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The Role of Energy Valuation of Agroforestry Biomass on the Circular Economy

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Abstract: The use of biomass has increased significantly in recent years. In this context, the use of not valued high-potential biomass (NVHPB) is emerging as a suitable alternative. This is the case of pruning vine, pruning kiwi, scrub (heather, gorse, broom) and forest pruning. The objective of this research was to study the potential of six selected agroforestry biomasses as biofuels in thermochemical processes. For that purpose, biomass was collected by specific machinery. Proximate and ultimate analyses were carried out as well as the inorganic compounds' determination. Then, natural and forced drying were conducted. Low heating values (LHV) between 17 and 20 MJ/kg (dry basis) were achieved in all analyzed cases. Granulometric reduction, biomass classification and densification took place. Finally, energy recovery tests through microcogeneration were carried out. Values close to 97% in cogeneration efficiency were reached (9% net electric yield and 88% thermal yield), offering an alternative to obtain clean energy.

Keywords: residual biomass; biomass collection; biomass pretreatment; thermochemical characterization; microcogeneration

1. Introduction

In recent years, the increase in the price of fossil fuels and the environmental impact associated with them have promoted the research of new energy resources. This is the reason why the use of renewable energies has acquired more importance, contributing approximately to 33% of the total energy demand in Spain [1,2] and to 42% of the demand in Portugal in 2017 [3]. According to Directive 2009/28/CE related to the promotion of energy from renewable sources, the final gross consumption of energy in the European Union should proceed at least 20% of renewable energies in 2020 (20% in the case of Spain and 31% in the case of Portugal) [4].

Among the renewable energies, biomass stands out. Its lower environmental impact and its contribution to improving competitiveness, employment and regional development show that it plays an important role against climate change [5]. In this context, the use of residual biomass (abandoned forests and typologies of biomass that are currently not being used) is particularly important to develop a circular economy [5–9]. During the last year, the contribution of biomass to the energy mix increased in Spain to values slightly lower than 2% [1,2,10] and to 5.1% in Portugal [3].

The Galicia-North Portugal Euroregion, which includes the area between the Cantabrian coast and the Douro River in the northwest of the Iberian Peninsula, has a significant number of forests and agricultural resources. The area devoted to agricultural use in the Euroregion is 1,567,415 ha, which corresponds to approximately 30% of the total area. Galicia contributes to this figure, with 843,657 ha (about 28% of its total area) and the North region of Portugal with 723,758 ha (34% of its total area). With regard to the forestry situation, the whole Euroregion covers a total of more than 2,706,000 ha, which corresponds to approximately 54% of its surface, of which Galicia is 2,039,574 ha (approximately 60% of the surface of this Autonomous Community) and the North of Portugal is 667,417 ha (31% of its total surface) [11]. These values show why the agricultural and forestry sectors have acquired a strategic status in the future economic and social development of the Euroregion.

Biomasses coming from the pruning of vineyards and kiwifruit are outlined as resources with great potential [12], since they are not being valued and have a high availability. In fact, Galicia has an area of more than 20,000 hectares of vineyards [13] and 672 [10] hectares of kiwi [14] and Northern Portugal has 86,400 hectares of vineyards and 1800 hectares of kiwi [15]. The quantity of scrub amounts to 1,000,000 ha, 530,000 ha of which is in Galicia and the rest in the north of Portugal.

Biomass cogeneration allows the simultaneous production of electricity and useful heat in the place of consumption, with consequent saving of primary energy (up to 40%) and of emissions into the atmosphere. In fact, cogeneration is considered as the main option for the replacement of traditional energy systems [16]. Taking this into account, microcogeneration (referred to as small power equipment, less than 50 kW) is emerging as a suitable alternative in the aforementioned small-scale applications [17]. One of the most promising techniques for electrical energy obtention through biomass is the so-called organic rankine cycle (ORC).The ORC follows the same principles as the traditional steam Rankine cycle used in most thermal power plants to produce electricity, but uses an organic fluid instead of water. This fluid (generally a fluorocarbon), has a high molecular weight and a boiling point below 100 °C, which allows to considerably simplify the traditional process in terms of complexity and cost.

In this work, the potential of six regional not valued biomasses with high potential (pruning vine, pruning kiwi, scrub (heather, gorse, broom) and forest pruning) as fuels for energy recovery through microgeneration was investigated. This was done firstly by means of their characterization (proximate and ultimate analyses, calorific value and inorganic compounds) and secondly through the use of one of those biomasses in a pilot ORC module (commercial unit named HRU-4 [18]) coupled to a boiler in order to determine microcogeneration feasibility in terms of global efficiency. Moreover, the whole collection and pretreatment of biofuels studied was optimized to maximize the overall energy gain of the whole process.

2. Materials and Methods

2.1. Materials

Six not valued biomasses with high potential (NVBHP) were recollected and studied in this research: pruning vine (*Vitis* spp.), pruning kiwi (*Actinidia* spp. (*A. deliciosa*, *A. chinensis*)), scrub (heather, gorse, broom) (*Erica* spp. + *Calluna vulgaris* (L.), *Ulex* spp., *Cytisus* spp.) and forest pruning (*Pinus* spp. (*Pinus pinaster*, *Pinus radiata*). In all the cases, biomasses were collected in different Galician and Portuguese plots.

2.2. Methods

2.2.1. Biomass Collection

The management of NVBHP has an elevated cost due to the shortage of specific machinery that allows the mechanized collection of these typologies. The need to incorporate new machinery to facilitate and reduce the costs of management and collection is mandatory.

In this work three machines were acquired, tested and implemented with the aim of optimizing the collection processes in the regions of Galicia and North of Portugal.

Integral Equipment for the Collection and Treatment of Biomass "Retrabio"

This prototype (Figure 1a) is composed of three parts:

- An automotive vehicle with integral 8 × 8 traction with mechanical/hydrostatic transmission and 3 differentials with a lock and a diesel engine with 300 hp power.
- A container of 24 m^3, located in the rear part of the vehicle, where the collected and crushed material is stored. A hydraulic system allows the lateral discharge of the material.
- A grinding head, located in the front of the equipment, collects and crushes the material. It has a hammer head with a suction system, which allows the collection of scrub biomass, with a working width of 2.1 m. Depending on the type of biomass to be processed, it can easily be replaced by another type of head, by using a hydraulic power transmission system.

(**a**) (**b**) (**c**)

Figure 1. Specific machine tested (**a**) "Retrabio", (**b**) Berti Picker and (**c**) Peruzzo Cobra Collina.

Berti Picker

This brushcutter (Figure 1b) has a feeding rotor or pick-up which collects the material from the ground and introduces it in a crushing chamber. A rotor of mobile hammers rotates at high speed, chopping the biomass. A container located in the rear part stores the produced splinter. A hydraulic device allows the discharge of the container. This machine has a working width of 160 cm.

Peruzzo Cobra Collina

The equipment (Figure 1c) has a feeding or pick-up rotor which collects the material from the soil and introduces it into a crushing chamber. In this case, the rotor had fixed teeth and a counter-blade to produce a more homogenous crushed material. A container located in the rear part stores the produced splinter. A hydraulic device allows to discharge the container. This machine has a working width of 120 cm.

2.2.2. Physicochemical Characterization

A thorough characterization of the different collected materials was carried out following the standards of the Committee CEN/TC 335 "Solid Biofuels" from the European Committee for Standardization (CEN).

Ultimate and Proximate Analyses

The ultimate analysis provides the total content of carbon, hydrogen, nitrogen, sulphur and oxygen of the sample. The proximate analysis determines its fixed carbon, volatile matter, moisture and ash content.

Regarding the proximate analysis, determination of moisture content was done according to UNE-EN ISO 18134-2 [19]. The ash content was determined according to UNE-EN ISO 18,122 [20].

Concerning the ultimate analyses, they were done according to ISO 16,948 [21] (C, H and N determination) and ISO 16,994 [22] (S). The chlorine content of the samples was also determined through the latter.

Calorific Value

The calorific value was determined according to UNE-EN ISO 18,125 [23] using a bomb calorimeter (high calorific value, HHV). Low heating value (LHV) was calculated by subtracting the heat of vaporization of water vapor from the higher heating value.

Inorganic Elements

The concentration of main trace elements (TEs) was determined through specific techniques. To determine the Hg content, cold vapor atomic absorption (CV-AAS) was employed. The rest of the trace elements were determined by ICP-MS according to norms ISO 16,967 [24] and 16,968 [25].

2.2.3. Biomass Pretreatment

Drying

It is necessary to dry the base material at a humidity of around 8–12% to obtain an acceptable biofuel.

With the aim of drying the material, outdoor drying was used when it was possible. Depending on the humidity obtained in the open air, drying could be necessary to make a final drying in an artificial drying chamber in order to achieve the objective humidity. In the case of materials that can be degraded or composted during storage, as in the case of the pruning kiwi, it was always necessary to make an artificial drying. To perform the drying, metallic trays were used and installed in a wood drying room (5 m^3), working with drying temperatures between 60 and 75 °C.

Granulometric Reduction

The granulometric reduction of the different typologies of biomass contemplates the following phases:

First grinding

This phase aims to reduce the size of the material of greater length to facilitate the handling of the material with automatic feeders. It also allows to realize the supply of the material to the final equipment of milling. When crushing equipment with hammers is performed for biomass collection, the collected material presents a great heterogeneity, especially in relation to its length. Due to this, 1st grinding is mandatory.

In order to carry out this first phase, a crusher equipment of a low-speed shaft with blades with vertical feeding by gravity was employed (manufacturer: Compacto Maschinenfabrik; Model: Shark 63). Moreover, this equipment has a hydraulic pusher to avoid the formation of vaults and to improve the feeding of the material to the crusher. In order not to generate many fines, mesh lights between 10 and 30 mm were used.

Second grinding

This phase aims to reduce the size of the material to the biofuel manufacturing requirements. For this grinding, it is imperative that all material be previously dry. Blade mill technology was employed.

In this case, the grinding process is produced by a cutting process, where blades fixed on a rotor that rotate at high speeds cut the material against other blades fixed in the chamber (manufacturer of the equipment employed: Peruzzo; Model: T/2 (5.5 kW). A perforated mesh defines the size of the material processed. Grinding tests with different mesh lights are performed. The biomass stays in the mill chamber until it passes across the mesh.

To carry out the granulometric classification of the material obtained in each experiment, a granulometric characterization is performed using a laboratory vibrator sieve with different mesh lights.

Biomass Classification

For this process, an industrial circular sieving machine with screens with direct material output in a maximum of 5 fractions was used.

Tests were carried out with different types of meshes in order to know the quality of each of these granulometries and especially its relation to the ash content. In this way, a formulation of material for the standardized manufacture of densified biofuels was possible.

Densification

The raw biomasses were compacted as cylindrical pellets, with an average size of 6 × 18 mm.

2.2.4. Valorization Tests

In order to demonstrate the feasibility of the use of microcogeneration as a system for energy recovery of the biomass previously presented, a pilot plant was used with the main following elements:

- A 60-kW multi-fuel boiler (hot source) equipped with a caterpillar burner, fed by a hopper and responsible for generating the thermal energy needed to produce electricity in the ORC (provided by hot water up to 90 °C).
- An ORC module thermal machine based on an organic Rankine cycle with a maximum power of 4 electric kW and designed for the use of heat at low temperature (up to 100 °C in water) by its conversion into electricity. This system employs an organic refrigerant fluid (R245fa).

Despite being a plant for cogeneration, the experimental system has an aerorefrigerator (cold source) to evacuate the heat from the condenser through a water circuit. This equipment is an air/water heat exchanger that drives air by forced convection to cool the incoming water. The system also has a heatsink in the form of resistors to prevent the injection of electricity generated by the grid. Finally, the plant has a data control and visualization system where all parameters relevant to the operation of the plant are displayed and recorded.

Figure 2 shows the scheme of the ORC module employed.

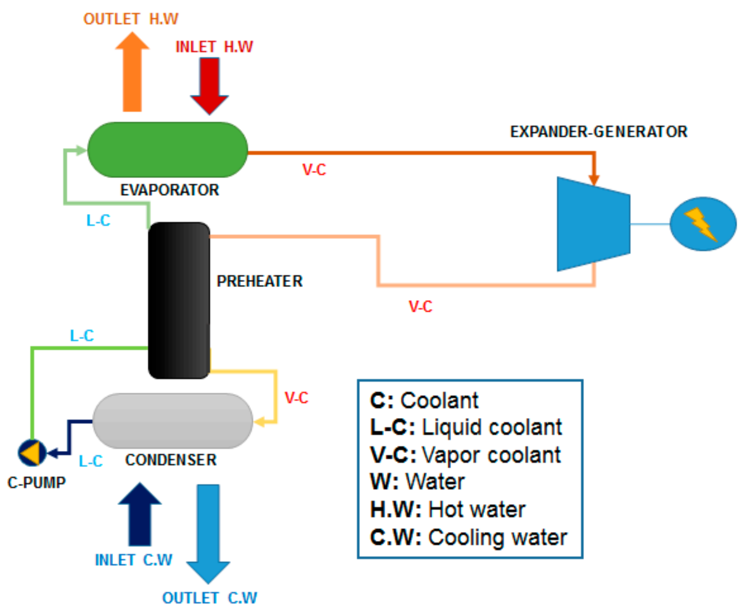


Figure 2. Drawing of the ORC module employed.

As is observed in Figure 2, once preheated, the liquid refrigerant is conducted to the evaporator where it changes its state to the vapor phase. It is then led to an expander on whose axis mechanical work is generated. That expander is coupled by a mechanical transmission to an asynchronous generator, producing electrical energy. Once the fluid leaves the expander, already with a reduced pressure, it gives part of the heat in the regenerator or preheater and then goes to a condenser where the vapor – liquid phase change occurs and the cycle can start again in the coolant pump.

Microcogeneration performance is assessed based on the global efficiency obtained (electrical plus thermal). Different tests were done with pruning vine. The results obtained were compared with a reference fuel (wood pellets). Equations (1) and (2) show the electrical and thermal efficiency calculation.

$$Ɗ_{el} = \textit{electrical power on terminals generator } (kW_e)/\textit{thermal power apported by the evaporator } (kW_t) \quad (1)$$

$$Ɗ_t = \textit{heat provided by the condensator } (kW_t)/\textit{heat captured by the evaporator } (kW_t) \quad (2)$$

3. Results

3.1. Energy Balance

In order to demonstrate the beneficial use of the renewable energy sources studied in this work, the energy balance of the whole process (collection and treatment of the materials and energy given by them) is presented in Table 1. Scrub is presented as an example but the balance would be similar with all the biofuels studied:

Table 1. Energy balance for scrub.

Scrub Biomass Harvested with Retrabio Equipment.	*Energy Consumption*	*Unit Conversion to Primary Energy*	*kWh/Dry ton*	
Phase 1—Harvest: between 3.8 to 5.9 L of diesel for dry ton of scrub biomass (it depends on several factors like slope of terrain, height of the scrubs, distance to the discharge area, . . .).	3.8 to 5.9 L diesel/dry ton biomass	10.28 kWh/L diesel	39	61
Phase 2—Transport to plant (in a truck): for a medium distance of 50 km, about 3–4 L of diesel for dry ton of biomass are required.	3 to 4 liters diesel/dry ton biomass	10.28 kWh/L diesel	31	41
Phase 3—Plant process:				
Biomass drying: we suppose 100% forced dry (normally low quality biomass is used as fuel). However in the factories is usually to combine an initial air drying, to make the process cheaper.	600,000 to 650,000 kcal/dry ton biomass	0.00116 kWh/kcal	698	756
Grinding	20–40 kWh electrical/dry ton biomass	2.21 * kWh/kWh electrical	44	88
Densification	55–75 kWh electrical/dry ton biomass	2.21 kWh/kWh electrical	122	166
		T. CONSUMPTION (kWh/dry ton biomass)	934	1112
Energy content. Dry scrub biomass.	19.5 MJ/dry kg	0.2778 kWh/MJ	5417	
		T. PRODUCTION (kWh/dry ton biomass)	5417	
ENERGY BALANCE (kWh/dry ton biomass)			4483	4305

* Note: promedium conversion factor electrical energy/primary energy, considering low voltage and in the point of consumption. Source: IDAE, GOVERNMENT OF SPAIN.

3.2. Physicochemical Characterization

The results of the proximate analyses for the six biomasses studied are shown in Table 2. As woody biomass is traditionally employed during combustion processes, the results obtained with a reference fuel (wood chips) are included for comparison [26,27]. All the products had a bulk density >600 kg/m^3 (ISO 17828). This is que requirement included in the EN ISO 17225-2:2014: Solid biofuels—fuel specifications and classes—Part 2: Graded wood pellets, for commercial and residential applications [28].

Table 2. Characterization of agroforestry biomasses studied.

	Forest				Agricultural		Reference Fuel
	Gorse Scrub	Broom Scrub	Heather Scrub	Forest Scrub	Pruning Kiwi	Pruning Vine	Wood Chips
%Humidity	45.8	51.2	38.6	48.2	57.9	44.7	8.8
%Ashes	1.1	1.1	1.6	1.1	2.5	2.6	0.5
LHV $_{d.b}$ * (MJ/kg)	19.48	19.54	20.13	19.72	17.39	18.19	18.51
LHV $_{a.r}$ ** (MJ/kg)	9.49	8.33	11.43	9.03	5.23	8.93	-
LHV$_{10\%}$ *** (MJ/kg)	17.28	17.34	17.87	17.50	15.40	16.13	-

* d.b: dry basis; ** a.r: as received, *** 10%: 10% humidity, - not determined.

Table 3 shows the results obtained during the elemental analyses conducted. The oxygen content of each material would be calculated by the difference between 100 and the rest of the elements.

Table 3. Ultimate analyses of biomasses studied.

COMBUSTION	SAMPLE	%N	%C	%H	%S	%Cl
1	Pruning vine	0.70	44.62	5.77	0.0500	0.0266
2		0.62	44.71	5.68		
3	Pruning kiwi	0.47	44.69	5.65	0.0577	0.0927
4		0.51	45.16	6.20		
5	Broom scrub	1.38	46.13	6.32	0.0566	0.1726
6		1.41	46.53	6.51		
7	Forest scrub	0.95	48.55	6.71	0.0648	0.0313
8		0.96	48.35	6.57		
9	Heather scrub	0.56	48.14	6.36	0.0594	0.0595
10		0.58	48.55	6.15		
11	Gorse scrub	0.84	46.70	6.22	0.0459	0.0724
12		0.85	46.79	6.25		
Reference fuel	Wood chips	0.16	49.55	6.5	0.0200	0.0200

Results of the determination of inorganic elements in the solid biomass feedstocks evaluated are shown in Table 4 (majority elements) and Table 5 (minority elements).

Table 4. Majority elements.

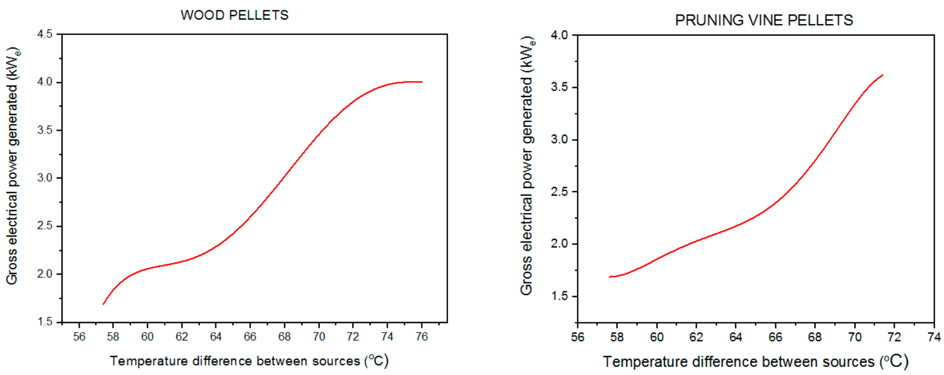
Majority Elements (mg/kg)	SAMPLE	Na	Mg	Al	Si	P	K	Ca	Mn	Fe
1	Pruning vine	252	883	659	1017	859	5197	8417	35	149
2	Pruning kiwi	213	1224	428	781	1019	5053	5156	11	99
3	Broom scrub	212	863	108	467	895	4610	1406	237	63
4	Forest scrub	223	626	920	1660	627	2616	3340	541	295
5	Heather scrub	308	508	1082	2373	331	2273	2222	446	343
6	Gorse scrub	576	991	108	922	493	2527	1849	159	97
Reference fuel	Wood chips	76	240	106	<6	78	540	1400	64	66

Table 5. Minority elements.

Minority Elements (mg/kg)	Sample	Cr	Cu	Ni	Zn	Hg
1	Pruning vine	3.62	26.93	1.57	37.80	<0.1
2	Pruning kiwi	1.82	35.62	1.62	30.89	<0.1
3	Broom scrub	1.01	8.38	3.03	29.80	<0.1
4	Forest scrub	1.74	4.07	1.45	31.47	<0.1
5	Heather scrub	2.38	6.95	4.19	10.38	<0.1
6	Gorse scrub	<1	3.01	1.83	15.87	<0.1
Reference fuel	Wood chips	<1	<1	2.08	5.25	<0.1

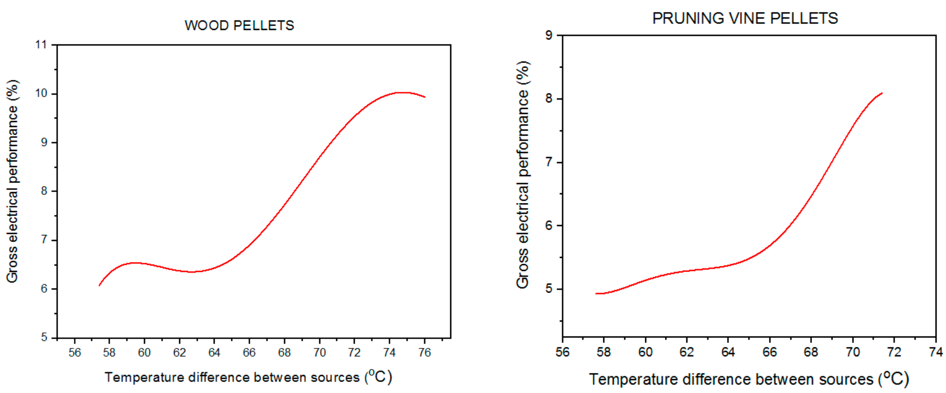
3.3. Valorization Tests

Microcogeneration tests were based fundamentally on varying dissipation conditions (temperature difference between hot and cold sources). To this end, the temperature of the hot source was modified between 82 °C, (temperature close to the minimum required by the ORC used to operate), and approximately 98 °C, (temperature close to which the automatic shutdown of the boiler occurs due to the risk of overheating). During the course of the tests, the temperature of the cold source was kept practically constant (it depends on the temperature of the ambient air on the day of the test). The same was done with the flow rates of hot and cold water and that of the organic fluid. As in the characterization part, analogue tests were carried out with a reference fuel (wood pellets). The results obtained are presented in Figures 3 and 4.



(**a**) (**b**)

Figure 3. Gross electrical power generated in the ORC according to dissipation conditions used: (**a**) pine pellets and (**b**) vine pruning pellets.



(**a**) (**b**)

Figure 4. Gross electrical performance of the ORC as a function of the dissipation conditions using pine pellets (**a**) and vine pruning pellets (**b**).

Finally, and in order to characterize the cogeneration module, Table 6 shows the most relevant characteristics of the system at the point of maximum efficiency observed (T = 98 °C).

Table 6. Main characteristics of ORC at the point of maximum efficiency observed.

Evaporator temperature water inlet (°C)	98
Condenser temperature water inlet (°C)	22.2
Gross electrical power (kW)	4.05
Net electrical power (kW)	3.51
Thermal power captured (kW)	39.03
Useful heat produced (kW)	34.35
Gross electrical efficiency (%)	10.39
Net electrical efficiency (%)*	8.99
Thermal efficiency (%)	88.03
Cogeneration efficiency (%)	97.02

* The net electrical efficiency is the gross electrical efficiency less the power consumed by the cooling pump.

4. Discussion

4.1. Energy Balance

Table 1 allows us to conclude that collection and treatment of biofuels studied represents about 17%–20% of the total amount of energy provided by them. Moreover, it has to be taken into account that for that calculation, we considered the most unfavorable situation during drying process (100% forced dry), something that it is not usual and that is the process with the major energy consumption. The results obtained suggest that the use of these fuels is highly efficient from the energetic point of view.

4.2. Physicochemical Characterization

As can be observed in Table 2 (proximate analyses), the values obtained allow us to differentiate between two large groups of materials, scrubs and pruning of forest-based conifers and the remains of agricultural kiwi and vine pruning.

The forest-based materials have lower ash content values (≈1.1%) than the agricultural pruning remnants (≈2.5%). These ash content values are an important constraint on the production of quality solid biofuels. The values obtained suggest that it will be necessary to work both in the pretreatment processes and in the incorporation of chemical additives in order to reduce ash content values and the associated problems in valorization processes (mainly risk of sintering), something confirmed by other authors that previously worked with these type of biofuels [29,30].

Referring to moisture content at the time of collection, the material with the lowest average moisture content was heather (38.6%) followed by vine pruning (44.7%) and gorse scrub (45.8%). On the other side, forest pruning (48.2%), broom (51.2%) and pruning kiwi (57.9%) had the highest values. The results obtained suggest the need for drying in all cases.

In relation to the net calorific value of each material, it was first analyzed with a humidity content of 10%, as this moisture is a reference value for the production of densified solid biofuels such as pellets and briquettes. In the case of forest material, this value was between 17.28 and 17.87 MJ/kg, always above the minimum value required for the manufacture of pellets for domestic use (requirement > 16.5 MJ/kg) [28]. However, in the case of agricultural material, average values of net calorific value at 10% moisture are always lower than this requirement, which are 15.40 MJ/kg in the case of pruning kiwi and 16.13 MJ/kg in the case of vine pruning [29,30].

With regards to the calorific value net to the collection humidity, pruning kiwi presents the lowest value with 5.23 MJ/kg. In the upper part, heather scrub had a result of 11.43 MJ/kg. The other materials are in the range of 8.33–9.49 MJ/kg.

The concentrations of N, S and CI in different biofuels are of major importance because they can cause gaseous emissions during combustion processes. Although the formation of these emissions also depends on other parameters such as excess oxygen and CO concentration in the flue gas, higher concentrations in the biofuel are the most important influencing variable for increasing the gaseous emission level [31].

According to elemental analyses performed (Table 3), it is necessary to point out the higher amount of nitrogen of studied biomasses respect to the reference fuel, something claimed by some other authors that have previously studied similar biofuels [30,32]. It is especially remarkable the high nitrogen content of broom scrub (values between 1.38–1.41%). Consequently, the release of nitrogen pollutants mainly as NO_X could be expected upon combustion [7,33].

The chlorine content of samples analyzed is moderately higher than reference fuel in all cases, and gorse scrub was the sample with the highest value (0.1726%). Thermochemical valorization with fuels with a high chlorine content can cause corrosion, slagging and fouling in downstream piping and equipment, apart from cause HCl formation [31,34]. However, combustion processes carried out with similar biofuels have shown generally low HCl emissions [35,36].

The rest of parameters considered in these analyses are close to that showed by the reference fuel except sulphur, which was resulted to be slightly higher in studied biomasses [30,32]. This compound may be responsible for corrosion and pollutants formation (SO_2) [31,37]. Some other authors claimed [35,36] that the released fractions of this compound during the combustion of similar biofuels resulted in only moderated SO_2 formation.

Finally, regarding to inorganic elements (Tables 4 and 5), it is particularly important to evaluate the quantity of those elements that can have a role on the ash melting (Na, K, P, Ca, Si, Mg) [38]. The higher the content in alkaline earth oxides regarding alkaline, the higher the sintering temperature and the lower the risk of sintering of each sample [39].

As can be observed in Table 4, the proportion of alkaline earth metals regarding alkaline is higher in reference fuel, which suggests that sintering problems may occur during thermochemical processes developed with studied biomasses [40]. An exhaustive control of the thermochemical valorization processes should be carried out [31,38].

With respect to minority elements (Table 5), toxic elements such as Hg, Cr and Zn are especially important due to their role on particulate matter emissions. They may also cause problems with ashes reutilization [38]. No relevant differences were observed in those elements' concentrations between NVBHP and the reference fuel. The most significative deviation is related to the Zn content, which was considerably higher in pruning vine, pruning kiwi, broom scrub and forest scrub. Measuring the possible emission of particles and checking the leachate of the ashes would be advisable. Also remarkable are the higher Cu values of agricultural biofuels with respect to the other biomasses and with respect to the reference fuel.

Even though the Zn and Cu results were higher than expected, all the studied fuels are within the ranges specified in the standards for wood pellets in Spain (UNE-EN ISO 17225-2:2014). No significant amounts of heavy metals were detected so the use of the ashes for other applications or their easy disposal in landfills could be feasible.

4.3. Valorization Tests

Figure 3 shows that as confirmed by other authors [41,42], the greater the temperature difference between the hot and the cold source, the greater the electrical power generated by the module studied. In the tests conducted, 4.05 kW was the maximum electrical power reached in the case of using pine pellets. A value of 3.63 kW was obtained when vine pruning pellets were employed. In this case, the difference between the powers reached was due to the fact that the temperature difference between sources was higher on the day that the pine pellets were used (76 °C), while the difference reached on the day of the test with the vine pruning pellets was 72 °C.

Regarding the electrical performance achieved by both fuels (see Figure 4), the tendency obtained is the same as in the case of the power, that is, it increases the greater the temperature difference between the hot and the cold source, as establishes the Carnot Theorem for any thermal machine. The maximum efficiency obtained is about 10% in the case of using pine pellets and 8% when the fuel used is vine pruning pellets while these values are reduced up to 6% (pine pellets) and a 5% (vine pruning pellets) when the temperature difference between the sources is lower. Again, the difference observed is due to the fact that the difference in temperature between sources was greater on the day when the tests were carried out with pine pellets.

It should be noted that the small differences that can be observed both in the power values and in the performance values obtained at the same temperature difference with the two materials used are due to the fact that, even if the temperature difference in absolute value is the same, more promising values will be obtained when the ORC is closer to the design conditions (this is T hot source = 100 °C, cold source T = 15 °C).

Finally and according to Table 6, using the ORC module used in the present investigation, cogeneration efficiencies close to 97% can be achieved, demonstrating its suitability for energy recovery from the residual biomasses studied.

5. Conclusions

The six not valued biomasses with high potential (NVBHP) studied in this research seem to be promising biofuels. However, they present a moderate ash content compared to the reference fuel. This suggests the need to work both in the pretreatment processes (the elimination of particles of smaller size or fines) and in the incorporation of chemical additives to minimize associated risks (sintering mainly). On the other hand, their humidity content is reasonably high, which makes drying mandatory. Finally, in all cases, the LHV obtained were very close to that obtained in the reference fuel, as agricultural biomasses were those with the lowest value.

The results obtained during the preliminary microcogeneration tests show that it is feasible to valorize the selected biomasses. The tests carried out make it possible to determine that the temperature differences between the hot and the cold source had a significant influence on the results obtained. In the conditions used in this work, cogeneration yields close to 97% can be obtained (9% net electric yield and 88% thermal yield).

This work is pioneering since it proves the feasibility of using regional residual biomasses as fuels for energy recovery optimizing the whole collection and pretreatment process. In addition, it provides highly promising results about simultaneous heat and electricity production instead of consuming biofuels, which opens the door to using the microcogeneration method presented with any residual biomass, which is applicable everywhere.

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