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Techno-economic study of a small scale gasifier applied to an indoor hemp farm: From energy savings to biochar effects on productivity

Simone Pedrazzi [b,*], Giulia Santunione [a,b], Marcello Mustone [c], Giuseppe Cannazza [a], Cinzia Citti [a], Enrico Francia [a], Giulio Allesina [b]

[a] Department of Life Science, University of Modena and Reggio Emilia, Via Giuseppe Campi, 287 – 41125 Modena, Italy
[b] Department of Engineering "Enzo Ferrari", University of Modena and Reggio Emilia, Via Pietro Vivarelli, 10 – 41125 Modena, Italy
[c] Società agricola Genesi srl, Soliera, MO, Italy

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ABSTRACT

The hemp market is fast growing due to demand for cannabidiol, nutraceutical and hemp fiber products. This work demonstrates the economical advantage of biomass gasification application to indoor hemp production. Gasifiers provide electrical energy, heat and biochar: these are highly valuable products for indoor growers where lights and thermal management are key costs of the business. Energy produced in an autonomous and renewable way increases the sustainability and in the facility. In this paper a small scale gasifier is fueled with certified "A1 plus" wood pellets to test its behavior and its biochar production rate. Biochar is used for hemp growing tests in an indoor hemp production facility. Results show how a 22 kW power plant is sufficient to guarantee almost complete sustainability in a 80 m^2 facility. In the best case scenario where energy saving, biochar and thermal energy selling are considered, the gasifier investment has a payback time of about 3.5 years. At the end of the gasifier lifespan, the Net Present Value reaches 249 k€ considering a discount rate of 6%. Consequential results were also obtained from biochar application to pot growing substrates: there was a 7.7% increase in dry flower production and a 33.9% increase in total plant fresh biomass. Cannabinoids profiles resulted not affected by biochar application.

1. Introduction

The hemp global sector is a fast growing market that is projected to grow from USD 4.6 billion in 2019 to USD 26.6 billion by 2025 thanks to the large variety of possible applications hemp is involved in [1,2]. Textile industries as well as sustainable building companies are increasing the demand for hemp fiber [3]. The food industry has found that hemp seeds and seed-derived oil provide a valuable source of Omega-3 and Omega-6 fatty acids and protein suppliers, while pharmaceutical and recreational industries are interested in the cannabinoid profile: cannabidiol (CBD) or delta-9-tetrahydrocannabinol (THC) of the unpollinated flowers [4–6]. Since hemp plants show high genetic variability, it is possible to choose a proper genotype, depending on the application, in order to maximize crop growth rate [7].

Compared to open field growth, controlled environment pot or hydroponic facilities allow the prevention of negative effects of biotic and abiotic stresses assuring higher biomass production and higher stability of CBD and THC profiles. On the other hand, indoor growing systems are affected by high specific energy consumptions leading to high OPEX (Operating Expense) and low overall sustainability of the facility. Mills, in 2012, suggested a total value of 6074 kWh/kg [8]. High costs are justified by the large margins guaranteed by the hemp market. Due to these margins, growers are likely to invest money in new technologies that assure slight increases in the amount of yielded material. Materials such as coco coir, bat guano and worm castings are commonly used in indoor and field application to provide high quality nutrients to the hemp culture [9].

Within the described framework of needs and aims for the hemp market, this work investigates the potential role that small gasification power generation systems can have in providing both energy independence and high quality soil amendment to indoor hemp farming. Biomass gasification is a thermo-chemical reaction that converts a solid feedstock into a gaseous fuel using a gasifying agent in a sub-stoichiometric environment [10]. Gasification has several different characteristics compared to other thermochemical processes, like pyrolysis and combustion. First of all, gasification is the most efficient way

* Corresponding author.
E-mail address: simone.pedrazzi@unimore.it (S. Pedrazzi).

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to convert biomass to electrical energy [11–14] and it covers a wide range of electrical power output requirements (from 1 kW to 1 MW) [10,12,13]. Secondly, gasification may accept some not-conventional biomasses as fuel thanks to peculiar architectures [15–18]. Furthermore, commercial gasification systems not only convert solid biomass (usually wood chips) into electrical energy and heat but they also produce biochar. Biochar consists of charcoal yielded from gasification and pyrolysis reactors. Biochar is a highly recalcitrant form of carbon, for which it is used as soil amendment, thus converting the fields into carbon sinks [19,20]. While the general literature on biochar is already consistent, its application to hemp farms is not reported.

An alternative technology for biomass use consists in direct combustion. Biomass boilers and furnaces are capable of processing different fuels with different moisture content. When compared to gasification, direct combustion has the advantage of higher simplicity. There is no need for gas-to-power systems (i.e. internal combustion engines or gas turbines) and, therefore, no need for gas conditioning (gas cooling and cleaning). On the other hand, incineration/direct combustion in small scale is rarely capable of producing electrical power. The only way consists in using externally fired/externally heated direct cycles such as Organic Rankine Cycles and Externally Fired Gas Turbines (EFGT). Those systems are expensive and difficult to manufacture in small/micro scale and usually result in overall efficiencies around 10–15% [10,12].

This work aims to assess the energy saving potential of gasification applied to indoor hemp production facilities. More specifically, the study wants to evaluate energy efficiency coming from independent use of both electrical and heat and biomass production through biochar application to the soil.

An indoor growing facility is used in this work to investigate the above mentioned advantages. In particular, Kompolti cultivar (*Cannabis sativa* sp.) is cultivated for CBD-rich flower production. CBD growing farms have been appearing in the Italian market since the Italian law 242/2016 (for the support and promotion of the cultivation and supply chain of hemp) was released. This law describes the limits for hemp production. A growing test was performed using gasification biochar in partial substitution of perlite as a component of growing substrate. The biochar used was obtained from a small scale gasifier fueled with A1 plus wood pellets. The choice to use wood pellets is described in the Material and Method Section and derived from from standardization requirements for the gasification test.

The energy consumption of the indoor facility for the entire growing period was evaluated and scenarios where the gasifier provides electricity and the thermal energy are discussed from the technical and economical point of view. The solution proposed has consequential impacts both on the business side, thanks to a higher productivity and lower OPEX cost of the activity, as well as on the environmental aspects due to carbon sequestration with the biochar and carbon offsets obtained through the self-produced renewable energy.

2. Material and methods

2.1. *Gasification facility & biochar production*

The technology chosen to be applied to the farm consists of a commercial micro-scale biomass gasifier. It is manufactured by the Californian company All Power Labs [21,22]. The model used in this work is the PP30 (Fig. 1 and Fig. 2), a compact power generation system that provides a fuel hopper, a multi-stage gasification reactor, a filtering system and a grid-tied internal combustion engine generator system within a footprint of $1.78 \times 1.42 \times 2.24$ m. The PP30 produces both CHP (combined heat and power) and biochar. CHP is composed of a 3-stage heat exchanger that recovers heat from 3 different sources: gas cooling, engine coolant and engine exhausts. All the heat sources converge to a plate heat exchanger used as a thermal interface between the machine and the local heat load (district heating grid or in situ heat usage). The gasifier PP30 is designed to work with various fuels, among which

Fig. 1. PP30 Power generation system [21].

woodchips is the best choice. The specific fuel consumption and biochar production can be rated at 1 kg/kWh and 0.1 $kg_{biochar}/kg_{biomass}$ respectively. In this work, the standard fuel used is A1 EN Plus fir pellets. Ultimate analysis of pellets is reported in Table 1. The choice of using pellets instead wood chips derives from the specific integration of the gasifier in the greenhouse facility. The wood pellet market is more globally developed compared to the wood chip market. Furthermore, the volumetric energy density and the bulk density of the pellets is higher compared to wood chips. The guide to specifying biomass heating systems of the FOREST European project [23] gives some values of volumetric energy density and the bulk density for wood pellets and wood chips. Wood pellets with 8% of moisture content have a volumetric energy density of 3100 kWh/m^3 and a bulk density of 650 kg/m^3; wood chips with 30% of moisture content have a volumetric energy density of 870 kWh/m^3 and a bulk density of 250 kg/m^3.

In greenhouses, all the space is used for cultivation. The choice of using wood pellets requires less storage space compared to wood chips. However, the PP30 gasifier is not originally designed to work with wood pellets, so the gasifier behavior using this specific fuel is evaluated through an experimental campaign reported in Section 3.1. One of the major advantages of wood pellets is the fuel standardization. Results obtained in this study with A1 plus pellets can be replicated in other studies that use the same reactor. This feature is not always true with other fuels such as wood chips, where external factors play important roles in fuel preparation (biomass moisture, trunk/branches diameter, previous chipping, wood chipper technology and many others). Other PP30 features and specs are reported in Table 2. In order to work with pellets, the PP30 was slightly modified. In particular, after discussing with the gasifier manufacturer, the drying stage in the hopper (commercially named drying bucket) was shouted off to avoid pellet disgregation before entering the reactor (Fig. 2 left). The machine has two different biochar collection points (as shown in Fig. 2 left). The larger char particles are extracted below the reactor hearth while fine particles are collected from a thermally-insulated cyclone. Once the whole system reaches steady state conditions, the temperature of the char outtake point below the gasifier heart exceeds the 600 °C (Fig. 2 right). This temperature is vastly above the PAH (polycyclic aromatic hydrocarbons) dew point [24], thus reducing the canche to encounter

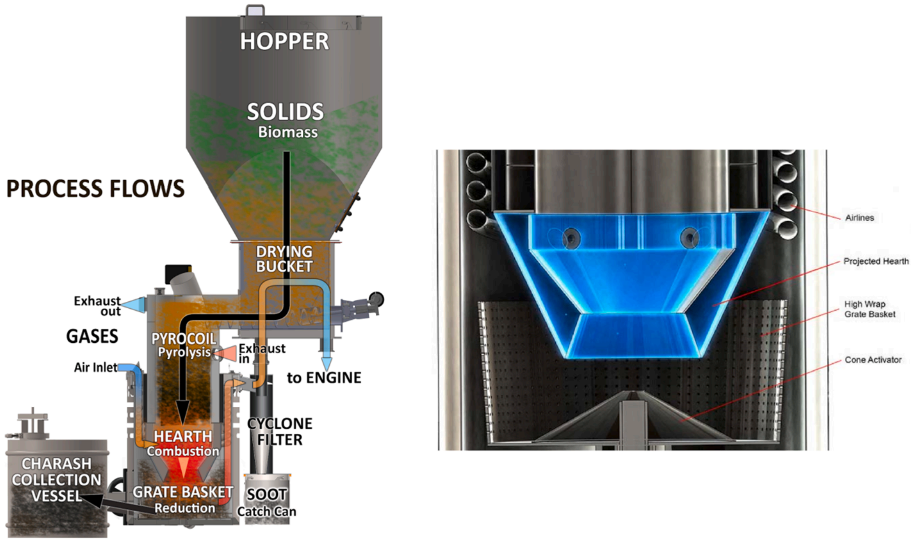

Fig. 2. PP30 gas generation unit schematic (left), reactor reduction zone (right) [21].

Table 1
A1 EN plus fir pellets ultimate analysis (as-received conditions).

Parameter	Content value
Carbon [% wt.]	45.31
Hydrogen [% wt.]	6.00
Nitrogen [% wt.]	0.12
Oxygen [% wt.]	40.29
Sulfur [% wt.]	/
Moisture [% wt.]	8
Ash [% wt.]	0.29
HHV* [MJ/kg]	18.71

*Calculated through the Milne equation [10].

Table 2
All Power Labs PP30 specs @ 50 Hz engine speed [21].

Electrictrical continuous power	22 kW
CHP thermal power output	44 kW
Biomass consumption (dry basis)	1 kg/kWh of electricity
Max. continuous operation	24 h
Electrical efficiency (wood to power)	23%
Gasification efficiency (wood to gas)	82%
Installed footprint	1.78 × 1.42 × 2.24 m
Cost without shipping and installation	55,000.00 €

PAH condensation within the char.

The gasification reactor has fixed-bed downdraft single throat architecture. The reactor worked with hearth temperatures that ranged from 860 to 950 °C. The heating process lasts around 30 min. The heating rate is not imposed, but instead derives from the equilibrium between combustion and reduction reactions. The reactor manufactured by All Power Labs is a patented Imbert-type design with a shaking and moving grate on the bottom. Char is discharged through an auger. The evaluation of the residence time starts from consumption and geometrical data of the grate basket. From basic calculation using char density, biomass consumption and grate basket volume data, the char residence time is about 4 h as reported in [24]. This specific power plant design uses "dry filtration" for gas cleaning. The gas is cooled down and filtered in felt bags above the water dewpoint. In such a way it is possible to filter the gas without the condensation of tarry-oil compounds that are instead held in the bag filter [25].

Char phytotoxicity was tested first using a standard method based on watercress germination. The test was then repeated using hemp seeds. Results of phytotoxicity tests are reported in Appendix A. The gasification unit chosen for this study does not allow direct use of hemp byproducts as fuel for the reactor. The reasons originate from the chemical composition of hemp and its physical form. In fact, hemp byproducts (fiber, hurd and leaves) are rich in silica. The high inorganic content is the basis for the ash melting phenomena in the reactor, leading to reactor hearth clogging. The second issue is the plant morphology itself. The tough fibers that run through all the plant stalk make it extremely difficult to cut them into pieces.

2.2. Hemp growth trial

Biochar represents a valiant soil amendment due to its ability to improve soil's physical and chemical properties, to enhance plant nutrient availability and soil water retention and to increase microbial population and activities [26,27]. Biochar has a known effect to increase plant growth and crop yield to 10% on average. At the same time, its chemical safety needs to be certified before use. Indeed, biochar is also a highly heavy-metal adsorbent due to its high microporosity which could represent a safety concern for plant growth when used as amendment [28,29]. Thus, the biochar applied in this study has been previously analyzed and is compliant to the thresholds defined by D.Lgs. n. 75/2010 in terms of copper content [30].

The controlled condition growth experiment was performed in a 80 m^2 greenhouse placed in Modena, Northern Italy (Fig. 3). Cuttings from Kompolti cultivar were planted into the indoor facility where temperature, relative humidity and light conditions were continuously controlled. A HVAC (heat, ventilation and air conditioning) system provides air into the greenhouse at a constant temperature of 27 °C and relative moisture of 70%. The average electrical power consumption of the HVAC system is about 5 kW. Each of the 39 led lights has an electrical power consumption of 480 W. Water and nutrients are provided to the plants using drip irrigation. Each pot has a net soil-substrate volume of 4.5 L. The 312 plants growing are subdivided in two macro-phases: vegetative (25 days) and flowering (50 days). During the vegetative growing, a light–dark cycle of 18 h of light and 6 h of darkness is adopted, while during flowering the light–dark cycle is 12–12 h. Single plant water irrigation is set to 0.108 l/day during the vegetative growing and to 0.175 l/day during flowering. The nutrients are dissolved in the irrigation water. Table 3 resumes water and electrical consumption of the green houses during the growing period. Fig. 4 illustrates the Sankey diagram of the electrical energy used in the greenhouse during a year where 4 growing cycles are made. A total energy of 114,624 kWh is

Fig 3. Hemp trial greenhouse facility.

Table 3
Electricity and water consumption of the greenhouse during each growing phase.

	Vegetative (25 days)	Flowering (50 days)	Total (75 days)	Per-plant data
Electrical consumption [kWh]	11,424	17,323	28,656	91.85 kWh/plant
Water consumption [l]	842.4	2730	3572.4	11.45 l/plant

taken from the grid to supply the LEDs and the HVAC system. Other small devices like water pumps and external lights are not taken into account.

2.3. Pot growing tests

Gasification biochar provided by the PP30 (Fig. 1) was used in this study as soil amendment and its effects were assessed through a pot growth test on *Cannabis s.* sp., Kompolti cultivar. Control pots were filled with coconut fiber (70%) and perlite (30%) and have been compared with two different percentages (thesis) of biochar: 5% v/v (5%B) and 10% v/v (10%B). The percentage of biochar replaced perlite in thesis pots. The preparation of the mixed substrates was performed adding the specific percentages v/v of the ingredients into a large tumbler and then mixed until fully homogenized.

The different substrate compositions and their chemical characterizations are shown in Table 4. In the present study, 15 replicated pots for each thesis (5%B and 10%B) were prepared; 15 more pots without biochar were used as the control. Hence, a total of 45 plants were considered for this study. After the harvesting, the whole-plant fresh weight was measured using a hanging hook scale (Scale House, DHSl). Hemp plants are processed in the following way: flowers are cut and then processed through mechanical trimmers. The pot soil (with and without biochar), plant stalk and leaves are sent to the municipal composting site. All the fresh flowers cut from each plant were weighed using a KERN scale (d = 0.01). The flowers were then dried arranging them on meshed screens and kept in the dark at low relative moisture, low temperature (18 °C) environment. 7 days later, the total dried mass of the flowers of each plant were obtained and the humidity content was back-calculated.

2.4. Cannabinoids analysis

Cannabinoids are a class of organic compounds with a terpenophenolic modular structure that are among the most studied components in

Table 4
Percentage composition of control substrate (CTRL) and the two experimental thesis substrates: 5% v/v biochar content (5%B), and 10% v/v biochar content (10%B) and chemical characterization parameter of three types of substrates.

	CTRL	5% B	10% B
Substrates composition	70% v/v Coconut Fiber; 30% v/v Perlite	70% v/v Coconut Fiber; 25% v/v Perlite; 5% v/v Biochar	70% v/v Coconut Fiber; 20% v/v Perlite; 10% v/v Biochar
pH	7.2	8.4	8.5
Electric conductivity [dSm^{-1}]	0.3	0.57	0.49
Copper [mg/kg]	1.7	2.4	3
N_{tot} [%]	0.6	0.5	0.5
Organic Carbon [%]	26.5	45.8	56.2
C/N	48.4	86.2	105.2

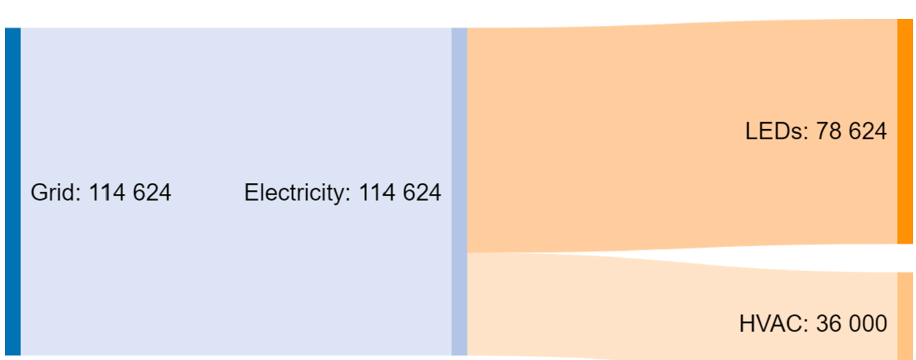

Fig 4. Sankey diagram of the annual electrical energy consumption of the greenhouse (Scenario A).

hemp [31] especially for their interesting pharmacological properties [32,33]. Monitoring their level in the plant is of utmost importance as it should comply with European and Italian legislation [34,35]. In particular, only hemp varieties included in the European Catalogue are allowed for cultivation and they should also meet the criteria dictated by the recent Italian law 242/2016 (for the support and promotion of the cultivation and supply chain of hemp). Therefore, in order to ensure the quality and safety of the product, cannabinoid concentrations were measured in all tested samples following a recently developed analytical method based on liquid chromatography coupled to an ultraviolet detector (HPLC-UV) [36,37]. About 1 g of dry flower biomass was harvested from each plant included in the experimental trial. Then 3 groups (A, B, C) of dry flowers were created combining the dry flower biomass coming from 5 plants of the same treatment (CTRL, 5%B, 10%B). After, all the samples were finely ground and 500 mg of each were extracted in three sequential steps with ethanol 96% (20, 12.5, and 12.5 ml), each time transferring the liquid phase into a 50 ml volumetric flask. After filling the flask with fresh ethanol up to 50 ml, 1 ml of the solution was filtered through a 0.45 μm cellulose membrane and transferred into a tube. After dilution (1:10) with a solution of internal standard in acetonitrile (1 μg/ml ibuprofene), 6 μl were injected into the HPLC system. The HPLC system was an Agilent 1220 Infinity LC equipped with a vacuum degasser, a binary pump, a manual injector with a 6 μl loop and a UV detector set at 228 nm. The stationary phase consisted of a C18 core–shell technology (Poroshell 120 SB-C18, 3.0 × 150 mm, 2.7 μm), and the mobile phase was a mixture of water and acetonitrile (30:70, v/v) with 0.1% formic acid (v/v). An isocratic elution was set from 0 to 26 min, whereafter the percentage of acetonitrile was increased to 100% and maintained for 5 min. Lastly the initial conditions were restored to equilibrate the column for 3 min. The total run time was 34 min. The results are the mean of 3 runs and are expressed in percentage of the dry weight of biomass (w/w) as mean ± standard deviation.

3. Results and discussion

3.1. Biochar and energy production through small scale gasification

Relevant results concerning the gasification test were obtained using standardized A1 EN Plus fir pellets, summarized in Table 5. The test was kept long enough to discard the influence of the startup period. In fact, Table 5 reports the length of the steady state period only. During this period of time, a constant electrical power of 10.5 kW was generated by the engine. The test was carried out until the complete consumption of the pellets (45 kg) without opening the hopper in order to prevent influences on the gasification behavior and efficiency. Air volumetric flow rate was measured using a G25 gas totalizer and syngas flow and total volume were backcalculated using the procedure reported by Allesina [22]. The choice to set the electrical output to 10.5 kW instead of the nominal value of 22 kW is driven by 2 main reasons: First, the machine design uses the engine suction force to draw the gas from the reactor and the filtration stage. As the filters start to clog, the maximum power output the machine is capable of holding reduces accordingly. Then, after the filter maintenance, the full power can be restored again. In this work, a condition "in between" was chosen as representative of the average power output produced by the engine. Second, the absence of the drying stage in the hopper reduces the temperature of the pellets entering the reactor, so a higher time is required for the pellets to reach a proper pyrolysis temperature with respect to conventional operation. This suggests lowering the power production in order to provide a right amount of time to the pellets to be converted into syngas fuel. Results report a lower gasification efficiency (70%) compared to manufacturer datasheet (82%). The reactor air nozzles and the grate are designed to work with wood chips (Fig. 2 right). Pellets have a higher density with respect to wood chips and probably do not allow a perfect air penetration into the combustion zone which decreases the combustion homogeneity and increases tar production, lowering the gasifier efficiency. Pellet char also creates a higher pressure drop with respect to wood chips in the reduction zone of the gasifier which increases the grate-shaking frequency, increasing the unconverted char that leaves the reactor, decreasing the gasification efficiency. In addition, the gasifier dimensions are designed for almost twice the syngas production a lower syngas production increases the weight of the thermal losses that occur on the wall of the gasifier, lowering again the gasification efficiency. A low cold gas efficiency decreases the electrical efficiency of the machine. In fact, an average electrical efficiency of about 15% was calculated using the procedure reported by Allesina et al. [22]. All Power Labs assesses an electrical efficiency of about 23%. It is probable the difference in performance is also given by the lower generator efficiency at partial load (22%) in respect to the nominal efficiency at full load (28%). Table 6 reports the syngas composition. Methane is slightly higher than what is suggested by literature [10]. For moving-bed downdraft reactors, methane should be 1–2% vol., in this case it is about 3%. A high amount of methane suggests high tar production [10,38] given by a nonhomogeneous and efficient gasification reaction. This was already highlighted by a decrease in the gasification efficiency. Furthermore, hydrogen percentage in the syngas (18%) is slightly lower than literature data (20–25%) [10]. This is probably given by a low Equivalence Ratio value (ER) of the gasification reaction. ER is defined as the oxygen amount that is involved in the gasification reaction divided by the stoichiometric oxygen amount for complete combustion. In autothermal gasification reactors, ER ranges from 0.2 to 0.4 [39,40]. An ER value lower than 0.2 suggests that the reaction is shifting from gasification to pyrolysis while an ER value higher than 0.4 indicates that the gasification reactions are moving towards combustion processes. It is plausible to think that due to the partial load operations (10.5 kW), in this test, the ER value is reaching the lower limit of gasification and the reaction is more similar to pyrolysis: this explains why a lower gasification efficiency and a higher methane concentration in the syngas it has been recorded compared to literature data.

3.2. PP30 gasifier as energy and biochar provider for the indoor hemp cultivation

As described in Section 2.2, the electrical consumption of the hemp greenhouse is far from being neglectable. Considering a specific cost for grid electricity of 0.2 €/kWh [41] and greenhouse electricity consuption of 114,624 kWh (Fig. 4), the annual cost of electricity totals 22′925,00 €. The major part of greenhouse electrical consumption derives from the

Table 5
Results of the gasification tests.

Variable	Value
Steady state test length [h]	03:12
Avg air volumetric flow [m^3/h]	13.614
Avg syngas volumetric flow [m^3/h]	25.37
Syngas volume [m^3]	81.184
Pellets used [kg]	45
Average electric load [kW]	10.5
Electrical energy produced [kWh]	34
Gasifier efficiency [%]	70.14
Electrical efficiency [%]	15.4
Specific consumption (dry basis) [kg/kWh]	1.192

Table 6
Syngas composition, as is and recalculated without oxygen (mean value of 8 samples).

H_2 [% vol.]	O_2 [% vol.]	N_2 [% vol.]	CH_4 [% vol.]	CO [% vol.]
13.275	4.526	48.215	2.194	21.567
H_2 Norm.[% vol.]	O_2 Norm.[% vol.]	N_2 Norm.[% vol.]	CH_4 Norm.[% vol.]	CO Norm.[% vol.]
17.823	0	41.638	2.928	28.495

LED lights (18.72 kW) and HVAC system (5 kW on average). The PP30 gasifier has a nominal electrical production of 22 kW, slightly lower than the greenhouse maximum electrical load (23.82 kW). In the scenario where the electrical grid is the energy provider (Scenario A), the owner of the greenhouse pays for all the electrical energy consumed. Instead, in the scenario where the PP30 is the main energy provider (Scenario B depicted in the Sankey diagram in Fig. 5), the owner of the greenhouse needs to sustain the cost of biomass, the cost of the gasifier maintenance and a small cost for the electricity that it is required to correctly supply the electrical loads equal to 7224 kWh during the whole year (Fig. 5).

Pellet cost is set at 0.2 €/kg [42] and maintenance costs are estimated to be about 0.05 €/kWh of electrical energy produced (All Power Labs [21]). The greater O&M effort is related to the gas filtering. The gas filtering is made through a felt bags system that is automatically cleaned with a mechanical shaking. According to the manufacturer, the filter lifespan is higher than the growing period of 75 days, so the O&M operations can be done during the harvesting period at the end of the growing period where there isn't any electrical load in the greenhouse. Once the felt bags are incapable of holding the desired gas flow rate, the filter is simply replaced. The operation takes around 40 min for an expert operator. In case it is necessary to have continuous operation, two filters can be implemented. One is used while the second is maintained.

Biochar can be sold to the market as soil improver at the cost of about 0.5 €/kg [43]. Also, the thermal energy produced can be used for district energy distribution for the standard selling price of about 0.045 €/kWh [44]. Several applications where biomass residues are used to provide thermal power are diffused in literature [45,46], however it is difficult to sell all the thermal energy generated during the year, especially during the hot season. For this reason, in the economical analysis only 30% of the thermal energy is sold to the market assuming that the thermal energy is selled only during the cold season. For example, 30% of the heat should be used in a district heating line for closest buildings in order to substitute natural gas heating. This limit is given by the heating period duration in Northern Italy which is about $^{1}/_{3}$ of the year.

The economical analysis takes into account the increasing of the dry biomass flowers obtained by the use of the biochar in the growth. In fact, an increase of 7.7% was achieved with the 5% biochar amendment treatment as discussed in the next paragraph. This application will increase the productivity of biomass flowers by about 11.356 kg per year, equal to an income for the company of 11,365 € considering an average selling price of 2 €/g.

Considering these assumptions, a Net-Present-Value analysis [47] was performed considering costs, savings and earnings using the gasifier as an energy provider (Scenario B) instead of the electrical grid (Scenario A). Table 7 contains the most valuable results of the analysis. Two cases were taken into consideration: Worst Case Scenario where no biochar is sold on the market; Best Case Scenario where biochar is sold on the market (except the 50 kg/year required in the greenhouse as soil improver). Fig. 6 reports the NPV trends in the two scenarios considering two discount rates (6% and 11%). The choice of these values derives

Table 7
NPV cost-benefit analysis.

INITIAL INVESTMENT		
All Power Labs PP30 gasifier cost	55'000.00 €	
Shipping and installation cost	10'000.00 €	
CAPEX	65'000.00 €	
ANNUAL RUNNING DATA AND EXPENDITURES		
Working hours	7200 h	
Gasifier electrical energy	107,400 kWh	
Gasifier thermal energy	214,800 kWh	
OPEX (O&M cost)	5'370.00 €	
Pellets consumption	107400 kg	
Biochar production	10740 kg	
Pellets cost	21'480.00 €	
Electricity cost	1'444.80 €	
PROFITS	Worst Case	Best Case
Energy saving income	21'480.00 €	21'480.00 €
Thermal energy income	2'899,80 €	2'899,80 €
Flower surplus selling income	22'730.00 €	22'730.00 €
Biochar sell income	0 €	5'370.00 €
Annual net profit	18'815.00 €	24'185.00 €
Gasifier pay-back time (discount rate 6%)	4.5 years	3.5 years
Gasifier pay-back time (discount rate 11%)	5.5 years	4 years
NPV value (30 years, discount rate 6%)	179'049.47 €	248'703.77 €
Internal rate of return IRR [%]	23.13	28.37

from the report "Renewable energy discount rate survey results – 2018" [48] where the lower unlevered discount rate found is 6% for Germany biomass projects the higher levered discount rate found is 11% for Ireland biomass projects. Literature indicates similar discount rate values for this kind of investment. Safarian et al. [13] suggests a discount rate in the range 8–13% regarding a waste gasification investment in

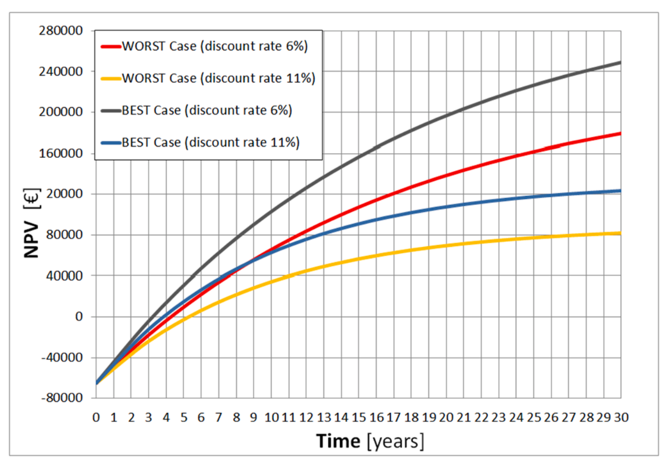

Fig. 6. NPV analysis of the investment.

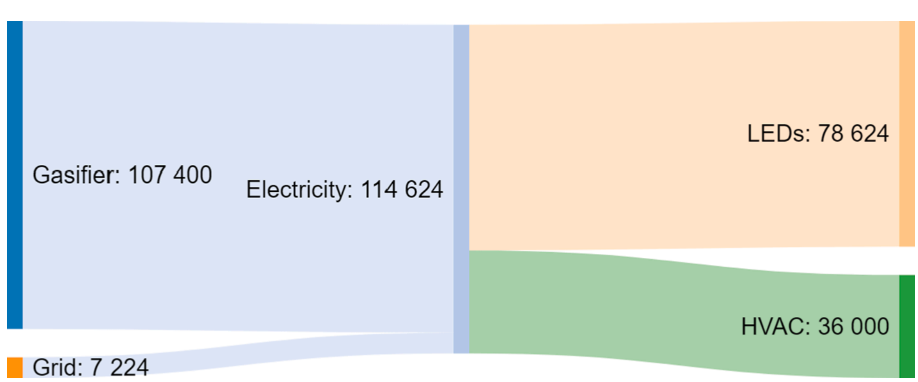

Fig. 5. Sankey diagram of the annual electrical energy consumption of the greenhouse considering the gasifier as the main energy source (Scenario B).

Iceland. Cardoso et al. [49] used a 10% discount rate in the NPV analysis of a small scale gasifier fueled with forest biomass.

The payback time in the Worst Case Scenario with discount rate of 11% is over the lifetime of the gasifier (30 years) while, considering the Best Case Scenario calculation with a discount rate of 6%, the payback time is about 3.5 years and the final NPV value is close to 249 k€.

A further important parameter of the analysis is the electrical energy specific cost per kg of dry flower biomass. Using the results obtained in the growing test (1 plant produces 116.2 g of dry flower biomass) the entire cultivation produces 36.254 kg every cycle using 28,656 kWh of electrical energy equivalent to 5′731.20 €. The specific energy cost is 158.08 €/kg of dry flower biomass (equal to 0.15808 €/g).

3.3. Pot growing test

75 days after plantation, Kompolti plants were harvested and fresh biomass measured. The mean biomass collected from each thesis is the result from 15 plants from the same substrate type. Plants grown in 5% B and 10% B soil produced more biomass than control plants: the mean value for treated plant masses were 1.16 ± 0.16 kg and 1.03 ± 0.12 kg respectively compared with 0.77 ± 0.13 kg of the control. The data reveal an increase in produced biomass of 33.9% for 5%B and of 18.5% for 10%B thesis. T-test performed between the two treated groups (5%B and 10%B) and the control all identify a highly significant difference (p-value < 0.05).

Fig. 7 (a, b) shows the results obtained from harvested flowers from 15 Kompolti plants: both biochar amendment treatments (5%B and 10% B) increase the amount of flower biomass produced compared to the control plants. The mean values obtained from fresh flower biomass of CTRL, 5%B and 10%B groups were 532.4 ± 93.3 g, 634.8 ± 74.0 g, 622.1 ± 80.3 g respectively. The mean increase in terms of fresh flower biomass was 19.2% for 5%B and 16.8% for 10%B compared with the control. One-way ANOVA statistical analysis highlights significant differences (p-value < 0.05) between CNTR and both treatments 5%B and 10%B considering fresh weights. Data obtained from dry flower biomass of the same groups were: 116.2 ± 21.5, 125.3 ± 16.6, 124.3 ± 35.9 respectively: 5%B and 10%B dry flower biomass is respectively 7.7% and 6.9% higher than the control. In this case, one-way ANOVA analysis didn't show statistically significant results. Notably, 5%B obtained the best results in terms of both fresh and dry flower mass.

Several studies have described the influences of biochar on soil both in pot and open field applications [50,51]. Biochar amendment properties have been tested and analyzed on different plant species, most species being of agronomic and economic interests [26,52], but a lack of scientific studies exists regarding the effects of biochar amendment on *Cannabis sativa* plants. Because *C. sativa* is a multi-use, multifunctional crop that provides raw material to a large number of traditional and innovative industrial applications, the interest in this plant is increasing. While fiber, seeds and ultimately also bioenergy productions are the main products, there is a growing interest over the valorization of hemp secondary metabolites both for therapeutic application and essential oils applications [53].

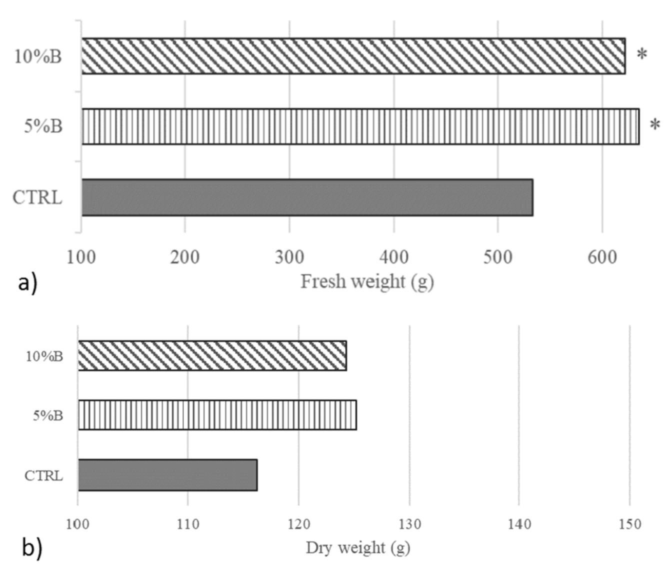

Fig. 7. Flower biomass produced by the Kompolti plant comparison among biochar treatments: all flowers collected from 15 plants have been considered for each treatment; (a) fresh weight mean values; (b) dry weight mean values.

The statistically significant results in terms of the increase in fresh whole biomass and fresh and dry inflorescences (Fig. 7) through biochar application (particularly 5% v/v rate) confirm the positive effects of biochar amendment also on *C. sativa*, a plant specie on which biochar application had not yet been investigated by the scientific community.

The indoor pot-growing farm allowed for the thorough monitorization each physical parameter which characterizes the growth room. However, through this experimental approach it is not possible to achieve any advantages from biochar in terms of climate mitigation potential. Thus, one of the future outlooks for biochar application to hemp crops could be its use on open field cultivation. Beyond the agricultural advantages coming from its chemical and physical properties, which increase biomass yield as shown in several studies [20,27], biochar applied to soil has a valiant carbon storage function. Indeed, due to its recalcitrant nature, biochar used as soil amendment has a climate mitigation potential. Photosynthesis is able to draw 120 Gt of CO2 from the atmosphere every year [54]; when this biomass is converted into biochar for open field plant growth, the carbon cycle becomes incredibly slow: the rapid release of carbon dioxide coming from organic matter decomposition process is avoided. Particularly, some model analysis [55] shows how sustainable biochar production and soil application can potentially offset a maximum of 12% of current anthropogenic CO2 equivalent. The effects of increased biomass production on the economy of the company depends mostly on the reselling price of the flower buds. The Italian market for this product has existed since late 2016 and has not reached steady state conditions. Despite the variability described, it is possible to assess that the increased flower production, for the chosen case study, is 11.356 kg, considering a selling price of 2 €/g for the Kompolti cultivar.

3.4. Cannabinoids analysis

The importance of monitoring the concentration of cannabinoids is related to the great variability of the hemp plant, which is highly susceptible to the external environment [33]. For this reason, the concentrations of the main cannabinoids CBDA, CBD, CBN, Δ^9-THC and THCA were calculated in the control samples (CTRL) and after each treatment (5%B and 10%B). The results are reported in Table 8. As evidenced by the data, no significant change can be observed after the treatments compared to the controls in terms of cannabinoids concentrations ($p > 0.99$ with One-way-Anova statistical analysis). This means that the treatments do not affect cannabinoids biosynthesis inside the trichomes of the plant.

These results in this study describe how biochar application on hemp crops can increase plant biomass and inflorescence fresh and dry weights without simultaneously involving the concentration of cannabinoids, which does not show significant variation. The missing changes in secondary metabolites production is fundamental in order to maintain the compliance on thresholds set by European legislation N° 2860/2000.

4. Conclusions

The use of gasification as partner technology in C. sativa growing facilities resulted in a favorable choice. A gasifier generator, with nominal power of 22 kW is capable of providing almost complete

Table 8
Results of the cannabinoids analysis.

Cannabinoid	CTRL			5%B			10%B		
	A	B	C	A	B	C	A	B	C
CBDA	9.01 ± 0.21	9.20 ± 0.19	10.08 ± 0.02	10.28 ± 0.04	10.64 ± 0.20	10.11 ± 0.01	9.38 ± 0.03	10.21 ± 0.22	9.19 ± 0.10
CBD	0.13 ± 0.01	0.13 ± 0.01	0.13 ± 0.01	0.11 ± 0.00	0.11 ± 0.00	0.12 ± 0.01	0.12 ± 0.01	0.13 ± 0.01	0.12 ± 0.00
CBN	<LOQ[a]	<LOD[b]	<LOD	<LOD	<LOD	<LOD	<LOD	<LOD	<LOD
Δ^9-THC	0.04 ± 0.00	0.03 ± 0.00	0.03 ± 0.00	<LOQ	0.03 ± 0.00	0.03 ± 0.00	0.03 ± 0.00	0.03 ± 0.00	0.03 ± 0.00
THCA	0.47 ± 0.01	0.47 ± 0.01	0.50 ± 0.01	0.49 ± 0.01	0.50 ± 0.01	0.49 ± 0.03	0.47 ± 0.03	0.54 ± 0.06	0.49 ± 0.07

[a]LOQ: limit of quantification (0.03% w/w); [b] LOD: limit of detection (0.01% w/w).

sustainability to a 80 m^2 indoor facility. All the major gasifier outputs resulted valuable in growing farms: the electricity produced is used to operate the lights and the HVAC system, heat will be useful during the winter season or to dry the waste streams while biochar as an amendment on growth increased biomass and flowers production. The machine chosen for this work was operated it with A1 plus pellets, it performed well even if a drop in the gasification efficiency was recorded. The economical sustainability of the proposed solution was evaluated and resulted in a payback time of 3.5 years. Notably, 5% biochar amended substrate enabled a growth with 7.7% more flower production. The carbon content measured in three soils (control, 5%B, 10%B) increased according to biochar application. These findings open the way to more sustainable methods for CBD plant cultivation involving a byproduct which represents a chemical-free and carbon storage amendment without affecting CBD and THC eligible contents.

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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.

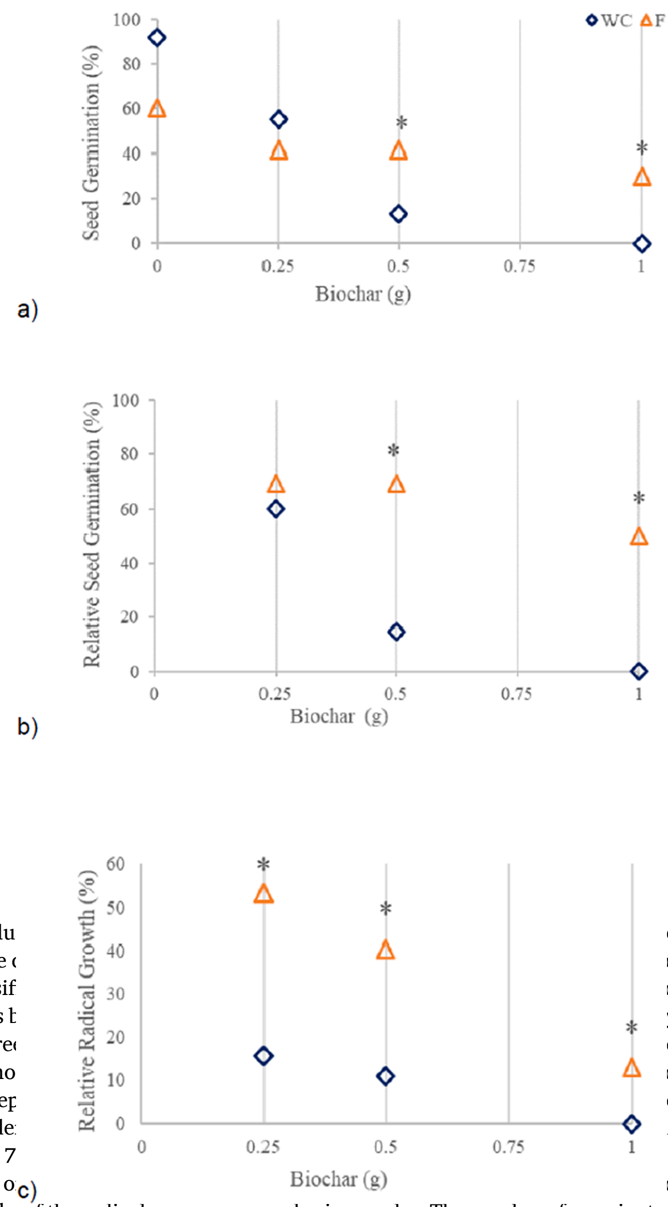

Fig. 8. (a) Seed Germination rate (SG), (b) relative seed germination rate (RGR) and (c) relative radical growth rate (RRG) comparison between watercress (WC) and finola (F).

Appendix A

Seeds germinability evaluation

Seed germination and radicle elongation tests are commonly used to evalu … e soil. Thus, the effects of biochar on the viability of hemp cv. finola seeds were … l plant. Biochar involved to run a germinability test was produced through gasif … d according to its granulometry, and only the finest part (diameter < 1 mm) has b … y were measured with pHmeter and results respectively 10.4 and 190 mV. Thre … e each dish contains wet Whatman filter paper, twenty seeds and a different amo … d with the control where only distilled water was added on filter paper. Three rep … e used and incubated at 25 °C for 36 h in the dark in a heating chamber (Binde … s been carried out with finola seeds, but in this case the incubation time was 7 …

A phytotoxicity test was performed to evaluate the influence of biochar o … d considering two aspects: radicle emergence and radicle elongation. The lengths of the radicals were measured using a ruler. The number of germinated seeds and the average length of roots were derived in order to calculate the following indexes:

$$SG(\%) = \frac{numberofgerminatedseeds}{numberoftotalseeds}x100 \quad (1)$$

$$RSG(\%) = \frac{numberofgerminatedseeds(sample)}{numberofgerminatedseeds(control)}x100 \quad (2)$$

$$RRG(\%) = \frac{totalradicallenghtofgerminatedseeds(sample)}{totalradicallengthofgerminatedseeds(control)}x100 \quad (3)$$

where SG (%) is seed germination rate; RSG (%) is relative seed germination rate, RRG (%) is relative radical growth rate. Then statistical analysis was done using Past3 statistical software. T-tests were performed to estimate the significant differences between the treatments and species seeds means ($p < 0.05$). The results of biochar phytotoxicity on watercress (WC) and finola hemp (F) seeds are shown in Fig. 6. WC seeds highlight high sensitivity to biochar compared with F seeds. The average WC seed germination rate (SG) results 91,7% in control samples, while it sharply decreases with the addition of biochar, in particular SG obtained is 55.0%, 13.3% and 0% respectively for 0.25 g, 0.5 g and 1 g of biochar added. Even if the control SG rate of F seeds (60.0%) is lower than WC seeds, finola seeds showed a significantly higher tolerance to the presence of 0.5 g and 1 g biochar during the germination phase (Fig. 8a). Relative Seed Germination rate (RSG) is shown in Fig. 8b: comparing the number of germinated seeds to each treatment type with the number of germinated seeds to the control in each considered specie, RSG clearly proves the higher tolerance of F seeds compared with WC seeds. Finola RSG is higher than watercress RSG in all germination thesis considered: 0.25, 0.5 and 1 g of biochar added. Specifically, it was 69.4%, 69.4% and 50% respectively, against 60.0%, 14.6% and 0% for WC seeds. While the difference for 0.25 g biochar treatment was not statistically significant, results from 0.5 and 1 g biochar treatments were highly statistically significant ($p < 0.05$). Furthermore, RRG index highlights the previous results: finola seeds better tolerate the presence of biochar. The index is the comparison between mean radicle length on three different biochar treatments and mean radicle length on control samples. RRG difference between WC and F was statistically significant (p-value < 0.05), as shown in Fig. 8c.

The results of this experimental evaluation of biochar on hemp seeds give us important information about its effects on the first stage of a life plant. Indeed seed germination represents the critical initial stage of plant growth, where the high sensitivity to environmental pollution and the short-period course play a crucial role in seedling and then plant growth.

References

[1] Schluttenhofer C, Yuan L. Challenges towards revitalizing hemp: a multifaceted crop. Trends Plant Sci 2017;22(11):917–29.
[2] Das L, Liu E, Saeed A, Williams DW, Hu H, Li C, et al. Industrial hemp as a potential bioenergy crop in comparison with kenaf, switchgrass and biomass sorghum. Bioresour Technol 2017;244:641–9.
[3] Ingrao C, Lo Giudice A, 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.
[4] Gupta A, Abraham RE, Barrow CJ, Puri M. Omega-3 fatty acid production from enzyme saccharified hemp hydrolysate using a novel marine thraustochytrid strain. Bioresour Technol 2015;184:373–8.
[5] Ascrizzi R, Ceccarini L, Tavarini S, Flamini G, Angelini LG. Valorisation of hemp inflorescence after seed harvest: cultivation site and harvest time influence agronomic characteristics and essential oil yield and composition. Ind Crops Prod 2019;139(February).
[6] Bonaccorso S, Ricciardi A, Zangani C, Chiappini S, Schifano F. Cannabidiol (CBD) use in psychiatric disorders: a systematic review. NeuroToxicology 2019;74 (August):282–98.
[7] Der Werf, W., Brouwer, K., Wijlhuizen, M., Withagen, J.C.M. 1995. "The Effect of Temperature on Leaf Appearance and Canopy Establishment in Fibre Hemp (Cannabis Sativa L.)." Annals of Applied Biology 126 (1995) 551-561. 126.
[8] Mills E. The Carbon Footprint of Indoor Cannabis Production. Energy Policy 2012; 46:58–67.
[9] Anthony, S., 2018. "United States Patent : 5861366 United States Patent : 5861366." New York 1:1–29.
[10] Basu P. Biomass Gasification, Pyrolysis and Torrefaction. Third Edition. Elsevier: Academic Press; 2018.
[11] Kirch T, Medwell PR, Birzer CH, van Eyk PJ. Small-scale autothermal thermochemical conversion of multiple solid biomass feedstock. Renewable Energy 2020;149:1261–70.
[12] Knoef, H., 2012. Handbook of Biomass Gasification, second ed. BTG.
[13] Safarian S, Unnthorsson R, Richter C. Techno-economic and environmental assessment of power supply chain by using waste biomass gasification in Iceland. Biophys Econ Sust 2020;5:7. https://doi.org/10.1007/s41247-020-00073-4.
[14] Pedrazzi S, Allesina G, Tartarini P. Effects of upgrading systems on energy conversion efficiency of a gasifier - fuel cell - gas turbine power plant. Energy Convers Manage 2016;126:686–96. https://doi.org/10.1016/j.enconman.2016.08.048.
[15] Cerone N, Zimbardi F, Contuzzi L, Baleta J, Cerinski D, Skvorčinskienė R. Experimental investigation of syngas composition variation along updraft fixed bed gasifier. Energy Convers Manage 2020;221:113116. https://doi.org/10.1016/j.enconman.2020.113116.
[16] Chang, S., Zhang, Z., Cao, L., Ma, L., You, S., Li, W., Co-gasification of digestate and lignite in a downdraft fixed bed gasifier: Effect of temperature, Energy Conversion and Management, Volume 213, 2020, 112798, ISSN 0196-8904, https://doi.org/10.1016/j.enconman.2020.112798.
[17] Pedrazzi S, Santunione G, Minarelli A, Allesina G. Energy and biochar co-production from municipal green waste gasification: a model applied to a landfill in the north of Italy. Energy Convers Manage 2019;187:274–82. https://doi.org/10.1016/j.enconman.2019.03.049.
[18] Tian H, Hu Q, Wang J, Liu L, Yang Y, Bridgwater AV. Steam gasification of Miscanthus derived char: the reaction kinetics and reactivity with correlation to the material composition and microstructure. Energy Convers Manage 2020;219:113026. https://doi.org/10.1016/j.enconman.2020.113026.
[19] Majumder S, Neogi S, Dutta T, Powel MA, Banik P. The impact of biochar on soil carbon sequestration: meta-analytical approach to evaluating environmental and economic advantages. J Environ Manage 2019;250(September):109466.
[20] You S, Ok Y, Chen SS, Tsang DCW, Kwon EE, Lee J, et al. A critical review on sustainable biochar system through gasification: energy and environmental applications. Bioresour Technol 2017;244:242–53.
[21] All Power Labs. 2020. "PP30 Data Sheet." Retrieved August 24, 2020 (http://www.allpowerlabs.com/pp30-power-pallet).
[22] Allesina G, Pedrazzi S, Allegretti F, Morselli N, Puglia M, Santunione G, et al. Gasification of cotton crop residues for combined power and biochar production in Mozambique. Appl Therm Eng 2018;139.
[23] FOREST European project. A guide to specifying biomass heating systems. Retrieved October 7, 2020 (https://ec.europa.eu/energy/intelligent/projects/sites/iee-projects/files/projects/documents/forest_guide_for_designers_and_architects_en.pdf).
[24] Pedrazzi, S., Allesina, G., Sebastianelli, L., Puglia, M., Morselli, N., Tartarini, P. Chemically enhanced char for syngas filtering purposes (2018) European Biomass Conference and Exhibition Proceedings, 2018 (26thEUBCE), pp. 694-698.
[25] Valderrama Rois, M.L., González, A.M., Silva Lora, E.E., Almazán del Olmo. O.A. 2018. "Reduction of Tar Generated during Biomass Gasification: A Review." Biomass and Bioenergy 108(December 2017):345–70.
[26] Lehmann J, Rillig MC, Thies J, Masiello CA, Hockaday WC, Crowley D. Biochar effects on soil biota—a review. Soil Biol Biochem 2011;43(9):1812–36.
[27] Vaccari FP, Baronti S, Lugato E, Genesio L, Castaldi S, Fornasier F, et al. Biochar as a strategy to sequester carbon and increase yield in durum wheat. Eur J Agron 2011;34:231–8.
[28] Chi T, Zuo J, Liu F. Performance and mechanism for cadmium and lead adsorption from water and soil by corn straw biochar. Front Environ Sci Eng 2017:11–5.
[29] Chen Y, Zhang X, Chen W, Yang H, Chen H. The structure evolution of biochar from biomass pyrolysis and its correlation with gas pollutant adsorption performance. Bioresour Technol 2017;246:101–9.
[30] Santunione, G., Bigi, A., Puglia, M., Morselli, N., Sebastianelli, L., Tartarini, P. 2019. "Study of copper content distribution through the thermochemical conversion chain of vine pruning biomass", 27th European Biomass Conference and Exhibition, 1952-1956.
[31] Citti C, Linciano P, Russo F, Luongo L, Iannotta M, Maione S, et al. A novel phytocannabinoid isolated from Cannabis Sativa L. with an in vivo cannabimimetic activity higher than δ9-tetrahydrocannabinol: Δ9-tetrahydrocannabiphorol. Sci Rep 2019;9(1):1–13.
[32] Novack GD. Cannabinoids for treatment of glaucoma. Curr Opin Ophthalmol 2016; 27(2):146–50.
[33] Russo EB. Cannabis and epilepsy: an ancient treatment returns to the fore. Epilepsy Behav 2017;70:292–7.
[34] Citti C, Braghiroli D, Vandelli MA, Cannazza G. Pharmaceutical and biomedical analysis of cannabinoids: a critical review. J Pharm Biomed Anal 2018;147:565–79.
[35] Pavlovic R, Panseri S, Giupponi L, Leoni V, Citti C, Cattaneo C, et al. Phytochemical and ecological analysis of two varieties of hemp (Cannabis Sativa L.) grown in a mountain environment of Italian Alps. Front Plant Sci 2019;10(October):1–20.
[36] Citti C, Ciccarella G, Braghiroli D, Parenti C, Vandelli MA, Cannazza G. Medicinal Cannabis: principal cannabinoids concentration and their stability evaluated by a high performance liquid chromatography coupled to diode array and quadrupole time of flight mass spectrometry method. J Pharm Biomed Anal 2016;128:201–9.
[37] Linciano P, Citti C, Luongo L, Belardo C, Maione S, Vandelli MA, et al. Isolation of a High-Affinity Cannabinoid for the Human CB1 Receptor from a Medicinal Cannabis Sativa Variety: Δ 9 -Tetrahydrocannabutol, the Butyl Homologue of Δ 9 -Tetrahydrocannabinol. J Nat Prod (Cd):1–19. 2019.
[38] Göransson, K., Söderlind, U., Zhang, W. Catalytic Reduction of Tar/CH4 by an Internal Reformer in a DFB Gasifier. 22nd European Biomass Conference and Exhibition (2014). DOI: 10.5071/22ndEUBCE2014-2AV.2.13.
[39] Safarian S, Richter C, Unnthorsson R. Waste biomass gasification simulation using aspen plus: performance evaluation of wood chips, sawdust and mixed paper wastes. J Power Energy Eng 2019;7:12–30. https://doi.org/10.4236/jpee.2019.76002.

[40] Sahar Safarianbana, Runar Unnthorsson, Christiaan Richter "Development of a New Stoichiometric Equilibrium-Based Model for Wood Chips and Mixed Paper Wastes Gasification by ASPEN Plus. ASME 2019 International Mechanical Engineering Congress and Exposition"November 11–14, 2019 Salt Lake City, Utah, USA.

[41] ARERA Prezzi e Tariffe Energia Elettrica Primo Quadrimestre 2020 Retrieved August 24, 2020 (https://www.arera.it/it/prezzi.htm) 2020.

[42] AIEL Mercato e Prezzi Biomasse 2019 Retrieved August 11, 2020 (https://www.aielenergia.it/public/pubblicazioni/Mercati-Prezzi1-2019.pdf) 2020.

[43] Campbell RM, Anderson NM, Daugaard DE, Naughton HT. Financial viability of biofuel and biochar production from forest biomass in the face of market price volatility and uncertainty. Appl Energy 2018;230(June):330–43.

[44] IREN. 2018. "Tariffe TRL Torino 2018." Retrieved August 24, 2020 (https://www.irenlucegas.it/documents/66424/283741/TORINO+tariffe+tele+I°+trim+2018.pdf/6b9a4feb-29f1-44cf-a7ba-5c9505b54a22).

[45] Allesina G, Pedrazzi S, Allegretti F, Tartarini P. Spent coffee grounds as heat source for coffee roasting plants: experimental validation and case study. Appl Therm Eng 2017;126.

[46] Puglia M, Pedrazzi S, Allesina G, Morselli N, Tartarini P. Vine prunings biomass as fuel in wood stoves for thermal power production. Int J Heat Technol 2017;35 (Special Issue 1).

[47] Hopkinson M. Net present value and risk modelling for projects. Taylor & Francis Ltd.; 2016.

[48] Renewable energy discount rate survey results –, A Grant Thornton and Clean Energy Pipeline initiative Retrieved October 07, 2020(https://www.grantthornton.co.uk/globalassets/1.-member-firms/united-kingdom/pdf/documents/renewable-energy-discount-rate-survey-results-2018.pdf) 2018.

[49] João Sousa Cardoso, Valter Silva, Daniela Eusébio, Inês Lima Azevedo, Luís A.C. Tarelho, Techno-economic analysis of forest biomass blends gasification for small-scale power production facilities in the Azores, Fuel, Volume 279, 2020, 118552.

[50] Mukherjee A, Lal R. Biochar impacts on soil physical properties and greenhouse gas emissions. Agronomy 2013;3:313–39.

[51] Sohi, S.P., Krull, E., Lopez-Capel, E., Bol, R. 2010. "A review of biochar and its use and function in soil, "Advances in Agronomy"105(1):47–82.

[52] Pandey V, Patel A, Patra DD. Biochar ameliorates crop productivity, soil fertility, essential oil yield and aroma profiling in basil (Ocimum basilicum L.). Ecol Eng 2016;90:361–6.

[53] Amaducci S, Scordia D, Liuc FH, Zhang Q, Guo H, Testa G, et al. Key cultivation techniques for hemp in Europe and China. Ind Crops Prod 2015;68:2–16.

[54] Sohi SP, Krull E, Lopez-Capel E, Bol R. A review of biochar and its use and function in soil. Adv Agron 2010;105:47–82.

[55] Woolf D, Amonette JE, Alayne Street-Perrott F, Lehmann J, Joseph S. Sustainable biochar to mitigate global climate change. Nature Commun. 2010;1(56).