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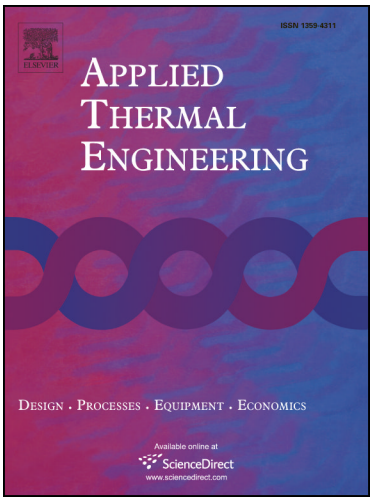

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Gasification of cotton crop residues for combined power and biochar production in Mozambique

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Abstract

Cotton agricultural industry is an important sector for some developing countries, whose energy consumption is dramatically rising. Here, biomass is the most important source of energy, but they are used in an inefficient way, causing atmospheric pollution and wasting resources. Combined energy generation and biochar production using cotton residues briquettes as fuel in a PP20 gasifier plant is investigated. The machine has demonstrated similar performances to its "conventional" use: 14% global efficiency and 1.16 kg/kWh$_{el}$ specific consumption of cotton briquettes are observed. It is calculated that one-hectare field can generate more than 4 MWh and about 130 kg of biochar per year. Biochar represents a valuable by-product; if used as amendment for cotton growth it can improve the soil conditions, both decreasing the need of fertilizers up to 50%. A circular economic model based on cotton waste gasification is proposed. Clean and affordable energy can be produced, in order to promote a sustainable development of rural areas.

Keywords: gasification, cotton waste, biochar, circular economy.

1. Introduction

The world energy consumption reached more than 13'000 million tonnes in oil equivalent [1] in 2015. Within this scenario, the role of developing countries is becoming increasingly important because of their rapid growth rate that will soon make them protagonists of intense changes in the electrical energy generation technology mix [2, 3]. As a consequence of the limited availability of energy resources and their unstable prices, supranational, national and local governments are trying to find new advantageous and creative solutions for a safe energy supply for citizens. As reported by the United Nations, the access to affordable and reliable energy is crucial to guarantee good living conditions, to promote job creation and to eradicate poverty through development in health, education, water supply and industrialization [4]. Sustainable development strategies are therefore necessary to strengthen the progress of our societies, to improve the economic growth and to fight global climate change [5].

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In particular, renewable energy plays a key-role in the energy panorama and, among them, biomass represent one of the resources that is arousing the most interest in the scientific community [6]. Besides from energy crops, enormous quantities of bio-waste are produced every year in different sectors, from agriculture, to intensive farming, to food industry and finally forest maintaining. This production is massive: more than 990 million tons of agricultural waste is produced every year. This datum derives from demanding-energy human activities, thus creating an ideal match between demand and resource [7, 8].

In the last few years, research has proposed various technologies for a more efficient energy production using biomass as fuel and, between these, gasification is one of the most promising [9]. Through a thermochemical process, a solid carbonaceous material is converted into a gaseous flammable fuel called syngas. Using it as fuel in an internal combustion engine, both thermal and electrical energy are generated. Energy production in large-scale gasification power plants (more than 100 kW_{el}) is well established and diffused technology within Northern European countries, North America and Asia [10]. On the other hand, research and application about micro-scale plants (below 100 kW_{el}) just started to hit the market. These power plants are becoming more and more interesting and efficient, and they can revolutionize the energy market due to the capability to provide amounts of distributed energy that match with the local energy demand and feedstock production [11].

Due to the discussed characteristics, micro scale gasifiers may offer a huge contribution even in developing countries [12]. The wide availability of biomass can meet the growing energy demand: micro-scale gasifiers can be located everywhere, because they do not need an advanced system of infrastructure. Micro-scale gasifiers represent an opportunity for those communities, like small isolated villages, rich in biomass resources that are often used in a hazardous and inefficient way.

The whole African continent is characterized by a rapid and impressive growth. Here the energy consumption has risen by 45% since 2000 [12]. Over 600 million Africans do not have safe and continuous access to electricity and almost 730 million depend on solid biomass for cooking. This process by itself generates enormous quantities of air pollutants and greenhouse gases [13]. Every year, more than 1.5 million people die prematurely, because of the prolonged exposure to indoor air pollution generated from wood combustion; it is even expected to increase to almost 9.8 million deaths by 2030 [14, 15].

Mozambique has for decades been among the world's least-developed countries [16], and the IEA (International Energy Agency) Africa Energy Outlook identifies this country as a large emerging energy producer, where solid biomasses, wood above all, are the primary energy sources [13]. About 78% of the territory is covered by forests or other wood type vegetation. Here wood is used in an

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inefficient way as fuel, thus wasting much of the energy available and contributing to environment depletion [16].

Similarly to other Sub-Saharan countries, Mozambique's economy is largely characterized by cotton cultivation [17]. This biomass constitutes the only sustenance source for several small villages [15]. Cotton industry generates thousands of tons of biomass residues: in 2006, about 241'000 tons of cotton plant residues were generated. The annual thermal energy potential through combustion is estimated to be around 4'000 TJ considering a biomass lower heating value of 16 MJ/kg [15]. Through the gasification process characterized by an average electrical efficiency of 25%, it is possible to obtain 277 GWh of electrical energy [18, 19]. As described in this work, an integration of the cotton industry with biomass gasification processes may be fruitful in terms of: energy recovery, waste management, water usage and crop productivity.

This paper focuses on the production site located in the Titimane village, in Niassa Province. Here the population counts 600 cotton farmers among 4000 inhabitants [20]. Local farmers cultivate cotton and after the harvest, they sell it to a local company. The wood waste from the cotton harvesting is burnt in field or re-used as fuel for domestic cooking. Titimane represents an interesting case for a sustainable development, based on energy production from crop residues. The investigated site is characterized by the consumption of energy for cotton production, while the site lacks in infrastructures.

In this work, the residues from cotton production are processed and converted into briquettes, then used as fuel in a micro scale gasifier. The final goal is to provide energy to the cotton processing company and for the village for new economic growth. The larger project, where gasification plays a key role, considers the generation of 232 MWh per year, by installing 100 kW solar PV panels and 4 biomass gasifiers generators with a nominal electrical power of 15 kW. The cotton processing plant consumes the needed energy while the remaining part is available for the village [20]. The selected biomass gasifier is an All Power Labs PP20 [21] gasifier that transforms solid wood biomass waste into electrical and thermal power.

For every kg of dry wood biomass, the All Power Labs gasifier is designed to generate 0.8-0.9 kWh of electrical energy, along with 50 g of biochar [21]. Biochar is the carbonaceous residue of the gasification process. It is demonstrated to be a fundamental resource for carbon sequestration and increased crop productivity when used as soil amendment [22]. This byproduct represents an additional opportunity for the overall cotton production chain in terms of economic and energy sustainability.

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The positive effects of biochar use derive from its physical properties (high porosity) along with unique chemical properties (high pH, high inorganic content). Its use affects the soil density, microbial characteristics and PAW (plant available water) due to water retention [23]. Biomass-based energy conversion processes (i.e. gasification or combustion) are generally considered carbon neutral [24], however biochar is a highly recalcitrant material that remains in a stable form in soils for decades. For this reason, its co-production during the gasification processes allows a shift from carbon-neutrality towards carbon negativity [25]. While this work focuses on the energy production from cotton residues, a further cotton growth test in biochar-enriched soil is performed to demonstrate the benefits of its application.

In the following paragraphs, a circular economy model for the cotton production chain is proposed and validated. Two areas are investigated experimentally: production of electrical energy from cotton waste briquettes via gasification and biochar amendment effects on cotton plant growth.

2. Materials and methods

2.1 Gasification and power production

A densification of the cotton residues is necessary to guarantee more transportable and easily-to-stock fuel. Therefore, the cotton waste was milled in Germany at Hushmann, a manufacturing company and the briquetting process took place in Italy (Figure 1). The briquettes diameter is 20 mm while the length varies between 40-70 mm. Moisture content was evaluated by weighing a sample of briquettes before and after the drying process in a Memmert Universal Oven UF30 for 24 h at 103 °C [26, 27]. The briquettes were sprinkled with cotton oil in order to reduce the chance of fuel degradation due to the steam released in the power pallet hopper during standard operation. Oil-biomass ratio is (36.5±0.4) $g_{oil}/kg_{biomass}$.

Figure 1. Cotton waste briquettes making process.

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2.1.1 The gasification system

The biomass gasifier power plant used in this research is a PP20 designed and manufactured in California by All Power Labs Inc [21]. The most relevant technical data along with the gasifier characteristics are illustrated in Table 1 and Figure 2. The Power Pallet is designed to use agricultural and forestry waste materials as fuel. The small scale allows sourcing feedstock near the power production site due to small biomass consumption, proven to be below 22 kg/h. Four main parts compose the machine: a 0.3 m^3 hopper, where the biomass is loaded, a gasifier reactor, where the thermochemical conversion of solid bio-waste takes place, a drum filter, where syngas is cleaned from particulate and tars, and a 3.0 liters *GM Vortec* IC engine connected with a *Meccalte* brushless generator in order to produce electrical energy.

Table 1. Power Pallet PP20 technical data [21]

Power pallet specifications	PP20
Max continuous power output	18 kW@60 Hz
Biomass consumption	22 kg per hour at 18 kW
Fuel moisture tolerance	Up to 30%
Dimensions	1.4 x 1.4 x 2.2 m
Weight	1065 kg
Feedstock hopper capacity	330 l

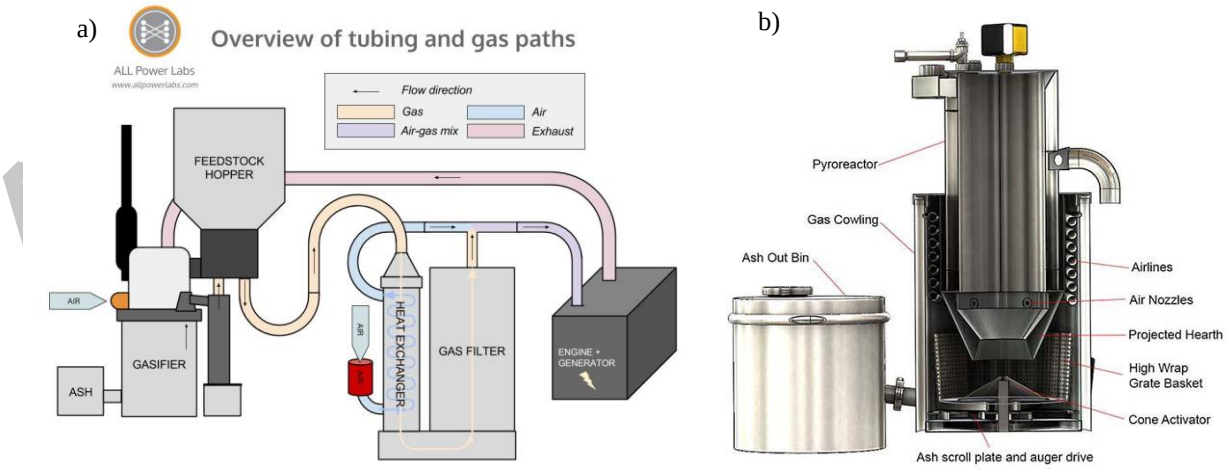

Figure 2. PP20 by APL. Scheme of the PP20 (a) and its reactor (b) [21].

Figure 2 (a) shows the gasifier scheme with the gas fluxes. The downdraft reactor architecture is depicted in Figure 2 (b). The first passage of the biomass in the reactor is the pyrolysis stage. A heat

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exchanger heated with the exhaust gases allows a pyrolysis reaction. Once pyrolyzed, the biomass reacts with hot air entering through air nozzles and generates a combustion zone where the pyrolysis tars are cracked producing hot gases. In the reduction zone, the gases react with the carbon to create CO, H_2 and CH_4 and other gases, whose composition will be discussed later. The part of the char that does not react with combustion gases is disposed of through an ash auger. In this part the generated gas is called syngas. The syngas passes through a passage between the outside wall of the reactor and the combustion zones, causing a heat exchange between the intake air and the outgoing syngas. Through a port at the top of the reactor, the pressure is checked. The port at the top of the reactor extends from the pyrolysis zone to just above the air nozzles.

2.1.2 Briquettes chemical properties and elemental analysis

Table 2 summarizes the results of the ultimate biomass analysis, the briquettes HHV (higher heating value) and LHV (lower heating value) are determined with the equations suggested respectively by Channiwala and Parikh [28] and Basu et al. [24]:

$$HHV = 349.1C + 1178.3H + 100.5S - 103.4O - 15.1N - 21.1Ash \ \left[\frac{kJ}{kg}\right] \ (1)$$

$$LHV = HHV - hg\left[\left(\frac{9H}{100}\right) + \left(\frac{M}{100}\right)\right]\left[\frac{kJ}{kg}\right] \ (2)$$

where:

hg is the latent heat of vaporization of water;

H is the hydrogen content in the dry biomass;

M is the moisture content in the dry biomass.

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Table 2. Cotton briquettes and biochar properties.

Element [%]	Cotton briquette fuel	Biochar
C	51.61	89.13
H	6.99	0.34
S	0	0
O	39.91	10.43
N	1.49	0.10
ASH	9.03	6.27
Moisture [%]	10.85	1
HHV [kJ/kg]	21914	-
LHV [kJ/kg]	20247	-
Stoichiometric ratio [kg_{air}/kg_{wood}]	6.18	-

2.1.3 Tar and particulate sampling

During the gasification process, tar (polycyclic aromatic compounds with molecular weight higher than that of benzene) and particulate matter are generated. These substances are dangerous both for the engine and for human health and it is therefore necessary to reduce their formation [29]. In order to estimate the particulate and tar content in the syngas, a modified version of the "Tar sampling protocol" [30] was implemented and shown in Figure 3. A certain syngas flow passes through 6 drechsel flasks: 5 containing 150 ml of isopropyl alcohol each, while the sixth is kept empty to allow the final condensate collection, avoiding solvent losses. The flasks are placed in a glycol and water bath at a constant temperature of - 18°C. A gas meter is used to measure the flow of syngas processed through the flasks. At the end of the sampling procedure, the isopropyl is filtrated with Whatman filter papers 1452-150 to separate the particulate (with dimension greater than 7µm) from the isopropyl-tar solution. Weighing the filter paper before and after the filtration shows the amount of particulate content in the syngas. Finally, considering the different boiling points of isopropyl and tar, respectively 82.6°C and more than 150°C, with a distillation process, it is possible to separate the tar from the solvent and calculate the amount by weighing them. In the original method [30], the particulate is filtered through a hot ceramic filter heated at about 300 °C, but this procedure it is not suitable in our case because the particulate content it is so high and can stuck in few minutes the filter as results of the not conventional biomass. For this reason, we decide to apply the post filtering procedure that it is not sensible to the high particulate number.

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Figure 3. Tar and particulate sampling apparatus before (left) and after (right) the test.

2.1.4 Fuel quality and system efficiency

Before starting the efficiency test, the gasifier ran for 40 minutes on the flare and then another 40 minutes on the engine at 10.3 kWel. The efficiency test was carried out at the load of 10.3 kW for a period of 3 hours and 17 minutes. The level of biomass in the hopper was measured at the start of the test, then, the remaining part of the biomass was weighed and used to refill the hopper. 14 hours after the test the level of the biomass was measured again and the quantity of biomass previously used was back calculated. The second day, a run of the gasifier was performed, in order to verify that briquette disintegration did not occur in the hopper. Knowing the electrical energy produced, an estimated value of kg/kWh could be determined.

The volume of syngas, necessary to calculate the gasifier efficiency, is calculated by combining the average air volumetric flow, determined through an anemometer, with the N_2 percentage in the syngas as follow:

$$V_{\text{syngas}} = V_{\text{air}} * \frac{0.781}{N_2} \quad (3)$$

where:

V_{syngas} is the volumetric flow of syngas in Nm^3/h;

V_{air} is the volumetric flow of air in Nm^3/h;

0.781 is the nitrogen percentage in the air;

N_2 is the nitrogen percentage in the syngas.

Gasifier efficiency, total efficiency and engine efficiency are calculated as follow:

$$\eta_{\text{gas}} = \frac{V_{\text{syngas}} * HHV_{\text{syngas}}}{m_{\text{bio,dry}} * HHV_{\text{bio,dry}}} \quad (4)$$

$$\eta_{\text{tot}} = E_{\text{el}} * 3.6 * \frac{HHV_{\text{bio,dry}}}{m_{\text{bio,dry}}} \quad (5)$$

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$$\eta_{eng} = \frac{\eta_{tot} * \eta_{gen}}{\eta_{gas}} \quad (6)$$

where:

η_{gas} is the gasifier efficiency;

HHV_{syngas} is the syngas higher heating value;

$m_{bio,dry}$ is the cotton briquettes mass used during the test;

η_{tot} is the total efficiency dry based;

$HHV_{bio,dry}$ is the cotton briquette higher heating value with oil, dry based.

E_{el} [kWh] is the electrical energy generated during the test;

η_{eng} is the engine efficiency;

η_{gen} is the generator efficiency.

To estimate the syngas composition, two different samples were collected. The syngas was analyzed in a Pollution Micro gas chromatographer GCX with the following characteristics: two analytic modules, one Carrier gas inlet and one sample line inlet [31].

2.2 Biochar production and use as soil amendment

The last part of this work focuses on the effects of gasification-derived biochar (Figure 4) on cotton crops. The major advantage of using the gasification process instead of carbonization or pyrolysis is the co-production of biochar and electrical power. The biochar was produced through a series of tests on the machine used in this work, operated with woodchips. The average temperatures recorded during the runs were: 834 °C for char reduction starting point and 695 °C for reduction ending point. The overall average temperature was 764 °C . The temperature determines the end of the reduction process.

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Figure 4. Biochar used as amendment: as received.

2.2.1 Evaluation of biochar as soil amendment

Five different substrates were been considered:

- standard soil, as the control sample

- soil enriched with 30% weight of biochar (B)

- soil enriched with 30% weight of compost (C)

- soil enriched with 30% weight of NPK (NPK) (nitrogen, phosphorus, and potassium amendment)

- soil enriched with NPK mixed with biochar (NPK+B).

In NPK+B the quantity of NPK is 50% less than the NPK pot. Seeds were planted into seven terracotta pots (9 x 8.5 cm) for each substrate type and placed into a greenhouse; in each pot 4 seeds of *Gossypium Herbaceum* were initially planted. Terracotta pots allow good vapor and gas exchange between roots and external air due to the porosity of the material of the pot. Each pot was filled up with 50 g of mixed substrate. The study was carried out indoors for 26 days in June, at the Department of Engineering "Enzo Ferrari" in Modena, Italy. Light, temperature and relative humidity of the greenhouse were monitored using Arduino hardware.

Figure 5. Cotton plants inside the greenhouse.

The greenhouse (Figure 5) was equipped with red and blue 21 W LED lights, model HY-MD-D 169-S. The Photosynthetically Active Radiation (PAR) was measured with a PAR sensor that shows the usefulness of the light provided for the photosynthesis process, in terms of wavelength and light flux. In the greenhouse, the average PAR measured was 200 ± 20 $\mu E/m^2/s$. The greenhouse was lit 12 hours per day. Each pot was watered with about 30 ml every two days. The relative humidity (RH) and temperature (T) of the greenhouse were maintained at 30-70% and 18-27°C.

To classify the soils performances, weights, heights and number of plants grown for each substrate are measured and compared. The weight is measured using a Radwag PS360/C/2 scientific grade

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scale, with a 0.001 g precision. The height of each seedling is measured with calipers and it is considered the mean of all plants.

3. Results and discussion

3.1 Gasification tests results

The tests demonstrated the possibility to use cotton waste briquettes as fuel. The efficiency evaluated through the discussed methodology resulted close to the value reported by the manufacturer for machines operated with wood chips.

3.1.1 Test efficiency results

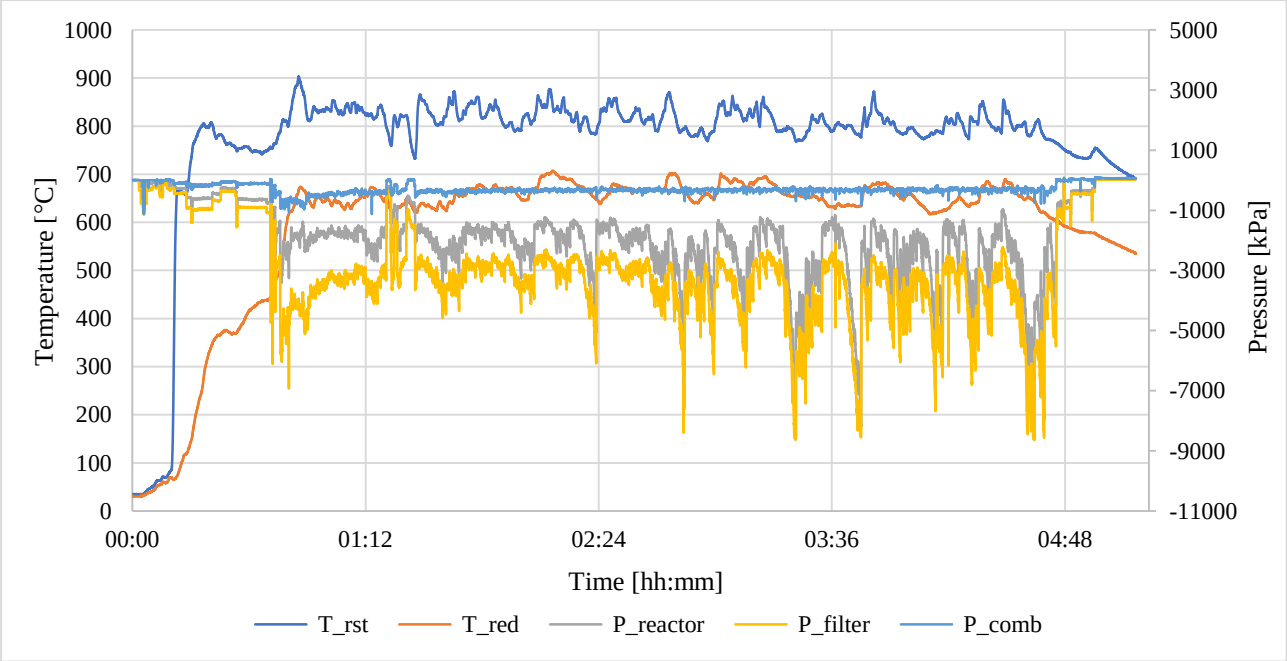

Figure 6. Temperature and pressure inside the gasifier during the test.

In Figure 6 and 7 the thermal behavior of PP20 can be observed. Figure 6 reports the data about pressure and temperature of the gas-generation and filtration. The relative pressure in the filter varies between -8000kPa to -1000kPa. Temperature at reduction zone start (T_rst) and temperature at reduction zone end (T_red) have values comparable to standard values of the machine with woodchips [21].

Gasification occurs between these two temperatures. The combustion zone is approximately at the same temperature of the reduction start zone. This value fluctuated around 830 °C. It is important that this temperature is not too high (over 950°C) in order to avoid thermal failures in the reactor core as well as sintering and slagging of ashes. The second step for the correct characterization of the fuel behavior in the reactor consists of the analysis of the gasifier pressure traces. The system log reports

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two pressures measured at the combustion zone (P_comb) and at the reactor outtake (P_reactor). It is fundamental that the ratio P_comb/P_reactor varies within a range of 0.50-1.49 kPa. A too wide difference between these two values outlines a packing of the biomass within the reactor that reduces the penetration of the air from the nozzles. On the other hand, when these pressure traces overlap it means that bridging is occurring in the reactor or the biomass void fraction is too big. The test reported a value within the suggested ones.

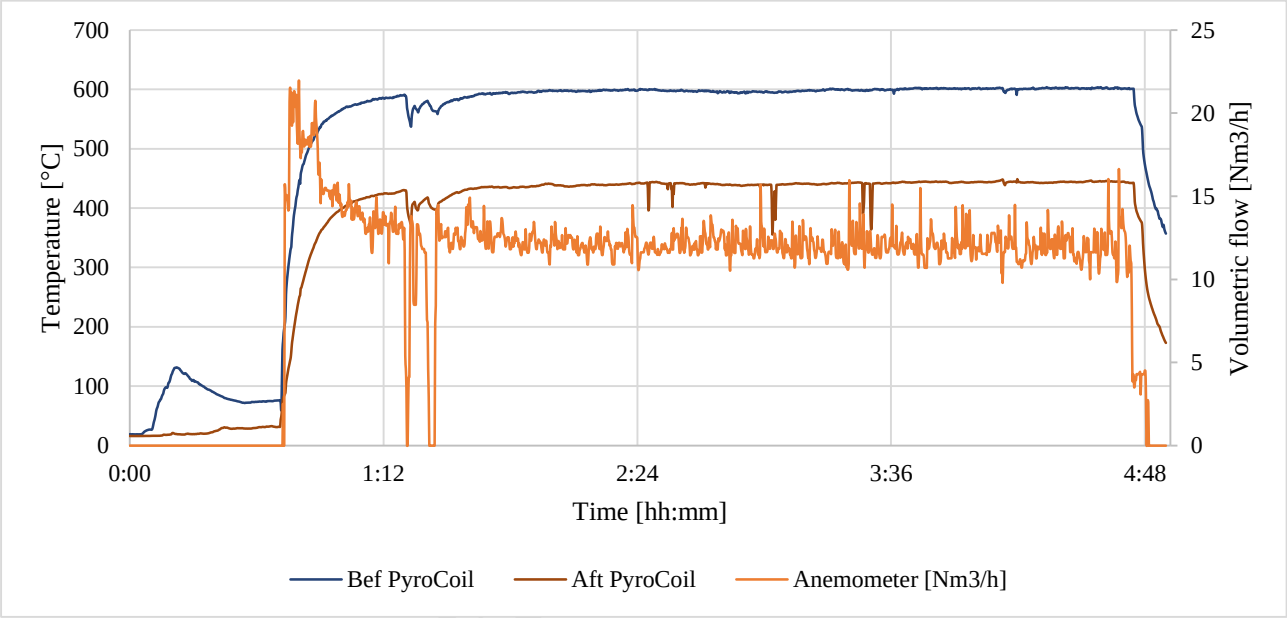

Figure 7. Volumetric flows and temperature during the test.

The machine operated under stable conditions during the test. The "Anemometer" line in Figure 7 shows that the engine turned off automatically twice in the initial run minutes, the problem suddenly disappeared and therefore is not considered related to this fuel in particular. As previously discussed, the anemometer measures the air entering the reactor. The recorded value fluctuates between 10-15 Nm^3/h. The engine exhaust temperature is measured and remained constant at 600° C during the whole test. The particular architecture of the PP20 uses part of the exhaust sensitive heat to initiate and sustain the pyrolysis stage. This process occurs in a specific part called "pyrocoil" [21]. The heat exchange between the exhaust gasses and the biomass in the pyrocoil can be observed through the temperature drop of the exhaust gasses that reaches, after the pyrocoil, a stable temperature around 440° C.

Table 3 summarizes the produced gas composition. It is comparable to the standard syngas values for downdraft reactors [32].

Table 3. Syngas composition

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Compound	Sample 1 [%]	Sample 2 [%]	Sample Average [%]	**Average [w/o O_2] [%]**	**Typical wood syngas [%]** *
CO	21.6	20.5	21.1	25.7	22.1
CO_2	6.8	9.1	8.0	9.7	10.2
H_2	16.8	18.1	17.5	21.3	15.2
N_2	46.8	43.6	45.2	37.9	50.8
CH_4	1.5	1.8	1.7	2.0	1.7
O_2	4.3	3.3	3.8	0	0
HHV_{dry} [MJ/Nm^3]	-	-	-	6.77	5.42

* All values referred to Handbook of Biomass Downdraft Gasifier Engine Systems, Reed and Das, 1988 [32].

To understand the behavior of the entire gasifier system, it is necessary to identify the different efficiencies that compose the global one. In Table 4, a gasifier efficiency of 64% and a total efficiency of 14.1% can be observed. Considering a generator efficiency of 80% as reported by the manufacturer [33], the specific consumption of dry fuel can be determined. The machine fuel consumption resulted in (1.16 ± 0.19) kg/kWh_{el}. This value is comparable to 1.2 kg/kWh_{el} reported in the product specifics by the manufacturer [21].

Table 4. Test efficiency calculation and results.

Efficiency		
Test length	3.28	h
Avg air volumetric flow	12.1	Nm^3/h
Avg syngas volumetric flow	24.9	Nm^3/h
Syngas volume	81.77	Nm^3
Wood mass used (dry)	39.39	kg
Avg electrical load	10.30	kW
Electrical energy produced	33.82	kWh
Gasifier efficiency	64.16%	
Total efficiency (dry)	14.1%	
Generator efficiency	80%	
Engine efficiency	27%	
Specific consumption (dry)	1.16	kg/kWh

3.1.2 Tar and particulate sampling results

Two other essential variables to describe the cotton waste use as fuel in a gasifier are the tar and the particulate contents. TSP (tar sampling procedure) results show a tar concentration of 0.497 g/Nm^3

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before the filter and a concentration of 0.192 g/Nm^3 after the filter. The particulate matter concentration after the filter is 1.2331 g/Nm^3.

The tar and particulate contents before, and especially after, the filter are above what suggested by literature for engine applications [34]. This is probably due to the nature of the briquettes: they are not the recommended fuel for this kind of gasifier and their mechanical resistance is not as high as the woodchips one. So, once they gasify in the reactor, thy break down, thus more particulate and tar are generated.

3.2 Biochar as amendment results

The goal of the greenhouse growth experiment is to evaluate the effects of biochar on the cotton plant. Two main specific characteristics are measured: weight and height. Every plant was measured in order to obtain the mean value for the whole group. NPK+B and NPK are the heaviest: 0.53 g. C mean weight is 0.3 g, S is 0.22g and B is 0.16 g. NPK is the tallest, 19.66 cm, that is comparable with the NPK+B one. In descending order, they are: C (13.26 cm), S (10.24 cm) and B (8.83 cm).

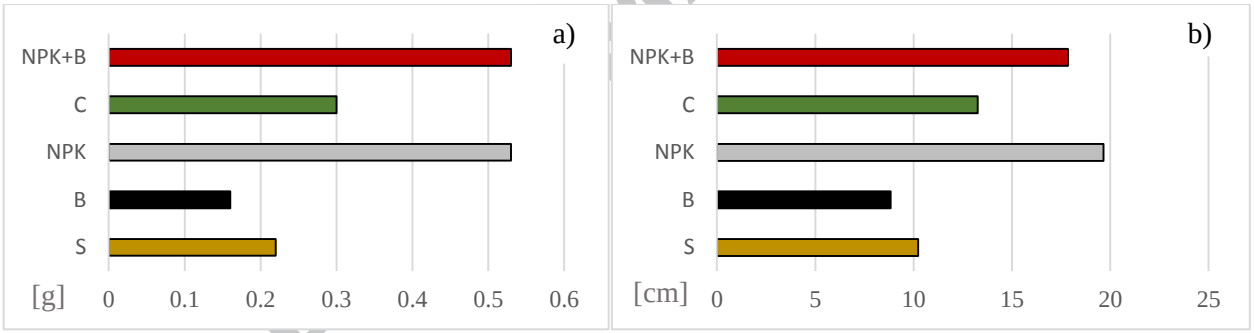

Figure 8. Seedlings average dry weights in grams (a) and heights in cm (b) of the cotton plants.

Biochar alone as amendment for the soil is not the best solution. As shown in Figure 8, the highest seedling weight is obtained with NPK alone and NPK+B. NPK has the greatest height, while NPK+B has a significant height. Compost is quite good for the plant growth, but not at the level of NPK+B.

Since NPK+B and NPK have comparable results and the NPK fertilizer quantity in (NPK+B) is 50% less than in NPK pot, an important consideration can be drawn: it is possible to obtain the same cotton growth performances using half the quantity of NPK as fertilizer, thanks to the biochar action on the soil.

3.3 Discussion

3.3.1 Gasification viability and biochar opportunities

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Few anomalies were identified in the biomass flow through the reactor feeding system. It was necessary to shake the hopper just one time to allow the briquettes to flow during the whole test. No kind of anomalies was found in the reactor during the test. The moisture content of the biomass collected from the hopper the next day was 11.40 %. This is in the range of normal briquette moisture content and it means that during the normal operation of the gasifier no condensation of gas vapors over the pellets occurs, neither the steam generated penetrates the briquettes during standard operations. There were no problems in the biomass flowability in the second day test, during the restart of the gasifier. The restart resulted as easy as usual, without anomalies. The fouling of the filter medium at the end of the tests is on average. As shown in Figure 7, there is no increase of the pressure drop over the filter during the test. Attention should be paid to the fouling of the filter inlet, which is quite clogged at the end of the test. Particulate built up in this zone increases the required maintenance operations. No condensates were found at the bottom of the filter and the engine throttle fouling is on average except for the formation of waxy concretions. They may derive from the reaction between gasification residuals of cotton oil and ashes. A future perspective can be the direct use of cotton stalks chips as fuel; the briquetting process would be unnecessary and the size of the pieces can be determined in order to obtain the PP20 required dimensions [21].

As the experiment with the cotton plants demonstrated, biochar opens very interesting possibilities, thanks to its unique structure:

a) The use of biochar can significantly reduce the need for chemical fertilizers, like NPK. It is possible that the biochar doses the nutrient elements to the plants during a long period of time [35, 36]. As a consequence of this, enormous quantities of greenhouse gases emitted by chemical fertilizers can be saved, as well as money.
b) Biochar allows to stock in the soil copious quantities of carbon, contributing to reduce climate change [22, 35].
c) Biochar has a positive impact on PAW (plant available water), dosing the water for the plants. The effects are remarkable, especially to fight droughts and water waste [23].
d) Biochar can absorb poisonous substances, producing a depurative action to the soil [22].

3.3.2 Circular economy (CE) model for cotton industries

In the last few years circular and blue economy are becoming increasingly important. By supporting the creation of circular production schemes within an economic system, CE aims to increase the efficiency of resource use, especially waste, to harmonize economy, environment and society [37]. This work demonstrates the possibility to develop a new model for a new development for any village whose economy is based on cotton crops with limited funds and infrastructures, but with significant

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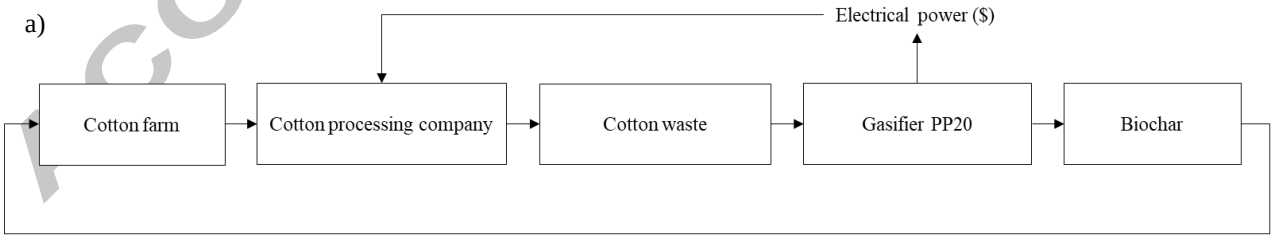
amount of biomass waste. Thanks to this model, it is possible to achieve relevant objectives, in order to guarantee economic growth: energy independence, sustainable valorization of waste and clean power production. Considering the PP20 technical specifications for thermal and electrical power generation and biochar production [21], and 2578 kg/ha per year dry residues produced on average in a cotton field, as described by Gemtos and Tsiricoglou [38], and a specific consumption of 1.16 kg/kWh, the machine can produce 2.22 MWh_{el} and 2.88 MWh_{th} and 128.9 kg of biochar per hectare per year. Finally, considering the fact that in Titimane there are 400 cotton farmers, who cultivate on average 1 hectare of cotton each, the potential energy derived from field residues is: 888 MWh_{el} and 1'152 MWh_{th} per year. Figure 9 shows the main step of the proposed circular economy model and the cotton supply chain flowchart.

a)



b)

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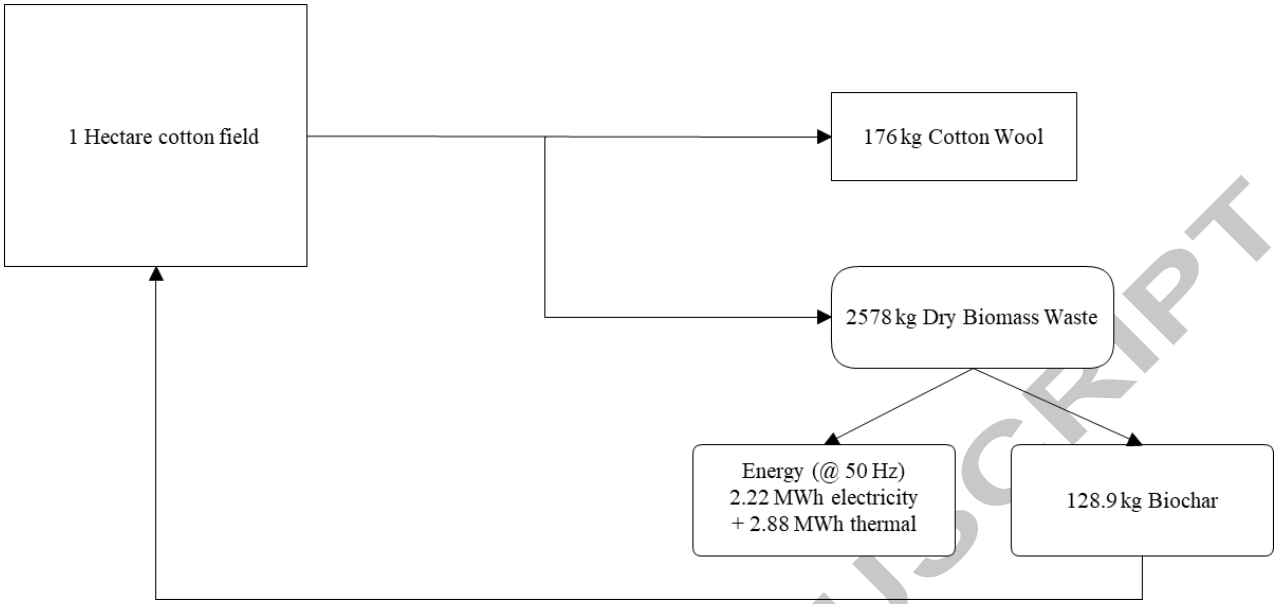

Figure 9. Circular economy proposed model (a). One-year cotton supply chain flowchart (b).

4. Conclusions

Developing countries are characterized by an impressive growth that carries increasing energy consumption. Here, there are abundant biomass resources, often used in inefficient ways to generate energy. Cotton agriculture represents an important business and it produces significant quantities of bio-waste. This work demonstrates the feasibility of cotton waste valorization through gasification, in order to produce both electrical energy and biochar. The gasifier plant, a PP20 machine by APL [21], fueled with cotton waste briquettes has performances comparable to the "conventional" use with woodchips. The gasifier and total efficiencies are respectively 64% and 14%. The fuel reliability is good and the operational maintenance is not invasive. The need for processing the cotton waste into briquettes may not be necessary; further experiments will be conducted to even decrease the operational cost. One-hectare cotton field can generate 2.22 MWh_{el}, 2.88 MWh_{th} and 128.9 kg of biochar per year. Biochar, which represents a by-product of the gasifier machine, has been tested for the cotton growth and the results are encouraging: by adding biochar, the need of fertilizers, like NPK, can be decreased up to 50%. By installing gasifier plants, bio-waste can be removed from the conventional burning on field and it is used as fuel to generate clean energy, reducing atmospheric pollution and creating a sustainable and virtuous economic circle.

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