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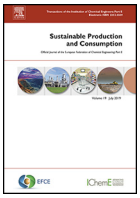

Research article

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

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ABSTRACT

The bio-wastes pyrolysis is a waste to energy strategy that converts bio-wastes into valuable products (bio-char, bio-oil) with wide use in the agri-food sector. However, limited efforts are paid to the investigation of its environmental sustainability: in this context, the study contributes the need towards the assessment of a wide range of environmental impacts for the pyrolysis process of different types of bio-wastes under different operating conditions. The study estimates the potential environmental impacts related to bio-char production from the pyrolysis of several different agro-industrial residues and different temperatures and identifies the process "hot spots". 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 affects the environmental impacts of the pyrolysis process more than the peak pyrolysis temperature. Among the biomasses tested, 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, followed by bio-wastes transportation. In detail, the contribution of the electricity to the total impact ranges from minimum values of about 44% (for cumulative energy demand) up to 91% (for terrestrial eutrophication), while transportation contributions range from a minimum of about 4% (for terrestrial and marine eutrophication) to 36% for mineral, fossil and renewable resource depletion.

Therefore, the use of more energy efficient processes and technologies and the diffusion of distributed pyrolysis systems near farms can significantly improve the environmental performance of the system examined.

1. Introduction

Energy and raw materials supply and waste management are key elements towards a more sustainable and circular economy transition (Beccali et al., 2001; European Commission, 2019, 2018). 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 (European Commission, 2015). 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 (Cusenza et al., 2021; European Commission, 2017; Vamvuka, 2011). 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 incineration, gasification, anaerobic digestion, pyrolysis, etc. (Saveyn et al., 2016). Among

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these technologies, pyrolysis of waste is receiving increasing attention (Barr et al., 2020; Chen et al., 2015; Fernandez-Lopez et al., 2015; Kim et al., 2020; Roy and Dias, 2017; Volpe et al., 2016, 2019). 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 a liquid product (bio-oil), a solid product (bio-char) and uncondensed vapour and gases. The outputs of the pyrolysis process of organic materials have several potential uses: bio-oil can be combusted in industrial boilers/furnaces or upgraded into biodiesel, bio-char can also be used for power generation and as a soil amendment to improve soil quality and sequester carbon (Roy and Dias, 2017). Additionally, small pyrolysis plants are compatible with existing agriculture and forestry infrastructure, providing considerable flexibility for the feedstock (Laird et al., 2009) and preventing long distance transportation. Pyrolysis processes can be categorized as slow, intermediate, fast and flash pyrolysis (IEA - International Energy Agency, 2007). Their differences depend on the heating rate and heating duration that entail a different output ratio (Kung and Zhang, 2015). 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. These studies focus mainly 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 (Kim et al., 2020). These ex-ante analyses at the early stage of development are important as offer the opportunity to improve the performances of new processes and technologies before their industrial production. Among these, Grycová et al. (2016) 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. (2015) treated pyrolysis experiments on citrus residues in a lab scale fixed bed reactor, in order to investigate the effects of peak temperature in mass and energy yields of bio-char and bio-oil. Bhattacharjee and Biswas (2019) conducted the pyrolysis of orange bagasse in order to investigate the effect of temperature, heating rate and N_2 gas flow rate on the product yields and their energy properties. Aguiar et al. (2008) 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. (2014) 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). Only few studies deal with the environmental impacts of bio-wastes pyrolysis process (Parascanu et al., 2018). The evaluation of the environmental impacts estimated for different operating conditions and the hot spots analysis of an innovative process at an early stage of development are of fundamental importance to mitigate any adverse impact at the design stage (eco-design) up to industrial scale (Tecchio et al., 2016; Tomatis et al., 2020). Fernandez-Lopez et al. (2015) estimated the greenhouse gas (GHG) emissions due to a pyrolysis treatment of swine and dairy manure samples. Authors compared the GHG associated to the pyrolysis process of the manure pre-treated through an anaerobic digestion (AD) process with those related to the pyrolysis process of not digested manure. The pyrolysis process was simulated using the Aspen Plus® software. The results showed that GHG emissions related to the pyrolysis process were lower for the samples that were pre-treated in the AD process. Ibarrola et al. (2012) compared the carbon equivalent abatement achievable through slow, fast pyrolysis and gasification treatments of biodegradable wastes or residues. The analysis showed that slow pyrolysis had the best performance in terms of carbon abatement. Ayer and Dias (2018) assessed the life cycle impact of producing bio-oil and bio-char from the fast pyrolysis process of forest harvest residues through the Life Cycle Assessment (LCA) methodology (ISO, 2020a) . The pyrolysis process analysis was based on primary data. The functional unit (FU) was 1 kg of bio-oil from the pyrolysis process, the system boundaries included the pyrolizer infrastructure, feedstock acquisition, transport and drying, the fast pyrolysis process and the electricity needed to power the pyrolizer. The impact categories chosen were photochemical oxidant formation, respiratory effects, acidification, global warming, eutrophication, and ozone depletion (TRACI 2.1 method). The main contribution (over 70%) to photochemical oxidant formation, respiratory effects, and acidification was due to the air emissions from the pyrolysis process, followed by the chipping of forest residues. The transportation process of the forest residues accounted for just over 25% of global warming and ozone depletion. A sensitivity analysis showed that when the transportation distance of the forest residues was increased from 40 to 100 km, the impact on global warming increased by 40%. Heidari et al. (2019) applied the LCA to the production process of bio-oil from eucalyptus wood via fast pyrolysis, at temperatures of 450°C, 500°C and 650°C. The FU was 1 kg of pyrolysis product of eucalyptus wood. The system boundaries included biomass transportation, biomass crushing and drying and bio-oil production. The processes were modelled using data inferred from laboratory experiments. The obtained results were the life cycle impacts based on CML 2 baseline (Guinée et al., 2002) and Product Environmental Footprint (PEF) methods (European Commission, 2013). Parascanu et al. (2018) performed the LCA of the pyrolysis treatment, at a temperature of 600°C, of olive pomace estimating the impact on a wide range (13) of environmental categories. In detail, authors simulated the pyrolysis process of olive pomace waste with the Aspen Plus® software. The FU was 100 kg of olive pomace, system boundaries included: biomass grinding and drying, pyrolysis, separation of gases and char by means of a cyclone and gas cooling using an air heat exchanger followed by a water one, and a last stage of separation of gases and tar in a flash separator. Results showed that electricity required to perform the whole pyrolysis process was responsible for the largest contribution to the examined impact categories. Mong et al. (2021) performed the LCA of the microwave pyrolysis of horse manure at a temperature of 550°C. The FU was 1 ton of dried manure and the system boundaries included biomass transportation, biomass drying, grinding, and feeding into the pyrolysis reactor, pyrolysis itself and a quenching process. The processes were modelled using data inferred from laboratory experiments. The authors assessed the impact on global warming, photo-oxidant formation, acidification, human toxicity, and eutrophication potential and identified the unit process responsible for the higher contribution to the impacts. The results highlighted that the biomass transportation accounted for the largest contribution to almost all the examined impact categories. The exception was global warming in which the heat required for pyrolysis contributed the greatest amount.

As a summary of the results of the literature review, it can be stated that the field of LCAs of pyrolysis process of bio-wastes is quite recent. The pyrolysis process modelling is based on laboratory experiments or simulation tools and the studies examined often focus on a limited number of impact categories.

In this context, the study aims at providing a reliable support towards the eco-design of the pyrolysis processes of residual bio-wastes from the agri-food sector. For this purpose, the authors perform an early LCA with primary data from a laboratory scale equipment and estimate the energy and environmental impacts associated to a slow pyrolysis process of residual biomasses highlighting the environmental hot spots. Moreover, to provide stakeholders with a set of data to support the choice of the best operating conditions from the point of view of energy - environmental impacts, the pyrolysis process of different biomass residues (i.e., olive tree trimmings, olive pomace, lemon peels and orange peels) under diverse operation conditions (i.e., pyrolysis temperature of 400, 500 and 650°C) is investigated. In addition, a sensitivity analysis is performed to:

- assess the impact of transportation on the results. Among the studies examined, only Ayer and Dias (2018) estimated the effects of residual biomasses transportation distance in LCA results.
- assess the impacts on the results of the methodological assumptions on the partitioning of the environmental burdens among the pyrolysis products (bio-char and bio-oil);
- provide a preliminary estimate of the potential benefits achievable by using electricity from renewable sources in the pyrolysis process.

In relation to the literature examined, the paper main contributions are:

- the LCA results of the pyrolysis process of bio-wastes, olive tree trimmings, olive pomace, lemon peels and orange peels, not previously investigated except for olive pomace. These results can be of interest for the Mediterranean context where the management of the organic wastes from olive and citrus processing industries is a widespread activity;
- the estimation of a wide range of energy and environmental impact categories covering the complexity of the environmental sustainability consistent with the aim of avoiding burden-shifting among impact categories;
- the assessment of the effect of the transportation distance on the impacts of the bio-wastes pyrolysis;
- the LCA results of the pyrolysis process of different types of bio-wastes under different operating conditions (i.e., pyrolysis temperature) allowing to estimate how these parameters effectively affect the obtained results;
- the estimation of the potential environmental benefits achievable, within the use of different bio-wastes and different operating conditions, by introducing a full circular economy management approach towards the management of co-products

The evaluation of early LCA results can identify potential opportunities for improvement and provide a reliable support to the industrial decision makers and product developers toward the sustainable design of bio-wastes pyrolysis processes up to industrial scale (Longo et al., 2017). Moreover, the sensitivity analysis of the transport distance can provide useful information in planning the installation of the pyrolysis plant taking into account the contribution of the biomasses transportation distance to the overall impacts, e.g., fixing a maximum supply distance based on the maximum contribution deemed acceptable for the transport phase.

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. Materials and method

2.1. The examined system

The pyrolysis reactor investigated is a real system installed at the laboratory of Environment and Energy of the University “Kore” of Enna (Sicily, Italy) (Fig. 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.

Fig. 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 N_2) 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 different 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 (IEA - International Energy Agency, 2007). 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.

The energy properties of bio-char derived from pyrolysis are related to pyrolysis temperature and biomass residues composition in input. In this study the bio-char obtained from the slow pyrolysis processes of olive tree trimmings (OT), olive pomace (OP), lemon peels (LP) and orange peels (OrP) bio-wastes under three different temperatures, i.e. 400, 500 and 650°C. Table 1 shows the higher heating values of bio-char and bio-oil produced under the examined pyrolysis processes.

2.2. Life cycle assessment

The LCA is carried out in compliance with the international standards of series ISO 14040 (ISO, 2020a,b).

2.2.1. Goal and scope definition

The main goals of the LCA 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 hot spots 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 envi-

Table 1
Higher heating values of bio-char and bio-oil obtained from bio-wastes pyrolysis (Volpe et al., 2015, 2014).

Peak temperature (°C)	Higher heating values [MJ/kg]							
	Olive tree trimmings		Olive pomace		Lemon peel		Orange peel	
	Bio-char[*]	Bio-oil[**]	Bio-char	Bio-oil	Bio-char	Bio-oil	Bio-char	Bio-oil
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

[*] Bio-char: solid output of the pyrolysis process of organic materials

[**] Bio-oil: liquid output of the pyrolysis process of organic materials

Table 2
Reference flows for each compared biomass residues and pyrolysis temperature.

Pyrolysis temperature [°C]	OT [kg]	OP [kg]	LP [kg]	OrP [kg]
400	3.63×10^{-2}	3.33×10^{-2}	3.28×10^{-2}	3.20×10^{-2}
500	3.76×10^{-2}	3.34×10^{-2}	3.20×10^{-2}	3.14×10^{-2}
650	4.13×10^{-2}	3.33×10^{-2}	3.23×10^{-2}	3.19×10^{-2}

ronmental 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, a transport distance of 100 km is assumed for biomasses supply 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 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. 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. The reference flows are calculated on the basis of the higher heating values of bio-char from bio-wastes pyrolysis (Table 1) are illustrated in Table 2.

The analysis follows a "from cradle-to-gate" approach. The system boundaries include the construction of the equipment, transport of the biomass residues to the laboratory (transport distance of 100 km), the pre-treatments consisting of drying and grinding the biomass residues before entering the pyrolysis reactor, the pyrolysis process including the energy and material consumption during the operational phase, the treatment of the wastewater process. The transportation process also includes the construction processes and the disposal at the end-of-life of the vehicle. Concerning the construction phase of the reactor only the components specifically realized for performing the pyrolysis experiments are included in the analysis. The lifetime of the reactor components is assumed equal to 5 years (5 years is the useful life of most reactor components). More details about the construction phase are available in Paragraph 2.2.2.3.

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

The impact assessment is based on the ILCD 2011 midpoint method and impact categories recommended by the European Commission (EC-JRC, 2012), 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 (EC-JRC - Institute for Environment and Sustainability., 2011). The ILCD 2011 method is chosen as it provides a large set of environmental indicators consistent with the sustainability objective of avoiding burden-shifting among impact categories (Hauschild et al., 2018). In addition, the ILCD impact categories are complemented by the cumulative energy demand (CED) method for the primary energy requirement estimation (Frischknecht et al., 2007).

2.2.2. 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 quantify, 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, wastes, products and co-products. Both primary and secondary data are used for the generation 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 phase. 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 (Wernet et al., 2016).

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.

2.2.3. 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 (Longo et al., 2020). The secondary dataset for the biomass residues transport process refers to transport with freight, lorry 16-32 metric ton from the Ecoinvent 3.6 Database.

2.2.4. 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

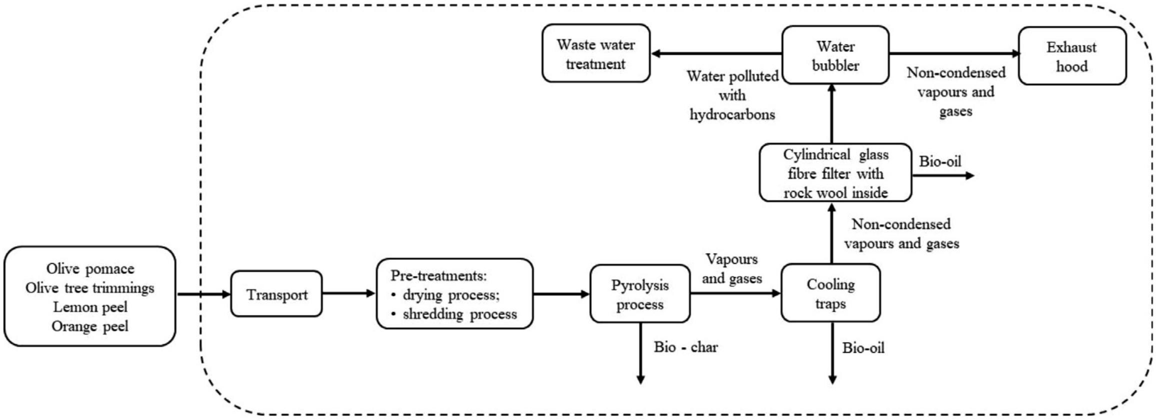


Fig. 2. Schematic representation of the system boundaries.

(1.3 kW) at a constant temperature of 105°C for 12 hours. After the drying phase, 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 1.56×10^{-2} kWh and 2.50×10^{-3} 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, inferred from the Ecoinvent 3.6 Database.

2.2.5. Pyrolysis process

Three slow pyrolysis tests, each of them characterized by a different temperature (400 – 500 – 650°C), have been performed 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 (Volpe et al., 2014). When the 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 (N_2) 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, 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 has a relatively high concentration of 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 (1.4 kW) to recover the bio-oil (Volpe et al., 2014). A schematic representation of the examined pyrolysis process is reported in in Fig. 3.

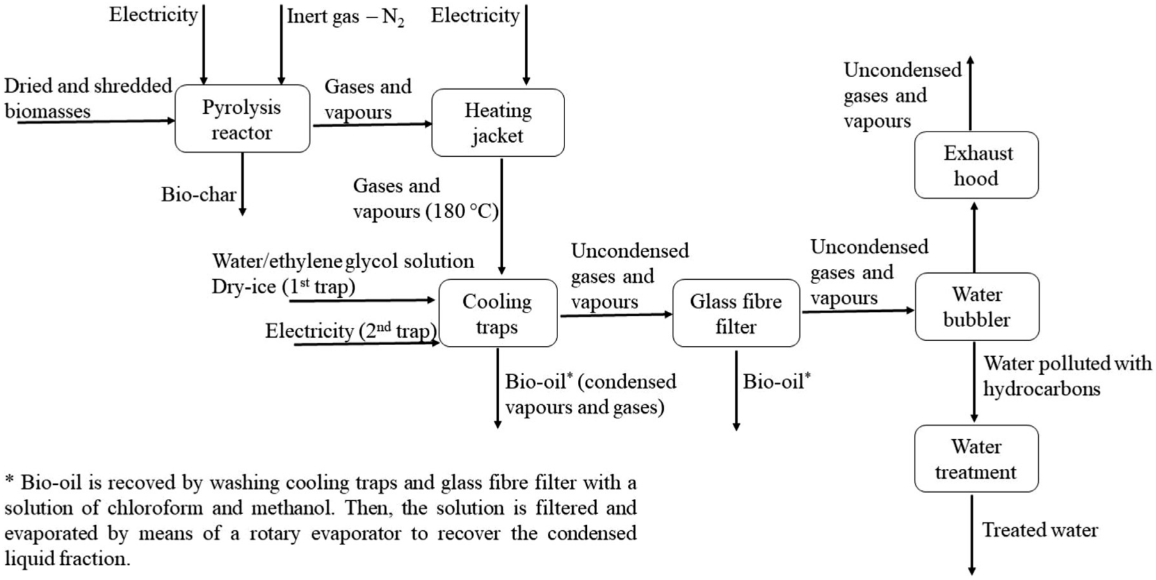
The inventory data for the pyrolysis reactor construction process modelling are shown in Table 3, while Table 4 shows the inventory data for the pyrolysis process. About the construction phase only the equipment specifically realised for performing pyrolysis experiments are accounted for. In particular, the construction process of the oven and the ultra-centrifugal mill used for pre-treating the biomass residues, the furnace used for heating the reactor and the rotary evaporator are not included in the analysis. Moreover, concerning the construction process of the reactor (Table 3) only the main materials of each component is made of are included in the analysis, while the energy consumed for the assembly process is not considered due to the lack of reliable data. Data for the pyrolysis reactor construction process in Table 3 are referred to a pyrolysis cycle. The impacts are allocated to a single pyrolysis cycle considering a maximum number of 1,000 experiments during the equipment lifetime hypothesized (5 years).

3. Results and discussion

3.1. 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 5. 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 worst 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 a bio-char with lower energy properties compared to the other ones. However, 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 clarify that the type of biomass influences the environmental impacts of the selected FU. In detail, the pyrolysis of orange peels shows the lower environmental impacts 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 performances. The impacts in all the energy and environmental categories 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 show, respectively, impacts higher than 6% and 3% compared to the OrP500°C configuration.



* Bio-oil is recoved by washing cooling traps and glass fibre filter with a solution of chloroform and methanol. Then, the solution is filtered and evaporated by means of a rotary evaporator to recover the condensed liquid fraction.

Fig. 3. Pyrolysis process.

Table 3
Inventory data used for the reactor construction process referring to a pyrolysis cycle.

Component	Material	Amount
Mobile supporting structure of the furnace [kg]	Steel	7.25×10^{-3}
Heating jacket		
Case [kg]	Steel	1.51×10^{-3}
Electrical resistance [kg]	Copper wire	2.48×10^{-9}
Biomass holder [kg]	Stainless steel	2.74×10^{-5}
Reactor and cap [kg]	Quartz	1.59×10^{-4}
Cooling traps		
First cooling trap [kg]	Glass	1.24×10^{-4}
Caps for the first cooling trap [kg]	Plastic	5.72×10^{-6}
Second cooling trap [kg]	Glass	1.26×10^{-4}
Cap for the second cooling trap [kg]	Plastic	1.53×10^{-5}
Casing for the second cooling trap [kg]	Aluminium	3.89×10^{-6}
Filter		
Case [kg]	Glass fibre	1.80×10^{-5}
Infill material [kg]	Rock wool	2.70×10^{-7}
Caps for the filter [kg]	Plastic	1.03×10^{-5}
Bubbler [kg]	Glass	3.34×10^{-4}
Junctions [kg]	Synthetic rubber	1.27×10^{-5}
Pipes [kg]	Synthetic rubber	2.16×10^{-4}

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

Pyrolysis process	Amount
Biomass residues [kg]	1.00×10^{-2}
Inert gas - N_2 [m^3]	4.50×10^{-2}
Dry ice [kg]	2.00×10^{-1}
Methanol [m^3]	6.00×10^{-6}
Chloroform [m^3]	2.40×10^{-5}
Water used in the bubbler (replaced every 4 cycles) [kg]	3.33×10^{-2}
Electricity - pyrolysis process (peak temperature: 400°C) [kWh]	2.43×10^{-1}
Electricity - pyrolysis process (peak temperature: 500°C) [kWh]	2.67×10^{-1}
Electricity - pyrolysis process (peak temperature: 650°C) [kWh]	3.02×10^{-1}
Electricity - heating jacket [kWh]	1.10×10^{-1}
Electricity-second cooling trap [kWh]	8.25×10^{-2}
Electricity – rotary evaporator [kWh]	1.40
Waste to end-of-life treatments	
Polluted water exiting the bubbler [kg]	3.33×10^{-2}
Output to technosphere	
Bio-char [kg]	6.00×10^{-3}
Bio-oil [kg]	3.00×10^{-3}
Uncondensed vapour and gases [kg]	1.00×10^{-3}

The trend of environmental impacts in different life cycle steps is quite similar for the different types of biomasses and process temperatures. Consequently, Fig. 4, referred to the OrP500°C configuration, can be considered representative of all the examined configurations.

The operation phase is responsible for the larger contribution to all the impacts considered, with percentages ranging from minimum values of about 44% (for EU_M) up to 91% (for EU_T). This result is in agreement with the studies developed by Ayer and Dias (2018) and Parascanu (2018). The contribution of the electricity to the total impact of the operational phase ranges from a minimum of about 40% (for EU_M) up to 92% (for MFRRD). A more detailed analysis of the impacts associated to the operational phase (excluding equipment construction, biomass residues transportation and wastewater treatment) 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

Table 5
Life cycle energy and environmental impacts – impacts refer to the defined FU.

Impact category	OT400°C	OT500°C	OT650°C	OP400°C	OP500°C	OP650°C
CED (MJ)	91.9	96.2	108.0	84.3	85.5	87.0
GWP (kg CO_{2eq})	5.41	5.65	6.32	4.96	5.02	5.10
ODP (kg CFC-11_{eq})	7.74×10^{-7}	8.07×10^{-7}	8.98×10^{-7}	7.10×10^{-7}	7.17×10^{-7}	7.25×10^{-7}
HT-nce (CTUh)	2.07×10^{-6}	2.15×10^{-6}	2.39×10^{-6}	1.90×10^{-6}	1.91×10^{-6}	1.93×10^{-6}
HT-ce (CTUh)	3.89×10^{-7}	4.05×10^{-7}	4.49×10^{-7}	3.57×10^{-7}	3.59×10^{-7}	3.63×10^{-7}
PM (kg $PM_{2.5eq}$)	2.61×10^{-3}	2.72×10^{-3}	3.04×10^{-3}	2.39×10^{-3}	2.42×10^{-3}	2.46×10^{-3}
IR-hh (kBq ${U^{235}}_{eq}$)	8.05×10^{-1}	8.43×10^{-1}	9.43×10^{-1}	7.39×10^{-1}	7.48×10^{-1}	7.61×10^{-1}
IR-E (interim) (CTUe)	2.34×10^{-6}	2.44×10^{-6}	2.73×10^{-6}	2.14×10^{-6}	2.17×10^{-6}	2.20×10^{-6}
POFP (kg $NMVOC_{eq}$)	1.22×10^{-2}	1.27×10^{-2}	1.42×10^{-2}	1.12×10^{-2}	1.13×10^{-2}	1.15×10^{-2}
AP (mol ${H^+}_{eq}$)	4.23×10^{-2}	4.44×10^{-2}	4.99×10^{-2}	3.88×10^{-2}	3.94×10^{-2}	4.03×10^{-2}
EU_T (mol N_{eq})	1.22×10^{-1}	1.29×10^{-1}	1.45×10^{-1}	1.12×10^{-1}	1.14×10^{-1}	1.17×10^{-1}
EU_F (kg P_{eq})	1.94×10^{-3}	2.02×10^{-3}	2.26×10^{-3}	1.78×10^{-3}	1.80×10^{-3}	1.82×10^{-3}
EU_M (kg N_{eq})	8.52×10^{-3}	8.87×10^{-3}	9.84×10^{-3}	7.82×10^{-3}	7.88×10^{-3}	7.95×10^{-3}
E_{FW} (CTUe)	95.2	99.9	112.0	87.4	88.7	90.6
MFRRD (kg Sb_{eq})	2.12×10^{-4}	2.21×10^{-4}	2.45×10^{-4}	1.95×10^{-4}	1.96×10^{-4}	1.98×10^{-4}
Impact category	LP400°C	LP500°C	LP650°C	OrP400°C	OrP500°C	OrP650°C
CED (MJ)	83.0	82.0	84.2	80.9	80.5	83.2
GWP (kg CO_{2eq})	4.88	4.82	4.94	4.76	4.73	4.88
ODP (kg CFC-11_{eq})	6.99×10^{-7}	6.88×10^{-7}	7.02×10^{-7}	6.81×10^{-7}	6.75×10^{-7}	6.94×10^{-7}
HT-nce (CTUh)	1.87×10^{-6}	1.84×10^{-6}	1.87×10^{-6}	1.82×10^{-6}	1.80×10^{-6}	1.85×10^{-6}
HT-ce (CTUh)	3.51×10^{-7}	3.45×10^{-7}	3.51×10^{-7}	3.42×10^{-7}	3.38×10^{-7}	3.47×10^{-7}
PM (kg $PM_{2.5eq}$)	2.35×10^{-3}	2.32×10^{-3}	2.38×10^{-3}	2.29×10^{-3}	2.28×10^{-3}	2.35×10^{-3}
IR-hh (kBq ${U^{235}}_{eq}$)	7.27×10^{-1}	7.18×10^{-1}	7.37×10^{-1}	7.09×10^{-1}	7.05×10^{-1}	7.28×10^{-1}
IR-E (interim) (CTUe)	2.11×10^{-6}	2.08×10^{-6}	2.13×10^{-6}	2.06×10^{-6}	2.04×10^{-6}	2.11×10^{-6}
POFP (kg $NMVOC_{eq}$)	1.10×10^{-2}	1.08×10^{-2}	1.11×10^{-2}	1.07×10^{-2}	1.06×10^{-2}	1.10×10^{-2}
AP (mol ${H^+}_{eq}$)	3.82×10^{-2}	3.78×10^{-2}	3.90×10^{-2}	3.72×10^{-2}	3.71×10^{-2}	3.85×10^{-2}
EU_T (mol N_{eq})	1.11×10^{-1}	1.10×10^{-1}	1.13×10^{-1}	1.08×10^{-1}	1.08×10^{-1}	1.12×10^{-1}
EU_F (kg P_{eq})	1.75×10^{-3}	1.72×10^{-3}	1.76×10^{-3}	1.71×10^{-3}	1.69×10^{-3}	1.74×10^{-3}
EU_M (kg N_{eq})	7.70×10^{-3}	7.56×10^{-3}	7.70×10^{-3}	7.50×10^{-3}	7.42×10^{-3}	7.60×10^{-3}
E_{FW}(CTUe)	86.0	85.1	87.7	83.8	83.5	86.6
MFRRD (kg Sb_{eq})	1.92×10^{-4}	1.88×10^{-4}	1.91×10^{-4}	1.87×10^{-4}	1.85×10^{-4}	1.89×10^{-4}

*Cumulative Energy Demand (CED); Global Warming Potential (GWP); Ozone Depletion Potential (ODP); Human Toxicity - no cancer effect (HT–nce); Human Toxicity - cancer effect (HT–ce); Particulate Matter (PM); Ionizing Radiation, human health (IR-hh); Ionizing Radiation, ecosystem (IR-e); Photochemical Ozone Formation (POFP); Acidification (AP); Terrestrial Eutrophication (EU_T); Freshwater Eutrophication (EU_F); Marine Eutrophication (EU_M); Freshwater ecotoxicity (E_{FW}); Mineral, fossil and renewable resource depletion (MFRRD).

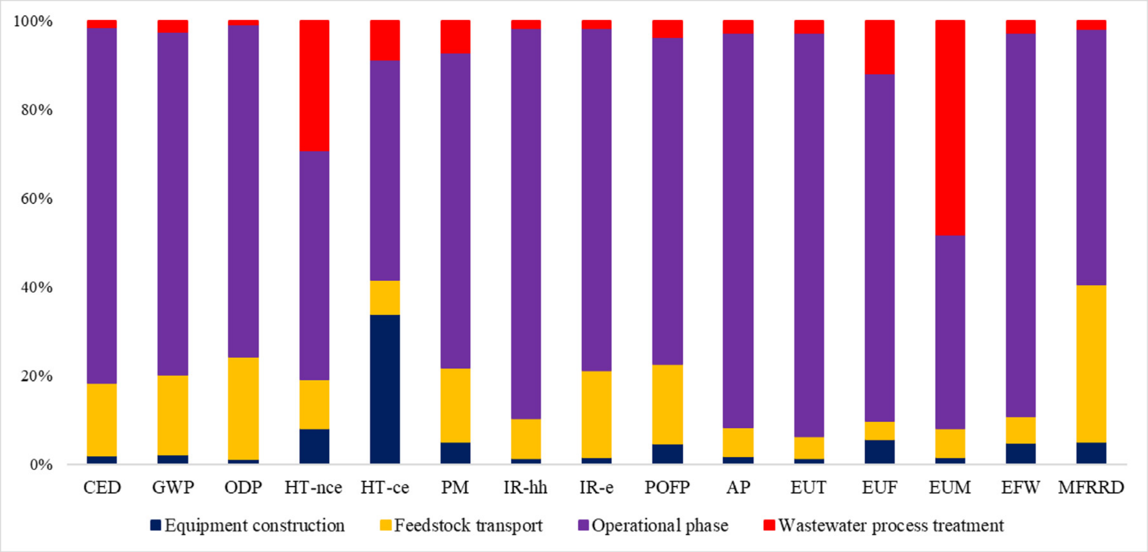


Fig. 4. Life cycle energy and environmental impacts – contribution analysis.

a minimum of about 11% (for MFRRD) up to 20% (for E_{FW}, 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%). Table 6 shows a detail of the energy and environmental impacts related to the electricity consumption during the operational phase.

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%).

Table 6
Energy and environmental impacts related to the electricity consumption during the operational phase – impacts refer to the defined FU.

Impactcategory	Drying and shredding processes	Pyrolysis process	Heating jacket	Cold trap	Rotary evaporator
CED (MJ)	7.74×10^{-1}	11.4	4.70	3.53	32.9
GWP (kg CO_{2eq})	4.12×10^{-2}	6.06×10^{-1}	2.50×10^{-1}	1.88×10^{-1}	1.75
ODP (kg CFC-11_{eq})	4.48×10^{-9}	6.61×10^{-8}	2.72×10^{-8}	2.04×10^{-8}	1.91×10^{-7}
HT-nce (CTUh)	9.33×10^{-9}	1.37×10^{-7}	5.67×10^{-8}	4.25×10^{-8}	3.97×10^{-7}
HT-ce (CTUh)	1.77×10^{-9}	2.60×10^{-8}	1.07×10^{-8}	8.05×10^{-9}	7.51×10^{-8}
PM (kg $PM_{2.5eq}$)	1.98×10^{-5}	2.92×10^{-4}	1.20×10^{-4}	9.02×10^{-5}	8.42×10^{-4}
IR-hh (kBq $U^{235}{}_{eq}$)	6.65×10^{-3}	9.80×10^{-2}	4.04×10^{-2}	3.03×10^{-2}	2.83×10^{-1}
IR-E (interim) (CTUe)	1.68×10^{-8}	2.47×10^{-7}	1.02×10^{-7}	7.64×10^{-8}	7.13×10^{-7}
POFP (kg $NMVOC_{eq}$)	9.47×10^{-5}	1.40×10^{-3}	5.76×10^{-4}	4.32×10^{-4}	4.03×10^{-3}
AP (mol $H^{+}{}_{eq}$)	4.31×10^{-4}	6.36×10^{-3}	2.62×10^{-3}	1.97×10^{-3}	1.84×10^{-2}
EU_T (mol N_{eq})	1.32×10^{-3}	1.95×10^{-2}	8.05×10^{-3}	6.04×10^{-3}	5.63×10^{-2}
EU_F (kg P_{eq})	1.34×10^{-5}	1.98×10^{-4}	8.16×10^{-5}	6.12×10^{-5}	5.71×10^{-4}
EU_M (kg N_{eq})	3.85×10^{-5}	5.67×10^{-4}	2.34×10^{-4}	1.75×10^{-4}	1.64×10^{-3}
E_{FW} (CTUe)	9.37×10^{-1}	13.8	5.69	4.27	39.9
MFRRD (kg Sb_{eq})	8.26×10^{-7}	1.22×10^{-5}	5.02×10^{-6}	3.76×10^{-6}	3.51×10^{-5}

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 3kW$_p$ slanted-roof installation			

Equipment construction is highly impacting on HT-nce (about 34%). From a dominance analysis of this step, it is noticeable that the support 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). The heating jacket causes 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 35% 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%). These results obtained are consistent with those obtained by Ayer and Dias (2018) that estimated a contribution over 25% for both GWP and ODP impacts for the biomasses transportation.

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%).

The LCA results of the analysis performed at the laboratory scale are not directly transferable to an industrial scale plant (Tecchio et al., 2016). In fact, although it is expected that energy related outputs obtained will not vary significantly in the scaling up of the process at the industrial scale, other process parameters can influence the environmental impacts. Many operations that in the laboratory are usually carried out manually, such as feeding the biomass into the reactor, extracting the bio-char, etc., could be automated at the industrial scale resulting in an additional consumption of electricity and, consequently, into higher environmental impacts. On the other hand, the process optimization and improvement related to the use of more efficient devices (for example to heat the pyrolysis reactor), the implementation of a thermal energy recovery system from bio-char and its employment for drying the biomasses in input, and the use of bio-oil and of a portion of bio-char to replace fossil fuels for heating the pyrolysis reactor (Ayer and Dias, 2018) could lead to lower environmental impacts associated to the bio-char produced by a slow pyrolysis process (Liu et al., 2013). Although the LCA results are not directly transferable to an industrial scale plant, they can provide useful information for orienting the research and the design up to industrial scale towards more sustainable solutions.

3.2. Sensitivity analysis

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

With reference to multifunctionality, 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), re-

Table 8
Sensitivity analysis results – multifunctionality management.

Impact category	OT400°C	OT500°C	OT650°C	OP400°C	OP500°C	OP650°C
CED (MJ)	64.5	66.2	72.7	59.1	59.0	60.1
GWP (kg CO_{2eq})	3.79	3.89	4.26	3.47	3.46	3.53
ODP (kg CFC-11_{eq})	5.43×10^{-7}	5.55×10^{-7}	6.06×10^{-7}	4.97×10^{-7}	4.94×10^{-7}	5.01×10^{-7}
HT-nce (CTUh)	1.45×10^{-6}	1.48×10^{-6}	1.61×10^{-6}	1.33×10^{-6}	1.32×10^{-6}	1.33×10^{-6}
HT-ce (CTUh)	2.73×10^{-7}	2.78×10^{-7}	3.03×10^{-7}	2.50×10^{-7}	2.48×10^{-7}	2.51×10^{-7}
PM (kg $PM_{2.5eq}$)	1.83×10^{-3}	1.87×10^{-3}	2.05×10^{-3}	1.67×10^{-3}	1.67×10^{-3}	1.70×10^{-3}
IR-hh (kBq $U^{235}{}_{eq}$)	5.65×10^{-1}	5.80×10^{-1}	6.36×10^{-1}	5.17×10^{-1}	5.16×10^{-1}	5.26×10^{-1}
IR-E (CTUe)	1.64×10^{-6}	1.68×10^{-6}	1.84×10^{-6}	1.50×10^{-6}	1.50×10^{-6}	1.52×10^{-6}
POFP (kg $NMVOC_{eq}$)	8.53×10^{-3}	8.75×10^{-3}	9.59×10^{-3}	7.81×10^{-3}	7.79×10^{-3}	7.93×10^{-3}
AP (mol $H^{+}{}_{eq}$)	2.97×10^{-2}	3.05×10^{-2}	3.36×10^{-2}	2.72×10^{-2}	2.72×10^{-2}	2.78×10^{-2}
EU_T (mol N_{eq})	8.59×10^{-2}	8.85×10^{-2}	9.76×10^{-2}	7.87×10^{-2}	7.88×10^{-2}	8.08×10^{-2}
EU_F (kg P_{eq})	1.36×10^{-3}	1.39×10^{-3}	1.52×10^{-3}	1.24×10^{-3}	1.24×10^{-3}	1.26×10^{-3}
EU_M (kg N_{eq})	5.98×10^{-3}	6.10×10^{-3}	6.64×10^{-3}	5.48×10^{-3}	5.43×10^{-3}	5.49×10^{-3}
E_{FW} (CTUe)	66.8	68.7	75.7	61.2	61.2	62.6
MFRRD (kg Sb_{eq})	1.49×10^{-4}	1.52×10^{-4}	1.65×10^{-4}	1.36×10^{-4}	1.35×10^{-4}	1.37×10^{-4}
Impact category	**LP400°C**	**LP500°C**	**LP650°C**	**OrP400°C**	**OrP500°C**	**OrP650°C**
CED (MJ)	62.9	62.4	63.8	63.6	63.5	65.5
GWP (kg CO_{2eq})	3.70	3.66	3.74	3.74	3.73	3.84
ODP (kg CFC-11_{eq})	5.29×10^{-7}	5.23×10^{-7}	5.32×10^{-7}	5.35×10^{-7}	5.33×10^{-7}	5.46×10^{-7}
HT-nce (CTUh)	1.42×10^{-6}	1.40×10^{-6}	1.42×10^{-6}	1.43×10^{-6}	1.42×10^{-6}	1.45×10^{-6}
HT-ce (CTUh)	2.66×10^{-7}	2.62×10^{-7}	2.66×10^{-7}	2.69×10^{-7}	2.67×10^{-7}	2.73×10^{-7}
PM (kg $PM_{2.5eq}$)	1.78×10^{-3}	1.77×10^{-3}	1.80×10^{-3}	1.80×10^{-3}	1.80×10^{-3}	1.85×10^{-3}
IR-hh (kBq $U^{235}{}_{eq}$)	5.51×10^{-1}	5.46×10^{-1}	5.59×10^{-1}	5.57×10^{-1}	5.57×10^{-1}	5.73×10^{-1}
IR-E (CTUe)	1.60×10^{-6}	1.58×10^{-6}	1.62×10^{-6}	1.62×10^{-6}	1.61×10^{-6}	1.66×10^{-6}
POFP (kg $NMVOC_{eq}$)	8.32×10^{-3}	8.24×10^{-3}	8.42×10^{-3}	8.41×10^{-3}	8.40×10^{-3}	8.64×10^{-3}
AP (mol $H^{+}{}_{eq}$)	2.89×10^{-2}	2.88×10^{-2}	2.95×10^{-2}	2.93×10^{-2}	2.93×10^{-2}	3.03×10^{-2}
EU_T (mol N_{eq})	8.38×10^{-2}	8.34×10^{-2}	8.58×10^{-2}	8.47×10^{-2}	8.50×10^{-2}	8.80×10^{-2}
EU_F (kg P_{eq})	1.32×10^{-3}	1.31×10^{-3}	1.34×10^{-3}	1.34×10^{-3}	1.34×10^{-3}	1.37×10^{-3}
EU_M (kg N_{eq})	5.83×10^{-3}	5.75×10^{-3}	5.83×10^{-3}	5.89×10^{-3}	5.86×10^{-3}	5.98×10^{-3}
E_{FW} (CTUe)	65.1	64.7	66,4	65.9	66.0	68.2
MFRRD (kg Sb_{eq})	1.45×10^{-4}	1.43×10^{-4}	1.45×10^{-4}	1.47×10^{-4}	1.46×10^{-4}	1.49×10^{-4}

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)	80.5	16%	33%
GWP (kg CO_{2eq})	4.73	18%	36%
ODP (kg CFC-11_{eq})	6.74×10^{-7}	23%	46%
HT-nce (CTUh)	1.80×10^{-6}	11%	22%
HT-ce (CTUh)	3.38×10^{-7}	8%	15%
PM (kg $PM_{2.5eq}$)	2.28×10^{-3}	17%	33%
IR-hh (kBq $U^{235}{}_{eq}$)	7.04×10^{-1}	9%	18%
IR-E (interim) (CTUe)	2.04×10^{-6}	20%	39%
POFP (kg $NMVOC_{eq}$)	1.06×10^{-2}	18%	36%
AP (mol $H^{+}{}_{eq}$)	3.71×10^{-2}	7%	13%
EU_T (mol N_{eq})	1.08×10^{-1}	5%	10%
EU_F (kg P_{eq})	1.69×10^{-3}	4%	8%
EU_M (kg N_{eq})	7.42×10^{-3}	6%	13%
E_{FW} (CTUe)	83.5	6%	12%
MFRRD (kg Sb_{eq})	1.84×10^{-4}	36%	71%

spectively. 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 grid electricity with electricity generated locally through a PV plant (renewable electricity scenario) are evaluated.

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

Concerning the sensitivity analyses for transport distance and renewable electricity, the results of only one configuration are illustrated since for these parameters the percentage variations between the impacts in the evaluated scenarios compared to the base one are the same as the configuration changes. In detail, the OrP500°C configuration is selected as representative configuration since it is the best among the examined ones in terms of environmental performances.

The sensitivity analysis highlights that the approach for solving multifunctionality can significantly affect the results of the assessment (Table 8). In particular, the environmental burdens associated to the FU decrease by 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 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 the 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.

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

The analysis shows that, compared to the reference scenario, the environmental impacts increase by 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. This outcome is consistent

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)	59.1	-27%
GWP (kg CO_{2eq})	2.34	-50%
ODP (kg CFC-11_{eq})	4.14×10^{-7}	-39%
HT-nce (CTUh)	1.73×10^{-6}	-4%
HT-ce (CTUh)	2.87×10^{-7}	-15%
PM (kg $PM2.5_{eq}$)	1.42×10^{-3}	-38%
IR-hh (kBq $U^{235}{}_{eq}$)	2.88×10^{-1}	-59%
IR-E (interim) (CTUe)	1.03×10^{-6}	-49%
POFP (kg NMVOCeq)	6.04×10^{-3}	-43%
AP (mol $H^{+}{}_{eq}$)	1.12×10^{-2}	-70%
EU_T (mol N_{eq})	2.23×10^{-2}	-79%
EU_F (kg P_{eq})	1.14×10^{-3}	-32%
EU_M (kg N_{eq})	5.35×10^{-3}	-28%
E_{FW} (CTUe)	111	33%
MFRRD (kg Sb_{eq})	2.74×10^{-4}	49%

with previous LCA studies (Ayer and Dias, 2018; Bacenetti et al., 2016; Cusenza et al., 2021) and highlights the importance of installing distributed biomasses energy valorisation plants powered by short supply chains. Moreover, the sensitivity analysis results show that the contribution of the biomasses transportation distance to the overall impacts ranging from 4% (for EFW) to 35% (for MFRRD) in the reference scenario, ranges from 8% (for E_{FW}) to about 52% (for MFRRD) in TD-200 and from 11% (for E_{FW}) to about 62% (for MFRRD) in TD-300 scenarios. This information can be useful in planning the pyrolysis plants installation as it provides a criterion to identify the best site based on a fixed maximum transportation contribution to the overall impacts, e.g., 20%."

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

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 energy and environmental perspective, following a life cycle approach. In detail, 1 MJ of thermal energy 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 developing. 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 worst 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 the FU are influenced by the type of input biomass: the lowest environmental impacts for each peak operation temperature are caused by the FU associated to the 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 eco-design 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 point out 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 the bio-oil is considered as a value product the best environmental performance is obtained for the pyrolysis of olive pomace residues instead of 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 significantly affects 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 results can support the designers and industrial decision makers in scaling-up the examined system and in identifying the best operational conditions and biomasses in terms of energy and environmental performances.

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.

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