/j.foreco.2013.11.013.

Metsa Group (2023). Sustainability Report: Finland. Metsa Group.

Mujuru, L., Gotora, T., Velthorst, E.J., Nyamangara, J. and Hoosbeek, M. R. (2014). Soil carbon and nitrogen sequestration over an age sequence of Pinus patula plantations in Zimbabwean Eastern Highlands. *Forest Ecology and Management*, 313, 254-265.

Mujuru, L. (2014). The Potential of Carbon Sequestration to mitigate against climate change in forests and agro ecosystems of Zimbabwe, 220 pages. PhD thesis, Wageningen University, Wageningen, NL (2014) With references, with summaries in Dutch and English. ISBN 978-90-6173-928-5.

Ndoye, O., Ruiz Perez, M. and Eyebe, A. (1998). The Markets of Non-Timber Forest Products in the Humid Forest Zone of Cameroon. *Rural Development Forestry Network Paper*.

Ngobi, J. (2020). Improvement of timber recovery from pine sawlogs using a band sawmill. *Journal Of Rural Development*, 4, 421-430.

Oderwald, R. and Popescu, S. (2003). A Simplified Method of Predicting Percent Volume in Log Portions. Southern Journal of Applied Forestry, 27. 10.1093/sjaf/27.3.149. DOI:10.1093/sjaf/27.3.149.

Pandey, S. (2022). Wood waste utilisation and associated product development from under-utilised low-quality wood and its prospects in Nepal. *Springer Nature Applied Sciences*, 4(6):168. https://doi.org/10.1007/s42452-022-05061-5.

Purser Tarleton Russell Ltd. (2025). Timber Measurement Manual: Standard procedures for the measurement of round timber for sale purposes in Ireland. Ireland.

Ramaux, J., Ziegler-Devin, I., Besserer, A. and Nouvel, C. (2024). 3D Printing of Wood Composites: State of the Art and Opportunities. *Polymers*, 16(19):2827. https://doi.org/10.3390/polym16192827.

R Core Team (2021). R: A language and environment for statistical computing. R Foundation for Statistical Computing. Vienna, Austria.

Rollinson, T. J. D. (1985). Thinning Control (Third Edition). Forestry Commission Field Book 2. ISBN 0 11 710256 3.

Rytter, L., Ingerslev, M., Kilpelainen, A., Torssonen, P., Lazdina, D., Lof, M., Madsen, P., Muiste, P. and Stener, L. G. (2016). Increased forest biomass production in the Nordic and Baltic countries – a review of current and future opportunities. *Siva Fennica*, 50(5), 1660. 33 p. https://dx.doi.org/10.14214/sf.1660.

Saal, U., Weimar, H. and Mantau, U. (2017). Wood processing residue. Springer International Publishing. https://doi.org/10.1007/10_2016_69.

Schubert, M., Panzarasa, G. and Burgert, I. (2022). Sustainability In Wood Products: A New Perspective For Handling Natural Diversity. *Chemical Reviews* 123(5). https://doi.org/10.1021/acs.chemrev.2c00360.

Shackleton, S., Shackleton, C. and Shanley, P. (2011). Non-Timber Forest Products in the Global Context. *Tropical Forestry*, January 2011. ISBNs 978-3-64-217982-2, 978-3-64-217983-9, 978-3-64-226755-0 https://doi.org/10.1007/978-3-642-17983-9.

Shaw, J.D. 2017. Introduction to the special section on Forest Inventory and Analysis. J. For. 115(4): 246–248. doi:10.5849/jof-2017-002R1.

Sist, P., Peña-Claros, M., Pablo, J., Calles, B., Derroire, G., Kanashiro, M., Ortega, K., Piponiot, C., Roopsind, A., Veríssimo, A., Vidal, E., Wortel, V. and Putz, F.E. (2023). Forest management for timber production and Forest landscape restoration in the amazon: the way towards sustainability policy brief science panel For the amazon Key messages. 10.55161/wXnQ3205.

Sofuoğlu, S. and Kurtoğlu, A. (2012). A survey for determination of wastage rates at massive wood materials processing. *Wood Research*, 57. 297-308.

Supriyadi, D., Damayanti, D., Veigel, S., Hansmann, C. and Gindl-Altmutter, W. (2025). Unlocking the potential of tree bark: Review of approaches from extractives to materials for higher-added value products. Materials Today Sustainability, 29. https://doi.org/10.1016/j.mtsust.2025.101074.

Tanzania Forestry Research Institute (2018). Proceedings of the first TAFORI scientific conference on forestry research for sustainable ndustrial economy in Tanzania. TAFORI.

Telles-Antonio, R., Jimenez-Perez, J., Alanis-Rodriguez, E., Aguirre-Calderon, O. A. and Trevino-Garza, E. J. (2022). Growth and yield of forest plantations: analysisof the current state of global trends. Agricultura, Sociedad y Desarrollo. https://doi.org/10.22231/asyd.v19i2.987.

The Wattle Company Limited (2006). The Wattle Company Nyanga Pine Division Five year management plan. The Wattle Company Limited. Zimbabwe.

The Wattle Company Limited (2025) Five year business plan and 2025 budgets. The Wattle Company Limited. Zimbabwe.

Thiffault, E., Gianvenuti, A., Zuzhang, X. and Walter, S. (2023). The role of wood residues in the transition to sustainable bioenergy – Analysis of good practices and recommendations for the deployment of wood residues for energy. Rome: Food and Agriculture Organisation of the Unitaed Nations. https://doi.org/10.4060/cc3826en.

USDA Forest Service (2023). Future of America's forest and rangelands: Forest Service 2020 Resource planning Act assessment. United States Government. Washington DC. https://doi.org/10.2737/WO-GTR-102.

USDA Forest Service (2022).: 2022 Forest Service Climate Adaptation Plan. Forest Service. U. S. Department of Agriculture. United States Government. Washington DC.

Uzu, J., Bettinger, P., Siry, J. and Mei, B. (2022). Timber business in West Africa: a review and outlook. *International Forestry Review*, 24(2):240-256(17). Commonwealth Forestry Association. https://doi.org/10.1505/146554822835629578.

Walkiewicz, J., Kawalerczyk, J., Mirski, R., Dziurka, D. and Wieruszewski, M. (2022). The Application of Various Bark Species as a Fillers for UF Resin in Plywood Manufacturing. *Materials*, 15(20), 7201; https://doi.org/10.3390/ma15207201.

West, P. W. (2004). Tree and Forest Measurement (Third Edition). Springer, ISBN 978-3-319-14707-9. https://doi.org/10.1007/978-3-319-14708-6.

World Bank. (2019). Forests generate jobs and incomes. Washington, DC: World Bank.

World Bank (2020). Sustainable forestry in South-East Asia. Washington DC. World Bank.

World Bank. (2021). The changing wealth of nations 2021: Managing assets for the future. Technical Report. The effects of forest degradation on ecosystem services. World Bank Group.

World Bank. (2024). "Framework for Implementing Green Growth in Bangladesh." Washington DC, The World Bank Group.

World Resource Institute (2020). Global Forest Review. Washington. World Resources Institute. https://research.wri.org/gfr/global-forest-review.

World Resource Institute (2022). Global Forest Review. Washington. World Resources Institute. https://research.wri.org/gfr/global-forest-review.

Appendix I

Clear felling **c**ompartments to be sampled per *Pinus species,* their total areas, sample areas and number of sample trees

Compartment	**Species**	**Area (Ha)**	**Sample Area (Ha)**	**Sample Trees**
NYR022	*P. patula*	7	0.21	95
NYR029	*P.patula*	5	0.15	68
NYR064	*P. patula*	2	0.06	27
NYR121	*P. patula*	20	0.60	270
MUA001	*P. patula*	10	0.30	135
MUA002	*P. patula*	10	0.30	135
MUD019	*P. patula*	3	0.09	41
MUE013	*P. patula*	15	0.45	203
MUK003	*P. patula*	8	0.24	108
MUK004	*P. patula*	17.5	0.525	236
MUK014	*P. patula*	2	0.06	27
MUM013	*P. patula*	12	0.36	162
NYI070	*P. patula*	8.8	0.264	119
NYI087	*P. patula*	16	0.48	216
NYI088	*P. patula*	14	0.42	189
NYI089	*P. patula*	3	0.09	41
NYI090	*P. patula*	12	0.36	162
NYI095	*P. patula*	4.5	0.135	61
NYI097	*P. patula*	17	0.51	230
NYI102	*P. patula*	15	0.45	203
NYI108	*P. patula*	19	0.57	257
NYI105	*P. patula*	24	0.72	324
NYS035	*P. patula*	14	0.414	186
NYS087	*P. patula*	14	0.447	201
Species Total	***P. patula***	**273**	**8.205**	**3696**
NYS054	*P. taeda*	24	0.72	324
NYR024	*P. taeda*	13	0.39	176
NYR027	*P.taeda*	13	0.39	176
NYI069	*P. taeda*	9	0.27	122
Species Total	***P. taeda***	**59**	**1.05**	**474**
GRAND TOTAL	***All species***	**332**	**9.255**	**4170**

Appendix II

Second thinning **c**ompartments to be sampled per *Pinus species,* their total areas, sample areas and number of sample trees.

Compartment	Species	Area (Ha)	Sample Area (Ha)	Sample Trees	Number of plots
NYR65	*P. patula*	7	0.21	95	4
NYR074	*P.patula*	16	0.48	113	11
NYR075	*P. patula*	18	0.54	127	12
NYR076	*P. patula*	16	0.48	113	11
NYR077	*P. patula*	16	0.48	113	11
NYR078	*P. patula*	15	0.45	106	10
NYR113	*P. patula*	7	0.21	50	4
MUE005	*P. patula*	24	0.72	170	16
MUE007	*P. patula*	14.5	0.44	103	10
MUE011	*P. patula*	13	0.39	92	9
MUF006	*P. patula*	5	0.15	35	3
MUH003	*P. patula*	23	0.69	163	16
MUJ006b	*P. patula*	6	0.18	43	4
MUJ007	*P. patula*	5	0.15	35	3
NYS092	*P. patula*	25	0.75	177	17
NYS097	*P. patula*	19	0.57	135	13
Species Total	***P. patula***	**229.5**	**6.885**	**1670**	**154**
NYR109	*P. taeda*	11	0.33	78	7
NYR112	*P. taeda*	11.5	0.345	81	8
NYR114	*P. taeda*	12	0.36	85	8
MUA008	*P. taeda*	11	0.33	78	7
MUC009	*P. taeda*	3	0.09	21	2
MUF005	*P. taeda*	4	0.12	28	3
MUH006	*P. taeda*	19	0.57	135	13
MUH008	*P. taeda*	13	0.39	92	9
MUH011	*P. taeda*	8	0.24	57	5
NYI016	*P. taeda*	7	0.21	50	4
Species Total	***P. taeda***	**99.5**	**2.985**	**704**	**66**
GRAND TOTAL	***All species***	**329**	**9.87**	**2374**	**220**

Appendix III

First thinning **c**ompartments to be sampled per *Pinus species*, their total areas, sample areas and number of sample trees.

Compartment	Species	Area (Ha)	Sample Area (Ha)	Sample Trees	Number of plots
NYR007	*P. patula*	11.1	0.333	142	8
NYR017	*P. patula*	9	0.270	115	6
NYN023a	*P. patula*	9.63	0.289	123	7
MUF001	*P. patula*	7	0.210	89	5
MUJ003	*P. patula*	5.27	0.158	67	4
MUJ004	*P. patula*	9.05	0.272	115	6
NYI001	*P. patula*	22	0.66	281	15
NYI025b	*P. patula*	9.7	0.291	124	7
NYI027b	*P. patula*	16.7	0.501	213	11
NYI043a	*P. patula*	20	0.6	255	14
NYS003	*P. patula*	24	0.720	306	16
NYS018a	*P. patula*	14.5	0.435	185	10
NYS098	*P. patula*	24	0.720	306	16
DUS006	*P. patula*	21	0.630	268	15
DUS120	*P. patula*	24	0.720	306	16
Species Total	***P. patula***	**227**	**6.81**	**2895**	**156**
MUD020	*P. taeda*	5	0.150	64	4
MUF007b	*P. taeda*	3	0.090	38	2
MUJ005	*P. taeda*	9	0.270	115	6
N**YR019**	*P. taeda*	10	0.300	128	7
NYR018	*P. taeda*	11	0.330	140	7
NYI010a	*P. taeda*	13	0.390	166	9
NYI047a	*P. taeda*	3	0.090	38	2
Species Total	***P. taeda***	**54**	**1.62**	**689**	**37**
GRAND TOTAL	***All species***	**281**	**8.43**	**3584**	**193**

Appendix IV: Turnitin Originality Check Results

Research Thesis for A. S. Mvududu BSc F.E.M. final revision.docx

ORIGINALITY REPORT

6%	5%	3%	1%
SIMILARITY INDEX	INTERNET SOURCES	PUBLICATIONS	STUDENT PAPERS

PRIMARY SOURCES

1	library.itc.utwente.nl Internet Source	<1%
2	elibrary.buse.ac.zw:8080 Internet Source	<1%
3	pdffox.com Internet Source	<1%
4	afforum.org Internet Source	<1%
5	edepot.wur.nl Internet Source	<1%
6	www.coursehero.com Internet Source	<1%
7	"Energy from Organic Materials (Biomass)", Springer Science and Business Media LLC, 2019 Publication	<1%
8	Thanh Tan Nguyen, Peter Biber, Hans Pretzsch. "Analysis and management of stand	<1%

dynamics of Vietnamese dipterocarp forests by applying a dynamic growth model", Annals of Forest Science, 2012
Publication

9	bibalex.org Internet Source	<1 %
10	www.wwct.org.uk Internet Source	<1 %
11	Submitted to University of South Africa Student Paper	<1 %
12	repository.ju.edu.et Internet Source	<1 %
13	Sarah J. Puls, Rachel L. Cook, Justin S. Baker, Jim Rakestraw, Andrew Trlica. "Modeling Wood Product Carbon Flows in Southern US Pine Plantations: Implications for Carbon Storage", Research Square Platform LLC, 2023 Publication	<1 %
14	Elias Hurmekoski, Ragnar Jonsson, Jaana Korhonen, Janne Jänis, Marko Mäkinen, Pekka Leskinen, Lauri Hetemäki. "Diversification of the forest industries: role of new wood-based products", Canadian Journal of Forest Research, 2018 Publication	<1 %
15	www.mdpi.com Internet Source	

		<1%
16	isb-cancer-genomics-cloud.readthedocs.io Internet Source	<1%
17	uis.brage.unit.no Internet Source	<1%
18	Carlos Alberto Silva, Andrew Thomas Hudak, Carine Klauberg, Lee Alexandre Vierling, Carlos Gonzalez-Benecke, Samuel de Padua Chaves Carvalho, Luiz Carlos Estraviz Rodriguez, Adrián Cardil. "Combined effect of pulse density and grid cell size on predicting and mapping aboveground carbon in fast-growing Eucalyptus forest plantation using airborne LiDAR data", Carbon Balance and Management, 2017 Publication	<1%
19	liboasis.buse.ac.zw:8080 Internet Source	<1%
20	link.springer.com Internet Source	<1%
21	ira.lib.polyu.edu.hk Internet Source	<1%
22	openscholar.dut.ac.za Internet Source	<1%

23	pasteur.epa.gov Internet Source	<1 %
24	fau.digital.flvc.org Internet Source	<1 %
25	impa.usc.edu Internet Source	<1 %
26	oro.open.ac.uk Internet Source	<1 %
27	parlinfo.aph.gov.au Internet Source	<1 %
28	pt.scribd.com Internet Source	<1 %
29	repo-dosen.ulm.ac.id Internet Source	<1 %
30	tel.archives-ouvertes.fr Internet Source	<1 %
31	Juwan Jin. "Properties of strand boards with uniform and conventional vertical density profiles", Wood Science and Technology, 03/26/2009 Publication	<1 %
32	atae.agr.hr Internet Source	<1 %
33	documents1.worldbank.org Internet Source	

<1%

34	dspace.unza.zm Internet Source	<1%
35	www.frontiersin.org Internet Source	<1%
36	Abegão, João Luís Ramalho. "Human Overpopulation Atlas", Universidade do Porto (Portugal), 2024 Publication	<1%
37	McLaughlin, Inga Marie. "Effects of fuel reduction treatments on species of Phytophthora and Leptographium in forest ecosystems", Proquest, 20111108 Publication	<1%
38	hdl.handle.net Internet Source	<1%
39	Forestry Sciences, 2014. Publication	<1%

Exclude quotes	Off	Exclude matches	Off
Exclude bibliography	On		