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BioTheRoS

Collaborative actions to bring novel **BIO**fuels **THE**rmochemical **RO**utes into industrial **S**cale

SUITABLE TECHNOLOGIES FOR BIOMASS PRE-TREATMENT FOR FEEDSTOCK CONDITIONING.

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List of abbreviations

AP	Apples pruning
a.r.	As Received
d.b.	Dry Basics
EUROSTAT	European Statistical System
FAO	Food and Agricultural Organization of the United Nations
GM	Grape pomace
GP	Grape pruning
GS	Gasification
IRENA	International Renewable Energy Agency
LHV	Lower Heating Value
OP	Olive pruning
OM	Olive pomace
PL	Potato leaves
PP	Potato peel
PY	Pyrolysis
RS	Rape seed pomace
SB	Sugar beet leave
SS	Sunflower seed leaves

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Executive Summary

This deliverable presents a comprehensive assessment of the necessary pre-treatment processes for the feedstocks identified in Task 2.1 of BioTheRoS Project. The objective is to define the required actions to ensure these feedstocks are optimized for processing in pyrolysis and gasification plants.

The process begins by identifying the specific physicochemical requirements that these feedstocks must meet to be compatible with the operational parameters of pyrolysis and gasification technologies. This includes analyzing key factors such as moisture content, ash levels, particle size, and other relevant properties that determine how efficiently a feedstock can be processed.

Next, based on the results of this analysis, the report identifies the most appropriate pre-treatment methods for each feedstock. The pre-treatment techniques considered include baling, chipping/shredding, screening, drying, and pelletizing. Each feedstock has different characteristics and will require specific treatments to ensure they are prepared for efficient transport and processing. For example, while drying may be essential for reducing moisture content in some feedstocks, others may require chipping or shredding to achieve the desired particle size, or screening to remove excessive ash. These treatments are tailored to optimize feedstock quality and logistics for each specific case.

Finally, the deliverable includes an estimation of the associated costs for both the capital investment and operational expenses of implementing each pre-treatment to the corresponding feedstock, allowing necessary information for a detailed economic assessment of the whole value chain (from the field to the pyrolysis/gasification plant) that will be covered in task 2.3.

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1. Introduction

The sustainable production of renewable fuels for the aviation and maritime sectors relies on the effective utilization of non-food biomass feedstocks. The BioTheRoS project, as detailed in the deliverable "D2.1: EU Status of Non-Food Biomass as Potential Feedstocks for Aviation and Maritime Biofuels Production" [1], identified key feedstocks based on their sustainability and technological compatibility with advanced conversion technologies, such as gasification and fast pyrolysis. These feedstocks are categorized according to Annex IX of the Renewable Energy Directive (RED II and III), with specific focus on categories such as (e) straw, (j) bagasse, (m) husks, (n) cobs cleaned of kernels of corn, (o) biomass fraction of wastes and residues from forestry and forest-based industries, (p) other non-food cellulosic material, and (q) other ligno-cellulosic material except saw logs and veneer logs.

Table 1 summarizes the biomass types considered under each category at the Global and European levels.

Table 1. Summary of feedstock and categories of Annex IX selected for the resource assessment.

Categories Annex IX	Biomass considered at World level	Biomass considered at European level
e) Straw	Maize Stalk	Maize Stalk
	Barley Straw	Barley Straw
	Wheat straw	Wheat straw
	Rice straw	Soya straw
	Sugar cane straw	Rye straw
	Soya beans straw	Oats straw
	Yams straw	Triticale straw
	-	Rape seed straw
j) Bagasse	Sugar cane bagasse	-
m) Husks	Wheat husk	Wheat husk
	Rice husk	-
n) Cobs cleaned of kernels of corn	Maize cob	Maize cob

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o) Biomass fraction of wastes and residues from forestry and forest-based industries	Primary residual forestry biomass	Primary residual forestry biomass
	Secondary forestry biomass	Secondary forestry biomass
p) Other non-food cellulosic material	Apples pruning	Fruits pruning
	Grape pruning	Grape pruning
	Grape pomace	Grape pomace
	Orange pruning	Potatoes leaves
	Potatoes leaves	Potatoes peel
	Potatoes peel	Sugar beet leaves
	Sugar beet leaves	Rape seed pomace
	Sweet potatoes leaves	Sunflower seed leaves
	Sweet potatoes peel	Olive pruning
	Yams peel	Olive pomace
q) Other ligno-cellulosic material except saw logs and veneer logs.	Forestry wood fuel	Forestry wood fuel

Building upon these findings, this report aims to explore the pre-treatment strategies necessary to optimize these feedstocks for thermochemical conversion processes. By addressing pre-treatment methods such as drying, chipping, and screening (logistic operations and the design of the value chain of these biogenic feedstocks will be analysed in task 2.3 of BioTheRoS), the study seeks to define the requirements specific to each category, ensuring the biomass achieves the desired specifications for efficient gasification or pyrolysis. This approach aims to support the development of a robust and sustainable supply chain for renewable fuel production.

Although the assessment of biomass potential was conducted at both Global and European levels, this study will focus exclusively on the European context to evaluate the pre-treatment strategies required for the selected feedstocks. This regional approach ensures the alignment of pre-treatment methods with the specific characteristics and availability of biomass within Europe.

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2. Requirements for BioTheRoS technologies.

For gasification and pyrolysis to work efficiently, the biomass used as feedstock needs to meet specific criteria, to identify these parameters, the technical partner of BioTheRoS of each technology (BEST and BTG) defined these requirements that are crucial to ensure stable operation and high-quality output.

Table 2 summarises the main requirements indicated, whose main conclusions are:

- Moisture Content: Gasification performs best with feedstocks containing 10-25% moisture, while pyrolysis is more demanding, requiring a lower range of 5-10%. In both cases if the moisture is too high, it reduces energy efficiency, and if it's too low, it can destabilize the process.
- Volatile Matter: Gasification can handle volatile matter between 50-90%, while pyrolysis prefers 75-99%. This parameter is essential because it determines how much combustible gas the biomass can produce.
- Ash Content: For both technologies, keeping ash content low is key. Gasification can tolerate up to 5%, but pyrolysis works best when ash levels are below 1%. High ash content can lead to operational issues and lower energy yields.
- Chemical Composition: Biomass with a carbon content of 40-60% and hydrogen levels of 5-12% is ideal for pyrolysis. Additionally, both processes require minimal nitrogen, sulfur, and chlorine to avoid equipment corrosion and harmful emissions.
- Energy Value: Biomass should have a sufficient energy value. For gasification, this means a low heating value above 10,000 kJ/kg. Pyrolysis requires even higher energy content, ranging from 15,000 to 30,000 kJ/kg.
- Size and Density: Particle size and density also play a significant role. Gasification can handle larger particles (5-50 mm), while pyrolysis needs smaller ones (2-5 mm) and a bulk density of 100-500 kg/m³ for optimal performance.
- Ash Melting Point: To avoid operational issues like slagging, the ash in the feedstock must have a high melting point. Gasification requires temperatures above 1,000°C, while pyrolysis can operate with slightly lower values, around 800-950°C.

Table 2. Optimal, not ideal, and K.O. characterization that of the feedstocks according to the technology selected.

Parameter	Unit	Biomass requirements gasification			Biomass requirements pyrolysis		
		Optimum	Not ideal	K.O.	Optimum	Not ideal	K.O.
Proximate analysis							
Moisture	% a.r.	10-25	< 10 or > 25	-	5,0	<5 or >10	50,0
Volatile matter	% d.b.	50-90	< 50 or > 90	-	75 - 99	<75	
Ash	% d.b.	< 5	5-50	> 50	0-1	1-5	>5
Ultimate analysis							

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C	% d.b.				40-60		
H	% d.b.				5-12		
N	% d.b.	< 1.0	1.0-3.0	> 3.0	0-2		
S	% d.b.	< 0.1	0.1-0.5	>0.5			
Cl	% d.b.	<0.5	0.5-2.0	>2.0			
Heating value							
Lower heating value	kJ/kg d.b.	> 10,000	5,000-10,000	< 5,000	15,000-30,000	<15,000	
Bulk density and size distribution							
Bulk density	kg/m3 d.b.				100-500		
Size distribution	mm	5-50	< 5 or > 50		2-5	0,5-2	<0,5
Ash fusibility temperatures							
Ash fusibility temperature	ºC	1000	900-1000	<900	800-950		<800

In summary, pyrolysis demands stricter specifications than gasification, particularly in terms of moisture, ash content, particle size, and energy value. Ensuring the feedstock meets these criteria is essential for efficient and reliable biofuel production.

The selected biomass feedstocks differ significantly in their initial properties. Variations in moisture content, ash levels, energy value, particle size, and chemical composition are inherent to different biomass types and depend on their origin and processing history. These differences mean that not all feedstocks are ready to meet the strict requirements of gasification or pyrolysis without prior conditioning.

To design effective pre-treatment strategies, it is essential to first establish the characteristic ranges of each selected biomass category. By understanding these baseline properties, it becomes possible to determine which pre-treatments are necessary to bring the biomass within the optimal range for gasification or pyrolysis.

Once these characteristic ranges are identified, specific pre-treatment methods can be applied to condition the biomass. For example: drying, grinding, screening, etc. By aligning the pre-treatment processes with the initial characteristics of each biomass category, the feedstock can be conditioned to meet the stringent requirements of these thermochemical conversion technologies. This tailored approach is critical for ensuring efficient, reliable, and sustainable biofuel production.

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3. Characterization of the selected biomass.

In this section, the initial characteristics commonly observed in the selected feedstocks will be identified and described. This will provide a basis for comparing their properties with the criteria outlined in Table 2, allowing for an assessment of how well each feedstock aligns with the specified requirements and highlighting any potential areas for further pre-treatment operations. In any case, it is important to emphasize that the values presented are approximate figures derived from the literature, since biomass is inherently heterogeneous, these values may vary to some extent for each specific type of biomass considered. Therefore, conducting an analysis of the local biomass under study is essential to assess its viability for their valorisation.

The requirements of gasification and pyrolysis processes must be taken into account to meet the criteria for biomass pre-treatment. The characteristics will be presented in a table format consistent with Table 2. However, in this case, two additional rows will be included for each parameter to specify the appropriate values for pyrolysis and gasification. To enhance clarity, a color-coding scheme will be applied: green to indicate full compliance, yellow for acceptable limitations, and red for significant deviations.

After the values for the different parameters have been established, it will be possible to assess which feedstocks will need pre-treatments to satisfy the requirements of various technologies. These data from the following tables were primarily sourced from these references: Stanislav V. Vassilev,2009[a] [2], ECN Phillys 2[b] [3], S2biom EU project-608622[c] [4], Stanislav V. Vassil,2012[d] [5], and Up_running EU project-691748[e] [6]. Those data that have not been referenced have been based according to CIRCE experience, and those where they are not given, it has not been possible to find them.

3.1 Category e) Straw

Table 3 presents the physicochemical characteristics of various feedstocks analyzed within the e) straw category, using the previously described color-coding scheme.

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Table 3. Physicochemical characterization of feedstock in category e)

Type	Unit	Method	Maize Straw	Barley Straw	Wheat Straw	Soya Straw	Rye Straw	Oats Straw	Rape seed Straw
Proximate analysis									
Moisture	(% ar)	GS	18[a]	11.5 [a]	10.1[a]		13.2[b]	8.2[a]	8.7[a]
		PY	18 [a]	11.5 [a]	10.1[a]		13.2 [b]	8.2 [a]	8.7[a]
Volatile Matter	(% db)	GS	73.1 [a]	76.2 [a]	74.8[a]		68.4 [b]	80.5 [a]	77.4[a]
		PY	73.1 [a]	76.2 [a]	74.8[a]		68.4 [b]	80.5[a]	77.4[a]
Ash	(%db)	GS	7.7 [a]	5.3 [a]	7.1[a]	6.0 [b]	4.57 [b]	5.6 [a]	4.7[a]
		PY	7.7 [a]	5.3 [a]	7.1[a]	6.0 [b]	4.57 [b]	5.6 [a]	4.7[a]
Ultimate analysis									
C	(% db)	GS	48.7 [a]	49.4 [a]	49.4[a]		47.49 [b]	48.8 [a]	48.5[a]
		PY	48.7 [a]	49.4 [a]	49.4 [a]		47.49 [b]	48.8 [a]	48.5[a]
N	(% db)	GS	0.7 [a]	0.7 [a]	0.7 [a]	0.83 [b]	0.46 [b]	0.5 [a]	0.5[a]
		PY	0.7 [a]	0.7 [a]	0.7 [a]	0.83 [b]	0.46 [b]	0.5 [a]	0.5[a]
H	(% db)	GS	6.4 [a]	6.3 [a]	6.1 [a]		5.54 [b]	6.0 [a]	6.4[a]
		PY	6.4 [a]	6.3 [a]	6.1 [a]		5.54 [b]	6.0 [a]	6.4[a]
S	(% db)	GS	0.08 [a]	0.13 [a]	0.17 [a]		0.06 [b]	0.08 [a]	0.10[a]
		PY	0.08 [a]	0.13 [a]	0.17 [a]		0.06 [b]	0.08 [a]	0.1[a]
CL	(% db)	GS	0.64 [a]	0.27 [a]	0.61 [a]		0.05 [b]	0.09 [a]	0.03[a]
		PY	0.64 [a]	0.27 [a]	0.61 [a]		0.05 [b]	0.09 [a]	0.03[a]
Heating value									
Lower heating value	MJ/kg d.b.	GS	17 [c]	17.43 [b]	15.95 [c]		15.33 [b]	17.01 [b]	24.8 [b]
		PY	17 [c]	17.43 [b]	15.95 [c]		15.33 [b]	17.01 [b]	24.8 [b]
Bulk density and size distribution									
Bulk density	kg/m3 a.r.	GS.	212 [c]	82-190 [b]	175 [c]		70-120 [b]	80-150 [b]	100-150 [b]
		PY	212 [c]	82-190 [b]	175 [c]		70-120 [b]	80-150 [b]	100-150 [b]

Based on these values (Table 3), it is evident that most straw feedstocks will require similar pre-treatment to meet the necessary parameters for pyrolysis or gasification processes. The key parameters that need to be addressed are ash content, volatile matter, and moisture. Specifically, the parameters highlighted in red must undergo treatment. For instance, screening will be essential to reduce the ash content in maize, wheat, soy, and oat straw to remove exogenous material resulting from harvesting operations, and if this

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still does not meet the required levels, other pre-treatments such as washing can be applied (effective treatment also for the removal of Cl).

As for the values associated with density, different types of ranges can be seen, depending on the level of compaction, therefore, bale production will be necessary as a pre-treatment to optimize logistics, otherwise the density is quite low.

Finally, the moisture content is lower than that of other feedstocks but still insufficient for direct use in the pyrolysis process, necessitating a minor drying step at the pyrolysis plant. Conversely, for gasification, the moisture content is slightly too low, which may require minimal rehydration of the material in certain cases.

3.2 Category m) Husks

Table 4 summarizes the physicochemical properties of the unique feedstocks categorized under m) husk (wheat husk), applying the color-coding scheme outlined earlier. In this case, it should be mentioned that it is difficult to find data about this feedstock, therefore ranges have been indicated between which it can be included each parameter.

Table 4. Physicochemical characterization of feedstock in category m)

Type	Unit	Method	**Wheat Husks**
Proximate analysis			
Moisture	(% ar)	GS	8-15
		PY	8-15
Volatile Matter	(% db)	GS	70-80
		PY	70-80
Ash	(% db)	GS	4-6
		PY	4-6
Ultimate análisis			
C	(% db)	GS	45-50
		PY	45-50
N	(% db)	GS	0.3-0.5
		PY	0.3-0.5
H	(% db)	GS	4-6
		PY	4-6
S	(% db)	GS	0.01-0.05
		PY	0.01-0.05
Cl	(% db)	GS	0.01-0.05

		PY	0.01-0.05
Heating value			
Lower heating value	MJ/kg d.b.	GS	16-18
		PY	16-18
Bulk density and size distribution			
Bulk density	kg/m3 a.r.	GS	70-150
		PY	70-150

From the values given in Table 4, associated with wheat husk, it can be concluded that the main parameter to pay attention to is its high ash content for both pyrolysis and gasification, additionally for pyrolysis this feedstock should be minimally dried, and the volatile content is not ideal, but not critical either.

3.3 Category n) Cobs cleaned of kernels of corn

Table 5 showcases the physicochemical properties of the feedstock examined under the n) cobs cleaned of kernels of corn category (maize cobs), utilizing the color-coding system described earlier.

Table 5. Physicochemical characterization of feedstock in category n)

Type	Unit	Method	Maize cobs
Proximate analysis			
Moisture	(% ar)	GS	7.04c
		PY	7.04 c
Volatile Matter	(% db)	GS	87.4 d
		PY	87.4 d
Ash	(%db)	GS	1.1 d
		PY	1.1 d
Ultimate analysis			
C	(% db)	GS	49 d
		PY	49 d
N	(% db)	GS	0.5 d
		PY	0.5 d
H	(% db)	GS	5.4 d
		PY	5.4 d
S	(% db)	GS	0.2 d
		PY	0.2 d
Cl	(% db)	GS	0.01 a

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		PY	0.01 a
Heating value			
Lower heating value	MJ/kg d.b.	GS	14-16 b
		PY	14-16 b
Bulk density and size distribution			
Bulk density	kg/m3 a.r.	GS	150-200 b
		PY	

As can be observed in **Table 5**, this feedstock meets almost all the requirements, with only minor deviations from the ideal values in a few parameters. As such, it may be regarded as a great choice for producing advanced biofuels. To attain ideal circumstances prior to treatment, the moisture content is the sole parameter that must be slightly changed (lower for pyrolysis and higher for gasification process).

3.4 Category o) Biomass fraction of wastes and residues from forestry and forest-based industries

Table 6 provides an overview of the physicochemical characteristics of feedstocks classified under the o) biomass fraction of wastes and residues from forestry and forest-based industries category, employing the previously detailed color-coding system.

These categories include different types of forestry feedstocks such as tree branches, bark, leaves, and sawdust. They are examples of forestry wastes and residues that are ideal feedstock to be used.

Table 6. Physicochemical characterization of feedstock in category o)

Parameter	Units	Technology	Primary residual forestry biomass	Secondary residual forestry biomass
Proximate analysis				
Moisture	(%ar)	GS	56.8 [a]	10 [c]
		PY	56.8 [a]	10 [c]
Volatile matter	(%db)	GS	79.9 [a]	
		PY	79.9 [a]	
Ash	(%db)	GS	3.2 [a]	1.5 [c]
		PY	3.2 [a]	1.5 [c]
Ultimate analysis				

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C	(%db)	GS	52.7 [a]	
		PY	52.7 [a]	
N	(%db)	GS	0.7 [a]	0.5 [c]
		PY	0.7 [a]	0.5 [c]
H	(%db)	GS	5.4 [a]	
		PY	5.4 [a]	
S	(%db)	GS	0.1 [a]	0.03 [c]
		PY	0.1 [a]	0.03 [c]
Cl	(%db)	GS	0.03 [a]	0.002 [c]
		PY	0.03 [a]	0.002 [c]
Heating value				
Lower heating value	MJ/kg db	GS	16-20	18.36 [c]
		PY	16-20	18.36 [c]
Bull density and size distribution				
Bulk density	kg/m3 a.r.	GS	100-250	236 [c]
		PY	100-250	236 [c]

Table 6 highlight that, in general, these feedstocks are very suitable for gasification and pyrolysis technology. Regarding primary residual forestry biomass, the main parameter to work on is the moisture content, which is very high, even for the logistics of this material, and on which it will be necessary to act prior to transport, as such high moisture considerably increases the cost of transport, and can even lead to the putrefaction of the material, and therefore its quality. The ash content also has a moderate value, as this is the usual for forestry residues.

On the other hand, secondary residual forestry biomass, does not show any critical values, although there may be small changes in the moisture content, ash content and N content.

3.5 Category p) Other non-food cellulosic material

Table 8 outlines the physicochemical characteristics of feedstocks grouped under the o) other non-food cellulosic material category, using the color-coding system explained earlier. In this case, due to the large number of feedstocks selected within this category, the following abbreviations (Table 7) are proposed, in order to better visualise the data in Table 8.

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Table 7. Abbreviations names for non-food cellulosic material parameters

Apples pruning=AP	Grape pomace=GM	Potato peel=PP	Rape seed pomace=RS	Olive pruning=OP
Grape pruning=GP	Potato leaves=PL	Sugar beet leave =SB	Sunflower seed leaves =SS	Olive pomace=OM

Table 8. Physicochemical characterization of feedstock in category p)

Parameter	Unit	Technology	AP	GP	GM	PL	PP	SB	RS	SS	OP	OM
Proximate analysis												
Moisture	(%ar)	GS	40-50 [e]	45 [e]				85 [c]	8.8 [b]	9.1 [a]	40-45 [e]	6.4 [b]
		PY	40-50 [e]	45 [e]					8.8 [b]	9.1 [a]	40-45 [e]	6.4 [b]
Volatile matter	(%db)	GS		76-79 [b]	74.4 [b]					76 [a]		70.8 [b]
		PY		76-79 [b]	74.4 [b]					76 [a]		70.8 [b]
Ash	(%db)	GS	3.5 [e]	3.1 [e]	4.2 [b]			4.8 [a]	5.4 [b]	3.1 [a]	4.0 [e]	10.9 [b]
		PY	3.5 [e]	3.1 [e]	4.2 [b]				5.4 [b]	3.1 [a]	4.0 [e]	10.9 [b]
Ultimate analysis												
C	(%db)	GS	49.17 [e]	49.10 [e]	54.94 [b]			44.5 [a]	53.5 [b]	50.1 [a]	47.90 [e]	52.0 [b]
		PY	49.17 [e]	49.10 [e]	54.49 [b]			44.5 [a]	53.5 [b]	50.1 [a]	47.90 [e]	52.0 [b]
N	(%db)	GS	0.68 [e]	0.57 [e]	2.09 [b]			1.84 [a]	4.9 [b]	1.1 [a]	0.50 [e]	1.62 [b]
		PY	0.68 [e]	0.57 [e]	2.09 [b]				4.9 [b]	1.1 [a]	0.50 [e]	1.62 [b]
H	(%db)	GS	5.93 [e]	6.30 [e]	5.83 [b]			5.9 [a]	7.3 [b]	5.5 [a]	6.10 [e]	6.91 [b]
		PY	5.93 [e]	6.30 [e]	5.83 [b]				7.3 [b]	5.5 [a]	6.10 [e]	6.91 [b]
S	(%db)	GS	0.06 [e]	0.05 [e]	0.21 [b]			0.13 [a]	0.54 [b]	0.03 [a]	0.06 [e]	0.18 [b]
		PY	0.06 [e]	0.05 [e]	0.21 [b]				0.54 [b]	0.03 [a]	0.06 [e]	0.18 [b]
Cl	(%db)	GS	0.04 [e]	0.01 [e]				0.053 [a]	0.03 [b]	0.1 [a]	0.06 [e]	0.2 [b]
		PY	0.04 [e]	0.01 [e]					0.03 [b]	0.1	0.06 [e]	0.2 [b]
Heating value												
Lower heating value	MJ/kg db	GS	15,93 [e]	17.93 [e]	20.53 [b]			16.6 [a]	22.69 [b]		17.55 [e]	17.6-19.3 [b]
		PY	15,93 [e]	17.93 [e]	20.53 [b]				22.69 [b]		17.55 [e]	17.6-19.3 [b]
Bulk density and size distribution												

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Bulk density	kg/m3 a.r.	GS	138.4 [e]	149.7 [e]							314.9 [e]	400-650
		PY	138.4 [e]	149.7 [e]							314.9 [e]	400-650

From **Table 8**, it can be concluded that the biomass from agricultural pruning (vineyard, olive, and apples trees) shows similar values. However, attention must be given to reducing moisture content and possibly screening the material to lower its ash content. The ash levels are likely higher than expected due to contamination during the collection process.

As for agricultural plant biomass (potato leaves, sunflower seed leaves, sugar beet leaves), the main takeaway is that most of them remain largely uncharacterized. Notably, they tend to have a high moisture content.

Lastly, secondary biomass (olive pomace, grape pomace, potato peel, rapeseed pomace) stands out for its relatively low moisture content (a result of prior drying during agro-industrial processing), high ash content, and, in some cases, concerning levels of nitrogen and sulfur.

In all cases, the calorific value is suitable, though densities vary significantly. Secondary biomass generally has the highest density, followed by woody agricultural biomass, and lastly, agricultural plant biomass.

3.6 Category q) Other ligno-cellulosic material except saw logs and veneer logs

Table 9 details the physicochemical properties of feedstock categorized as q) other lignocellulosic material except saw logs and veneer logs, being in this case forestry wood fuel, incorporating the previously explained color-coding scheme.

Table 9. Physicochemical characterization of feedstock in category q)

Type	Unit	Method	Foresty wood fuel
Proximate analysis			
Moisture	(% ar)	GS	12.2 [a]
		PY	12.2 [a]
Volatile	(% db)	GS	78 [a]

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Matter		PY	78 [a]
Ash	(%db)	GS	3.5 [a]
		PY	3.5 [a]
Ultimate analysis			
C	(% db)	GS	52.1 [a]
		PY	52.1 [a]
N	(% db)	GS	0.4 [a]
		PY	0.4 [a]
H	(% db)	GS	6.2 [a]
		PY	6.2 [a]
S	(% db)	GS	0.08 [a]
		PY	0.08 [a]
CL	(% db)	GS	0.02 [a]
		PY	0.02 [a]
Heating value			
Lower heating value	MJ/kg d.b.	GS	16-21 [a]
		PY	16-21 [a]
Bulk density and size distribution			
Bulk density	kg/m3 d.b.	GS	450-700 [a]
		PY	450-700 [a]

From **Table 9** it can be concluded that in general terms forestry wood fuel, it is a good feedstock to be processed for the production of advanced biofuels, with minor pre-treatments to be considered.

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4. Pre-treatment operations

The proposed pre-treatment operations of these section are focused on optimizing the logistics operations before delivery to a pyrolysis or gasification plant and considering the initial characteristic of the different biomass indicated in section 3. Given the wide variety of biomass types and the diverse logistical and operational challenges that may arise, this section offers a generalized perspective on the most common pretreatments used in practice. While it is important to recognize that specific scenarios can vary greatly depending on the unique characteristics of each biomass and its intended use, the focus here is on outlining the standard approaches that are most frequently applied across different contexts.

Each pre-treatment is described in broad terms to provide an understanding of its purpose and application. Following these general descriptions, a table is presented to summarize which pretreatments are commonly applied to the various types of biomasses under study. This approach allows for a clear and concise comparison, highlighting which processes are typically relevant to each biomass type and ensuring that logistical planning and processing efficiency are well-aligned.

The proposed pre-treatments are mainly physical, with the objective of improving the homogeneity, density and quality of the feedstock considered.

4.1 Baling

The goal of baling is to increase the density of feedstock to optimize transportation efficiency. This can be done either directly in the field (most common practice) or at a nearby site where the material is gathered and processed for easier distribution. The choice of location depends on the specific needs of each operation.

Two main types of balers are commonly used:

- Rectangular balers: These create uniform, high-density bales that are ideal for long-distance transport due to their stackability and efficient use of space. They are often preferred in large-scale operations where consistency is key.
- Round balers: These produce cylindrical bales that work well with less uniform materials. Although they are generally less dense than rectangular bales, their shape makes them more durable in tougher conditions.

Table 10 outlines which types of feedstocks are best suited for each baling method to optimize logistics.

Table 10. Baling operation recommended to optimise the logistics of the feedstock under consideration.

Categories Annex IX	Biomass considered at European level	Baling	Comments
e) Straw	Maize Stalk	YES	In most cases, this feedstock is baled in the field to optimise its transport. It can be either rectangular or round bales.
	Barley Straw		
	Wheat straw		
	Soya straw		
	Rye straw		
	Oats straw		
	Triticale straw		
	Rape seed straw		
m) Husks	Wheat husk	NO	It is not usual to have to bale this feedstock.
n) Cobs cleaned of kernels of corn	Maize cob	NO	It is not usual to have to bale this feedstock.
o) Biomass fraction of wastes and residues from forestry and forest-based industries	Primary residual forestry biomass	Optional	Although it is not usual to have to bale it, it is sometimes carried out, especially if it has to be transported considerable distances without being able to carry a granulometric reduction.
	Secondary forestry biomass	NO	It is not usual to have to bale this feedstock.
p) Other non-food cellulosic material	Fruits pruning	Optional	Prunings usually have a very low density, so they are shredded on the field or either transported to a nearby site to be shredded to increase their density, or at harvesting they must be baled to optimise their transport.
	Grape pruning		
	Olive pruning		

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	Potatoes leaves	NO	Not because their high moisture content and decomposition rate make them impractical for long-distance transport. If it is dried before could be baled to optimise the logistics.
	Sugar beet leaves		
	Sunflower seed leaves		
	Grape pomace	NO	It is not usual to have to bale this feedstock.
	Olive pomace		
	Rape seed pomace		
	Potatoes peel		
q) Other ligno-cellulosic material except saw logs and veneer logs.	Forestry wood fuel	Optional	Although it is not usual to have to bale it, it is sometimes carried out, especially if it has to be transported considerable distances without being able to carry a granulometric reduction.

4.2 Chipping/shredding

The objective of these operations is to increase the density of the feedstock for being transported, thereby optimizing transportation efficiency. This process can be carried out either directly in the field or in a nearby location where the material must be gathered and processed for more efficient distribution to the next stakeholder. The choice of location depends on the specific circumstances of each case.

To achieve granulometric reduction, two main types of equipment are commonly used:

- Chippers: These machines use knives to cut the material, producing a more homogeneous output. However, they are more susceptible to wear and damage if exogenous materials like sand or stones are present in the feedstock.
- Shredders: These rely on hammers to reduce material size through by tearing (shredding) it apart. While the resulting material is more heterogeneous, shredders are generally more robust and better suited for handling feedstock with exogenous materials.

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As a result, chippers are typically preferred for raw materials from the forestry sector, as they generally contain fewer contaminants. Conversely, shredders are more commonly used for agricultural feedstock during the initial size reduction phase.

Table 11 indicates which feedstock is most associated with chipping and shredding treatments in order to optimise feedstock logistics.

Table 11. Chipping and/or shredding operation recommended to optimise the logistics of the feedstock under consideration.

Categories Annex IX	Biomass considered at European level	Chipping and/or shredding	Comments
e) Straw	Maize Stalk	NO	This type of feedstock is typically distributed in bale form. While the baling process may involve minor chipping, this is integrated directly into the baling machine itself, eliminating the need for an additional processing stage.
	Barley Straw		
	Wheat straw		
	Soya straw		
	Rye straw		
	Oats straw		
	Triticale straw		
	Rape seed straw		
m) Husks	Wheat husk	NO	They are usually already small in size, making this type of operation unnecessary.
n) Cobs cleaned of kernels of corn	Maize cob	Shredding	Although crushing maize cobs is not strictly necessary, it can be beneficial for optimizing logistics.
o) Biomass fraction of wastes and residues from forestry and forest-based industries	Primary residual forestry biomass	Chipping	Whether in the forest or at an intermediate location, chipping is generally carried out to reduce particle size and optimize the amount of material to be transported.
	Secondary forestry biomass	NO	They generally have a small particle size, as they are

			byproducts (already processed) from the wood industry.
p) Other non-food cellulosic material	Fruits pruning	Shredding	It should be properly shredded either in the field or at an intermediate location to improve its density and optimize transportation.
	Grape pruning		
	Olive pruning		
	Potatoes leaves	Chipping or Shredding	Low-density material that needs to have its granulometry reduced and become more homogeneous before transportation.
	Sugar beet leaves		
	Sunflower seed leaves		
	Grape pomace	NO	These materials already have a low granulometry, so further reduction is not critical for optimizing logistics.
	Olive pomace	NO	
	Rape seed pomace	NO	
	Potatoes peel	NO	
q) Other ligno-cellulosic material except saw logs and veneer logs.	Forestry wood fuel	Chipping	Whether in the forest or at an intermediate location, chipping is generally carried out to reduce particle size and optimize the amount of material to be transported.

4.3 Screening

The goal of screening operations is to remove unwanted contaminants, such as sand, stones, and other impurities, that can increase the ash content in the feedstock and affect its quality for further processing. This step is essential to ensure that the material meets the required standards before being transported or processed further.

Screening typically takes place at intermediate locations, such as processing facilities near collection points, as it’s not as common to perform this operation directly in the field or forest due to logistical challenges and the need for specialized equipment.

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To achieve effective separation, two main types of equipment are commonly used:

- Vibratory Screens: These machines use vibration to move material across a mesh, allowing smaller particles to pass through while larger ones are retained. Vibratory screens are effective for sorting materials into different sizes, but they can be sensitive to characteristics like moisture content or stickiness.
- Rotary Screens: These feature a rotating drum with perforated holes that separate larger particles from finer ones. They are more robust and can handle materials with higher moisture content or irregular shapes, making them ideal for agricultural feedstocks or materials with more variability.

In general, vibratory screens are preferred for materials with more consistent sizes, while rotary screens are better suited for more mixed feedstocks or those with higher levels of impurities.

Table 12 shows which types of feedstocks are most commonly associated with each type of screening, helping to optimize both material quality and logistics.

Table 12. Screening operation recommended to optimise the quality and logistics of the feedstock under consideration.

Categories Annex IX	Biomass considered at European level	Screening	Comments
e) Straw	Maize Stalk	NO	Although it is an agricultural resource that can be contaminated with impurities during collection such as stones, sand, etc. However, since the bales are produced in the field without screening the material, performing screening afterward would require unpacking the bales and re-baling them, which would significantly increase costs.
	Barley Straw		
	Wheat straw		
	Soya straw		
	Rye straw		
	Oats straw		
	Triticale straw		
	Rape seed straw		
m) Husks	Wheat husk	NO	It should not be necessary, as it is a byproduct that has already been separated and classified within the agroindustry.
n) Cobs cleaned of kernels of corn	Maize cob	NO	It should not be necessary, as it is a byproduct that has already been separated and

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			classified within the agroindustry.
o) Biomass fraction of wastes and residues from forestry and forest-based industries	Primary residual forestry biomass	Optional	As primary residual forestry biomass, there is a higher likelihood of containing more exogenous material during collection compared to wood that comes solely from the tree trunk.
	Secondary forestry biomass	NO	It should not be necessary, as it is a byproduct that has already been separated and classified within the wood industry.
p) Other non-food cellulosic material	Fruits pruning	Recommended	These are agricultural crops collected in the field, and therefore, there is a high likelihood of contamination with sand or stones during the associated harvesting operations.
	Grape pruning		
	Olive pruning		
	Potatoes leaves	Recommended	These are agricultural crops collected in the field, and therefore, there is a high likelihood of contamination with sand or stones during the associated harvesting operations.
	Sugar beet leaves		
	Sunflower seed leaves		
	Grape pomace	NO	It should not be necessary, as it is a byproduct that has already been separated and classified within the agroindustry.
	Olive pomace	NO	
	Rape seed pomace	NO	
	Potatoes peel	NO	
q) Other ligno-cellulosic material except saw logs and veneer logs.	Forestry wood fuel	Optional	As primary residual forestry biomass, there is a higher likelihood of containing more exogenous material during collection compared to wood

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			that comes solely from the tree trunk.

4.4 Drying

The objective of drying operations is twofold: to prevent the degradation of the biomass during storage and transport and to avoid transporting biomass with a high moisture content, which effectively means transporting water instead of the target material. This drying step ensures that transport is more efficient and cost-effective, leaving the achievement of the final moisture content to the facilities responsible for pyrolysis or gasification. These plants are equipped with dryers capable of reaching the very low moisture levels required, especially for pyrolysis.

Drying can be performed using either natural or forced methods, depending on the desired moisture reduction:

- Natural drying: This method involves exposing the material to the open air for a period before proceeding with collection, chipping, or shredding. It is a low-cost approach and can range from simple field drying to more elaborate setups that enhance air circulation. However, natural drying is weather-dependent and may not achieve very low moisture levels.
- Forced drying: This method uses energy-intensive processes, such as heat or controlled air circulation, to significantly reduce the moisture content of the biomass. Although more expensive, forced drying allows for faster and more precise moisture reduction, making it suitable when lower moisture levels are required.

In all cases, the purpose of this drying step is to optimize transportation efficiency rather than achieve the final target moisture content, which remains the responsibility of the pyrolysis or gasification plants.

Table 13 indicates which types of feedstocks are most linked with drying operations to improved material quality and transportation efficiency.

Table 13. Drying operation recommended to optimise the quality and logistics of the feedstock under consideration.

Categories Annex IX	Biomass considered at European level	Drying	Comments

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e) Straw	Maize Stalk	NO	Biomass derived from straw and stalks typically has a moisture content of less than 20%. As a result, drying is generally unnecessary for this type of material. However, if the farmer allows it, the material is often left in the field for about a week after harvesting before baling. This practice helps reduce the moisture content naturally.
	Barley Straw		
	Wheat straw		
	Soya straw		
	Rye straw		
	Oats straw		
	Triticale straw		
	Rape seed straw		
m) Husks	Wheat husk	NO	These materials typically have moisture contents below 20%, making drying unnecessary.
n) Cobs cleaned of kernels of corn	Maize cob	NO	These materials typically have moisture contents below 20%, making drying unnecessary.
o) Biomass fraction of wastes and residues from forestry and forest-based industries	Primary residual forestry biomass	Natural drying is recommended	Forestry biomass typically has a moisture content of around 50% after harvesting, which is relatively high. Whenever possible, natural drying should be carried out before transportation to reduce the moisture content to a range of 25-40%. These levels can often be achieved through natural drying, although the outcome will depend on climatic conditions.
	Secondary forestry biomass	NO	These materials typically have moisture contents below 20%, making drying unnecessary.
p) Other non-food cellulosic material	Fruits pruning	Natural drying is recommended	Agricultural pruning typically has a moisture content of around 40-50% after
	Grape pruning		

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	Olive pruning		harvesting, which is relatively high. Whenever possible, natural drying should be carried out before transportation to reduce the moisture content to a range of 25-40%. These levels can often be achieved through natural drying, although the outcome will depend on climatic conditions.
	Potatoes leaves	Forced drying	The moisture content in most cases exceed 65%. This high moisture level typically requires forced drying to reduce it.
	Sugar beet leaves		
	Sunflower seed leaves		
	Grape pomace	Forced drying	Although the moisture content of these byproducts depends on the extraction process, in most cases, it exceeds 60%. This high moisture level typically requires forced drying to reduce it. In many instances, this drying process is carried out within the agroindustry itself before the byproducts are sold.
	Olive pomace		
	Rape seed pomace		
	Potatoes peel		
q) Other ligno-cellulosic material except saw logs and veneer logs.	Forestry wood fuel	Natural drying is recommended	Forestry biomass typically has a moisture content of around 50% after harvesting, which is relatively high. Whenever possible, natural drying should be carried out before transportation to reduce the moisture content to a range of 25-40%. These levels can often be achieved through natural drying, although the

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			outcome will depend on climatic conditions.

4.5 Pelletising

It is a mechanical process that compacts biomass into small, dense, cylindrical pellets. This treatment is aimed at improving the biomass's handling, storage, and transport efficiency while also enhancing its energy density and combustion characteristics. However, the pelletisation process involves a relatively high cost, which can only be justified if the biomass needs to be transported over considerable distances. Additionally, producing pellets requires several other pretreatments beforehand, including chipping, screening, drying, and milling, further contributing to the overall complexity and expense of the process. All these operations must be carried out in a nearby intermediate facility.

Table 14 shows on which types of raw materials it may make more sense to pelletise them, always considering that this is conditioned by the associated cost.

Table 14. Pelletising operation recommended to optimise the logistics (if long distances needs to be covered) of the feedstock under consideration

Categories Annex IX	Biomass considered at European level	Pelletising	Comments
e) Straw	Maize Stalk	Optional	Straw is normally transported in bales whose density is usually less than 200 kg/m^3 (although this may vary), but if it is converted into pellets, it should be around 600 kg/m^3, which means that three times the amount per m^3 would be transported.
	Barley Straw		
	Wheat straw		
	Soya straw		
	Rye straw		
	Oats straw		
	Triticale straw		
	Rape seed straw		
m) Husks	Wheat husk	NO	These materials already have a small particle, so it does not usually make much sense to

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			pelletise them, due to the cost involved.
n) Cobs cleaned of kernels of corn	Maize cob	NO	Although its density is not excessively high, it is usually a complicated material to pelletise, and therefore this operation is not usually carried out.
o) Biomass fraction of wastes and residues from forestry and forest-based industries	Primary residual forestry biomass	Optional	Primary residual forestry biomass is normally transported in chips whose density is usually less than 250 kg/m^3 (although this may vary according to the moisture content), but if it is converted into pellets, it should be around 600-650 kg/m^3, which means almost three times the amount per m^3 would be transported.
	Secondary forestry biomass	Optional	These materials already have a small particle size and higher density that residual forestry biomass, even though the pelletisation can be done to optimise long distance.
p) Other non-food cellulosic material	Fruits pruning	Optional	Agricultural pruning is normally transported shredding whose density is usually less than 200 kg/m^3 (although this may vary according to the moisture content), but if it is converted into pellets, it should be around 600-650 kg/m^3, which means almost three times the amount per m^3 would be transported.
	Grape pruning		
	Olive pruning		
	Potatoes leaves	NO	

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	Sugar beet leaves		This vegetable biomass can be difficult to pelletise.
	Sunflower seed leaves		
	Grape pomace	NO	These materials already have a small particle size and high density, so it does not usually make much sense to pelletise them, due to the cost involved.
	Olive pomace		
	Rape seed pomace		
	Potatoes peel		
q) Other ligno-cellulosic material except saw logs and veneer logs.	Forestry wood fuel	Optional	Forestry wood fuel is normally transported in chips or firewood whose density is usually less than 250 kg/m^3 (although this may vary according to the moisture content), but if it is converted into pellets, it should be around 600-650 kg/m^3, which means almost three times the amount per m^3 would be transported.

4.6 Other pre-treatments

There are additional treatments that could be implemented; however, it is more likely that, if needed, they would be more logically carried out at the gasification or pyrolysis plant. Some of these treatments include:

- Forced drying: As indicated before, the aim of forced drying is to reduce the moisture content of the feedstocks, therefore in order to reach the target moisture content indicated in Table 2, on the one hand forced drying will probably be necessary for all types of biomass in the pyrolysis plant, on the other hand in the gasification plant it will depend on the type of biomass, as it is not so restrictive in this respect.
- Milling: It is a mechanical operation aimed at reducing the particle size of biomass to achieve smaller, uniform dimensions. This process involves the application of mechanical forces using specialized equipment, such as hammer mills. The primary objective is to break down the biomass into fine particles, facilitating its subsequent handling, processing, or conversion into biofuels or other products. By reducing the particle size, milling enhances the material's surface area, improving its reactivity and efficiency in downstream processes like gasification and pyrolysis (with the latter being a more necessary operation according to the criteria indicated in Table 2).

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- Washing: It is a pretreatment process designed to reduce the chlorine content and remove other impurities present in biomass. This operation involves soaking or rinsing the biomass with water or other solvents, often combined with agitation, to dissolve and extract unwanted compounds. The primary goal is to lower the levels of chlorine, alkali metals, and other contaminants that can negatively affect downstream processes, such as gasification or pyrolysis. However, this process increases the moisture content of the biomass, requiring an additional drying step afterward to restore optimal conditions for subsequent processing.

Table 15 summarises the pre-treatments associated with each of the feedstocks analysed in this section.

Table 15. Summary of the pretreatments associated with each feedstock considered.

Categories Annex IX	Biomass considered at European level	Baling	Chipping / Shredding	Screening	Drying	Pelletising
e) Straw	Maize Stalk	Yes	No	No	No	Optional
	Barley Straw					
	Wheat straw					
	Soya straw					
	Rye straw					
	Oats straw					
	Triticale straw					
	Rape seed straw					
m) Husks	Wheat husk	No	No	No	No	No
n) Cobs cleaned of kernels of corn	Maize cob	No	Shredding	No	No	No

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o) Biomass fraction of wastes and residues from forestry and forest-based industries	Primary residual forestry biomass	Optional	Chipping	Optimal	Natural drying is recommended	Optional
	Secondary forestry biomass	No	No	No	No	Optional
p) Other non-food cellulosic material	Fruits pruning	Optional	Shredding	Recommended	Natural drying is recommended	Optional
	Grape pruning					
	Olive pruning					
	Potatoes leaves	No	Chipping or shredding	Recommended	Forced drying	No
	Sugar beet leaves					
	Sunflower seed leaves					
	Grape pomace	No	No	No	Forced drying	No
	Olive pomace					
	Rape seed pomace					
	Potatoes peel					
q) Other ligno-cellulosic material except saw logs and veneer logs.	Forestry wood fuel	Optional	Chipping	Optional	Natural drying is recommended	Optional

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5. CAPEX and OPEX of pre-treatments operations.

This section aims to provide an overview of the costs associated with the pre-treatments. It is important to note that these cost estimates are highly indicative and can vary significantly depending on numerous factors. Nevertheless, they offer a reference for understanding the typical cost range for each of these pretreatment operations.

In order to carry out this cost analysis, reports or databases from FAO [7], Eurostat [8], IRENA [9], IEA Bioenergy Task 32 and 43 [10] and Sokhansanj, Shahab ,2006 [11] have been analysed. In addition, more detailed studies for each specific pre-treatment have been taken into account (indicated in the corresponding section).

5.1 Baling

Baling operations for biomass feedstocks involves significant investment and operational costs that vary depending on the type of feedstock, the equipment used, and the region where the activity takes place. In addition to the above biographical sources, in this section the following sources have been considered S.V.Lemons et al,2014 [12].

5.1.1 CAPEX of baling

The upfront cost of baling equipment represents a significant portion of CAPEX. The price of balers depends on their size, capacity, and technological sophistication. For small-scale operations, equipment costs typically range from 20,000 € to 50,000 €, while larger, high-capacity balers designed for industrial-scale operations can cost between 50,000 € and 150,000 €.

The type of baler also plays an essential role. Round balers are generally less expensive but produce bales that may be less space-efficient for transport and storage compared to square bales. Advanced balers equipped with automation or multi-feedstock capabilities will also have higher costs, though they may yield better efficiency in the long term.

Additionally, the characteristics of the feedstock can impact CAPEX. For instance, tougher materials like forestry residues require more durable and specialized machinery, which increases the capital investment needed.

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5.1.2 OPEX of baling

OPEX includes all recurring costs associated with baling operations, such as fuel, maintenance, and labor. On average, OPEX can range from 7 to 23 € per ton of biomass, but this varies based on multiple factors.

Fuel costs are a significant component, typically ranging between 3 and 10 € per ton, influenced by machine efficiency and the energy density of the feedstock. Maintenance costs, which cover repairs, servicing, and spare parts, usually fall between 3 and 7 € per ton. Labor costs add another 1 to 6 € per ton, depending on regional wage differences and the degree of automation in the operation.

The type of feedstock significantly affects OPEX. Denser or more abrasive materials, such as forestry residues, lead to higher wear and tear on equipment, increasing maintenance and fuel consumption. Conversely, lighter materials like straw are less demanding on machinery, resulting in lower operational costs.

5.1.3 Regional variation in the EU

The costs of baling operations also vary geographically across the EU due to differences in labor expenses, equipment availability, and climatic conditions. In Northern and Western Europe, CAPEX and OPEX tend to be higher due to elevated machinery and labor costs. However, these regions often benefit from renewable energy subsidies, which can offset some expenses.

Southern Europe, with its favorable climatic conditions, often sees moderate costs, particularly for agricultural feedstocks like straw and pruning. Lower labor costs also contribute to more competitive OPEX. In Eastern Europe, costs are generally the lowest due to reduced labor expenses. However, limited access to advanced machinery can sometimes necessitate higher CAPEX for imported equipment.

Table 16 summarise the CAPEX and OPEX estimates cost for each of the feedstock identified in section 4.1 that could need to be baled.

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Table 16. Summary of CAPEX and OPEX cost for baling operations.

Feedstock	CAPEX (€)	OPEX (€/t)	Remarks
Straw	20,000 - 100,000	7 - 15	Lower wear and tear, widely available baling equipment.
Forestry Residues	50,000 - 150,000	10 - 20	Higher wear due to woody material; requires robust machinery.
Agricultural Pruning	30,000 - 120,000	8 - 18	Variability due to pruning size and density.
Forestry Wood Fuel	50,000 - 150,000	12 - 23	Dense material increases fuel, wear, and maintenance costs.

5.2 Chipping/shredding

The chipping or shredding of biomass is a crucial step in the preprocessing of feedstocks for bioenergy applications. The costs associated with this operation, both in terms of capital expenditure (CAPEX) and operational expenditure (OPEX), vary based on the type of feedstock, the capacity of the machinery, and regional factors. Below is an analysis of these costs for selected feedstocks: maize cob, primary residual forestry biomass, agricultural pruning, vegetable pruning, and forestry wood fuel, which are the feedstock identified in section 4.2 that needs these operations.

In addition to the above biographical sources, in this section the following sources have been considered Eunjai Lee et al.,2017 [13].

5.2.1 CAPEX of chipping/shredding

The CAPEX for chipping or shredding primarily depends on the type and capacity of the equipment used. Smaller, entry-level chippers or shredders suitable for lighter feedstocks like maize cobs or vegetable pruning can cost between 10,000 and 50,000 €. For larger-scale operations that handle denser or more abrasive materials such as forestry wood fuel or residual forestry biomass, the cost of industrial-grade chippers can rise to 100,000–250,000 €.

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Feedstock properties heavily influence CAPEX. Lightweight materials like maize cobs and agricultural prunings can be processed using less robust equipment, whereas dense or fibrous materials such as forestry wood fuel and primary forestry residues require more powerful machinery, increasing initial investment.

5.2.2 OPEX of chipping/shredding

OPEX encompasses costs related to fuel, maintenance, and labor. These costs vary significantly with feedstock type and operational conditions:

- Fuel Costs: Shredders and chippers consume fuel based on the feedstock's density and moisture content. Lighter feedstocks like vegetable prunings may incur fuel costs of 2–5 € per ton, while denser materials like forestry wood fuel may range between 5–10 € per ton.
- Maintenance Costs: Wear and tear are higher when processing woody or abrasive feedstocks, leading to maintenance costs of 3–8 € per ton for forestry residues or wood fuel, compared to 2–4 € per ton for softer materials like maize cobs.
- Labor Costs: Labor costs are generally consistent across feedstocks, ranging between 1–3 € per ton, depending on regional wage rates and the level of automation in the operation.

Overall, total OPEX for chipping or shredding operations typically ranges from 5 to 18 € per ton, with lighter feedstocks on the lower end and dense, abrasive materials at the higher end.

5.2.3 Regional variation in the EU

The costs of chipping or shredding operations in the EU are influenced by regional differences in labor availability, feedstock types, and access to machinery.

In Northern and Western Europe, the use of advanced, high-capacity chippers is common, especially for forestry residues and woody biomass. These regions experience higher CAPEX due to the preference for cutting-edge machinery designed for efficiency and durability, with OPEX also rising because of higher labor and fuel costs. However, these costs can be partially offset by renewable energy subsidies and incentives that are prevalent in these countries.

In Southern Europe, CAPEX is moderate, as many operations rely on mid-range shredders capable of handling agricultural prunings or maize cobs, OPEX tends to be lower due to fuel costs and labor costs in Southern Europe are also more competitive, further improving the cost-effectiveness of these operations.

In Eastern Europe, chipping and shredding costs are generally the lowest across the EU, driven by lower labor expenses and the widespread use of smaller or older machinery. While this results in lower CAPEX for operations processing agricultural residues and lighter feedstocks, the lack of access to modern, high-

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capacity chippers can increase costs when handling denser materials like forestry wood fuel. Despite this, abundant local biomass resources help maintain low operational costs overall.

Table 17 summarise the CAPEX and OPEX estimates cost for each of the feedstock identified in section 4.2 that could need to be chipped/shredded.

Table 17. Summary of CAPEX and OPEX cost for chipping/shredding operations.

Feedstock	CAPEX (€)	OPEX (€/t)	Remarks
Maize Cob	10,000 - 50,000	5 - 10	Lighter feedstock; suitable for smaller-scale chippers.
Forestry Residues	50,000 - 250,000	10 - 18	Requires industrial-grade equipment; high wear and fuel costs.
Agricultural Pruning	20,000 - 100,000	7 - 15	Moderate density; requires medium-scale shredders.
Vegetable Pruning	10,000 - 50,000	5 - 12	Soft material; lower maintenance and fuel costs.
Forestry Wood Fuel	50,000 - 250,000	12 - 18	Dense and abrasive; highest wear and maintenance costs.

5.3 Screening

Screening is an optional operation in biomass preprocessing, aimed at removing foreign materials like sand, stones, and debris. The degree of contamination and the physical characteristics of each biomass type significantly influence the choice of screening equipment and the associated costs. Ash content can be reduced through this operation. The feedstocks that were identified for this operation in section 4.3 were: primary forestry residues, agricultural pruning, vegetable pruning and forestry wood fuel.

5.3.1 CAPEX of screening

The CAPEX for screening equipment depends on the feedstock's contamination level and physical properties:

- Agricultural Pruning and Vegetable Pruning: Probably (it depends of the feedstock harvesting practice) high contamination with sand and stones requires robust screening systems, pushing

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CAPEX to 20,000–50,000 € for medium-capacity equipment and up to 80,000 € for high-capacity setups.

- Forestry Residues and Wood Fuel: Forestry biomass tends to have moderate contamination levels, requiring durable but less complex equipment. CAPEX ranges from 30,000 to 80,000 €, with higher-end systems designed for large-scale operations.

5.3.2 OPEX of screening

OPEX reflects recurring costs such as energy consumption, maintenance, and labor. Feedstocks with higher contamination levels typically incur greater OPEX due to increased maintenance and energy requirements.

- Energy Costs: Agricultural and vegetable prunings, with higher sand and stone contamination, result in energy costs of 1.5–3.5 € per ton. Forestry biomass, with less abrasive contamination, has energy costs of 1–2.5 € per ton.
- Maintenance Costs: The abrasive nature of sand and stones significantly increases wear and tear on screens. Maintenance for agricultural and vegetable prunings costs between 1.5–3 € per ton, while forestry biomass costs range from 1–2.5 € per ton.
- Labor Costs: Labor costs remain consistent across feedstocks, ranging from 0.5–1.5 € per ton, depending on the level of automation.

Overall, OPEX for agricultural pruning is the highest due to its contamination profile, ranging from 3.50 to 8.00 € per ton, while forestry biomass generally incurs lower OPEX, at 2.5 to 6 € per ton.

5.3.3 Regional variation in the EU

Screening costs can vary across different regions in the European Union due to differences in labor costs, energy prices, and equipment availability, in the same way as it was mentioned for other operations. In Northern and Western Europe, higher labor costs drive the adoption of more automated screening systems, which results in increased CAPEX but lower labor-related OPEX. These regions also benefit from greater access to advanced technologies, which can improve energy efficiency and reduce operational costs over time.

In Southern Europe, labor and energy costs are more moderate, making operations generally more competitive, particularly for feedstocks like agricultural and vegetable prunings that require robust screening solutions. This region often employs medium-capacity systems that strike a balance between durability and affordability.

Eastern Europe stands out due to its lower labor costs, which contribute to reduced overall OPEX. However, the limited local availability of advanced screening equipment can drive up CAPEX, as machinery often

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needs to be imported. These regional differences highlight the importance of tailoring screening solutions to local conditions and feedstock types to optimize costs and efficiency.

Table 18 summarises the CAPEX and OPEX estimates cost for each of the feedstock identified in section 4.3 that could need to be screened.

Table 18. Summary of CAPEX and OPEX cost for screening operations.

Feedstock	CAPEX (€)	OPEX (€/t)	Remarks
Primary Forestry Residues	30,000 - 80,000	2.5 - 6	Moderate contamination; requires durable systems but with lower wear rates.
Agricultural Pruning	20,000 - 80,000	3.5 - 8	High contamination with sand and stones; leads to greater wear and costs.
Vegetable Pruning	20,000 - 50,000	3.5 - 7	Similar contamination profile to agricultural pruning; requires robust systems.
Forestry Wood Fuel	30,000 - 80,000	2.5 - 6	Lower contamination but denser material; energy-efficient systems favored.

5.4 Drying

Drying could be an important operation in biomass pre-processing (with the goal of optimizing the logistic operations), as it reduces moisture content to enhance energy efficiency, storage stability, and ease of handling. Depending on the biomass type and moisture levels, drying can be conducted through natural or forced methods. Below is a detailed breakdown of CAPEX, OPEX, and regional variations in costs for these operations, the feedstock considered were primary residual forestry biomass, agricultural pruning and forestry wood fuel for natural drying and agricultural vegetables, agricultural pomace and potatoes peel for forced drying (section 4.4).

In addition to the above biographical sources, in this section the following source have been considered Sebastian Paczkowski et al.,2021 [14].

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5.4.1 CAPEX of drying

The CAPEX for drying operations depends significantly on the drying method:

- Natural drying: This method requires minimal infrastructure, such as drying platforms, racks, or covered areas. CAPEX ranges from 5,000 to 30,000 €, depending on the scale and sophistication of the setup. It is typically used for biomass with moderate initial moisture levels, such as primary forestry residues, agricultural pruning, and forestry wood fuel.
- Forced drying: This method involves specialized equipment like drum dryers, hot air systems, and fans. CAPEX is considerably higher, ranging from 50,000 to 500,000 €, based on capacity and technology. Biomass with high initial moisture content, such as agricultural vegetables, pomace, and potato peels, often requires forced drying to achieve desired moisture levels efficiently.

5.4.2 OPEX of drying

OPEX is influenced by energy consumption, maintenance needs, and labor:

- Natural Drying:
  - Energy costs: Negligible, as natural drying relies on environmental conditions.
  - Maintenance Costs: Primarily for maintaining drying areas, ranging from 0.50 - 1 € per ton.
  - Labor costs: Costs for material handling and turning biomass range from 0.50 - 1.5 € per ton.
  - Overall, OPEX for natural drying is low, averaging 1 - 2.5 € per ton.
- Forced Drying:
  - Energy costs: Significant, especially for high-moisture biomass. Costs range from 5 to 12 € per ton, depending on the energy source and drying efficiency.
  - Maintenance costs: Equipment wear and tear results in maintenance costs of 1 - 3 € per ton.
  - Labor costs: Labor for equipment operation and monitoring adds 1 - 2 € per ton.
  - Overall, OPEX for forced drying ranges from 7 - 17 € per ton, depending on system efficiency and scale.

5.4.3 Regional variation in the EU

Regional factors, such as climate, labor costs, and energy prices, play a significant role in drying costs:

- Southern Europe: Ideal for natural drying due to warm and dry climates, which minimize drying time and labor costs. Forced drying operations benefit from access to solar-powered systems, reducing energy expenses.
- Northern and Western Europe: Cooler and wetter climates necessitate forced drying for most biomass. These regions often integrate renewable energy, such as biomass boilers, to lower long-term OPEX despite higher initial CAPEX.

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- Eastern Europe: Lower labor costs make both natural and forced drying operations more affordable. However, limited access to advanced drying technology may increase CAPEX for forced drying, as equipment often needs to be imported.

Table 19 summarise the CAPEX and OPEX estimates cost for each of the feedstock identified in section 4.4 that could need to be dried.

Table 19. Summary of CAPEX and OPEX cost for drying operations.

Drying method	Feedstock	CAPEX (€)	OPEX (€/t)	Remarks
Natural	Primary Forestry Residues	5,000 - 30,000	1 - 2.50	Suitable for low-humidity climates like Southern Europe.
Natural	Agricultural Pruning	5,000 - 30,000	1.50 - 2.50	Simple infrastructure; labor costs may rise in wetter climates.
Natural	Forestry Wood Fuel	5,000 - 30,000	1 - 2.50	Effective for dense, low-moisture feedstocks in dry climates.
Forced	Agricultural Vegetables	50,000 - 300,000	7 - 15	Energy-intensive due to high initial moisture.
Forced	Agricultural Pomace	100,000 - 500,000	10 - 17	High-capacity systems required due to high initial moisture.
Forced	Potato Peel	50,000 - 300,000	7 - 15	Energy-intensive due to high initial moisture.

5.5 Pelletising

Pelletising is a key step in the production of dense, energy-rich biomass suitable for storage, transportation, and use in various energy systems. The process involves compressing biomass into uniform pellets using pellet mills, which require precise control over feedstock properties, such as particle size and moisture content. It should be noted that this section only includes the estimated costs associated with the pelleting process, although in many cases a preliminary stage of chipping, drying and milling is necessary prior to pelletising.

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Below is a detailed analysis of the capital expenditure (CAPEX), operational expenditure (OPEX), and regional cost variations for pelletizing operations across different biomass types indicated in section 4.5, which are: straw, primary forestry biomass, secondary forestry biomass, agricultural pruning and forestry wood fuel.

In addition to the above biographical sources, in this section the following sources have been considered Sebastian Paczkowski et al., 2021 [14], Hassan Shahrukh et al ., 2016 [15] .

5.5.1 CAPEX of pelletising

The CAPEX for pelletizing depends on the capacity and technology of the pellet mill, as well as feedstock characteristics:

- Small-scale pellet mills: These are often used for straw, agricultural pruning, and forestry wood fuel at smaller production volumes. CAPEX ranges from 50,000 to 300,000 €, depending on the system's size and features like moisture control and automation.
- Industrial-scale pellet mills: High-capacity systems, commonly used for processing primary and secondary forestry residues, require substantial investment. CAPEX ranges from 500,000 to 3,000,000 €, with costs driven by equipment capacity, drying and cooling systems, and energy efficiency features.

5.5.2 OPEX of pelletising

OPEX for pelletizing is influenced by energy consumption, maintenance, and labor costs:

- Energy costs: Pelletizing is energy-intensive due to the need for high-pressure compression. Energy costs range from 7 to 15 € per ton, depending on feedstock density and moisture.
- Maintenance costs: Pellet mills experience significant wear and tear, especially with abrasive feedstocks like straw or forestry residues. Maintenance costs typically range from 3 to 6 € per ton.
- Labor costs: Automated systems require minimal labor, while semi-automated or small-scale operations involve more manual oversight. Labor costs add approximately 2 to 5 € per ton.

OPEX for pelletizing ranges from 12 to 26 € per ton, depending on the scale of the operation and feedstock properties. If the whole pelleting process is covered, the cost of operation can be around 90 - 130 €/t.

5.5.3 Regional variation in the EU

Pelletizing costs vary across European regions due to differences in energy prices, labor costs, and access to advanced technologies:

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- Northern and Western Europe: High labor costs incentivize the use of fully automated systems, which reduce OPEX over time. Renewable energy integration, such as biomass boilers or wind-powered systems, lowers energy costs in the long run.
- Southern Europe: Moderate labor and energy costs make medium-scale operations cost-effective, especially for straw and agricultural prunings. However, higher temperatures during production may require additional cooling systems, increasing CAPEX slightly.
- Eastern Europe: Lower labor costs significantly reduce overall OPEX, making pelletizing operations more affordable. However, limited access to advanced pellet mill technologies may increase CAPEX due to equipment importation.

Table 20 summarise the CAPEX and OPEX estimates cost for each of the feedstock identified in section 4.5 that could need to be pelletised.

Table 20. Summary of CAPEX and OPEX cost for pelletising operations.

Feedstock	CAPEX (€)	OPEX (€/t)	Remarks
Straw	50,000 - 300,000	12 - 22	Small-scale systems preferred; abrasive nature increases maintenance costs.
Primary Forestry Biomass	500,000 - 3,000,000	15 - 26	High-capacity systems needed; energy-intensive due to high-density material.
Secondary Forestry Biomass	500,000 - 3,000,000	15 - 26	Suitable for industrial-scale operations; moderate wear and energy needs.
Agricultural Pruning	50,000 - 300,000	12 - 22	Semi-automated systems common; contamination can affect maintenance.
Forestry Wood Fuel	500,000 - 3,000,000	15 - 26	High-quality pellets for energy markets; automation reduces labor costs.

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All the information given in this section is summarised in Table 21.

Table 21. Summary of the CAPEX and OPEX associated with each feedstock considered.

Categories Annex IX	Biomass considered at European level	Baling		Chipping / Shredding		Screening		Drying		Pelletising	
		CAPEX (€)	OPEX (€/t)	CAPEX (€)	OPEX (€/t)	CAPEX (€)	OPEX (€/t)	CAPEX (€)	OPEX (€/t)	CAPEX (€)	OPEX (€/t)
e) Straw	Maize Stalk Barley Straw Wheat straw Soya straw Rye straw Oats straw Triticale straw Rape seed straw	20,000 - 100,000	7 - 15	-	-	-	-	-	-	50,000 - 300,000	12 - 22
m) Husks	Wheat husk	-	-	-	-	-	-	-	-	-	-
n) Cobs cleaned of kernels of corn	Maize cob	-	-	10,000 - 50,000	5 - 10	-	-	-	-	-	-

o) Biomass fraction of wastes and residues from forestry and forest-based industries	Primary residual forestry biomass	50,000 - 150,000	10 - 20	50,000 - 150,000	10 - 18	30,000 - 80,000	2.5 - 6	5,000 - 30,000	1 - 2.5	500,000 - 3,000,000	15 - 26
	Secondary forestry biomass	-	-	-	-	-	-	-	-	500,000 - 3,000,000	15 - 26
p) Other non-food cellulosic material	Fruits pruning	30,000 - 120,000	8 - 18	20,000 - 100,000	7 - 15	20,000 - 80,000	3.5 - 8	5,000 - 30,000	1.5 - 2.5	50.000 - 300.000	12 - 22
	Grape pruning										
	Olive pruning										
	Potatoes leaves	-	-	10,000 - 50,000	5 - 12	20,000 - 50,000	3.5 - 7	50,000 - 300,000	7 - 15	-	-
	Sugar beet leaves										
	Sunflower seed leaves										
	Grape pomace	-	-	-	-	-	-	100,000 – 500,000	10 - 17	-	-
	Olive pomace										
	Rape seed pomace										

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	Potatoes peel										
q) Other ligno-cellulosic material except saw logs and veneer logs.	Forestry wood fuel	50,000 - 150,000	12 - 23	50,000 - 250,000	12 - 18	30,000 - 80,000	2.5 - 6	5,000 - 30,000	1 - 2.5	500,000 - 3,000,000	15 - 26

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6. Conclusions

This deliverable provides a comprehensive assessment of the necessary pre-treatment processes for the feedstocks identified in Task 2.1, aiming to optimize their processing in pyrolysis and gasification plants. The evaluation began by identifying the specific physicochemical requirements that these feedstocks must meet to be compatible with the operational parameters of pyrolysis and gasification technologies. Key factors such as moisture content, ash levels, and particle size were analyzed to determine the most appropriate pre-treatment methods for each feedstock, including baling, chipping/shredding, screening, drying, and pelletizing. Subsequently, both capital investment and operational expenses associated with implementing each pre-treatment were estimated on a per-feedstock basis, providing a detailed financial assessment to inform decision-making.

Based on this comprehensive analysis, the following specific recommendations have been formulated for each biomass category:

- Straw: Baling is necessary to facilitate handling and transportation, with operational costs (OPEX) estimated between 7 and 15 € per ton. Additionally, if transportation distances are significant, pelletizing could be a viable option, incurring an additional OPEX of 12 to 22 € per ton associated solely with the pelletizing process.
- Wheat husk: No specific pre-treatment is deemed necessary for this type of biomass, suggesting that its current characteristics are suitable for processing without additional modifications.
- Maize cob: Shredding is recommended to increase its density, with an associated OPEX ranging from 5 to 10 € per ton. This pre-treatment enhances the efficiency of transportation and storage of the biomass.
- Primary residual forestry biomass, agricultural pruning, and forestry wood fuel: These categories could benefit from all identified pre-treatments; however, chipping/shredding is prioritized, with an OPEX of 7 to 18 € per ton, to increase density and optimize transportation. Additionally, natural drying, costing 1 to 2.5 € per ton, is advisable to prevent product quality degradation.
- Secondary forestry biomass: In this case, only optional, if the transport would be considerable its conversion to pellets (15-26 €/t).
- Agricultural plant biomass: Both crushing, with an OPEX of 5 to 12 € per ton, and forced drying, with an OPEX of 7 to 15 € per ton, are necessary to optimize transportation and ensure biomass quality during processing.
- Secondary agricultural biomass: Forced drying is the primary identified pre-treatment, with OPEX ranging from 10 to 17 € per ton, to reduce moisture and improve combustion properties.

In addition to the operational costs mentioned, there are investment costs associated with implementing these pre-treatments. These investment costs can vary significantly depending on the selected technology, productivity, and autonomy of the chosen equipment. Therefore, a detailed analysis of each case is recommended to determine the economic feasibility of the proposed pre-treatments.

It's important to acknowledge that the cost estimates provided are approximate and may vary depending on the specific circumstances of each case. Therefore, it's advisable to assess each situation individually. In any case, by integrating these estimates with the feedstock potential evaluation from Task 2.1 and the insights on feedstock mobilization and value chain design from Task 2.3, it will allow a first approximation of where it may make sense to focus specific studies to locate new pyrolysis and gasification plants (Task 2.4).

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