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A preliminary evaluation of different residual biomass potential for energy conversion in a micro-scale downdraft gasifier

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ABSTRACT

Residual biomass can be a promising alternative to replace fossil fuels for energy production. Through small-scale gasification systems it is possible to obtain a fuel gas from solid biomass that can be used for electrical and thermal energy generation. In this work, six different biomasses (five agro-industrial residues and A1 ENplus pellets) were tested in a lab-scale prototype. For each tested feedstock, elemental and ash analyses were carried out. The contaminant amount in the produced gas was measured as well as the mass and energy fluxes to calculate the gasification efficiency. The ratio between the pressure drop across the reactor and the gas flow raised to the square was introduced to compare the gasifier behavior at different power outputs. The results showed that with the exclusion of the tests run with cork, the other tested agro-industrial residues (pistachio shell, hemp and driftwood) performed acceptably in terms of efficiency, providing also a char with a carbon content over 70% as by-product.

Introduction

Energy resources are strategic and fundamental to safeguard the economy of the nations and to guarantee social development [50]. However, energy prices are highly susceptible to geopolitical risks, this is because energy resources are characterized by scarcity, spatial separation of demand and supply and low price elasticity of demand [50]. Furthermore, climate change is one of the most urgent problems [34] caused mostly by CO_2 emission derived by fossil fuel exploitation [54]. Within this context, biomass is a promising alternative to replace fossil fuel through bioenergy production because it is widely available and uniformly distributed as well as a carbon neutral energy source [13,33,61].

Moisture content is an important parameter for the selection of the conversion route of biomass into energy or fuels. In case of a wet feedstock, there are processes which do not require the evaporation of most of the water such as biological routes, which produce secondary fuels with the help of enzymes and microorganisms (e.g. manure anaerobic digestion), or hydrothermal conversion at high pressure. For dried biomass (like the kind of feedstocks investigated in this work), the most common conversion processes are: pyrolysis, direct combustion and gasification [64]. Pyrolysis is the thermal decomposition of biomass that occurs in an oxygen free environment. It has attracted interest in recent years especially for production of biochar and liquid fuels such as bio-oil [15,19]. Direct combustion is, on the other hand, the exothermic reaction between oxygen and biomass [6]. It is a well-known biomass conversion process and the majority of the energy generated in this way is utilized in residential heating and cooking [19]. Gasification involves chemical reactions in an oxygen-deficient environment and allows the production of various products with different end-use such as fuels or intermediates for chemical synthesis (e.g. food flavorings, resins, agrichemicals, fertilizers, and emissions control agents) [6,62,9]. The combustible gas blend produced by means of biomass gasification is mostly composed of methane (CH_4), hydrogen (H_2), carbon monoxide (CO), carbon dioxide (CO_2), and if air is the gasification medium, also nitrogen (N_2) [7]. In the next years, industry 4.0, digitalization, and energy transition will produce a significant increase in the electric energy demand. In this scenario, gasification is the most suitable biomass to electric energy technology considering its higher efficiency compared to direct combustion, as well as its lower emission output (especially for

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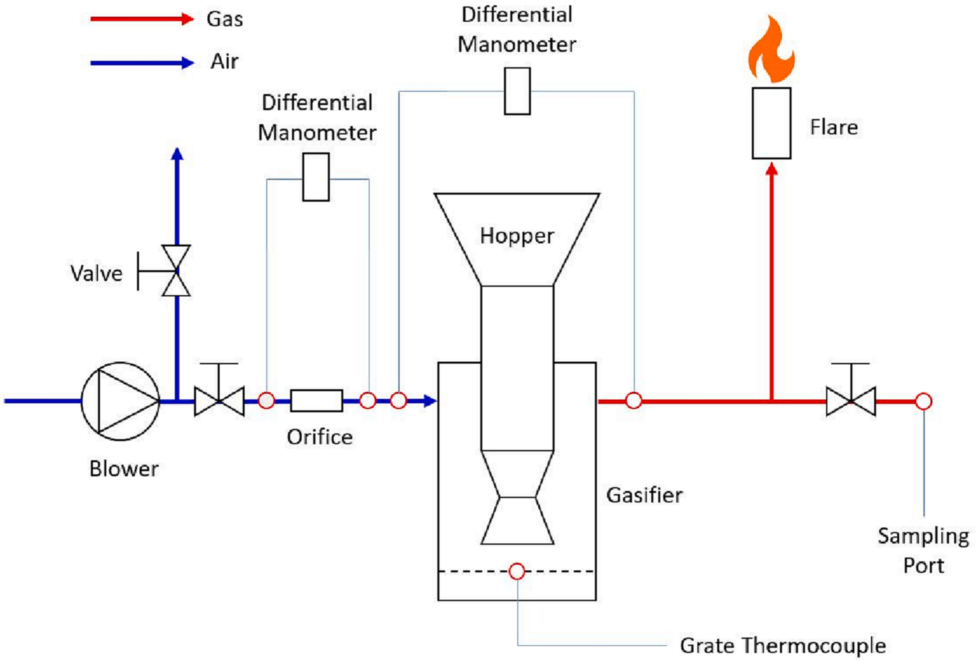

Fig. 1. Scheme of the experimental apparatus.

Table 1
Biomasses and chars ultimate analysis, ash content, *HHV* (dry basis) and moisture content *M*.

Biomass	C [%]	H [%]	S [%]	N [%]	O [%]	Ash [%]	M [%]	HHV [MJ kg^{-1}]
Pistachio shells	42.7	5.6	/	/	50.5	1.2	7.4	16.3
Pistachio shells char	80.9	1.6	/	0.2	12.0	5.23	/	28.8
Chipped hemp	45.3	5.8	/	0.3	47.7	0.9	9.9	17.7
Chipped hemp char	79.1	2.4	/	0.6	6.4	13.9	/	32.1
Hemp pellets	47.8	6.0	/	0.3	44.1	1.8	8.4	19.2
Hemp pellets char	86.0	1.1	/	0.3	2.6	10.1	/	30.8
Cork	62.5	8.0	/	0.7	28.2	0.5	3.0	28.3
Cork char	85.7	2.5	/	1.0	6.4	4.4	/	32.1
Driftwood pellets	44.9	6.0	/	0.4	41.7	7.1	7.0	18.2
Driftwood pellets char	70.7	0.4	0.1	0.4	/	29.1	/	24.6
A1 pellets	48.9*	6.3*	/	0.1*	44.1*	0.6*	5.7	19.9*
A1 pellets char	97.8*	0.8*	/*	0.9*	/*	1.6*	/	35.0*

* [48].

Table 2
Contaminant amount sampled in the gas.

Biomass	Particulate matter >7 μm [g m^{-3}]	Tar [g m^{-3}]
Pistachio shells	1.76	2.20
Chipped hemp	0.70	5.43
Hemp pellets	0.33	1.53
Cork	1.20	8.86
Driftwood pellets	0.31	2.62
A1 pellets	0.40	4.72

NO$_X$ and SO$_X$) [63]. Gasification systems can be divided into three main types: fixed bed, fluidized bed and entrained-flow bed, each of them includes other subcategories [7]. Each gasifier typology is usually more suitable for a particular application or a specific fuel. Fixed-bed are used for small size applications (<10 MWth) and commonly operate with biomass, while fluidized-bed and entrained-flow are suitable for large size and they operate with coal [7]. The gasifier architecture with the lowest tar content in the fuel gas is the fixed bed downdraft design, namely a co-current reactor where the gas medium enters at a certain height below the top, the feedstock is fed from the upper part, and the gas flows downward and leaves the gasifier from the bottom. Thanks to the low tar production, downdraft gasifier can be easily coupled to internal combustion engines [30] and, indeed, this is one of the most common small scale applications thanks to the high conversion efficiency, the power density over footprint, the relative simplicity and the low investment costs [30,62,17,2].

However, the drawback of these systems is that they have tight feedstock specifications (namely low moisture and narrow size distribution) that limit the diffusion of this technology [62]. In fact, literature reports that for small-scale gasification systems only high quality biomass (namely moisture content below 12% and ash content below 1%) is used as feedstock to guarantee undisrupted operation [45].

For this reason, it is fundamental to expand the variability of biomasses that can be used as fuel, overcoming the fuel inflexibility of these systems [62,21,32]. In this way it would be possible to exploit the various benefits of this technology, including distributed thermal and electrical power generation and the carbon sequestration through the use of biochar, a particular kind of char mainly intended for soil application, that meets the requirements reported in the European Biochar Certificate or by the International Biochar Initiative [2,52,22,26].

In this work, a preliminary evaluation on various biomasses was performed through a series of gasification tests carried out using a lab-scale downdraft gasifier.

Six typologies of biomass were taken into account, namely: pistachio shells, chipped hemp, pellets made of hemp and fir sawdust, triturated cork, pelletized driftwood residues from river maintenance and A1

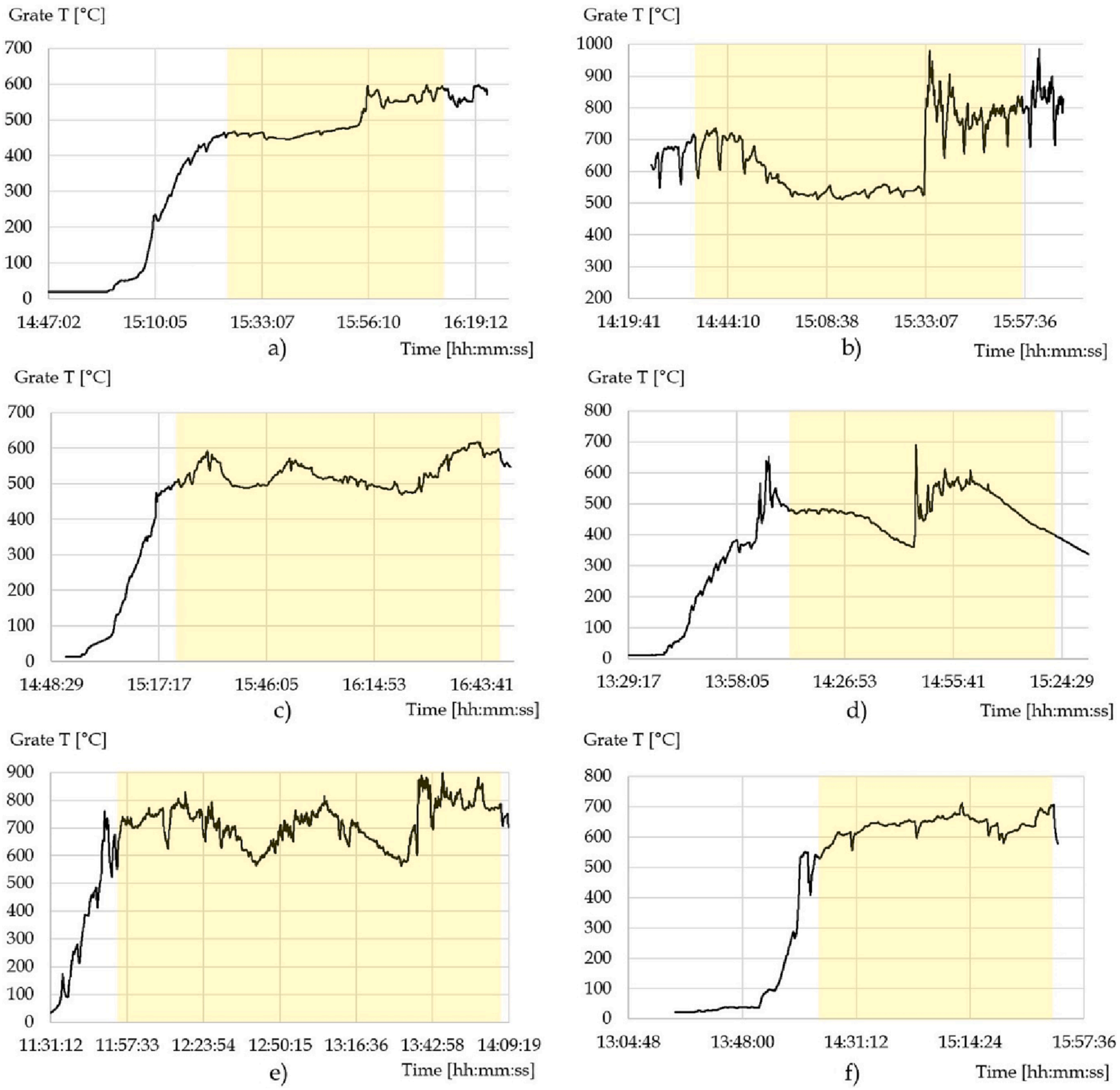

Fig. 2. Measured grate temperature trends during the various tests: a) pistachio shells b) chipped hemp c) hemp pellets d) cork e) driftwood pellets f) A1 pellets.

Table 3
Average pressure drop – gas flow^2 ratio during the various tests.

Biomass	Pressure drop/gas flow^2 [Pa (h m^{-3})^2]
Pistachio shells	200±100
Chipped hemp	130±80
Hemp pellets	300±300
Cork	200±600
Driftwood pellets	100±100
A1 pellets	50±20

ENplus pellets.

Materials and methods

The six biomass examined varieties are presented below.

Table 4
Average gas composition during the tests.

Biomass	H_2 [%]	N_2 [%]	CO [%]	CO_2 [%]	CH_4 [%]	HHV [MJ m^{-3}]
Pistachio shells	13.3	47.3	17.5	8.8	0.7	4.2
Chipped hemp	11.2	53.1	15.6	12.5	1.2	3.8
Hemp pellets	14.7	47.1	16.4	11.4	0.8	4.3
Cork	6.1	68.0	7.6	7.4	0.0	1.8
Driftwood pellets	11.0	50.9	17.2	12.3	1.6	4.2
A1 pellets	11.1	52.9	17.8	11.3	1.3	4.2

Pistachio shells

The shells of *pistacia vera*, commonly called pistachio shells, are a food processing waste. A consistent amount of this residue is generated and disposed of by burning. In Turkey (the third biggest pistachio

Table 5
Main parameters averaged over the duration of the efficiency test.

Biomass	Biomass Flow [kg h^{-1}]	Gas Flow [m^3 h^{-1}]	Thermal Power Output [kW]	Cold Gas Efficiency [%]	Efficiency Test Duration [minutes]	Ambient Temp. [°C]
Pistachio shells	1.12	2.93	3.42	67	45	12
Chipped hemp	0.89	2.66	2.81	64	89	11
Hemp pellets	0.92	2.30	2.71	55	88	11
Cork	0.25	0.60	0.29	15	58	8
Driftwood pellets	1.49	4.66	5.43	72	137	30
A1 pellets	0.94	3.14	3.73	63	93	23

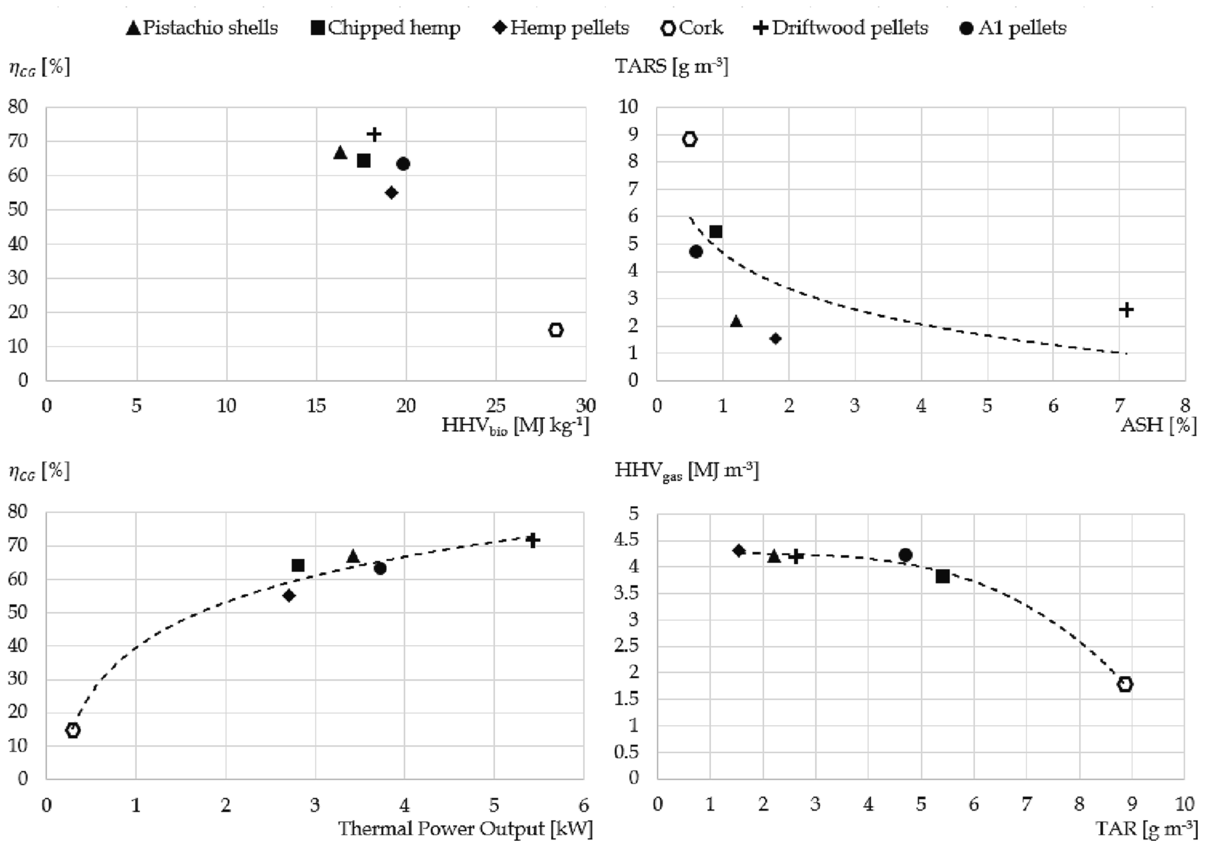

Fig. 3. Interaction and mutual influence of the main gasification parameters.

producer) there is a pistachio production of 120 thousand tons every year [44].There are several studies on thermochemical valorization of pistachio shells. Açıkalın et al. [1] studied the effect of pyrolysis condition on the product characteristics while Komnitsas et al. [35] studied of the potential of pistachio shell biochar to remove heavy metals. This biomass has low ash content and a good hardness [44], for this reason for da Silva et al. [18] it can represent a favorable energy resource in thermochemical processes such as combustion. Sharma & Kaushal [59,60] obtained encouraging results using pistachio shells as fuel for an open core downdraft reactor concerning the energy content of the gas. For these reason, further investigation on the prospect of using pistachio shells as fuel for small-scale downdraft can be extremely useful.

Hemp

The *cannabis sativa* (hemp) global sector is projected to grow from USD 4.6 billion in 2019 to USD 26.6 billion by 2025 [47].

Hemp fiber has a high demand in the textile industry as well as for sustainable building constructions and hemp hurd, a by-product of hemp fiber production, is usually employed as filler for construction material like bricks or tiles [27]. However, when flower and seed production is the main goal of hemp cultivation, the cultivar is not selected looking at the quality of fiber and hurd, therefore the economic value of these two byproducts is neglected [40,55]. Pyrolysis of hemp byproduct was explored in various research for biochar production [8,14,65] as well as its possible application in combustion facilities for energy purposes [36,10]. Gasification of hemp byproducts can be a win-win solution for the concomitant production of energy and biochar and it's the ideal for partner technology in hemp cultivation itself. This is because hemp gasification can provide heat and electricity to the indoor facilities, and biochar amendment for its growth [47]. For this reason, it was explored the possibility of chipping directly the entire stalk of the plant (*chipped hemp* from now on) without the separation of fiber and hurd and using these chips as fuel for a downdraft gasifier.

The process of chipping the stalk turned out to be challenging, due to the tendency of the fiber to wind and to make agglomerates extremely tenacious to break.

In order to test a more standardized fuel, a fraction of the chips was milled and pelletized. However, it was necessary to add about 50% of fir sawdust to make pellets with a satisfying structural strength. The result

Fig. A1. A) pistachio shells, b) chipped hemp, c) hemp pellets, d) cork, e) driftwood pellets and f) a1 pellets.

is called *hemp pellets* from now on.

Triturated cork

The cork industry consumes more than 280 thousand tons of cork worldwide every year and between 20% and 30% of the raw material received by the processing units is rejected [38]. Nowadays, from 40% to 70% of cork waste produced by the industry is sent to landfill, both in powder form and in triturated form, when its recycling or its composting or its use in agriculture is uneconomical [51]. Cork residues combustion in pellet form was investigated by Nunes et al. [43] and by Mediavilla et al. [39] with promising outcomes. The latter tested cork residues combustion in a blend with vine shoots. Cork-derived biochar produced through slow pyrolysis showed high adsorption capacity and speed as demonstrated by Wang et al. [66]. Even in this case, it was explored the possibility of using the triturated fraction of cork (*cork* from now on) as fuel in a downdraft gasifier, to obtain both biochar and energy from this residue and improve the environmental impact of its disposal. The literature concerning this route is very scarce the best of the authors' knowledge.

River driftwood

The presence of plastic debris, wood logs and branches in rivers can form jams or accumulations increasing the flow resistance [25,56] resulting in excessive increase in backwater that can cause the flooding in nearby areas [57]. Furthermore, plastic pollution has a negative effect also on the ecosystem health [53]. For this reason, identifying a profitable route for the recovery and exploitation of river waste is very important. Driftwood collected from rivers is usually burned or landfilled and other possible utilizations, such as fuel for thermochemical processes, are little investigated [49,5]. In this work, wood logs collected from a river in Italy were separated from plastic waste, dried, chipped and pelletized (*driftwood pellets* from now on) to fit with the reactor dimensions and to explore their use for energy production through gasification.

A1 ENplus pellets

The thermal utilization of A1 ENplus pellets (*A1 pellets* from now on) is a well-known and widely used application. The estimated worldwide production of A1 pellets in 2019 was more than 11 million tons [20] and for this reason were used as a standard benchmark for the comparison between the various tests.

First of all, ultimate analysis was performed on the different tested biomasses through a FLASH 2000 Organic Elemental Analyzer. In this way, it is possible to determine the mass percentage of carbon (*C*), hydrogen (*H*), sulfur (*S*) and nitrogen (*N*) [42].

Following the ISO 18122:2015[28], the ash content *(Ash)* of the various fuels was measured by weighting the sample before and after

Fig. A2. Femto Gasifier during a test.

Fig. A3. Clinker formed during driftwood pellet gasification.

being heated in a furnace at 550 °C for at least 60 min. A rough estimation of the oxygen content (O) of the various biomasses was made through the following formula:

$$O(\%) = 100 - C(\%) - H(\%) - N(\%) - S(\%) - Ash(\%) \tag{1}$$

Knowing the elemental composition, it is possible to evaluate the higher heating value of the biomass (HHV_{bio}) using the Channiwala and Parikh equation [12]:

$$\begin{aligned} HHV_{bio}(MJ/kg) = & 0.3491C(\%) + 1.1783H(\%) + 0.1005S(\%) - 0.1034O(\%) \\ & + -0.0151N(\%) - 0.0211Ash(\%) \end{aligned} \tag{2}$$

Before every gasification test, the moisture content on wet basis of the various samples was measured by drying them in an oven at 105 °C until constant mass is achieved, following the (ISO 18134–1:2015(E)) [29].

The gasification tests were carried out using a lab-scale gasifier called “Femto Gasifier”. This prototype was designed and developed by the authors at the University of Modena and Reggio Emilia, with the purpose of running preliminary tests with different kinds of biomasses.

It is an Imbert downdraft reactor with the throated hearth machined from a solid block of stainless steel. Flue insulation wraps the reactor to reduce thermal dissipation. It was specifically sized for tests with a limited amount of fuel.

The gasifier was operated under positive pressure, positioning the blower upstream the reactor. In this way the blower was preserved from being fouled by tars and particulates as well as easing the gas sampling operations. An orifice meter coupled to a differential pressure sensor *MPXV5004DP* (*NXP Semiconductors*) was used to measure the air volume flow rate entering the gasifier adjusted through two gate valves. Knowing the air entering in the gasifier ($\dot{V}_{air}$) and the nitrogen percentage in the gas ($\%N_{2,gas}$) and in the air ($\%N_{2,air}$), it is possible to calculate the gas flow rate ($\dot{V}_{gas}$) with the formula [46]:

$$\dot{V}_{gas} = \frac{\dot{V}_{air} \bullet \%N_{2,air}}{\%N_{2,gas}} \tag{3}$$

Another differential pressure sensors was used to monitor the pressure drop across the reactor. A *TC-Direct* K-type thermocouple (1 mm diameter, 310 stainless steel sheath) was used to measure the temperature of the reduction zone at the gasifier grate and another one to measure the ambient temperature. The tests were performed outdoors, hence the ambient temperature can influence the gasifier performances due to the small size of the reactor even if it is enveloped in flue insulating material. The gas produced was burned in a flare. In Fig. 1 it is possible to see a scheme of the system.

The gasifier is normally operated featuring a hopper, however this can be removed when fuels with a low flowability are used. In this way, the chances of a bridging event are reduced and the eventual intervention is easier. In this series of gasification tests, the hopper was used except for chipped hemp and cork. The biomass entering in the gasifier was monitored using a *Kern* precision balance (readability 0.01 g, reproducibility 0.02 g). Through the sampling port it was possible to assess the gas composition and its amount of contaminant (tars and particulate matter). Concerning the gas composition, various samples of gas were aspirated and analyzed in a *Pollution MicroGC GCX*, calibrated for the non-condensable gases H_2, O_2, N_2, CO, CO_2, and CH_4. The higher heating value of the gas (HHV_{gas}) was calculated as the weighted average of the HHV of the combustible components considering their volumetric fraction. Regarding the tars contained in the gas, they were assessed flowing the gas through a series of impinger bottles filled with acetone and consequent distillation as described by [16,41]. Particulate matter was estimated filtering the acetone with a Whatman quantitative filter paper 1452–150 to separate the particles bigger than 7 μm from the solvent. It was chosen this particle dimension because it is one of interest for internal combustion engines, since they can tolerate particulates with size lower than 10 μm [24,37]. The measured value does not represent the real particulate matter content of the gas but gives just a qualitative indication because the sampling was not performed in isokinetic conditions.

The cold gas efficiency (η_{CG}), defined by the Eq. (4) [31] was calculated considering a fraction of the test where the behavior of the gasifier was considered stable after the start up, measuring the biomass flow entering in the gasifier ($\dot{m}_{bio}$).

$$\eta_{CG} = \frac{ThermalPowerOutput}{BiomassPowerInput} = \frac{\dot{V}_{Gas} \bullet HHV_{Gas}}{\dot{m}_{bio} \bullet HHV_{bio}} \tag{4}$$

The gasifier steady state was considered reached when the temperature at the grate was slightly constant and above 450 °C and the gas was calorific enough to sustain the combustion at the flare.

The ratio trend between the pressure drop across the reactor (Pa) and the gas flow raised to the square $(m^3\ h^{-1})^2$ was calculated to evaluate and compare the behavior of the gasifier with different fuel at different power outputs.

A stable and low ratio indicates a smooth operation of the gasifier, while a growing ratio shows that the reactor is going to clog. The *Ansatz* is that the pressure drops and the gas flows of various tests carried out at different power outputs can be compared by normalizing these two quantities through this ratio. This is because the pressure loss (R) over the system is directly proportional to the square of the velocity of the gas flow ($R \propto w_{PG}^2$), the velocity of the gas is directly proportional to the gas volume flow, and therefore to the pressure loss is directly proportional to the square of the gas volume flow ($R \propto V_{gas}^2$) [11]. At the end of each test, a sample of the char was collected at the bottom of the gasifier (on the grate) and analyzed to assess the elemental composition and the ash content. The six gasification test were then analyzed and compared through the main monitored parameters.

Results

The results of the ultimate and ash analysis performed on the various samples of biomasses and char produced are reported in Table 1 together with the moisture content at the moment of the test and their higher heating value.

All the biomasses investigated have a high heating value ranging from 16.3 MJ kg^{-1} (pistachio shells) to 19.9 MJ kg^{-1} (A1 pellets), values typical for biomasses of interest for thermochemical valorization [6] while cork show an especially high HHV (28.3 MJ kg^{-1}). The ratio between the carbon content of the char and the biomass remained fairly constant between the various tests, from 1.6 for driftwood pellets to 2 for A1 pellets, with the exception of cork that amounted to 1.4. In any case, all the produced chars showed a high carbon content and, if other characteristics such as a low polycyclic aromatic hydrocarbons content and a well-developed porosity were confirmed by further analysis, it would be applicable as soil amendment or for other industrial applications (catalyst preparation, polymers production, tar cracking etc.) [45].

Table 2 shows the amount of contaminant measured in the gas streams in the various tests.

Concerning the tar production, all the biomasses produced an amount of tar of the same order of magnitude and between 1.53 g m^{-3} (Hemp pellets) and 8.86 g m^{-3} (cork). These tar contents are not suitable for the direct utilization of the gas in an internal combustion engine [4] unless the implementation of a filtration system. No correlation between the pelletization of the fuel and the tar content in the gas was identified.

In Fig. 2 the grate temperature trends measured during the various tests are reported. The yellow boxes indicate the test fractions where the energy fluxes were monitored for the cold gas efficiency calculation.

It can be seen that the grate temperature has a smoother trend during the tests performed with the hopper (pistachio shells, hemp pellets, driftwood pellets and A1 pellets). This is due to a less frequent shutdown of the blower concomitantly to the biomass feeding.

Table 3 reports the calculated average pressure drop – gas flow^2 ratio during the various tests together with its relative standard deviation in the form (Average ± Standard Deviation).

It is possible to see that the biomass that has guaranteed the smoother operation was A1 pellets, followed by driftwood pellets. The worst performance in terms of pressure drop – gas flow^2 ratio were shown by hemp pellets (with regard to the average value) and by cork (with regard to the standard deviation, and therefore variability).

Table 4 summarizes the average gas composition detected during the various tests and the calculated HHV.

Despite different fuels have resulted in quite different gas compositions, the final heating value of the obtained gas was quite similar, ranging from 3.8 MJ m^{-3} (chipped hemp) to 4.3 MJ m^{-3} (hemp pellets), except for cork, that showed a heating value of only 1.8 MJ m^{-3}, considerably lower compared to the other biomasses.

Table 5 reports the main parameters monitored during the fraction of the test in which the cold gas efficiency was monitored.

Except for the test with cork, where the biomass flow was particularly low (0.25 kg h^{-1}), during the other tests it ranged from 0.89 kg h^{-1} (chipped hemp) up to 1.49 kg h^{-1} (driftwood pellets). For all the tests, the ratio between the gas volume obtained and the biomass processed ranged between 2.4 $m^3\ kg^{-1}$ (cork) and 3.3 $m^3\ kg^{-1}$ (A1 pellets), in line with the values reported in literature for gasifiers with similar architecture but greater size [23]. Concerning the gasification efficiency, the best performance was shown by driftwood pellets. It outperformed the other biomasses even if, as shown in Table 3, it was not the fuel with the lowest pressure drop – gas flow^2 ratio. This discrepancy was probably due to the longer test duration (that has given to the gasifier the possibility to heat up properly) as well as being the test carried out with the highest ambient temperature. Fig. 3 shows the relations between the main parameters monitored during the gasification test in order to identify their interaction and mutual influence.

Cold gasification efficiency seems to be not influenced by the heating value of the biomass and the extremely low efficiency obtained during the cork gasification test can be attributed to the inadequacy of the gasification system for that specific biomass. Tars were usually lower for biomasses with higher ash content. This could be due to the ash catalytic effect on tar reduction and reforming [58,3]. It is also possible to see that the higher is the tar content in the gas stream, the lower is the heating value of the gas, revealing that part of the energy shifted from the non-condensable fuel gases to the tars. No correlation between the tar amount in the gas and the efficiency can be outlined, while it is clear that the higher efficiencies were reached during the test at higher power outputs. This can be explained with a lower influence of the heat losses on the gasifier operation.

Concerning driftwood pellet, it is not a simple fuel to use for long run despite the good performance in terms of efficiency. This is due to its high ash content that has led to clinker formation near the nozzles of the gasifier.

The elemental analysis carried out on a collected clinker sample showed a content of carbon of about 1% and an ash content over 99%. A solution to avoid this undesired issue can be reducing the residence time of the biomass at the high temperature zone (e.g. by varying the grate movement) [67].

Conclusion

In this work, six biomasses (five residues and A1 ENplus pellets) were tested as fuel in a lab-scale downdraft gasifier prototype. Six gasification tests were performed after a preliminary evaluation of the physical characteristics of the biomasses. Various parameters were monitored including contaminants in the gas, gas composition, grate temperature and gasification efficiency.

The produced chars were analyzed too, by measuring their elemental composition and ash content, and carbon content was always over 70%, except for cork. The ratio between the pressure drop across the reactor and the gas flow raised to the square was proposed to compare tests carried out at different power outputs. Cork has shown the worst performances in basically all the indicators, especially cold gas efficiency, indicating that its utilization in small-scale downdraft gasifiers can be problematic, at least through the tested architecture. A possible solution could be cork pelletization to increase its density as reported by Nunes et al. [43] and therefore its flowability inside the reactor. Good performances were shown by driftwood pellets even if it is necessary to pay particular attention to clinker formation, and by pistachio shells and chipped hemp. Concerning hemp thermochemical valorization through gasification, the tests have shown that chips performed better than pellets even if it should be noted that chipping this biomass was particularly challenging due to the tenacity of the fiber. Through this preliminary evaluation it is possible to assess that excluding cork, the tested biomasses showed a sufficiently smooth gasifier operation and an acceptable cold gas efficiency. Furthermore, the correlation between high ash content in the biomass and the detected low tar content in the gas could be a not insignificant point in favor of biomass usually considered too poor for energy generation. For this reason, hemp residues, pistachio shells and driftwood should be taken into account as possible fuel for small-scale downdraft biomass gasifiers. Their use for electrical and thermal energy generation can be an example of circular economy practice, and it can support the decarbonization through biochar production. Longer runs are necessary for an effective analysis of every biomass used and for a better understanding of the limits and the performances in the long term.

The next steps will be the test of these residual biomasses in a small scale commercial downdraft gasifier equipped with an internal combustion engine. In addition, the application of a pre-pyrolysis stage in order to increase the efficiency and to decrease the tar content in the gas flow will be evaluated.

CRediT authorship contribution statement

Marco Puglia: Conceptualization, Methodology, Investigation, Data curation, Writing – original draft. **Nicolò Morselli:** Methodology, Investigation, Writing – review & editing. **Filippo Ottani:** Methodology, Investigation, Writing – review & editing. **Simone Pedrazzi:** Writing – review & editing, Visualization. **Paolo Tartarini:** Supervision. **Giulio Allesina:** Writing – original draft, Visualization.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A

Fig. A1 shows the six samples of residual biomasses tested in this work.

Fig. A2 shows the lab-scale downdraft gasifier (Femto Gasifier) used for the test.

Fig. A3 displays the clinker collected in the nozzles section after the test with driftwood pellet.

References

[1] Açıkalın K, Karaca F, Bolat E. Pyrolysis of pistachio shell: Effects of pyrolysis conditions and analysis of products. Fuel 2012;95:169–77.

[2] Allesina G, Pedrazzi S. Barriers to Success: A Technical Review on the Limits and Possible Future Roles of Small Scale Gasifiers. Energies 2021;14:6711.

[3] Ashok J, Das S, Yeo TY, Dewangan N, Kawi S. Incinerator bottom ash derived from municipal solid waste as a potential catalytic support for biomass tar reforming. Waste Manag 2018;82:249–57.

[4] Baldinelli A, Cinti G, Desideri U, Fantozzi F. Biomass integrated gasifier-fuel cells: Experimental investigation on wood syngas tars impact on NiYSZ-anode Solid Oxide Fuel Cells. Energ Conver Manage 2016;128:361–70.

[5] Bartocci P, Barbanera M, D'Amico M, Laranci P, Cavalaglio G, Gelosia M, et al. Thermal degradation of driftwood: Determination of the concentration of sodium, calcium, magnesium, chlorine and sulfur containing compounds. Waste Manag 2017;60:151–7.

[6] Basu P. Biomass Gasification and Pyrolysis: Practical Design and Theory. Elsevier Inc.; 2010. ISBN 978-0-12-374988-8.

[7] Basu P. Biomass Gasification and Pyrolysis: Practical Design and Theory. 2nd ed. Elsevier Inc.; 2013.

[8] Branca C, Di Blasi C, Galgano A. Experimental analysis about the exploitation of industrial hemp (Cannabis sativa) in pyrolysis. Fuel Process Technol 2017;162:20–9.

[9] Bridgwater AV. Renewable fuels and chemicals by thermal processing of biomass. Chem Eng J 2003;91(2–3):87–102.

[10] Burczyk H, Grabowska L, Kołodziej J, Strybe M. Industrial Hemp as a Raw Material for Energy Production. Journal of Industrial Hemp 2008;13(1):37–48.

[11] Çengel Y. A., Cimbala J. M., Turner R. H., Fundamentals Of Thermal-Fluid Sciences, Fifth Edition, Published by McGraw-Hill Education, 2 Penn Plaza, New York, NY 10121. Copyright © 2017 by McGraw-Hill Education. All rights reserved. Printed in the United States of America, ISBN 978-0-07-802768-0.

[12] Channiwala SA, Parikh PP. A unified correlation for estimating HHV of solid, liquid and gaseous fuels. Fuel 2002;81(8):1051–63.

[13] Chaves LI, da Silva MJ, Melegari de Souza SN, Secco D, Rosa HA, Camargo NC, et al. Small-scale power generation analysis: Downdraft gasifier coupled to engine generator set. Renew Sustain Energy Rev 2016;58:491–8. ISSN 1364–0321.

[14] Chen F, Zhang F, Yang S, Liu H, Wang H, Hu J. Investigation of non-isothermal pyrolysis kinetics of waste industrial hemp stem by three-parallel-reaction model. Bioresour Technol 2022;347:126402.

[15] Chen R, Sheng Q, Dai X, Dong B. Upgrading of sewage sludge by low temperature pyrolysis: Biochar fuel properties and combustion behavior. Fuel 2021;300:121007.

[16] Chen Y., Wang Y., Pezzola L., Mussi R., Bromberg L., Heywood J., Kasseris E., A novel low-cost tar removal technology for small-scale biomass gasification to power, Biomass and Bioenergy, Volume 149, 2021, 106085, ISSN 0961-9534.

[17] Dabai F, Paterson N, Millan M, Fennell P, Kandiyoti R. Tar Formation and Destruction in a Fixed-Bed Reactor Simulating Downdraft Gasification: Equipment Development and Characterization of Tar-Cracking Products. Energy Fuels 2010;24(8):4560–70. https://doi.org/10.1021/ef100681u.

[18] da Silva, J.C.G., Alves, J.L.F., Galdino, W.V.d. R. de F. P. M. Moreira, H. J. José, R. F. de Sena, S. L. F. Andersen, Combustion of pistachio shell: physicochemical characterization and evaluation of kinetic parameters. Environmental Science and Pollution Research 25, 21420–21429 (2018).

[19] Duc BV, Phuong VH, Phuong NH, Quang DX, Tuyen ND, Tuan PM, et al. Techno-economic assessment and logistics management of biomass in the conversion progress to bioenergy. Sustainable Energy Technol Assess 2023;55:102991.

[20] Bioenergy Europe, European Pellet Council, 2019, Bioenergy Europe Statistical Report 2019, Report Pellet, available online at: https://epc.bioenergyeurope.org/wp-content/uploads/2020/02/SR19_Pellet_final-web-1.pdf (accessed on 27 February 2023).

[21] Erlich C, Fransson TH. Downdraft gasification of pellets made of wood, palm-oil residues respective bagasse: Experimental study. Appl Energy 2011;88(3):899–908. ISSN 0306–2619.

[22] EBC (2012–2022) 'European Biochar Certificate—Guidelines for a Sustainable Production of Biochar'. European Biochar Foundation (EBC), Arbaz, Switzerland. Version 10.1 from 10 January 2022. Available online: http://european-biochar.org (accessed on 25 May 2022).

[23] FAO Forestry Department, FAO FORESTRY PAPER 72, FOOD AND AGRICULTURE ORGANIZATION OF THE UNITED NATIONS, Wood gas as engine fuel, Rome, Chapter 2, 1986, ISBN 92-5-102436-7.

[24] Hasler P, Nussbaumer Th. Gas cleaning for IC engine applications from fixed bed biomass gasification. Biomass Bioenergy 1999;16(6):385–95.

[25] Honingh D, van Emmerik T, Uijttewaal W, Kardhana H, Hoes O, van de Giesen N. Urban River Water Level Increase Through Plastic Waste Accumulation at a Rack Structure; Frontiers. Earth Sci 2020;8.

[26] IBI (2015) Standardized Product Definition and Product Testing Guidelines for Biochar That Is Used in Soil, International Biochar Initiative. http://www.biocharinternational.org/characterizationstandard (accessed on 25 May 2022).

[27] Ingrao C, Lo GA, Bacenetti J, Tricase C, Dotelli G, Fiala M, et al. Energy and environmental assessment of industrial hemp for building applications: A review. Renew Sustain Energy Rev 2015;51:29–42.

[28] ISO 18122:2015 Solid biofuels-Determination of ash content.

[29] ISO 18134-1:2015(E) Solid biofuels-Determination of moisture content-Oven dry method.

[30] Kamble P, Khan Z, Gillespie M, Farooq M, McCalmont J, Donnison I, et al. Biomass gasification of hybrid seed Miscanthus in Glasgow's downdraft gasifier testbed system. Energy Procedia 2019;158:1174–81.

[31] Khosasaeng T, Suntivarakorn R. Effect of Equivalence Ratio on an Efficiency of Single Throat Downdraft Gasifier Using RDF from Municipal solid waste. Energy Procedia 2017;138:784–8.

[32] Kjellström B., Arvidsson A., Forslund H. and Martinac I. Renewable energy technologies for decentralised rural electricity services. SEI climate and energy programme, Swedish Environment Institute (SEI), Stockholm, Sweden. 2005.

[33] Kim GS, Choi S. K., Seok J. H., Does biomass energy consumption reduce total energy CO2 emissions in the US?, Journal of Policy Modeling, Volume 42, Issue 5, 2020, Pages 953-967, ISSN 0161-8938.

[34] Ko CH, Chaiprapat S, Kim LH, Hadi P, Hsu SC, Leu SY. Carbon sequestration potential via energy harvesting from agricultural biomass residues in Mekong River basin, Southeast Asia. Renew Sustain Energy Rev 2017;Volume 68, Part 2: 1051–62. ISSN 1364–0321.

[35] Komnitsas K, Zaharaki D, Pyliotis I, Vamkuva D, Bartzas G. Assessment of Pistachio Shell Biochar Quality and Its Potential for Adsorption of Heavy Metals. Waste Biomass Valor 2015;6:805–16.

[36] Kraszkiewicz A, Kachel M, Parafiniuk S, Zając G, Niedziółka I, Sprawka M. Assessment of the Possibility of Using Hemp Biomass (Cannabis Sativa L.) for Energy Purposes: A Case Study. Appl Sci 2019;9(20):4437.

[37] Laurence LC, Ashenafi D. Syngas Treatment Unit for Small Scale Gasification - Application to IC Engine Gas Quality Requirement. Journal of Applied Fluid Mechanics 2012;5:95–103.

[38] Matos AM, Nunes S, Sousa-Coutinho J. Cork waste in cement based materials. Mater Des 2015;85:230–9. ISSN 0264–1275.

[39] Mediavilla I, Fernández MJ, Esteban LS. Optimization of pelletisation and combustion in a boiler of 17.5 kWth for vine shoots and industrial cork residue. Fuel Process Technol 2009;90(4):621–8.

[40] Moscariello C, Matassa S, Esposito G, Papirio S. From residue to resource: The multifaceted environmental and bioeconomy potential of industrial hemp (Cannabis sativa L.). Resour Conserv Recycl 2021;175:105864.

[41] Neeft J. P. A., Knoef H. A. M., Zielke U., Sjoestroem K., Hasler P., Simell P. A., Dorrington M. A., Thomas L., Abatzoglou N., Deutch S., Greil C., Buffinga G. J., Brage C., Suomalainen M., Guideline for Sampling and Analysis of Tar and Particles in Biomass Producer Gases, Version 3.3, Netherlands, 2002. Energy project ERK6-CT1999-20002 (Tar protocol).

[42] Nelissen V, Kumar ShB, Ruysschaert G, Boeckx P. Effect of different biochar and fertilizer types on N2O and NO emissions. Soil Biol Biochem 2014;70:244–55.

[43] Nunes LJR, Matias JCO, Catalão JPS. Energy recovery from cork industrial waste: Production and characterisation of cork pellets. Fuel 2013;113:24–30. ISSN 0016–2361.

[44] Okutucu C, Duman G, Ucar S, Yasa I, Yanik J. Production of fungicidal oil and activated carbon from pistachio shell. J Anal Appl Pyrol 2011;91(1):140–6. ISSN 0165–2370.

[45] Patuzzi F, Basso D, Vakalis S, Antolini D, Piazzi S, Benedetti V, et al. State-of-the-art of small-scale biomass gasification systems: An extensive and unique monitoring review. Energy 2021;223:120039.

[46] Pedrazzi S, Allesina G, Morselli N, Puglia M, Rinaldini CA, Savioli T, et al. Modified Diesel Engine Fueled by Syngas: Modeling and Experimental Validation. 24th European Biomass Conference and Exhibition 2016:880–3.

[47] Pedrazzi S., Santunione G., Mustone M., Cannazza G., Citti C., Francia E., Allesina G., Techno-economic study of a small scale gasifier applied to an indoor hemp farm: From energy savings to biochar effects on productivity, Energy Conversion and Management, Volume 228, 2021, 113645, ISSN 0196-8904.

[48] Puglia M., Morselli N., Tartarini P., Design and First Test of a Lab Scale (2 kg/h) Gasifier, 27th European Biomass Conference and Exhibition, 2019, Pages 797 - 801, https://doi.org/10.5071/27thEUBCE2019-2CV.2.12.

[49] Qatarneh AF, Dupont C, Ruiz-Villanueva V, da Silva Perez D, Ashour RM, Piégay H, et al. Evaluating river driftwood as a feedstock for biochar production. Waste Manag 2021;134:197–205.

[50] Qin Y, Hong K, Chen J, Zhang Z. Asymmetric effects of geopolitical risks on energy returns and volatility under different market conditions. Energy Econ 2020;90: 104851.

[51] Ramos A., Berzosa J., Clarens F., Marin M., Rouboa A., Environmental and socio-economic assessment of cork waste gasification: Life cycle and cost analysis, Journal of Cleaner Production, Volume 249, 2020, 119316, ISSN 0959-6526,.

[52] Ravenni G, Sárossy Z, Ahrenfeldt J, Henriksen UB. Activity of chars and activated carbons for removal and decomposition of tar model compounds – A review. Renew Sustain Energy Rev 2018;94:1044–56.

[53] Roebroek CTJ, Harrigan S, van Emmerik THM, Baugh C, Eilander D, Prudhomme C, et al. Plastic in global rivers: are floods making it worse? Environ Res Lett 2021;16(2):pp.

[54] Rubino M, Etheridge DM, Thornton DP, Howden R, Allison CE, Francey RJ, et al. Revised records of atmospheric trace gases CO_2, CH_4, N_2O, and $\delta^{13}C$-CO_2 over the last 2000 years from Law Dome. Antarctica, Earth System Science Data 2019;11: 473–92.

[55] Salentijn EMJ, Petit J, Trindade LM. The Complex Interactions Between Flowering Behavior and Fiber Quality in Hemp, Frontiers. Plant Sci 2019;10.

[56] Schalko I., Schmocker L., Weitbrecht V., Boes R. M., Backwater rise due to large wood accumulations: Effect of organic fine material; 19th EGU General Assembly, EGU2017, proceedings from the conference held 23-28 April, 2017 in Vienna, Austria., p.6646;.

[57] Schmocker L, Weitbrecht V. Driftwood: Risk Analysis and Engineering Measures. J Hydraul Eng July 2013;Volume 139 Issue 7:-.

[58] Shahbaz M, Yusup S, Inayat A, Patrick DO, Ammar M. The influence of catalysts in biomass steam gasification and catalytic potential of coal bottom ash in biomass steam gasification: A review. Renew Sustain Energy Rev 2017;73:468–76.

[59] Mohit S., Kaushal R., (2020) Enhanced producer gas generation by utilizing pistachio shells as a biomass feedstock in an open core downdraft gasifier, Energy Sources, Part A: Recovery, Utilization, and Environmental Effects.

[60] Sharma M, Kaushal R. Performance and exhaust emission analysis of a variable compression ratio (VCR) dual fuel CI engine fuelled with producer gas generated from pistachio shells. Fuel 2021;283:118924.

[61] Singh S, Chakraborty JP, Mondal MK. Pyrolysis of torrefied biomass: Optimization of process parameters using response surface methodology, characterization, and comparison of properties of pyrolysis oil from raw biomass. J Clean Prod 2020;272: 12251.

[62] Simone M, Barontini F, Nicolella C, Tognotti L. Gasification of pelletized biomass in a pilot scale downdraft gasifier. Bioresour Technol 2012;116:403–12. ISSN 0960–8524.

[63] Situmorang YA, Zhao Z, Yoshida A, Abudula A, Guan G. Small-scale biomass gasification systems for power generation (<200 kW class): A review. Renew Sustain Energy Rev 2020;117:109486.

[64] Van Swaaij W., Kersten S., Palz W, Biomass Power for the World: Transformation to Effective Use, Pan Stanford Series on Renewable Energy - Volume 6, Chapter 1, 2015, ISBN 978-981-4669-24-5.

[65] Wallace CA, Afzal MT, Saha GC. Effect of feedstock and microwave pyrolysis temperature on physio-chemical and nano-scale mechanical properties of biochar. Bioresources and Bioprocessing 2019;6:33.

[66] Wang Q, Lai Z, Mu J, Chu D, Zang X. Converting industrial waste cork to biochar as Cu (II) adsorbent via slow pyrolysis. Waste Manag 2020;105:102–9.

[67] Siddiqui H, Thengane SK, Sharma S, Mahajani SM. Revamping downdraft gasifier to minimize clinker formation for high-ash garden waste as feedstock. Bioresour. Technol 2018;266:220–31.