Wood Processing Waste Valorization in a Commercial *Pinus patula* Plantation in Colombia: *A Risk Assessment Approach*

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Abstract –This study proposes alternatives for the valorization of waste generated during the wood transformation process in a commercial Pinus patula plantation in Boyacá, Colombia. Using quantitative analysis and engineering tools, more than 16,000 tons of annual waste were assessed, identifying that 60% of scrap wood and 85% of sawdust and wood shavings can be reused.

A risk-based approach was incorporated to identify and prioritize critical risks associated with residue accumulation, particularly fire hazards and operational inefficiencies. Based on this analysis, valorization strategies such as wooden slat production and by-product commercialization were evaluated, demonstrating economic feasibility with estimated annual revenues of COP $248,500,000.

The results show that waste valorization enhances resource efficiency while contributing to risk reduction and environmental sustainability in the forestry sector.

Keywords-- Utilization, Forest residues, Operational processes, Wood processing

I. INTRODUCTION

Forestry activity in Colombia is both economically and environmentally important, especially in relation to the timber industry. However, one of the main challenges is the proper management of waste derived from wood processing. These byproducts—such as sawdust, shavings, and scraps—tend to accumulate in large quantities and, in many cases, are not used efficiently, representing a loss for both organizations and the environment [2].
The study begins by contextualizing forestry activity in the country and identifying the problems associated with the storage of solid waste generated during wood processing in a commercial patula pine plantation. Based on this problem, the objectives and methodology were established.

Subsequently, the waste is characterized and diagnosed, analyzing operational processes to quantify the magnitude of the problem and estimate its potential for recovery. In the second phase, various recovery strategies are proposed and evaluated using engineering tools and multi-criteria assessment, selecting those with the greatest environmental, economic, and market viability. Finally, a cost-benefit analysis of the chosen alternatives is included in evaluating their financial and environmental impact.This study seeks not only to mitigate the environmental impact resulting from the accumulation of forest waste, but also to demonstrate that its valorization can become a significant source of income and a replicable model of circular economy for the Colombian forestry sector.

II. BACKGROUND

The wood processing industry generates various types of waste, including liquid, gaseous, and solid. However, solid waste, such as wood chips, sawdust, and bark, is of greatest interest for utilization. This waste can have different uses and values within the production chain, whether for energy generation, the manufacture of byproducts, or reuse in internal processes [1].

The utilization of forest residues has become a significant area of interest, driven by the need to reduce dependence on natural resources and promote a circular economy. This approach not only seeks to minimize pollution and conserve forest ecosystems but also has the potential to generate significant economic and social benefits [3]. However, this utilization faces considerable challenges in terms of logistics, technology, and regulation.

In this regard, the use of wood waste is proposed as an alternative to reduce pollution and promote more sustainable industrial practices [1]. This approach highlights the need to recognize the potential of this waste as a valuable raw material, instead of discarding or storing it, as often happens in some timber companies.

A study focusing on wood waste from wood processing highlights that this waste constitutes between 40% and 60% of sawn timber, underscoring the importance of its recovery for the creation of higher value-added products [4]. This work focuses on diverse applications, from energy to biotechnology, and on the conventional production of boards, activated carbon, and compost. It emphasizes maximizing the value and utility of this waste to reduce waste in the timber industry.

The use of forest residues in the form of biochar has been studied to improve the yield and quality of wood, as evidenced in research focused on Acacia mangium Willd trees [5-6]. These explorations seek to find economically viable solutions for the use of residues derived from pruning and thinning in forest agroecosystems.

Furthermore, innovative practices for the utilization of forest residues are being applied in different regions. In Argentina, xerophytic caldén forests produce large volumes of residual biomass which, if not managed properly, can become an environmental risk due to its accumulation and high flammability. However, its use in production systems can generate economic benefits if viable scales and competitive prices are established for agricultural producers [7].

In Mexico, community forestry enterprises have demonstrated that integrating waste into production chains can increase the profitability and sustainability of the sector, as well as promote the conservation of natural capital through participatory governance practices [8-9].

Finally, innovative technologies such as plasma gasification and biomass-based cogeneration have proven to be viable alternatives for converting forest waste into electricity. These solutions help reduce dependence on fossil fuels and decrease carbon emissions in key industrial sectors [10].

A. *Byproducts of the wood transformation process*

Forest residues are those resulting from silvicultural activities and timber harvesting carried out in the forest environment. These residues vary according to the different activities performed in the plantation, such as felling, pruning, timber collection, or the extraction of other forest products. The process of utilizing and evaluating these residues depends on various factors, such as the type of forest species, the age of the plants, the density of the vegetation, as well as the diameter and height of the species [11].

The different types of solid waste generated during production are sawdust, shavings, and scrap.

- Sawdust: Sawdust is the collection of particles or dust that comes off wood when it is sawn; it also contains minute particles of wood produced during the process and handling of this. [12].
- Chip: It is a fragment of residual material in the form of a curved or spiral sheet, extracted by means of a plane or other tools, such as drill bits, when performing planing, roughing or drilling work. [13-14].
- Wood scrap: Wood remnants of various shapes and dimensions that are generated mainly in companies related to the wood sector. [15].

On average, a medium-sized company engaged in wood processing generates the waste shown in Table 1:

Table 1. Relationship of amount of waste

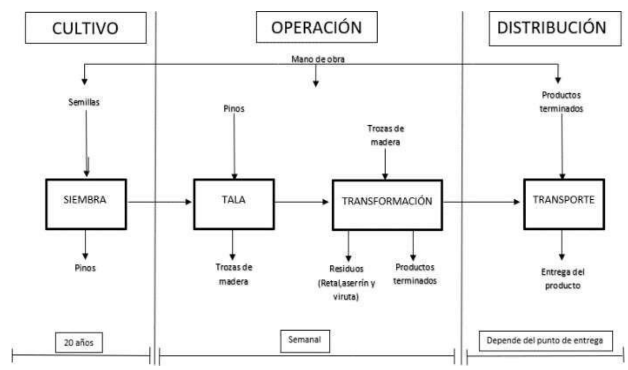
Residue	Quantity (Tn)
Remnant	85
Sawdust	46
Wood shavings	32

Source: Authors, (2023)

According to the information presented in the table above, it can be observed that the amount of waste stored in the company is approximately 163 tons, of which scrap has the most significant percentage with approximately 52%, followed by sawdust which represents an approximate total of 28% and shavings with 20% [16].

Figure 1 shows the block diagram where the different processes of the company are integrated, and it can also be seen that most of the problems related to waste occur in the wood transformation process that takes place in the operation stage.

Figure 1. Block diagram of the cultivation, operation and distribution process



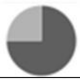
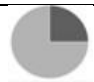
Source: Authors based on information from the company (2023).

Figure 2 presents the mass balance of the product called "tongue and groove boards," which is obtained by generating three types of solid waste (scraps, sawdust, and shavings). The data show that when 10 tons of Patula pine are used in the production of tongue and groove boards, approximately 5.27 tons of waste are generated, while the approximate yield of the product is 4.73 tons. It is evident that the production of this product generates more waste than final product [14].

Figure 2. Mass balance of the "Machimbre" product

Table 2 shows a waste assessment scale estimated based on the amount of waste generated in an average forestry company, categorized as follows: Poor, Fair, Good, and Very Good. This will allow for a diagnosis of waste management practices in production and the development of utilization strategies.

Table 2. Waste management assessment scale

	76%-100% There is evidence of poor waste management.
	51%-75% Evidence suggests REGULAR waste management
	26%-50% Good waste management is evident
	0%-25% Very good waste management is evident.

Source: Authors based on Contreras and Castañeda (2018)

According to the evaluation criteria used, companies engaged in wood processing often exhibit inadequate management of the waste they generate, which can be classified as deficient when these byproducts are stored without any form of utilization. The analytical tools reveal that this type of industry generates significant volumes of waste, and that its inefficient management represents both an environmental problem and a loss of economic value [15].

One alternative to address this problem is the implementation of waste utilization strategies, both conventional and non-conventional, aligned with the principles of the circular bioeconomy, understood as an economic model that integrates the circular economy with the sustainable use of renewable biological resources. This approach seeks to maximize resource use efficiency, promote regeneration, and encourage the reuse of materials, thus contributing to environmental sustainability and economic development [16].

Waste generated during wood processing can be valued as byproducts, as it offers recovery opportunities that allow its reintegration into new value chains. This utilization not only reduces the environmental impacts associated with waste disposal but can also become an additional source of income, strengthening the competitiveness and sustainability of companies in the forestry sector.

B. Determination of the Amount of Usable Wood

Accurate determination of the amount of usable timber is fundamental, as it allows for estimating the volume of waste that will be generated during the processing. Information from forest inventories and harvesting licenses is a key basis for projecting this waste, since these instruments describe in detail the available resources and establish the conditions for the sustainable use of forest resources (Table 3)[17].

Table 3. Number of trees per species

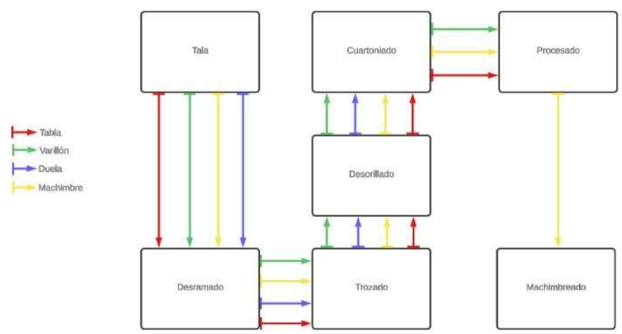
NAME		Number of Trees	VOLUME m³
COMMON	SCIENTIST		
Pine	*Pinus Patula*	63024	76907
TOTAL		**63024**	**76907**

Source: Corpoboyaca (2025)

Forestry companies in Boyacá [14], Colombia, employ diverse operational processes for wood transformation, which are fundamental to generating value and achieving organizational objectives. These processes enable the conversion of forest resources into products that meet market and customer requirements. The resulting products can be classified according to the level of transformation required, distinguishing between those that complete all stages of the production process to reach final specifications and those that require partial processes to obtain the desired dimensions and characteristics. This reflects the diversity of production flows present in the regional forestry industry.

Figure 3 below shows the Flow shop diagram which illustrates the sequence of the wood transformation process for each product carried out in forestry companies.

Figure 3. Shop Flow Diagram



Source: Authors (2025)

In the flow shop systems used by forestry companies in Boyacá, Colombia, it is evident that most products follow an ordered operational sequence, passing through all stages of the production process. This is because, to achieve the dimensions and specifications required by the client, the wood must undergo machining processes that define its final characteristics. However, some products require additional or specific processes to achieve profiles, which are usually carried out in the final stages of transformation.

Likewise, the flow diagram (figure) allows for the identification of the processes developed from tree felling, delimbing, and bucking, to transport to the processing area, where the different products are manufactured. This analysis facilitates the understanding of the logical sequence of processes, the estimation of production times, and the evaluation of the plant layout, providing a comprehensive view of the operational functioning of forestry companies in the region.

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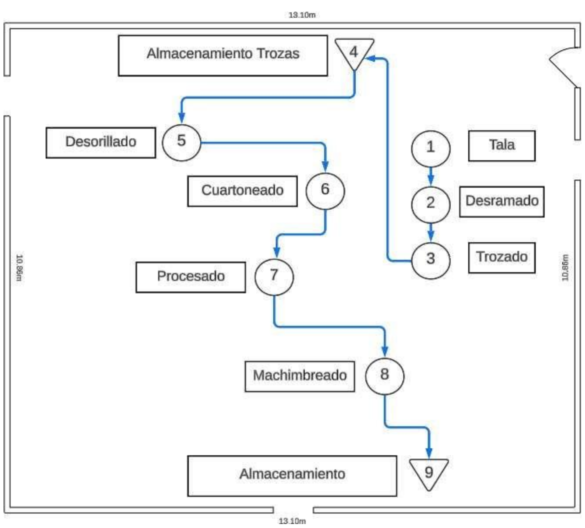
Likewise, the flow diagram (Figure 4) allows for the identification of the processes involved, from tree felling, delimbing, and bucking to transport to the processing area, where the different products are manufactured. This analysis facilitates understanding the logical sequence of processes, estimating production times, and evaluating the plant layout, providing a comprehensive view of the operational functioning of forestry companies in the region.

Figure 4. Route diagram of forestry companies



Source: Authors, (2025)

C. *Characterization of Forest Residues*

The characterization of forest residues is a key process for identifying their composition and physical properties. This type of analysis, which is descriptive in nature, integrates quantitative and qualitative information that allows for an understanding of the characteristics and dynamics associated with the residues. [19].

Through this detailed characterization (Table 4), a clear view of the nature and scope of forest waste can be obtained, facilitating the implementation of effective management and sustainable use strategies.

Table 4. Characterization of forest residues

Tipo de residuo	Etapa de proceso	Descripción	Posibilidad de aprovechamiento	Razón
Aserrín	Tala	Conjunto de partículas o polvillo que se desprende de la madera cuando ésta es aserrada.	No	Residuos producidos en plantación, haciendo inviable su aprovechamiento.
Ramas	Desramado	Tallos secundarios que nacen del tronco o tallo principal de una planta, en los que brotan, por lo común, hojas, flores y frutos.	No	Residuos producidos en plantación, haciendo inviable su aprovechamiento.
Aserrín	Trozado	Conjunto de partículas o polvillo que se desprende de la madera cuando ésta es aserrada.	No	Residuos producidos en plantación, haciendo inviable su aprovechamiento.
Retal Aserrín	Desorillado	Conjunto de partículas o polvillo que se desprende de la madera cuando ésta es aserrada. Restos de madera de forma y dimensiones variadas que se generan sobre todo en las empresas relacionadas con el sector de la madera.	Si	Recolección y almacenamiento viable y asequible
Aserrín	Cuartoniado	Conjunto de partículas o polvillo que se desprende de la madera cuando ésta es aserrada.	Si	Recolección y almacenamiento viable y asequible
Aserrín	Procesado	Conjunto de partículas o polvillo que se desprende de la madera cuando ésta es aserrada.	Si	Recolección y almacenamiento viable y asequible

Source: Torres, 2025.

D. *Quantification of Waste*

Trees do not have a regular shape that allows for precise calculation of their volume. Therefore, it is necessary to approximate it to the closest regular geometric shape in order to determine and quantify the amount of waste.

To calculate the scrap, the logs of wood are considered, which do not have a perfectly cylindrical shape, but rather resemble the geometry of a truncated cone; it is through this approximation that the approximate volume of the residue called scrap is estimated (Table 5).

$$\frac{h\pi}{3} * (R1^2 + R2^2 + R1 * R2)$$

(Equation 1. Volume of a truncated cone)
R = radius - h = height

Table 5. Average width of logs

Sample	Extremely Thin cm			Extreme Width cm		
	Measure 1	Measure 2	Average	Measure 2	Measure 3	Average
1	19	18.5	18.75	19	20.5	19.75
2	12.7	13	12.85	15	15	15
3	20.5	19	19.75	22	21.5	21.75

Source: Authors based on (2025)

Once the results of the average diameters of the different samples have been obtained, the radii are then obtained and the formula for a truncated cone is applied (Table 6).

$$\frac{Promedio\ Diámetro}{2}$$ (Equation 2. Radius)

Table 6. Calculation of Radii

Sample	Extremely thin		Extremely Wide	
	Average (cm)	Radius (cm)	Average (cm)	Radius (cm)
1	18.75	9.38	19.75	9.88
2	12.85	6.43	15	7.50
3	19.75	9.88	21.75	10.88

Source: Authors (2025)

Applying the truncated cone volume formula, the volumes are obtained (Table 7).

$$\frac{h\pi}{3} * (R1^2 + R2^2 + R1 * R2)$$

(Equation 3. Volume of a truncated cone)
R = radius - h = height

Table 7. Volume of truncated cone

Sample	Radio1 (cm)	Long (cm)	Radio2 (cm)	Volume (cm^3)
1	9.38	300	9.88	87,287.09
2	6.43	300	7.50	45,755.49
3	9.88	300	10.88	101,475.97

Source: Authors, (2025)

The cuts that must be made to the log in the edging are started from the thin end of the log, since in this way it is guaranteed that no bark will remain along the resulting parallelepiped, using the original diameter as the hypotenuse of a right triangle, find the legs using the Pythagorean theorem and finally the volume of this parallelepiped (Table 8).

Table 8. Internal volume of the parallelepiped of the truncated cone

Sample	Diameter Thin end (cm)	Pythagoras (cm)	Length (cm)	Volume Parallelepiped (cm^3)
1	18.75	13.26	300	52,734.38
2	12.85	9.09	300	24,768.38
3	19.75	13.97	300	58,509.38

Source: Authors, (2025)

To find the amount of waste resulting from the edge-cutting process, it is necessary to find the difference in volumes of the parallelepiped (useful wood) and the truncated cone (Table 9).

Table 9. Difference in volumes between Parallelepiped and Truncated Cone

Sample	Truncated cone (cm^3)	Parallelepiped(cm^3)	Volume Residue (cm^3)	Residue %
1	87,287.09	52,734.38	34,552.72	39.59
2	45,755.49	24,768.38	20,987.12	45.87
3	101,475.97	58,509.38	42,966.59	42.34

Source: Authors, (2025)

To convert these results to kilograms, it is necessary to apply the theoretical density of green pine wood, which, as stated by Sena in its article "The Woods of Colombia (2020)," is 0.96 g/cm3 (Table 10).

Table 10. Kilograms of waste

Sample	Waste (cm^3)	Kilograms
1	34,552.72	33.17
2	20,987.12	20.15
3	42,966.59	41.25

Source: Authors, (2025)

To total the amount of scrap, the data on the number of trees delivered in the resolution authorizing the Environmental Corporation of Boyacá Corpoboyacá (2021) is taken, data delivered after the technical evaluation carried out as a mandatory requirement for legalization of the exploitation, averaging the kilograms of waste, and is multiplied by 5, which is the average amount of 300 cm logs delivered by the trees (Table 11).

Table 11. Average Kilograms of Waste

Sample	Kilograms
1	33.17
2	20.15
3	41.25
Average	31.52

Source: Authors, (2025)

To determine the theoretical amount of scrap waste, the average weight of the log is multiplied by the number of logs a tree has and finally by the number of trees in the commercial Patula pine plantation (Table 12).

Table 12. Theoretical amount of waste

Average residue per log (Kg)	Average Logs per Tree	Number of Trees	Theoretical quantity of kilograms of scrap
31.52	5	63.024	9,932,582.4

Source: Authors, (2025)

To calculate the sawdust waste generated during the wood processing, it is important to consider the dimensions of the final products. The number of cuts required to meet these requirements significantly impacts the theoretical calculations. Therefore, standard cuts for all products will be considered, including edging. This process involves using a saw blade that occupies 0.5 cm and the band saw blade that occupies 0.3 cm (Table 13).

Table 13. Sawdust Residue Saw Cuts

Sample	Number of Courteous	Sides (cm)	Long (cm)	Size of Cut (cm)	Volume Sawdust (cm^3)
1	4	13.26	300	0.5	7,954.95
2	4	9.09	300	0.5	5,451.79
3	4	13.97	300	0.5	8,379.22

Source: Authors, (2025)

The average amount of sawdust generated in the saw where a 0.5cm cut is made is shown below (Table 14).

Table 14. Kilograms of Sawdust per Saw

Sample	Volume (cm^3)	Kilograms
1	7,954.95	7.64
2	5,451.79	5.23
3	8,379.22	8.04
Average		6.97

Source: Authors, (2025)

To determine the total amount of sawdust waste generated in the sawmill, the average weight of sawdust in kilograms per log is multiplied by the number of logs from a tree and finally by the number of trees in the organization's commercial Patula pine plantation (Table 15).

Table 15. Theoretical amount of sawdust waste per saw

Average residue per log (Kg)	Average Logs per Tree	Number of Trees	Theoretical Kilograms of Waste
6.97	5	63.024	2,196,386.40

Source: Authors, (2025)

In the case of the band saw, 4 cuts were taken into account, where the cut size is approximately 0.3cm. There, 3 samples were taken to determine the volume of sawdust generated in this operational process (Table 16-17).

Table 16. Sawdust residue from screw conveyor cuts

Sampl e	Number of Courts	Side (cm)	Length (cm)	Cutting Size (cm)	Sawdust Volume (cm^3)
1	4	13.26	300	0.3	4,772.97
2	4	9.09	300	0.3	3,271.08
3	4	13.97	300	0.3	5,027.53

Source: Authors, (2025)

The following shows the average amount of sawdust generated in the screw conveyor where a 0.3cm cut is made.

Table 17. Kilograms of sawdust per screw conveyor

Sample	Sides (cm^3)	Kilograms
1	4,772.97	4.58
2	3,271.08	3.14
3	5,027.53	4.83
Average		4.18

Source: Authors, (2025)

To determine the total amount of sawdust waste generated in the screw conveyor, the average weight of sawdust in kilograms per log is multiplied by the number of logs from a tree and finally by the number of trees in the organization's commercial Patula pine plantation (Table 18).

Table 18. Theoretical quantity of sawdust waste per screw conveyor

Average residue per log	Average Logs per Tree	Number of Trees	Theoretical Kilograms of Waste
4.18	5	63.024	1,317,201.60

Source: Authors, (2025)

Tongue and groove boards are the final operational process used to add value to the wood. With typical dimensions of 9 cm x 1 cm x 300 cm, the products processed at this stage are also the lowest-selling items for the organization, representing approximately 20% of total plantation sales. Therefore, the percentage of the total 57,680 cubic meters indicated in Resolution 1021 of 2021, where Corpoboyacá authorizes the harvesting, will be calculated.

Table 19 below shows the calculation of the percentage of wood that would be used in the tongue and groove operating process, where the residue called shavings is generated.

Table 19. Percentage of tongue and groove wood

Cubic Meters	Percentage	Total (m $^{3)}$
57,680	20%	11,536

Source: Authors, (2025)

The number of tongue and groove boards projected to be generated from 20 percent of the plantation is presented below in Table 20.

Table 20. Percentage Cubic Capacity for Tongue and Groove

Cubic Meters	Cubing Tables	Total Tables
11,536	0.0027	4,272,592.59

Source: Authors, (2025)

The tongue and groove process reduces the thickness of the planed board by between 0.2 and 0.3 cm; therefore, the average will be taken, resulting in 0.25 cm, which generates approximately 675 cm^3 of chips. To determine the amount of chips generated in this operational process, the number of boards is multiplied by the approximate amount of chips generated per board. (Table 21).

Table 21. Chip volume per tongue and groove joint

Tables	Wood chip (cm^3)	Total (cm^3)
4,272,592,593	675	2,884,000,000

Source: Authors, (2025)

Subsequently, using the density formula (Table 22), the theoretical amount of chips generated in the tongue and groove operating process is obtained.

Table 22. Chip weight tongue and groove

Chip Volume (cm^3)	Density (g/cm)	Total (kg)
2,884,000,000	0.96	2,768,640

Source: Authors (2025)

According to the quantification results, it was determined that scrap wood is the most generated forest residue, reaching approximately 9,932 tons, which represents about 61% of the total waste produced during the wood processing. Sawdust is the second most generated residue, at approximately 3,514 tons, corresponding to about 22% of the total, while wood chips, mainly associated with the tongue and groove process, reach a volume of approximately 2,769 tons, equivalent to 17% of the waste generated. These figures demonstrate that more than 68% of the initial raw material is transformed into waste, confirming the magnitude of the existing potential for utilization and highlighting the importance of implementing differentiated valorization strategies for each type of residue, aimed at improving the efficiency of the production process and reducing associated environmental impacts.

III. RISK ASSESSMENT FRAMEWORK

This study incorporates a structured risk assessment approach to complement the quantitative analysis of forest residues generated during the wood transformation process. The objective of this framework is to identify, evaluate, and prioritize the risks associated with the accumulation and management of these residues, as well as to support decision-making regarding their valorization.

A. Risk Identification

The identification of risks was carried out based on the analysis of operational processes involved in wood transformation and the characterization of generated residues. The main risks associated with the accumulation of forest waste were classified into four categories:

- Environmental risks: accumulation of combustible biomass increasing the probability of forest fires, soil degradation, and contamination of water sources.
- Operational risks: inefficiencies in storage, handling, and transportation of residues affecting production flow.
- Economic risks: loss of potential revenue due to underutilization of byproducts and increased operational costs.
- Safety risks: exposure of workers to hazardous conditions during handling and storage of residues.

B. Risk Analysis Based on Waste Quantification

The results obtained from the quantification of forest residues were integrated into the risk analysis. The high proportion of waste generated (68.57% of total processed wood) represents a significant risk factor, particularly in environmental and operational terms.

Scrap wood, which accounts for more than 60% of total waste, was identified as the most critical residue due to its volume and accumulation potential. This significantly increases the probability of fire hazards and inefficient use of storage space.

Similarly, sawdust and wood shavings contribute to environmental risks due to their fine particle nature, which facilitates dispersion and potential contamination. The proposed waste utilization strategies were evaluated not only in terms of economic and operational feasibility but also considering their potential to reduce identified risks.

- Each strategy was assessed according to:
- Reduction of environmental risk
- Reduction of operational inefficiencies
- Economic benefit generation
- Implementation feasibility

Integrating risk assessment into the analysis provides a more comprehensive understanding of the implications of forest residue management. This approach allows organizations to move from a reactive perspective focused only on waste accumulation towards a proactive strategy that prioritizes risk mitigation and value generation.

The incorporation of risk-based criteria strengthens the decision-making process and aligns the proposed strategies with sustainable and resilient operational practices within the forestry sector.

C. Risk Matrix and Prioritization

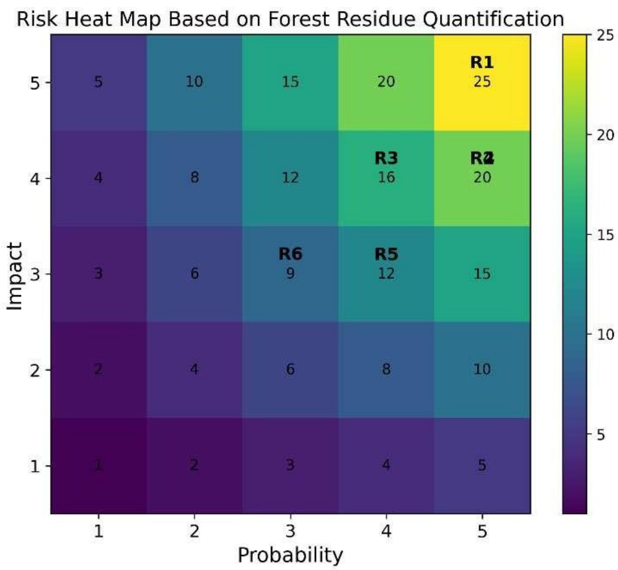
Based on the identified risks and the quantitative results obtained from waste generation, a risk matrix was developed to prioritize the most critical risks associated with forest residue accumulation in the wood transformation process.

Each risk was evaluated according to its probability of occurrence and its potential impact on operational, environmental, and economic performance.

The risk heat map integrates the quantitative results of forest residue generation into the risk assessment framework. It can be observed that risks associated with scrap wood are located in the critical zone due to its high proportion (61% of total waste), which increases both the probability and impact of fire hazards and storage saturation.

Similarly, sawdust-related risks are positioned in high-risk zones due to their dispersion capacity and economic implications, while wood shavings present moderate risk levels associated with operational variability. This representation strengthens the analytical consistency of the study by directly linking risk prioritization with empirical data.

Figure 6. Risk Heat Map Based on Forest Residue Quantification



Source: authors, 2026.

R1: Scrap accumulation – Fire risk
R2: Scrap accumulation – Storage saturation
R3: Sawdust – Environmental dispersion
R4: Sawdust – Economic loss due to underutilization
R5: Operational inefficiencies in handling
R6: Wood shavings – Operational variability

The use of coded risk identification (R1–R6) improves the clarity of the analysis by avoiding visual saturation in the heat map. As shown in Figure 6, R1 and R2 are in the critical zone, confirming that scrap accumulation represents the most significant risk due to its high proportion within total waste.

Similarly, risks associated with sawdust (R3 and R4) are positioned in high-risk areas, while operational risks (R5 and R6) present moderate levels. This structured visualization strengthens the prioritization of risk mitigation strategies and supports decision-making for waste valorization.

IV. RESULTS

The characterization of wood processing byproducts generated during operational processes revealed that each process produces waste. It is important to note that some of this waste is not usable, such as branches produced during the delimbing process and sawdust resulting from felling and bucking. This waste cannot be utilized primarily because it is generated within the plantation, making its collection, storage, and transportation impractical.

However, the quantification of waste, such as sawdust, shavings and scrap, generated in the wood transformation process, is presented in Table 23 for one hectare and Table 23 for the plantation.

Table 23. Quantification of waste in 1 Hectare

Residue	Theoretical quantity (Kg)	Theoretical quantity (Ton)	Percentage (%)
Remnant	248,314.56	248.32	61.26%
Sawdust	87,839.7	87.84	21.67%
Wood shavings	69,216	69.22	17.07%

Source: Authors (2025)

Table 24. Quantification of waste in the plantation

Residue	Theoretical quantity (Kg)	Theoretical quantity (Ton)	Percentage (%)
Remnant	9,932,582.4	9,932.6	61.26%
Sawdust	3,513,588	3,513.6	21.67%
Wood shavings	2,768,640	2,768.6	17.07%

Source: Authors (2025)

According to the calculated theoretical amount of waste, it is observed that scrap predominates, representing more than 50% of the waste generated in the wood transformation process in forestry companies, followed by sawdust (21.67%) and wood shavings (17.07%).

As shown in Figure 6, this distribution has a direct impact on the risk profile of the process. Scrap wood, due to its high volume (61% of total waste), is associated with the most critical risks (R1 and R2), particularly those related to fire hazards and storage saturation.

Similarly, sawdust contributes to high-risk scenarios (R3 and R4), mainly due to its dispersion capacity and its economic implications when not properly utilized. In contrast, wood shavings present moderate risks (R6), associated with operational variability and lower volume.

This relationship between waste composition and risk levels highlights the importance of prioritizing valorization strategies that target the most critical residues, particularly scrap and sawdust, to reduce both environmental and operational risks. In addition, the percentage of waste was calculated at the level of the entire plantation, which can be seen in Table 25.

Table 25. Percentage of total waste

Average log size (cm3)	Log weight (kg)	Log weight per tree (kg)	Log weight at plantation (kg)	Percentage of waste (%)
78,172.85	75.05	375.2	23,648,475.73	68.57

Source: Authors (2025)

The calculated theoretical waste percentage is 68.57%, a significantly high figure, but according to López (2019), in his article on the use of wood waste, he states the following: many authors agree that sawmills generate between 45% and 65% waste per ton of wood processed; in other words, the yield of the process of transforming roundwood (logs) into sawn wood is between 35% and 55%.

Next, production efficiency is calculated, based on the previously determined percentage of waste.

$$1 - \frac{\%\,RG\ 68{,}57}{100}\ x100\% = 31{,}43\%$$

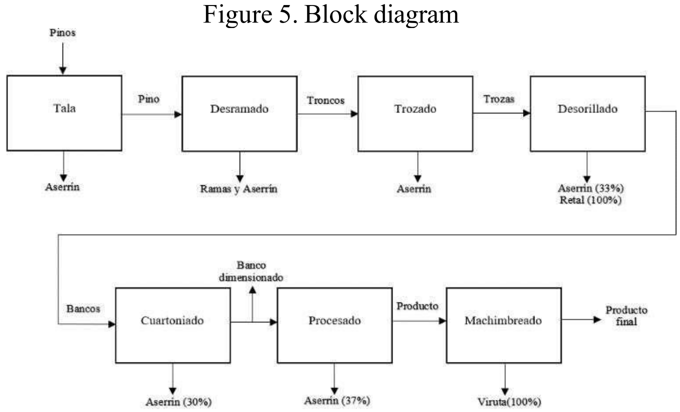
(Equation 6. Production efficiency percentage)

% RG = Percentage of waste generated

Production efficiency is estimated at 31.43%, a value calculated from the analysis of waste generated during the wood processing. This percentage represents the degree of raw material utilization. However, it is important to note that this figure can vary depending on different operational factors, such as the adjustment and condition of the saws, which directly affect the precision of the cuts, the experience and training level of the personnel operating the machinery, as well as the age and general condition of the equipment used in the process.

Taking the above into account, the block diagram (Figure 5) details the percentage of byproducts from the wood transformation process, showing each input and the percentage of waste generated. It is important to note that the initial operational processes—felling, delimbing, and bucking—could not be quantified because these byproducts are generated in the hillside plantation, making their storage for later quantification difficult.

Figure 5. Block diagram



Source: Authors, (2025)

Within the operational processes where waste quantification has been carried out, the edging process stands out as the primary source of scrap generation. As indicated in Figure 6, this residue is directly linked to the highest risk levels identified in the assessment.

This finding reinforces the need to prioritize interventions in this stage of the process, as reducing scrap accumulation would significantly decrease critical risks such as fire hazards and storage inefficiencies.

On the other hand, sawdust, generated proportionally during the wood transformation process—including edging, quartering, and processing—is the second most produced waste product in wood processing, in terms of both volume and weight. Finally, wood chips, whose generation is limited to the tongue-and-groove operation, are produced in smaller quantities compared to the other waste products, considering volume and weight.

Finally, the amount of forest waste generated in the transformation of wood was evidenced; this data is relevant for the proposal of different strategies for the use of forest waste.

A. Actions for the Use of Forest Waste

The field of forest residue utilization is characterized by its diversity in terms of recovery possibilities. In this context, this chapter presents and analyzes four specific strategic options: boards made from scrap wood, charcoal production, marketing of wood chips and sawdust, and finally, pellets made from sawdust and wood chips.

These alternatives were subjected to an evaluation using a set of the same industrial engineering tools, which allowed for the establishment of an objective criterion for their comparative evaluation.

The results obtained through the decision matrix show that, among the strategies considered, those related to the waste materials known as wood chips and sawdust offer the greatest advantages in terms of environmental impact, cost, and demand. Specifically, the commercialization of these materials stands out as a highly favorable option in several aspects.

On the other hand, an analysis of forestry waste known as offcuts reveals that producing slats from this material is an unconventional utilization strategy. This approach allows for harnessing the value of waste by transforming it into useful and profitable products.

This improvement would bring significant benefits by improving the handling of byproducts from the transformation process and, at the same time, contributing to the reduction of the environmental impact associated with their current final disposal.

V. CONCLUSIONS

The study revealed that wood processing in commercial forest plantations generates a significant amount of solid waste, primarily scrap, sawdust, and shavings, which represent a high proportion of the total volume of raw material processed. The results show that the percentage of waste can exceed 60%, confirming the need to implement management and utilization strategies to reduce losses and improve production efficiency.

The characterization and quantification of forest residues was a key tool for understanding their origin, magnitude, and potential for utilization. The analysis determined that scrap wood is the predominant residue, followed by sawdust and wood chips, which allowed for the development of specific valorization alternatives tailored to the physical and operational characteristics of each byproduct.

The evaluated utilization strategies, both conventional and non-conventional, proved to be technically and economically viable. In particular, the production of slats from scrap and the direct sale of sawdust and shavings show high implementation potential, allowing for the utilization of up to 60% of scrap and 85% of sawdust and shavings. These alternatives not only contribute to reducing the environmental impact associated with the storage and final disposal of waste but also generate new sources of income for companies in the forestry sector.

From an economic standpoint, the results indicate that utilizing forestry waste can translate into significant financial benefits, improving the profitability of operations and engthening business competitiveness. Likewise, from an environmental perspective, valorizing this waste reduces risks associated with the accumulation of combustible material, soil and water source contamination, and promotes practices aligned with the principles of the circular bioeconomy.

In conclusion, the integrated management of forest waste, supported by industrial engineering tools and sustainability criteria, represents a strategic opportunity for the Colombian forestry sector. Adopting these strategies, along with staff training and operational improvements, can contribute to the development of more efficient, sustainable, and replicable production models in other regions of the country.

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