

Environmental assessment of a waste-to-energy practice: the pyrolysis of agro-industrial biomass residues

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Abstract

Bio-wastes from agri-food sector represent an issue in terms of added cost and environmental impacts because of disposal processes. Waste-to-energy (WtE) strategies are gaining increasing interest as bio-wastes management practices allowing to obtain bio-fuels from bio-wastes in compliance with the circular economy principles. Pyrolysis of bio-wastes is a WtE strategy that converts bio-wastes into valuable products (bio-char, bio-oil) that can be used in energy applications as renewable fuels. In order to provide stakeholders with reliable environmental data, this study estimates the potential environmental impacts related to bio-char production from the pyrolysis of several different agro-industrial residues: olive tree trimmings, olive pomace, lemon and orange peels wastes, under three different operating conditions (i.e. peak pyrolysis temperature of 400, 500 and 650 °C). The analysis is carried out through the life cycle assessment methodology. The functional unit for the analysis is 1 MJ of thermal energy potentially released during the complete combustion of bio-char obtained from the pyrolysis process. The study highlights that, under the examined conditions, the type of biomass in input affects the environmental impacts of the pyrolysis process more than the peak pyrolysis temperature. Bio-char obtained from orange peels has the lower environmental impacts, with an average percentage difference of about 16% compared to bio-char obtained from olive tree trimmings that has the worst environmental performance. For each biomass, the impacts associated to bio-char obtained with different operational temperatures have percentage differences in general lower than 5%. A contribution analysis shows that the electricity consumed during the operational phase is responsible for the largest impacts in all the examined impact categories.

The obtained results can support the scaling-up process of the examined system and the identification of the best bio-waste typology and operational conditions from an environmental perspective.

Keywords: Life cycle assessment, sustainable energy supply, circular economy, bio-waste, bio-char, waste-to-energy, pyrolysis

1 Introduction

Energy and raw materials supply and waste management are key elements towards a more sustainable and circular economy transition [1] [2] [3]. The European Commission stresses that the transition to a cleaner and sustainable economy requires strategies involving the products life cycle, from production to the creation of markets for secondary (i.e. waste-derived) raw materials [4]. In this framework, waste-to-energy (WtE) practices are gaining increasing interest as practices allowing at increasing the sustainability of both energy supply and waste management [5] [6] [7]. WtE is a broad term that encompasses various waste treatment processes generating energy (e.g. in the form of electricity/or heat or waste-derived fuels). WtE includes combustion, incineration, gasification, anaerobic digestion, pyrolysis, etc. [8]. Among these

technologies, pyrolysis of waste is receiving increasing attention [8–14]. The pyrolysis process involves the thermal decomposition of organic materials at temperature typically ranging between 400 and 800 °C, in the absence of oxygen or in an inert atmosphere, and its conversion into mainly two outputs including a liquid product (bio-oil) and a solid product (bio-char). Pyrolysis is one of the few processes that can handle a wide range of bio-feedstocks. In addition, the outputs have several potential uses: bio-oil can be combusted in industrial boilers/furnaces or upgraded into biodiesel, bio-char can be used for power generation and as a soil amendment to improve soil quality and sequester carbon [11]. Additionally, small pyrolysis plants are compatible with existing agriculture and forestry infrastructure, providing considerable flexibility for the feedstock [15] and preventing long distance transportation. Pyrolysis processes can be categorized as slow, intermediate, fast and flash pyrolysis [16]. Their differences depend on the heating rate and heating duration that entail a different output ratio [17]. Slow pyrolysis produces less bio-oil and more bio-char, whereas fast pyrolysis produces less bio-char and more bio-oil.

Several studies are available in literature on pyrolysis of bio-wastes; however they do not investigate the environmental impacts associated with these processes [18]. Most of them focus on laboratory experiments with subsequent assessment of the quantity and quality of the individual products of pyrolysis, corresponding to different input materials and process conditions [9]. Among these, Grycová et al. [19] illustrated pyrolysis experiments of waste cereals and waste peanuts crisps and analysed the mass balance of the outputs corresponding to the different inputs, their energy properties in terms of high and low heating values and the gas composition at different process temperature. Volpe et al. [20] treated pyrolysis experiments on citrus residues in lab scale fixed bed reactor, in order to investigate the effect of peak temperature in mass and energy yields of bio-char and bio-oil. Bhattacharjee and Biswas [21] conducted the pyrolysis of orange bagasse in order to investigate the effect of temperature, heating rate and N₂ gas flow rate on the product yields and their energy properties. Aguiar et al. [22] investigated the influence of temperature and particle size on the yields and characteristics of the products obtained through the pyrolysis of orange peels residues. Hmid et al. [23] investigated the influence of temperature and heating rate on the yield and properties of bio-char derived from pyrolysis of solid olive mill waste (pomace).

Based on the author knowledge, few studies deal with the environmental impacts of bio-waste pyrolysis process. Fernandez-Lopez et al. [8] estimated the greenhouse gas emissions due to a pyrolysis treatment of swine and dairy manure. Wang et al. [24] calculated the life cycle impact on global warming potential and resource depletion of a bio-based levoglucosan production process through fast pyrolysis of cotton straw. Ibarrola et al. [25] evaluated the carbon equivalent abatement achievable through slow and fast pyrolysis treatments of biodegradable wastes or residues. Among the examined studies only Parascanu et al. [18] performed a Life Cycle Assessment (LCA) of the pyrolysis treatment of olive

pomace estimating the impact on a wide range (13) of environmental categories; however, the authors did not provide a detailed analysis of the contribution of each phase of the pyrolysis process.

In this context, this work aims at analysing a slow pyrolysis process of different biomass residues under different operation conditions from an environmental point of view and assuming a life cycle approach and at identifying the “hot spots” of the examined system. In addition, a sensitivity analysis is carried out in order to assess how transport distance of biomasses and methodological assumptions on the partitioning of the environmental burdens among the pyrolysis outputs can affect the environmental outcomes and to provide a preliminary estimate of the potential benefits achievable by using electricity from renewable sources in the pyrolysis process. LCA provides scientific based environmental indicators useful in planning strategies towards more sustainable practices [26]. Specifically, the obtained results can support the stakeholders in the eco-design of scaled – up pyrolysis systems.

The paper is organized as follows. Section 2 presents the examined pyrolysis reactor. The application of the LCA methodology to the examined system, the estimated environmental indicators and the results interpretation are illustrated in Section 3. Section 4 provides some final remarks.

2 The examined system

The examined pyrolysis reactor is a real system installed at the laboratory of Environment and Energy of the University “Kore” of Enna (Sicily, Italy) (Figure 1). It consists of a horizontal fixed bed cylindrical reactor made of quartz 340 mm long, with a 20 mm internal diameter, closed at one end and provided with a 29/32 mm open end. A quartz cap is inserted in the open side of the reactor.



Figure 1. The examined pyrolysis reactor

The quartz cap is equipped with a fitting and an 8 mm diameter inner tube through which an inert gas (such as N₂) flows into the biomass sample during the reaction, allowing maintaining the inert ambient required by the pyrolysis process and removing the pyrolysis gas residues. A 1 kW external furnace heats the reactor.

The pyrolysis reactor can be loaded with several residual biomasses, which are pre-treated before entering the reactor. The pre-treatments consist of drying and grinding the feedstock in order to minimize its water content and give sufficiently small particles to the reactor [16]. At each pyrolysis cycle, approximately 10 g of biomass residues are loaded in the reactor; under the examined slow pyrolysis conditions the obtained outputs are in average 60% of bio-char, 30% of bio-oil and 10% of uncondensed gases and vapours, on a dry basis.

Further detail on the examined system are reported in Section 3.2.3.

3 Life cycle assessment

The authors apply the LCA methodology to bio-char obtained from the slow pyrolysis processes of olive tree trimmings, olive pomace, lemon peels and orange peels bio-wastes under three different temperatures, i.e. 400, 500 and 650 °C. The LCA is carried out in compliance with the international standards of series ISO 14040 [27,28].

3.1 Goal and scope definition

The main goals of the study are:

- to estimate the potential environmental impacts related to bio-char produced by a slow pyrolysis process of several biomass residues under three different temperatures, in order to identify the most sustainable production route;
- to identify the hotspots of the production process examined;
- to provide a preliminary estimate of the potential benefits achievable through the use of renewable energy technologies for the generation of electricity used in the pyrolysis process;
- to assess how the transport distance of biomasses affects the environmental outcomes;
- to identify the influence of the methodological assumptions of the partitioning the environmental burden among the pyrolysis outputs on the final results.

With reference to the last three points, a sensitivity analysis is performed. In detail, in order to estimate the potential environmental benefits achievable through the implementation of renewable technologies for electricity generation it is hypothesized to substitute the electricity from the grid with electricity locally generated through a PV plant installed in the laboratory roof (renewable electricity scenario – RES).

Concerning the transport phase, in order to avoid misleading conclusions and recommendations, although biomasses come from different places, the same transport distance of 100 km is assumed for all of them in the base scenario. The

sensitivity analysis is performed by considering two scenarios, TD200 and TD300, assuming a transport distance of 200 and 300 km, respectively. Concerning the last point, as bio-char is the main product of the examined system, the environmental burdens are entirely attributed to it (reference scenario – RS). However, in order to evaluate the influence of this assumption on the results of the assessment, an alternative scenario (named allocation scenario – AS) is investigated, in which the environmental burdens are partitioned between bio-char and bio-oil based on the respective higher heating values (HHVs). The uncondensed gases and vapours are neglected due to the exiguous amount produced in the considered operation conditions and to the negligible contribution to the environmental impacts (a preliminary screening highlighted that the contribution to the impacts is lower than 0.05%).

The functional unit (FU) selected as reference for the LCA analysis is 1 MJ of thermal energy potentially released during the complete combustion of bio-char.

Both pyrolysis temperature and biomass residues in input influence the energy properties of bio-char derived from pyrolysis. Then, the reference flow, i.e. the amount of the product (bio-char) able to potentially release 1 MJ of thermal energy, changes based on the residual biomass in input and the temperature of the pyrolysis process. Table 1 shows the reference flows for each examined biomass and pyrolysis temperature. The reference flows are calculated on the basis of the gross calorific value of bio-char from bio-wastes pyrolysis (Table 2). Table 2 also shows the gross calorific value of bio-oil.

Table 1. Reference flows for each compared biomass residues and pyrolysis temperature.

Pyrolysis temperature [°C]	OT [kg]	OP [kg]	LP [kg]	OrP [kg]
400	3.63E-02	3.33E-02	3.28E-02	3.20E-02
500	3.76E-02	3.34E-02	3.20E-02	3.14E-02
650	4.13E-02	3.33E-02	3.23E-02	3.19E-02

Table 2: Gross calorific values of bio-char and bio-oil obtained from bio-wastes pyrolysis [20,29]

Peak temperature (°C)	Gross calorific values [MJ/kg]							
	Olive tree trimmings		Olive pomace		Lemon peel		Orange peel	
	Char	Tar	Char	Tar	Char	Tar	Char	Tar
400	27.53	23.44	30.01	25.67	30.48	19.54	31.27	17.05
500	26.63	24.12	29.98	26.96	31.24	19.68	31.84	16.96
650	24.23	23.37	30.01	26.83	31.00	19.81	31.37	16.992

The analysis follows a “from cradle-to-gate” approach. The system boundaries include the transport of the biomass residues to the laboratory (transport distance of 100 km), the pre-treatments consisting of drying and grinding biomass residues before entering the pyrolysis reactor, the pyrolysis process including the energy and material consumption during the operational phase, the end-of-life treatment of process waste. In addition, the construction phase of the reactor components with a lifetime less than/equal to 5 years (5 years is the useful life of most reactor components) is included in the analysis.

Figure 2 shows a schematic representation of the unit processes included in the system boundaries.

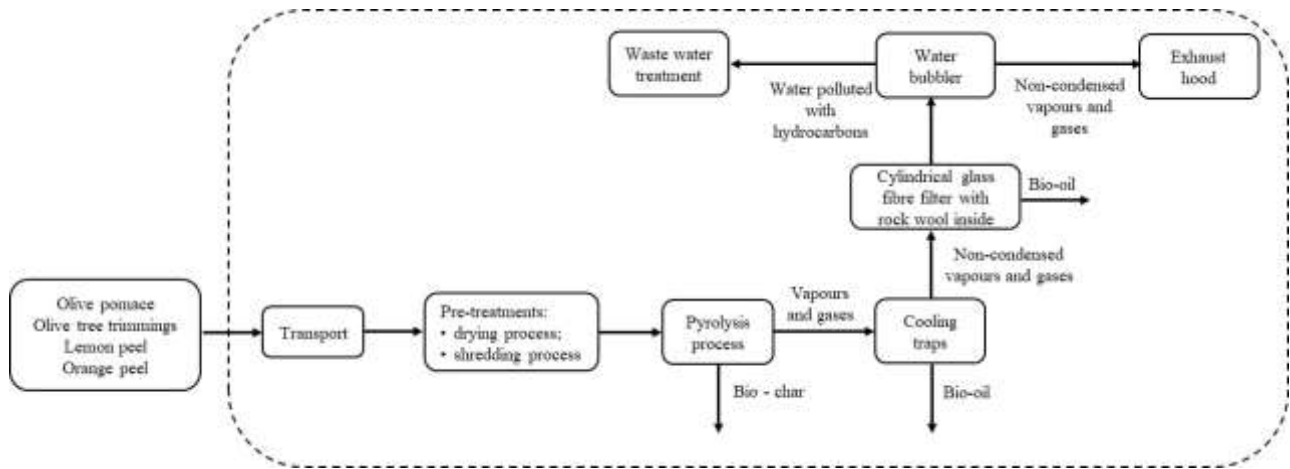


Figure 2. Schematic representation of the system boundaries.

The impact assessment is based on the ILCD 2011 midpoint method and impact categories recommended by the European Commission [30], with the exceptions of “Land use” and “Water resource depletion” impact categories that are excluded because of the high uncertainty of the background LCI data [31]. In addition, the ILCD impact categories are complemented by the cumulative energy demand (CED) method for energy impact estimation [32].

The examined energy and environmental impact categories are listed in Table 3.

Table 3. Investigated energy and environmental impact categories

Impact category	Acronym	Unit of measure
Cumulative Energy Demand	CED	MJ
Global Warming Potential	GWP	kgCO _{2eq}
Ozone Depletion Potential	ODP	kgCFC-11 _{eq}
Human Toxicity - no cancer effect	HT-nce	CTUh
Human Toxicity - cancer effect	HT-ce	CTUh
Particulate Matter	PM	kgPM _{2.5eq}
Ionizing Radiation, human health	IR-hh	kBqU ²³⁵ _{eq}
Ionizing Radiation, ecosystem	IR-e	CTUe
Photochemical Ozone Formation	POFP	kgNMVOC _{eq}
Acidification	AP	molH ⁺ _{eq}
Terrestrial Eutrophication	EU _T	molN _{eq}
Freshwater Eutrophication	EU _F	kgP _{eq}
Marine Eutrophication	EU _M	kgN _{eq}
Freshwater ecotoxicity	E _{FW}	CTUe
Mineral, fossil and renewable resource depletion	MFRRD	kgSb _{eq}

3.2 Life Cycle Inventory

The inventory analysis consists of the data collection and calculation procedures necessary for modelling the life cycle phases of the product system examined. During the inventory analysis, it is necessary to reconstruct, with reference to each phase of the life cycle and each unit process included in the analysis, the input flows in terms of consumption of materials and energy resources, and outputs in terms of emissions of pollutants into the air, water and soil, waste, products

and co-products. Both primary and secondary data are used for the compilation of the inventory. In particular, specific primary process data relating to the consumption of energy and materials associated to the foreground process are collected directly in the laboratory. Secondary data for modelling the background processes, i.e. the eco-profiles of materials and energy sources, are inferred from the Ecoinvent 3.6 database [33].

The detail of the foreground life cycle inventory is provided in the following. The collected data refer to a pyrolysis cycle during which 0.01 kg of biomass is treated. Then, they are processed to be referred to the selected FU.

3.2.1 Feedstock supply

Feedstock supply includes only the biomass residues transport process. In fact, biomass residues are wastes of olive and citrus transformation processes in food items, then a zero-burden approach is adopted and only the impact related to their transportation is accounted for [34].

3.2.2 Pre-treatment biomass processes

The biomass is pre-treated before being introduced into the reactor. The first treatment consists of drying the biomass in an oven (1.3 kW) at a constant temperature of 105 °C for 12 hours. After drying, the sample is subjected to a shredding process using an ultra-centrifugal mill (0.75 kW). The electricity consumed is estimated based on the rated power and the operation hours monitored by the laboratory operators. It is 1.56E-02 kWh and 2.50E-03 kWh for the drying and shredding processes of 0.01 kg of biomass, respectively. The secondary dataset for electricity refers to low voltage electricity generated in Italy.

3.2.3 Pyrolysis process

Three slow pyrolysis tests, each of them characterized by a different peak temperature (400 – 500 – 650 °C), have been carried out on OT, OP, LP and OrP wastes.

The pyrolysis process starts with the biomass entering the reactor. The feedstock is fed into the reactor by means of a stainless steel feedstock holder [29]. The heating rate is 50 °C/min. When the set peak temperature is reached, it is kept constant until the end of the pyrolysis process. The reaction time is 30 minutes. During the pyrolysis, an inert gas (N₂) flows into the reactor to sweep out the gases and vapours generated during the thermal treatment. The flow rate is kept constant at 1.5 l/min. At the end of the reaction, the furnace is slid out and the reactor leaves cooling to room temperature. Bio-char is collected from the reactor and it is analysed in order to determine its energy properties.

The gases and vapours removed by the inert gas flow exit the reactor and enter a heating jacket. The heating jacket keeps vapours and gases at the constant temperature of approximately 180 °C to avoid their condensation before reaching two cold traps located downstream. The first trap is a U-shaped tube immersed in a 2 litres water/ethylene glycol and dry ice bath. It is a stable solution and does not need to be replaced. Therefore, the contribution of the water/ethylene glycol solution to the overall impact of a single pyrolysis process is considered negligible. The second trap is a glass finger

equipped with a 150 W refrigerating system. A glass fibre filter with rock wool inside is located downstream of the second trap to avoid the loss of the bio-oil not condensed in the traps. The glass fibre filter is connected to a water bubbler connected to the discharge hose. The water exiting the bubbler is polluted with hydrocarbons. Therefore, it undergoes a purification treatment before being discharged into the receiving water body. The cooling traps, the glass fibre filter and other reactor parts, e.g. pipes, are washed using a solution of chloroform and methanol in the ratio of 4:1. The obtained organic solution is filtered and it is evaporated by means of a rotary evaporator (rotovap) (1.4 kW) to recover the bio-oil [29]. A schematic representation of the examined pyrolysis process is reported in in Figure 3.

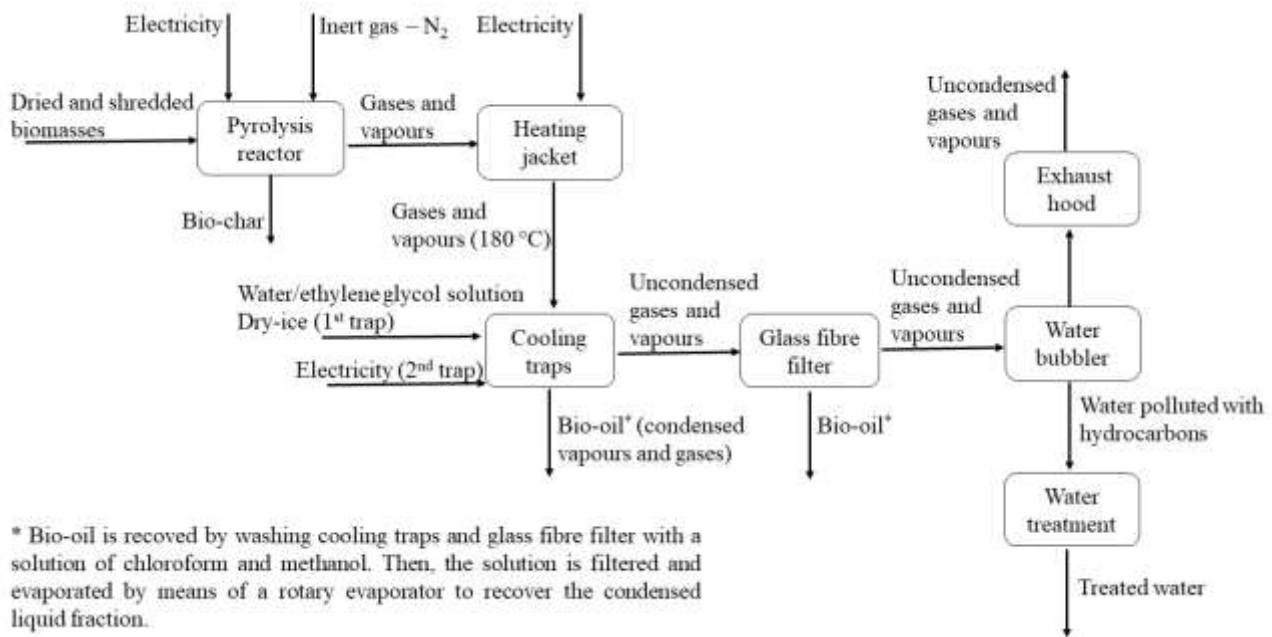


Figure 3. Pyrolysis process

The inventory data for the pyrolysis reactor construction process modelling are shown in Table 4, while Table 5 shows the inventory data for the pyrolysis process.

Table 4. Inventory data used for the reactor construction process referring to a pyrolysis cycle

Component	Material	Amount
Mobile supporting structure of the furnace [kg]	Steel	7.25E-03
Heating jacket		
Case [kg]	Steel	1.51E-03
Electrical resistance [kg]	Copper wire	2.48E-09
Biomass holder [kg]	Stainless steel	2.74E-05
Reactor and cap [kg]	Quartz	1.59E-04
Cooling traps		
First cooling trap [kg]	Glass	1.24E-04
Caps for the first cooling trap [kg]	Plastic	5.72E-06
Second cooling trap [kg]	Glass	1.26E-04
Cap for the second cooling trap [kg]	Plastic	1.53E-05
Casing for the second cooling trap [kg]	Aluminium	3.89E-06

Filter	Case [kg]	Glass fibre	1.80E-05
	Infill material [kg]	Rock wool	2.70E-07
Caps for the filter [kg]		Plastic	1.03E-05
Bubbler [kg]		Glass	3.34E-04
Junctions [kg]		Synthetic rubber	1.27E-05
Pipes [kg]		Synthetic rubber	2.16E-04

Table 5. Inventory data used for the pyrolysis process modelling referring to a pyrolysis cycle

Pyrolysis process	Amount
Biomass residues [kg]	1.00E-02
Inert gas - N ₂ [m ³]	4.50E-02
Dry ice [kg]	2.00E-01
Methanol [m ³]	6.00E-06
Chloroform [m ³]	2.40E-05
Water used in the bubbler (replaced every 4 cycles) [kg]	3.33E-02
Electricity - pyrolysis process (peak temperature: 400 °C) [kWh]	2.43E-01
Electricity - pyrolysis process (peak temperature: 500 °C) [kWh]	2.67E-01
Electricity - pyrolysis process (peak temperature: 650 °C) [kWh]	3.02E-01
Electricity - heating jacket [kWh]	1.10E-01
Electricity-second cooling trap [kWh]	8.25E-02
Electricity - rotovap [kWh]	1.40E+00
Waste to end-of-life treatments	
Polluted water exiting the bubbler [kg]	3.33E-02
Output to technosphere	
Bio-char [kg]	6.00E-03
Bio-oil [kg]	3.00E-03
Uncondensed gases [kg]	1.00E-03

3.3 Results and discussion: Life Cycle Impact assessment and interpretation

The life cycle impact assessment (LCIA) of the FU for each considered feedstock and each pyrolysis operation temperature is illustrated in Table 6. Data analysis highlights that the best environmental performances are obtained at 400°C peak operation temperature for olive tree trimmings and olive pomace and at 500°C for orange and lemon peels waste. For each feedstock the worse life cycle environmental performances are obtained in correspondence of the pyrolysis process performed at 650°C. In fact, under this operating condition the pyrolysis process presents a higher consumption of electricity and provides bio-char with lower energy properties compared to the other ones.

However, under the examined conditions, the operation pyrolysis temperature for each examined biomass shows a negligible influence on the environmental impacts with differences lower than 5%, except for olive tree trimmings, for which percentage differences higher than 10% are observed between OT400/500 °C and OT650 °C.

The results pointed out that the type of biomass influences the environmental impacts of the selected FU. In detail, the pyrolysis of orange peels presents the lower environmental impact for each peak operation temperature compared to the other feedstocks, with orange peels pyrolysis at 500°C peak temperature (OrP500°C) as the best configuration. The

pyrolysis of OT presents the worst environmental performance. The environmental impacts associated to OT400 °C, OT500 °C and OT650 °C configurations are, respectively, 15%, 20% and 33% higher than those associated to the OrP500 °C one. Bio-chars from OP and LP pyrolysis at the different peak temperatures examined present, respectively, impacts higher than 6% and 3% compared to the OrP500 °C configuration.

Table 6. Life cycle environmental impacts – Impacts refer to the defined FU

Impact category	OT400 °C	OT500 °C	OT650 °C	OP400 °C	OP500 °C	OP650 °C
CED (MJ)	9.19E+01	9.62E+01	1.08E+02	8.43E+01	8.55E+01	8.70E+01
GWP (kg CO _{2eq})	5.41E+00	5.65E+00	6.32E+00	4.96E+00	5.02E+00	5.10E+00
ODP (kg CFC-11 _{eq})	7.74E-07	8.07E-07	8.98E-07	7.10E-07	7.17E-07	7.25E-07
HT-nce (CTUh)	2.07E-06	2.15E-06	2.39E-06	1.90E-06	1.91E-06	1.93E-06
HT-ce (CTUh)	3.89E-07	4.05E-07	4.49E-07	3.57E-07	3.59E-07	3.63E-07
PM (kg PM _{2.5eq})	2.61E-03	2.72E-03	3.04E-03	2.39E-03	2.42E-03	2.46E-03
IR-hh (kBq U ²³⁵ _{eq})	8.05E-01	8.43E-01	9.43E-01	7.39E-01	7.48E-01	7.61E-01
IR-E (interim) (CTUe)	2.34E-06	2.44E-06	2.73E-06	2.14E-06	2.17E-06	2.20E-06
POFP (kg NMVOC _{eq})	1.22E-02	1.27E-02	1.42E-02	1.12E-02	1.13E-02	1.15E-02
AP (mol H ⁺ _{eq})	4.23E-02	4.44E-02	4.99E-02	3.88E-02	3.94E-02	4.03E-02
EU _T (mol N _{eq})	1.22E-01	1.29E-01	1.45E-01	1.12E-01	1.14E-01	1.17E-01
EU _F (kg P _{eq})	1.94E-03	2.02E-03	2.26E-03	1.78E-03	1.80E-03	1.82E-03
EU _M (kg N _{eq})	8.52E-03	8.87E-03	9.84E-03	7.82E-03	7.88E-03	7.95E-03
E _{FW} (CTUe)	9.52E+01	9.99E+01	1.12E+02	8.74E+01	8.87E+01	9.06E+01
MFRRD (kg Sb _{eq})	2.12E-04	2.21E-04	2.45E-04	1.95E-04	1.96E-04	1.98E-04
Impact category	LP400 °C	LP500 °C	LP650 °C	OrP400 °C	OrP500 °C	OrP650 °C
CED (MJ)	8.30E+01	8.20E+01	8.42E+01	8.09E+01	8.05E+01	8.32E+01
GWP (kg CO _{2eq})	4.88E+00	4.82E+00	4.94E+00	4.76E+00	4.73E+00	4.88E+00
ODP (kg CFC-11 _{eq})	6.99E-07	6.88E-07	7.02E-07	6.81E-07	6.75E-07	6.94E-07
HT-nce (CTUh)	1.87E-06	1.84E-06	1.87E-06	1.82E-06	1.80E-06	1.85E-06
HT-ce (CTUh)	3.51E-07	3.45E-07	3.51E-07	3.42E-07	3.38E-07	3.47E-07
PM (kg PM _{2.5eq})	2.35E-03	2.32E-03	2.38E-03	2.29E-03	2.28E-03	2.35E-03
IR-hh (kBq U ²³⁵ _{eq})	7.27E-01	7.18E-01	7.37E-01	7.09E-01	7.05E-01	7.28E-01
IR-E (interim) (CTUe)	2.11E-06	2.08E-06	2.13E-06	2.06E-06	2.04E-06	2.11E-06
POFP (kg NMVOC _{eq})	1.10E-02	1.08E-02	1.11E-02	1.07E-02	1.06E-02	1.10E-02
AP (mol H ⁺ _{eq})	3.82E-02	3.78E-02	3.90E-02	3.72E-02	3.71E-02	3.85E-02
EU _T (mol N _{eq})	1.11E-01	1.10E-01	1.13E-01	1.08E-01	1.08E-01	1.12E-01
EU _F (kg P _{eq})	1.75E-03	1.72E-03	1.76E-03	1.71E-03	1.69E-03	1.74E-03
EU _M (kg N _{eq})	7.70E-03	7.56E-03	7.70E-03	7.50E-03	7.42E-03	7.60E-03
E _{FW} (CTUe)	8.60E+01	8.51E+01	8.77E+01	8.38E+01	8.35E+01	8.66E+01
MFRRD (kg Sb _{eq})	1.92E-04	1.88E-04	1.91E-04	1.87E-04	1.85E-04	1.89E-04

The variation in the contribution of the different life cycle phases in correspondence with the different types of biomass and process temperatures examined is negligible. Consequently, Figure 4, referred to the OrP500 °C configuration, can be considered representative of all the examined configurations.

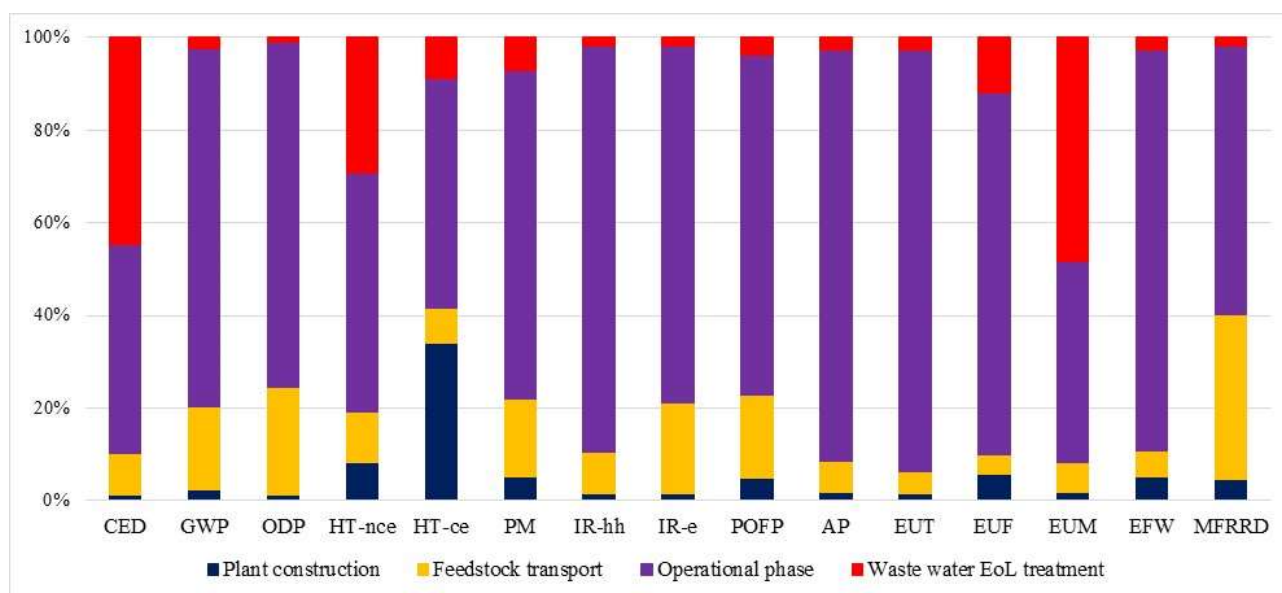


Figure 4. Life cycle environmental impacts – Contribution analysis

The operation phase is responsible for the larger contribution to all the impacts considered, with percentages ranging from minimum values of about 44% (for CED) up to 91% (for EU_T). The contribution of electricity to the total impact of the operational phase ranges from a minimum of about 50% (for MFRRD) up to 90% (for EU_T). A more detailed analysis highlights that the electricity consumed in the rotary evaporator is relevant in all the impact categories examined. Specifically, its contribution to the impacts ranges from 33% for MFRRD to 58% for EU_T. In addition, it contributes for about 55% to AP and E_{FW}, and for about 50% to CED, GWP, PM and POFP impact categories. The electricity consumed to heat the pyrolysis reactor accounts for a contribution ranging from a minimum of about 11% (for MFRRD) up to 20% (for EU_T and AP). The electricity consumed by the heating jacket accounts for a contribution to the impacts ranging from about 5% for ODP and MFRRD to about 8% for AP, EU_T and E_{FW}. The electricity consumption for grinding and drying the biomass has a negligible contribution to the impacts (lower than 1%).

The dry ice used in the first cooling trap is highly impacting for MFRRD (about 46%), HT-nce (about 30%), HT-ce and EU_F (about 25%) and GWP, IR-hh, IR-e (about 20%). The contribution of chloroform is relevant for ODP (about 27%) and negligible for the other categories examined. The water used in the bubbler and the methanol account for a negligible contribution to all the impact categories (lower than 1%).

Plant construction is highly impacting on HT-nce (about 34%). From a dominance analysis of this step, it is noticed that the supporting structure is the main responsible for the impact in all the categories investigated. Specifically, its contribution ranges from a minimum of about 51% (for MFRRD) up to 82% (for HT-ce). Heating jacket represents on average 15% of the impact of all the categories investigated. Bubbler and cooling traps contribute for 20% and 16% to the MFRRD, respectively. The other components of the system have a low impact (below 7% for all the considered categories).

The contribution of the transport to the total impact is ranging from a minimum of about 4% for EU_T and EU_M to 36% for MFRRD. In addition, transport is responsible for a non-negligible impact on IR-e (about 20%), ODP (about 18%), and POFP, GWP and PM (about 17%). A deeper contribution analysis highlights that the transport impact contribution is due to diesel consumption for ODP, GWP and POFP, lead and zinc employed in the truck construction process for MFRRD and treatment processes of non-exhaust brake and tyre wear emissions for PM. Finally, wastewater treatment is highly impacting for EU_M (48%), CED (45%) and HT-nce (30%).

3.3.1 Sensitivity analysis

A sensitivity analysis is carried out to assess the influence of a different approach for solving multifunctionality related to the co-production of bio-char and bio-oil, the influence of biomasses transport distance and to provide a preliminary estimate of the potential benefits achievable through the implementation of renewable energy technologies for the generation of electricity used in the pyrolysis process.

With reference to the multifunctionality handling, according to the scope of the study, the RS, in which the environmental burdens are entirely attributed to bio-char, is compared with the AS scenario, in which the environmental burdens are allocated between bio-char and bio-oil based on the respective HHVs. Concerning the transport distance, two scenarios are investigated considering a biomass transport distances of 200 km (TD-200) and 300 km (TD-300), respectively. These scenarios are compared with the RS, in which a transport distance equal to 100 km is assumed (TD-100). Finally, the potential environmental benefits achievable by substituting the process electricity from the grid with electricity locally generated through a PV plant (renewable electricity scenario) are evaluated.

The sensitivity analyses for transport distance and renewable electricity scenarios are carried out with reference to the OrP500 °C configuration (RS), since for these parameters the obtained outcomes are non-affected by the biomasses in input and pyrolysis temperature.

The parameters used for the sensitivity analysis are recapped in Table 7.

Table 7. Main assumptions of the sensitivity analysis

Sensitivity analysis				
Multifunctionality management scenario	OT	OP	LP	OrP
Allocation factors	Bio-char	Bio-char	Bio-char	Bio-char
400 °C	0.701	0.7	0.757	0.786
500 °C	0.688	0.69	0.76	0.79
600 °C	0.675	0.691	0.758	0.787
Transport scenario	Transport distance - TD (km)			
TD-RS	100			
TD-200	200			
TD-300	300			
Renewable electricity scenario				
Renewable energy technology for electricity generation	Electricity production from photovoltaic plant, multi-Si panel 3kWp slanted-roof installation			

The sensitivity analysis highlights that the approach for solving multifunctionality can affect significantly the results of the assessment (Table 8). In particular, the environmental burdens associated to the selected FU decrease by percentage values ranging from 21% (for OrP500 °C configuration) to 32.5% (for OT600 °C configuration) when bio-oil is considered a value product. In addition, under this assumption, the bio-char with the better environmental performance is that obtained from the pyrolysis of olive pomace at 500 °C (OP500 °C configuration) since the corresponding bio-oil presents higher HHV compared to the other bio-oils (Table 1). Specifically, bio-char from OP500 °C configuration is responsible for the lower impact in all the examined categories with the exception of AP, EU_T and E_{FW} in which bio-char from OP400 °C configuration causes the lowest impact.

Table 8. Sensitivity analysis results – Multifunctionality management

Impact category	OT400 °C	OT500 °C	OT650 °C	OP400 °C	OP500 °C	OP650 °C
CED (MJ)	6.45E+01	6.62E+01	7.27E+01	5.91E+01	5.90E+01	6.01E+01
GWP (kg CO _{2eq})	3.79E+00	3.89E+00	4.26E+00	3.47E+00	3.46E+00	3.53E+00
ODP (kg CFC-11 _{eq})	5.43E-07	5.55E-07	6.06E-07	4.97E-07	4.94E-07	5.01E-07
HT-nce (CTUh)	1.45E-06	1.48E-06	1.61E-06	1.33E-06	1.32E-06	1.33E-06
HT-ce (CTUh)	2.73E-07	2.78E-07	3.03E-07	2.50E-07	2.48E-07	2.51E-07
PM (kg PM _{2.5eq})	1.83E-03	1.87E-03	2.05E-03	1.67E-03	1.67E-03	1.70E-03
IR-hh (kBq U ²³⁵ _{eq})	5.65E-01	5.80E-01	6.36E-01	5.17E-01	5.16E-01	5.26E-01
IR-E (CTUe)	1.64E-06	1.68E-06	1.84E-06	1.50E-06	1.50E-06	1.52E-06
POFP (kg NMVOC _{eq})	8.53E-03	8.75E-03	9.59E-03	7.81E-03	7.79E-03	7.93E-03
AP (mol H ⁺ _{eq})	2.97E-02	3.05E-02	3.36E-02	2.72E-02	2.72E-02	2.78E-02
EU _T (mol N _{eq})	8.59E-02	8.85E-02	9.76E-02	7.87E-02	7.88E-02	8.08E-02
EU _F (kg P _{eq})	1.36E-03	1.39E-03	1.52E-03	1.24E-03	1.24E-03	1.26E-03
EU _M (kg N _{eq})	5.98E-03	6.10E-03	6.64E-03	5.48E-03	5.43E-03	5.49E-03
E _{FW} (CTUe)	6.68E+01	6.87E+01	7.57E+01	6.12E+01	6.12E+01	6.26E+01
MFRRD (kg Sb _{eq})	1.49E-04	1.52E-04	1.65E-04	1.36E-04	1.35E-04	1.37E-04
Impact category	LP400 °C	LP500 °C	LP650 °C	OrP400 °C	OrP500 °C	OrP650 °C
CED (MJ)	6.29E+01	6.24E+01	6.38E+01	6.36E+01	6.35E+01	6.55E+01
GWP (kg CO _{2eq})	3.70E+00	3.66E+00	3.74E+00	3.74E+00	3.73E+00	3.84E+00
ODP (kg CFC-11 _{eq})	5.29E-07	5.23E-07	5.32E-07	5.35E-07	5.33E-07	5.46E-07
HT-nce (CTUh)	1.42E-06	1.40E-06	1.42E-06	1.43E-06	1.42E-06	1.45E-06
HT-ce (CTUh)	2.66E-07	2.62E-07	2.66E-07	2.69E-07	2.67E-07	2.73E-07
PM (kg PM _{2.5eq})	1.78E-03	1.77E-03	1.80E-03	1.80E-03	1.80E-03	1.85E-03
IR-hh (kBq U ²³⁵ _{eq})	5.51E-01	5.46E-01	5.59E-01	5.57E-01	5.57E-01	5.73E-01
IR-E (CTUe)	1.60E-06	1.58E-06	1.62E-06	1.62E-06	1.61E-06	1.66E-06
POFP (kg NMVOC _{eq})	8.32E-03	8.24E-03	8.42E-03	8.41E-03	8.40E-03	8.64E-03
AP (mol H ⁺ _{eq})	2.89E-02	2.88E-02	2.95E-02	2.93E-02	2.93E-02	3.03E-02
EU _T (mol N _{eq})	8.38E-02	8.34E-02	8.58E-02	8.47E-02	8.50E-02	8.80E-02
EU _F (kg P _{eq})	1.32E-03	1.31E-03	1.34E-03	1.34E-03	1.34E-03	1.37E-03
EU _M (kg N _{eq})	5.83E-03	5.75E-03	5.83E-03	5.89E-03	5.86E-03	5.98E-03
E _{FW} (CTUe)	6.51E+01	6.47E+01	6.64E+01	6.59E+01	6.60E+01	6.82E+01
MFRRD (kg Sb _{eq})	1.45E-04	1.43E-04	1.45E-04	1.47E-04	1.46E-04	1.49E-04

The sensitivity analysis results of the transport distance are illustrated in Table 9.

Table 9. Sensitivity analysis results – Transport distance, percentage variations between the scenarios examined and the reference scenario

Impact category	OrP500 - RS	OrP500 - TD200 (%)	OrP500 - TD300 (%)
CED (MJ)	8.05E+01	16%	33%
GWP (kg CO _{2eq})	4.73E+00	18%	36%
ODP (kg CFC-11 _{eq})	6.74E-07	23%	46%
HT-nce (CTUh)	1.80E-06	11%	22%
HT-ce (CTUh)	3.38E-07	8%	15%
PM (kg PM _{2.5eq})	2.28E-03	17%	33%
IR-hh (kBq U ²³⁵ _{eq})	7.04E-01	9%	18%
IR-E (interim) (CTUe)	2.04E-06	20%	39%
POFP (kg NMVOC _{eq})	1.06E-02	18%	36%
AP (mol H ⁺ _{eq})	3.71E-02	7%	13%
EU _T (mol N _{eq})	1.08E-01	5%	10%
EU _F (kg P _{eq})	1.69E-03	4%	8%
EU _M (kg N _{eq})	7.42E-03	6%	13%
E _{FW} (CTUe)	8.35E+01	6%	12%
MFRRD (kg Sb _{eq})	1.84E-04	36%	71%

The analysis shows that, compared to the reference scenario, the environmental impacts increase of percentages ranging from 4% (for EU_F) up to 36% (for MFRRD) in the TD-200 scenario, and from 8% (for EU_F) up to 71% (for MFRRD) in the TD-300 scenario. Then, the transport distance affects the results obtained significantly.

The sensitivity analysis results of the renewable electricity scenario are illustrated in Table 10.

Table 10. Sensitivity analysis results – Renewable electricity, percentage variations between the scenarios examined and the reference scenario

Impact category	OrP500 °C (RES)	Percentage variation (RES-RS)/RS
CED (MJ)	5.91E+01	-27%
GWP (kg CO _{2eq})	2.34E+00	-50%
ODP (kg CFC-11 _{eq})	4.14E-07	-39%
HT-nce (CTUh)	1.73E-06	-4%
HT-ce (CTUh)	2.87E-07	-15%
PM (kg PM _{2.5eq})	1.42E-03	-38%
IR-hh (kBq U ²³⁵ _{eq})	2.88E-01	-59%
IR-E (interim) (CTUe)	1.03E-06	-49%
POFP (kg NMVOC _{eq})	6.04E-03	-43%
AP (mol H ⁺ _{eq})	1.12E-02	-70%
EU _T (mol N _{eq})	2.23E-02	-79%
EU _F (kg P _{eq})	1.14E-03	-32%
EU _M (kg N _{eq})	5.35E-03	-28%
E _{FW} (CTUe)	1.11E+02	33%
MFRRD (kg Sb _{eq})	2.74E-04	49%

The sensitivity analysis highlights that the implementation of renewable energy technologies for the electricity generation has a large effect on the results obtained since the electricity consumed during the operational phase is the major

contributor to the total impacts. The environmental impacts decrease in all the examined impact categories with the exception of the E_{FW} and MFRRD categories.

4 Conclusions

In this paper, bio-char obtained from the pyrolysis process of different biomass residues under different operation conditions is investigated from an environmental point of view, following a life cycle approach. In detail, 1 MJ of thermal energy potentially released during the completely combustion of bio-char obtained from the pyrolysis of olive tree trimmings, olive pomace, lemon peels and orange peels wastes under three different temperatures, i.e. 400, 500 and 650 °C, is assumed as reference for the LCA. The analysis is based on a real pyrolysis system and on primary data directly collected in the laboratory.

The study highlights that, under the examined conditions, the pyrolysis temperature has a negligible influence on the environmental impacts of the selected FU. Indeed, for each biomass, the percentage differences among the environmental impacts associated to the FU from bio-char obtained from pyrolysis processes carried out at temperatures of 400, 500 and 650 °C are, in most cases, lower than 5%. The best environmental performances are obtained at 400 °C peak operation temperature for olive bio-wastes and at 500 °C for citrus bio-wastes. For each feedstock, the worse environmental performances are obtained in correspondence of the pyrolysis process performed at 650 °C, due to the higher electricity requirement and the lower energy properties of the bio-char at this temperature compared to the other ones.

Conversely, the environmental impacts of FU are influenced by the type of input biomass. Specifically, the lowest environmental impacts for each peak operation temperature are caused by the FU associated to bio-char from the pyrolysis of orange peels wastes. In detail, an average percentage decreases of about 16% of the impacts is observed if compared with those of the FU associated to bio-char from the pyrolysis of olive tree trimmings, that is the worst configuration among those examined from an environmental sustainability point of view. These outcomes confirm the importance to carry out experimental campaigns and LCA studies in order to identify the biomasses and operating conditions allowing to obtain bio-char with the best energy performance and lower environmental impacts associated with its production.

The contribution analysis allows to identify the most impactful process, and then to identify the potential area of improvement of the examined pyrolysis process. In detail, the contribution analysis shows that the electricity consumed during the operational phase is responsible for the largest impacts in all the examined impact categories. Therefore, to increase the sustainability of the examined system it is necessary to adopt more energy efficient processes and technologies. In particular, in a scaled – up pyrolysis system a significant improvement can be achieved by employing cleaner energy sources (e.g. RESs) for the electricity generation, or by installing a combustion system self-fuelled with bio-char obtained from the pyrolysis process to provide the thermal energy required by the process.

The sensitivity analysis highlights that if the environmental burdens are partitioned between bio-char and the co-product bio-oil, the impacts associated to the selected FU decreases significantly. This result confirms the importance of implementing a full circular economy management strategy by enhancing all the co-products leaving a production system in order to improve its efficiency and consequently reduce its environmental impacts. In addition, the sensitivity analysis results show that when bio-oil is considered as a value product the best environmental performance is obtained for the pyrolysis of olive pomace residues and not for the pyrolysis of orange peel residues. This outcome highlights the importance of analysing a system as a whole in order to obtain a complete and reliable environmental assessment suitable for supporting decision makers.

Transport distance affects significantly the results of the environmental assessment. This outcome allows recommendation to reduce transport distance through the adoption of distributed pyrolysis systems near farms powered by local or short-chain biomasses. Therefore, it is important to plan a local biomass logistics that allows the maximum exploitation of the available potential, reducing losses and economic and environmental costs connected to biomasses transport.

Finally, the sensitivity analysis results of the renewable electricity scenario show that the implementation of a PV plant can be a suitable solution for the examined product system in order to increase its environmental sustainability.

The obtained results can support the designers in scaling-up the examined system and in identifying the best operational conditions and biomasses in terms of energy and environmental performance, and the decision makers in planning strategies and financial resources to maximize the obtained benefits relative to the effort expended.

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