YIELDS AND COSTS OF MECHANIZED HARVESTING WITH A HARVESTER-MULCHER OPERATING IN A ROCKROSE (*Cistus laurifolius* L.) SHRUBLAND

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ABSTRACT: The mechanized clearing of scrub is a common practice in forest fire prevention work in Mediterranean countries. The technical feasibility of biomass harvesting from shrublands in areas suitable for mechanization has been demonstrated, which contributes to reduce wildfire risk by obtaining sustainable solid biofuels from shrubslands of high flammability risk. The aim of this research is to evaluate the performance of a harvester-mulcher system (López-Garrido TBA 2300 series) never used before for rockrose (*Cistus laurifolius* L.) biomass collection. The biomass collection tests using this equipment yielded satisfactory results and provided better results than other tested systems for clearing and collecting rockrose. The shrub clearing itself was acceptable and the low biomass collection efficiency was enough to reduce the vertical continuity of fuel in fire prevention work. The average collected biomass was 6.9 tDM/ha (12.9 tWM/ha), which represented 31.3% of the standing shrub biomass load. The weight productivity was 2.8 tWM/PMH (1.5 tDM/PMH) and the surface productivity 0.22 ha/PMH. The total net costs of the tractor with the harvester-mulcher were estimated at 85.95 €/PMH and 30.33 €/tDM. Rockrose is a low-cost solid fuel that will generate low emissions of NOx, SO_2, HCl, and trace elements, without causing clogging problems due to slag formation. Due to its ash content, it is preferred for industrial use rather than residential use in thermo-chemical facilities.
Keywords: scrub, clearings, wildfires, pretreatment, biofuels, quality

1 INTRODUCTION

The decline of traditional agricultural and livestock activities, as a consequence of rural depopulation, leads to a marked abandonment of land management. This, in turn, results in the continuous expansion of shrub cover at the expense of croplands and pastures, as well as landscape homogenization and the accumulation of combustible material, which contributes to an increased risk of forest fires—especially in the current context of climate change, with forecasts of increasingly intense and prolonged heatwaves and droughts. Shrub biomass collection can contribute to the reduction of wildfire prevention costs by obtaining solid biofuels from shrublands that pose a high fire risk, using mechanical harvesting methods that have not been sufficiently tested in shrub formations. This is especially true in Mediterranean countries, such as Spain, the second country in Europe in terms of fire incidence after Portugal, where more than half of the total burnt forest area in the last decade, was covered by shrubland [1-2].

The most interesting shrublands from the perspective of biomass production are the serial types, often resulting from human intervention, which form dense stands with a high biomass load per hectare, such as rockrose, heaths, broom, and gorse shrublands, covering more than 5 million hectares in Spain [2]. Most of these vegetation masses have an anthropogenic origin derived from repeated fires or the abandonment of extensive livestock farming. They are formations at a very early successional stage, usually inhabiting soils poor in organic matter, with low fertility and poorly developed texture and structure, at least in their upper horizons [2-3]. Rockrose shrublands are Mediterranean shrub formations belonging to the *Cistaceae* family, found on acidic or decalcified calcareous soils with marked summer drought. They occur from the thermomediterranean to the supramediterranean zones and under semi-arid to lower sub-humid ombroclimates [4-5], typically replacing sclerophyllous evergreen forests. The species *Cistus laurifolius*, known as laurel-leaved rockrose or mountain rockrose, is a pyrophytic species and exhibits allelopathic effects that inhibit the growth of seedlings of other species, thereby eliminating competition and becoming a colonizing species [5-6]. The use of certain shrubland formations for biomass production is an increasingly important resource in the EU, especially in Mediterranean countries, and can serve as an incentive for improved local forest management that helps reduce the risk and severity of forest fires [2,7]. To achieve this, it is necessary to deepen the understanding of biomass utilization from different shrubland formations, starting with the technical and economic feasibility of mechanized harvesting and continuing with their characterization as biofuel for subsequent use in thermal conversion equipment. The aim of the research is to evaluate the performance of the harvester-mulcher system (López-Garrido TBA 2300 series) for collecting rockrose (*Cistus laurifolius* L.) shrub biomass. This is the first time that a full-scale mechanized rockrose harvesting test has been carried out using the harvester-mulcher López-Garrido TBA 2300 equipment. Evaluating the technical and economic viability of this harvesting system is key to the mechanized use of these shrublands. The results obtained (biomass production, yields and operating costs) can be extended to other rockrose areas in the central-northern Iberian Peninsula.

This research is framed in the CBE4I project “Clean Bioenergy for Industry” (EU Horizon Europe program, Grant Agreement Nº 101122292), which aims to develop a novel fuel flexible highly efficient and close-to-zero emissions combined biomass gasification and combustion technology for industrial applications. The collected rockrose biomass will be one of the low-cost biomass resources from southern Europe to be used in gasification trials.

2 MATERIALS AND METHODS

2.1 Study area

The study was carried out on 4 ha of abandoned pastureland covered by rockrose (*Cistus laurifolius* L.) in Moncalvillo, Burgos (Spain), on Public Utility Forest nº 240. The central point UTM coordinate (ETRS 89) of the study area was (30N 483823 4641296), at an altitude of 1070 m above sea level. The scrub had an average age of 15 years, 70% crown cover, 1.4 m average height and 1 m crown diameter. Soil conditions were similar in the whole area: gentle slope, low terrain roughness and no stoniness. Soil conditions were similar in the whole the area: gentle slope, sandy soil with slight roughness and no stoniness.

2.2. Biomass collection system

Biomass was collected with a commercial harvester-mulcher equipment López-Garrido TBA 2300 series. This machine, powered by a Valtra T194D tractor (154 kW) adapted to forest work and with an inverted driving position, is coupled to the tractor's three-point hitch and driven by the tractor's power take off shaft at 540 rpm and the hydraulic circuit. The harvester-mulcher has a working width of 2300 mm. The cutting cylinder is composed by 40 mobile hammers. Two skids in the lateral parts of the machine and one roller in the lower part adapt the machine to the soil for avoiding soil stuck problems in the mulcher. Behind the hammers, the machine has an endless screw that directs the biomass to a turbine that drives the mulched biomass through the tube that ends in a biomass container. There are two hydraulic windows in the top of the endless screw that assist the operator in accessing this part of the machine. At the front, the tractor is equipped with a 5 m³ container with a maximum load capacity of 1,400 kg to store the shredded material, which is pneumatically conveyed from the shredder (Figure 1).



Figure 1: Harvester-mulcher (López-Garrido TBA 2300 series) coupled to a tractor equipped with a biomass container.

2.3 Solid biofuel preparation

A 90 kW pre-shredder with a production capacity of 1000 kg/h (Silmisa Lince-45/140) was used to reduce the size of rockrose biomass in order to ensure a proper boiler feed and optimum efficiency in a gasification system. The material was pressed against a monorotor by a hydraulic feeder with a pusher stroke of 1100 mm. This rotor (ϕ 450 mm, 1400 mm length) was provided with 102 embedded blades (40×40 mm) that milled the biomass by passing it through a 30 mm mesh. Subsequently, the biomass was screened using a 2 mm mesh to reduce the fine particle content.

2.4 Experimental design

2.4.1 Biomass collection

The mechanized harvesting trial was designed to determine the following parameters:

a) Weight productivity (tDM/PMH) –tonnes of dry matter per productive machine hour.

b) Surface productivity (ha/PMH) –harvested hectares per productive machine hour.

c) Operational costs (€/tDM) – expressed in euros per tonne of collected dry matter.

d) Biomass harvesting efficiency (CE, %) – calculated as the ratio between the weight of the collected biomass and the weight of the biomass present before collection (sum of collected biomass and losses on the ground after the machine's passage).

For the performance study, operational collection times were recorded using the Valtra Connect telemetry service implemented in the tractor, which allows remote monitoring of various parameters, including productive working hours, tractor speed, fuel and additive consumption, as well as displaying a map of the areas where the tractor has operated. The weighing of the collected biomass was carried out on a vehicle weighing scale at the CEDER-CIEMAT facilities. Samples of fresh biomass (4 kg of biomass for each cleared daily polygon) were collected and sent to Laboratory of Biomass Characterization (LCB) for moisture determination. The analytical samples were prepared according to ISO standard 14780. Moisture content was determined by drying the biomass at 105 ºC following the ISO 18134-2:2015 standard.

2.4.2 Costs analysis

Hourly costs were estimated using the machine rate approach described by Ackerman et al., 2014 [8]. This procedure categorized net equipment costs into three classes: fixed, variable and operator costs. Net costs were calculated by combining productive hourly costs with the production rates recorded in the test.

The purchase price of the tractor (154 kW) and the harvester-mulcher, excluding VAT and tractor tyre costs, were 132,359 € and 68,878 €, respectively, according to the updated acquisition price paid by CEDER-CIEMAT in 2015 and 2019 respectively. The operation lifetime of the tractor and the harvester-mulcher were assumed to be 12,000 h. Repair and maintenance costs were estimated at 50% of the purchase price. The tractor's average diesel consumption was 28 liters/ha. The rest of the variable costs (fuel, oil and lubricants, hammers) were based on actual costs recorded during the test. Operator costs were calculated by taking the gross salary paid by CEDER-CIEMAT for a person doing this kind of work (average net wage 14.78 €/h). Subsistence allowance and operator transport were estimated considering that operators have to work so remotely that they cannot travel home 75% of the days and need accommodation and full board. Gross costs include net costs (the total cost of operating the machines – fixed, variable and operator costs), company overheads and management costs (15% over net costs) and profit margin (6% over the sum of the previous two amounts).

2.4.3 Solid biofuel production

To obtain a solid biofuel of suitable size (P45 according to ISO 17225-9) for gasification in the CBE4I pilot plant, the material was ground using a 30 mm mesh.

To reduce the fine content, a 2 mm sieve was used.

During the biomass pre-treatment tests (shredding and sieving), the specific mass flow and the specific energy consumed in the different processes were recorded when the equipments reached steady state conditions. The specific mass flow (MF, kgDM/h kW) was obtained by dividing the mass of the processed material (kgDM) by the time used to shred and sieve it (h) and by the power of the corresponding equipment (kW). To obtain the specific energy (E, kWh/tDM), the active electric energy (kWh) required by the shredder, was divided by the mass of the processed material (tDM).

2.4.4 Analytical procedures

The physical and chemical characterization of the rockrose biofuel was analyzed in the Laboratory of Biomass Characterization at CEDER-CIEMAT following the standards given Table I.

Table I: Parameters and standards applied in the physical and chemical characterization.

Property		**Standard**
Moisture		ISO 18134-2
Bulk density		ISO 17828
Particle size distribution		Optical method (HAVER)
Proximate analysis	Moisture	ISO 18134-2
	Ash	ISO 18122
	Volatile	ISO 18123
Ultimate analysis	C, H, N	ISO 16948
	S, Cl	ISO 16994
Calorific value		ISO 18125
Minor elements		ISO 16968
Ash melting behaviour		ISO 21404

3 RESULTS AND DISCUSSION

3.1 Biomass collection

The average collected biomass was 6.9 tDM/ha, tonnes of dry matter per hectare, (12.9 tWM/ha, tonnes of wet matter per hectare), what represents 31% of the standing shrub biomass load (Table II). It is worth noting that with this equipment, higher collection efficiency figures—above 80%—were achieved when working on rockrose shrublands. However, in this trial, the brushcutter was operated at a higher-than-usual cutting height to avoid incorporating soil sand into the biomass.

Table II: Shrub biomass load estimation, collected biomass per hectare and collection efficiency with a harvester-mulcher (López-Garrido TBA 2300).

Description	Unit	Value
Harvested area	ha	3.87
Harvested biomass	tWM/ha	12.9
Moisture content	%	46.6
Harvested biomass	tDM/ha	6.9
Biomass losses	tDM/ha	15.1
Standing shrub biomass load	tDM/ha	22.0
Collection efficiency	%	31

tWM: tonnes of wet matter; tDM: tonnes of dry matter

This equipment provided better results than other tested systems for clearing and collecting rockrose, like the harvester-baler Biobaler WB55, which offered a weight productivity of 2.3 tDM/ha and a collection efficiency of 24.3% operating on rockrose shrublands [10-11].

The weight productivity per productive machine hour (PMH) was 2.8 tWM/PMH (1.5 tDM/PMH) and the surface productivity was 0.22 ha/PMH (Table III).

The total net costs of the tractor with the harvester-mulcher, excluding profit margin, were estimated at 85.95 €/PMH and 30.33 €/tDM (56.80 €/tWM, 46.6% moisture content) (Table IV).

Table III: Productivity of the harvest-mulching process.

Description	Unit	Value
Weight productivity	tWM/PMH	2.8
Weight productivity	tDM/PMH	1.5
Surface productivity	ha/PMH	0.22

tWM: tonnes of wet matter; tDM: tonnes of dry matter; PMH: productive machine hour

Table IV: Fix, variable and operator costs of a 154 kW tractor with a harvester-mulcher (López-Garrido TBA 2300) working in a rockrose shrubland in Moncalvillo (Burgos, Spain).

Description	€/PMH	€/tDM
Fixed costs	25.51	8.96
Variable costs	28.62	10.04
Operator costs	31.82	11.33
Total Net costs	85.95	30.33
Company overheads and MC	12.89	4.55
Profit margin, before tax	5.93	2.09
Total Gross costs	104.77	36.97

MC: management costs-, PMH: productive machine hour; tDM: tonnes of dry matter

3.2 Rockrose biofuels

The values of specific mass flow and specific energy consumption of the pre-treatment tests (shredding and sieving processes) are shown in Table V. The specific energy consumption of the pretreatment test was similar to that of other rockrose 30 mm shredding processes carried out in the same equipment (11.7 kWh/tDM in [9]). However, the specific mass flow was significantly lower (4.2 kgDM/h kW) due to the subsequent screening process, which slowed down the final preparation time of the biofuel, reducing it to one-fourth when screening to 2 mm was implemented.

Table V: Results of rockrose 30 mm shredding and 2 mm sieving processes

Description	Unit	Average value
MF	kgDM/ h kW	4.2
E	kWh/tDM	11.0
Moisture	wt.% (w.b.)	13.0

MF: specific mass flow; E: specific energy

The physical and chemical characterization of the rockrose biofuel (30 mm milled material sieved to 2 mm) is shown in Table VI. The fraction below 3.15 mm is 4.3% and the one above 45 mm is 11%, so 85% of the particles are between 3.15 mm and 45 mm, and the fraction above 63 mm is zero, which means that a P45 classification is fulfilled according to table 1 of the ISO 17225-9 standard.

Moisture is generally high (> 30 wt.% w.b.) in shrubs at harvest time. Moisture content for rockrose studied in this work was 16%, which was reached with outdoor storage for some days and the ulterior pretreatment.

Ash content is an important property from a quality perspective, as it causes emissions in the effluents of the thermal processes, as well as a reduction of the heat exchanged in a boiler due to the ash layer that adheres to the tubes of the heat exchangers. The produced biomass exhibited 3.0 % ash. According to ISO 17225-9 [12], if this biomass was used to produce hog fuels, they would be classified as class I1 (≤ 3% ash) for industrial use.

S, N and Cl content in the solid fuel has been previously correlated with the formation of SO2, NOx and HCl emissions during combustion or gasification. The contents of N, S and Cl as well as minor elements in the rockrose fulfilled the I1 class of ISO 17225-9, even fulfilled the A2 or B class of ISO 17225-2 (wood pellet) for domestic use [13]. This means that quality pellets could be produced if it were not for its high ash content.

Table VI: Physical and chemical characterization of rockrose biofuels (milled to 30 mm and sieved to 2 mm).

Parameter	Unit	Rockrose biofuel	ISO 17225-9 (I1 class)
Moisture	wt.% (w.b.)	16.1	≤ 45
Bulk density	kg/m^3 (w.b.)	190	NA
Fines Fraction<3.15 mm	%	4.3	NA
Coarse Fraction>45 mm	%	11	NA
Coarse Fraction>63 mm	%	0.0	NA
Calorific value:			
NCV	MJ/kg (w.b.)/(d.b.)	15.14/18.52	NA
Proximate analysis:			
Ash	wt.% (d.b.)	3.0	≤ 3
Volatile matter	wt.% (d.b.)	82	NA
Ultimate analysis:			
Carbon	wt.% (d.b.)	49.3	NA
Hydrogen	wt.% (d.b.)	5.9	NA
Nitrogen	wt.% (d.b.)	0.53	≤ 0.5
Sulphur	wt.% (d.b.)	0.04	≤ 0.05
Chlorine	wt.% (d.b.)	0.02	≤ 0.05
Minor elements:			
As	mg/kg (d.b.)	0.2	≤ 1
Cd	mg/kg (d.b.)	0.52	≤ 2.0
Cr	mg/kg (d.b.)	2.4	≤ 20
Cu	mg/kg (d.b.)	2.6	≤ 30
Hg	mg/kg (d.b.)	0.008	≤ 1.0
Ni	mg/kg (d.b.)	2.4	≤ 10
Pb	mg/kg (d.b.)	0.82	≤ 10
Zn	mg/kg (d.b.)	40	≤ 100
Ash melting behaviour:			
SST	ºC	1220	NA
DT	ºC	1270	NA
HT	ºC	1400	NA
FT	ºC	1450	NA

NCV: net calorific value; wt.%: weight %; w.b.: wet basis; d.b.: dry basis. SST: shrinkage staring temperature; DT: deformation temperature. HT: hemisphere temperature. FT: fluid temperature. NA: not applicable.

In principle, no problems of slag formation are expected, because the DT is higher than 1200 ºC (Table VI) with a fluid temperature of 1450 ºC.

4 CONCLUSIONS

A harvester-mulcher system was operated to harvest a typical Mediterranean shrub formation. The shrub clearing itself was acceptable and the low biomass collection efficiency was enough to reduce the vertical continuity of fuel in fire prevention work. However, if livestock use of the shrubland is foreseen after mechanized harvesting, it is advisable to subsequently use a conventional chain brush cutter to promote the production of herbaceous vegetation and facilitate livestock transit. It would be interesting to evaluate the influence of the machine working speed and the vegetation age on biomass productivity and collection efficiency.

The hog fuels produced from this raw material could be classified as class I1 according to the ISO 17225-9 standard. Rockrose is a low-cost solid fuel that will generate low emissions of NOx, SO_2, HCl, and trace elements, without causing clogging problems due to slag formation. Due to its ash content, it is preferred for industrial use rather than residential use in thermo-chemical facilities.

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7 LOGO SPACE