Science of the Total Environment 718 (2020) 137316

Contents lists available at ScienceDirect

Science of the Total Environment

journal homepage: www.elsevier.com/locate/scitotenv

Experimental and feasibility study of spent coffee grounds upscaling via pyrolysis towards proposing an eco-social innovation circular economy solution

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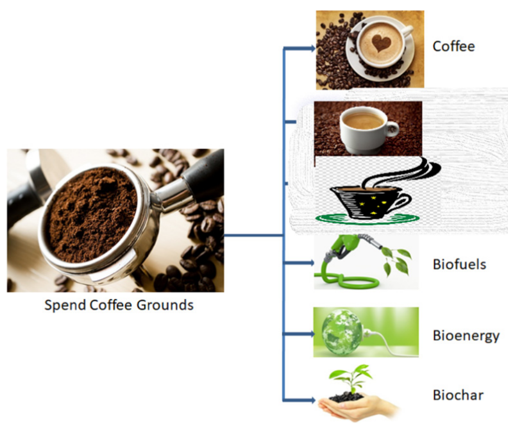
HIGHLIGHTS

- SCG pyrolysis to biochar and energy offers energy and material closed loops.
- Pyrolysis of 2566 t/yr can bring an annual revenue of 47€/t of SCG.
- The economic indicators ROI = 0.24, POT = 2.6 are positive.
- An eco-social innovation business model of circular economy is proposed.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 29 October 2019
Received in revised form 11 February 2020
Accepted 13 February 2020
Available online 14 February 2020

Editor: Bolzonella D.

Keywords:
Circular economy
Food wastes
Spent coffee grounds (SCG)
Pyrolysis: Economic study
Eco-social innovation

ABSTRACT

There is a need for eco-social business models in the food waste sector that are more cascading and circular-based, while having economic, environmental and social benefits. The aim of this study is to bring insights and data of spent coffee grounds large-scale slow pyrolysis, to seize new opportunities for eco-innovative solutions in the circular economy, by identifying upcycling opportunities for resource recovery of this waste. First, an experimental study was conducted, and a set of pyrolysis experiments were carried out at a temperature range from 450 to 750 °C, with a heating rate of 50°/s, under helium atmosphere, to explore the products' yields and the best process' conditions. Second, an economic study was conducted for a standalone pyrolysis plant fueled with the spent coffee grounds streams from coffee shops of a city with 150,000 inhabitants, in central Greece, aiming at the cost and the profitability of the endeavor estimation. The calculations were based on the features of a slow pyrolysis rotary kiln technology designed at Aristotle University, and co-developed with an Irish company, under the funding of an EU LIFE+ project. For an estimated capacity of 2566 t/yr of SCG, the revenue of the endeavor was calculated at 47€/t of SCG. The economic indicators ROI and POT (ROI = 0.24, POT = 2.6), are very

Abbreviations: CE, circular economy; FL, food loss; FW, food waste; HHV, higher heating value; LHV, lower heating value; POT, payout time; ROI, return on investment; SCG, spent coffee ground; GC, gas chromatograph.

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https://doi.org/10.1016/j.scitotenv.2020.137316

positive, suggesting pyrolysis of SCG as an efficient circular economy management solution, providing an eco-social innovation business in the coffee shop industry, engaging also consumers in the circular economy.

1. Introduction

The re-use of coffee drink wasted matter remains today a major environmental concern (Caramão et al., 2018). Yet, many practices for the utilization of the solid coffee grains (SCG) is proposed in the international literature, including its direct use for biogas and electricity (Economou et al., 2018), soil amendment (Santos et al., 2017; Jin et al., 2018), green composites (García-García et al., 2015), and biodiesel production (Son et al., 2018; Kookos, 2018).

Over the last 5–10 years, circular economy (CE) has gained increasing interest (Reike et al., 2018). The traditional linear system including the steps of 'extract-produce-use-dispose' of both materials and energy is no longer sustainable (Honkasalo et al., 2017). European Union is gradually introducing a CE action plan that includes legislative proposals (Reike et al., 2018). It was estimated that economic transitions based on CE could generate 600 billion euros profit per year, only from the food industry sector (Honkasalo et al., 2017).

Waste recycling in the food and drink sector can offer innovative eco-social business models that can be more cascading and circular-based. However, innovation for more waste-based sustainable valorization systems is not limited to technological applications, but it needs systemic innovative solutions towards more resource efficient economies with significantly reduction of food waste.

The aim of this work is to investigate the feasibility of SCG upcycling via pyrolysis towards biochar and energy production, proposing a CE scenario for the efficient utilization of SGC produced in the city of Larisa, Greece, providing an effective SCG waste management. The study does not intend to bring technical innovation beyond the state of the art, but to use a pyrolysis technology that proved its innovation. The pyrolysis plant used is a prototype rotary kiln pyrolysis system that has designed and developed at the Aristotle University, Greece, funded by an EU LIFE+ project some years ago (DEPOTEC - Depolymerisation Technology for Rubber with Energy Optimisation to produce Carbon Products-LIFE10 ENV/IE/000695 DEPOTEC project). The technical features of this technology will help the estimation of the investment cost and the profitability of the proposed scenario.

The SCG used in this study provided by coffee shops in Larisa city, Greece. The sample used is mixed SCG from various coffee varieties. Prior to pyrolysis, SCG went under extraction for the recovery of polyphenols and polysaccharides, for a more cascading and circular-based valorization. However, this study is limited to the pyrolysis of subjected to extraction SCG and has assessed the economic benefit of SCG pyrolysis only, without assessing the economic benefits and material recovery efficiency of the potential polyphenols and polysaccharides extraction, in a biorefinery approach, which will be the subject of a next study.

The specific scientific objectives of the study are:

a) The experimental proof of concept of SCG pyrolysis in a laboratory experimental reactor, at TRL3. It is known that every biomass and waste are characterized by different thermal decomposition temperature, contributing to the process results in a different way (Biogreen, 2018), therefore SCG experimental investigation at TRL3 is needed. Thus, study of the slow pyrolysis process fueled by SCG and investigation of pyrolysis temperature effect on the yields of products was performed.
b) Techno-economic assessment of a pyrolysis plant representing a circular economy scenario for the management of SCG produced by the coffee shops in a city of 150.000 inhabitants, in Greece. The features of a pyrolysis unit at TRL7 used for the techno-economic assessment. For the large-scale pyrolysis techno-economic assessment, technological features of a unit at TRL7 considered adequate.

The novelty of this study is the linking of SCG pyrolysis to produce biochar to a more conceptual practice of CE, by acknowledging the energy/material recovery potential of SCG, and contributing in development of businesses with social and environmental interest in a CE. Biochar could be potentially used not only as an efficient source of the fuel production, but also as suitable material for soil amendment because it can support the direct nutrient absorption whith retardation of their leaching, which helps crops growth (Tangmankongworakoon, 2019). Biocha, as a pyrolytic product, has a crucial influence on soil C mineralization, including its positive or negative priming of microorganisms involved in soil C cycling. Researchers have shown that pyrochar application is preferable than raw SCG application to soils due to the SCG's increased phytotoxicity. Massive amount of dissolved organic carbon can be released from SCG, while pyrochar does not exhibit phytotoxicity due to the fact that organic matter were already removed during pyrolysis process (Kim et al., 2014).

The insights of the study can support recycling business in circular processes implementation, by moving from one-off resource synergies to a systematic application of resource synergies, to increase resource productivity and competitiveness and engage consumers in the recycling.

2. The biochar maker - pyrolysis of SCG upcycling

The demand for renewable energy sources is high due to climate change (Bok et al., 2012). Thermochemical processes are used for the production of energy and biofuels from wastes. Pyrolysis is a thermochemical process that can be applied to any organic (carbon-based) product.

Pyrolysis is an upscaling waste process that allows the formation of products with a different, often superior character than the original waste. With pyrolysis, the carbon-containing materials are converted into bio-oil, biogas and biochar. Thanks to these features, pyrolysis is becoming a process of increasing importance for the industry, in the CE, as it makes it possible to yield much greater value to common materials (Biogreen, 2018).

During pyrolysis, the biomaterial is exposed to high temperature in the absence of oxygen (Biogreen, 2018), undergoing under thermal and chemical decomposition and not combustion (Abbott and Stott, 1999). Decomposition occurs due to the limited thermal stability of the chemical bonds of the materials and leads to the formation of new smaller molecules.

There are several types of pyrolysis, including conventional or slow, vacuum, fast and flash pyrolysis. The choice of the type of process depends on the desired products (Arni, 2018). Most studies in the international literature are focused on fast pyrolysis of biomass, mainly woody biomass. For residual materials such as, agricultural waste and food waste, the fast pyrolysis process is considered appropriate only for biooil production as the end-product, (Cordiner et al., 2018).

The fast pyrolysis process is preferred whenever the main goal is the production of liquid products (Cordiner et al., 2018), because it produces up to 75% w/w biooil. In fast pyrolysis, the raw material are finely milled for rapid heat transfer and the process involves rapid heating at a temperature of 450–600 °C (Manson-Whitton and Roddy, 2012). The

Table 1
Ultimate and proximate analysis of spend coffee grounds (SCG).

Moisture (%)	7.25 ± 0.57
HHV (MJ/kg)	13.93
Ultimate analysis (%wt)	
C	47.96
H	1.57
O	44.05
N	6.42

produced bio-oil is a complex mixture of organic compounds, containing carboxylic acids, esters, ketones, phenols and aromatics (Jin et al., 2018). Several types of biomass tested for fast pyrolysis feedstock, such as agricultural waste and energy crops. Each type of biomass presents its own optimal pyrolysis conditions and different characteristics of the liquid products (Bok et al., 2012). The drawback of pyro-oil (pyrolysis oil) produced via fast pyrolysis is that this oil is a highly oxygenated, needing upgrading.

Slow pyrolysis is a low temperature pyrolysis, in which biomass is subjected to longer residence times, and low heating rates, to obtain high amounts of biochar and energy. A pyrolysis process is considered slow, if the heating time required to reach the pyrolysis temperature is greater than the typical pyrolysis reaction time (<3 s), (Manson-Whitton and Roddy, 2012). Several technologies for slow pyrolysis have been explored, including fluid bed reactor, drifting, moving bed reactor (vacuum, transportable, stirred, horizontal, etc.), rotary kiln, microwave and rotating cone reactor (Bar-Ziv et al., 2018). The rotary kiln pyrolysis shows many advantages, including the flexible conversion of different types of biomass (multi-feedstock), good heat transfer to the fuel (Manson-Whitton and Roddy, 2012), and the relatively low capital cost (Bovee et al., 2015).

Among batch and continuous pyrolysis processes, continuous one exhibits some drawbacks, such as the non-ideal flow characteristics and deviations of residence time, due to stratification or unwanted mixing.

Pyrolysis has a high cost of equipment and is therefore dependent on low-cost feedstock. For large-scale pyrolysis the ideal raw material should be a low-cost and non-edible biomass, abundant and easily accessible and free from toxic chemicals, such as sulfur and nitrogen. Considering these features, SCG is a low cost raw material for fueling pyrolysis for pyrochar (pyrolysis char) production, because it complies with the above features (Karmee, 2018). Pyrochar can be used as an energy source, adsorbent, soil modifier with application to carbon capture (Bovee et al., 2015). The use of pyrochar as biochar is a very interesting option, because biochar is known to reduce nitrogen loss from the ground, improve nutrient retention capacity and soil cation exchange capacity, and improve the physical, chemical and biological properties of the soil, soil health and plant growth in general, closing the loop with agriculture (Manson-Whitton and Roddy, 2012).

3. Materials and methods

The coffee shops of Larisa city in Greece provided SCG used in this study. The sample used is SCG from various coffee varieties. Prior to pyrolysis, SCG went under extraction for the recovery of polyphenols and polysaccharides. From the extracted material, 0.5 g is used in each experiment.

Experiments conducted by varying the pyrolysis temperature. Each experiment repeated 3 times so that the variability associated with the effect of temperature on the products yields could be estimated. The values obtained by each experiment varied from 2 to 8%. Due to the small reactor capacity, the pyrolysis products were produced in small amounts, therefore during the collection of tar/liquid and char, the losses occurred, when given in percentages, were important but unavoidable.

3.1. SCG characteristics

The chemical composition of SCG depends on the type of the coffee plant, the location where the plant was grown, the age of the plant, the climate and the soil conditions of the region (Karmee, 2018).

SCG contain polysaccharides, oligosaccharides, lipids, aliphatic acids, amino acids, proteins, alkaloids (e.g. caffeine, trigonelline) and phenolics, minerals, lignin, melanidines and volatile compounds. Some chemical compounds present in SCG, such as caffeine, tannins and chlorogenic acid create ecotoxicological concerns and limit the vast range of SCG upcycling applications (Janissen and Huynh, 2018).

Compared to other lignocellulosic materials, SCG contain only relatively small amount of cellulose (about 10% by weight) and have high content of hemicelluloses (30–40% by weight). The concentration and composition of polysaccharides in SCG depends mainly on the conditions of cultivation and the brewing method (Kovalcik et al., 2018).

The ultimate and proximate analyses of used SCG, in this study, are presented in Table 1. The high heating value (HHV) of SCG is calculated using the following Eq. (1) (Francavilla et al., 2015):

$$HHV = 0.3491 * C + 1.1783 * H + 0.1005 * S - 0.1034 * O - 0.0151 * N - 0.0211 * Ash \tag{1}$$

3.2. Pyrolysis process protocol

The experimental apparatus used in this study is consisted by a laboratory scale wire mesh captive sample type reactor, a liquid

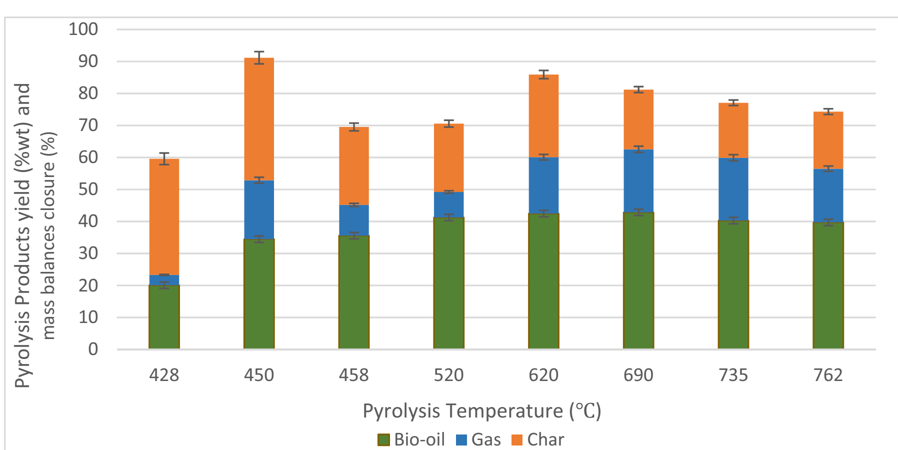

Fig. 1. Effect of temperature on pyrolysis products yield (wt%) and mass balances closure.

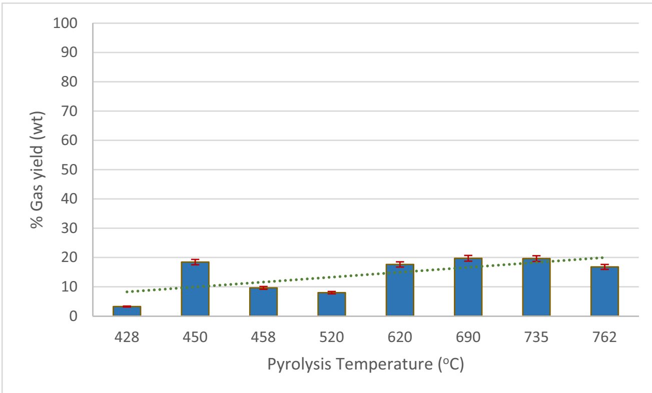

Fig. 2. Effect of temperature on gas yield (wt%).

hydrocarbon filter, a tar filter, a gas cooling system, a moisture trap, a gas collection system and a GC system for gas analyses. The reactor is heated by applying voltage from an electric circuit. A thermocouple inside the rector, connected with a computer through program, provides the relation between temperature and time. The experimental apparatus is described in another work of the authors (Ktori et al., 2017). 0.5 g sample used in each experiment.

The produced gas analyzed in a gas chromatograph (GC) (6890N, Agilent Technology). The two columns used were Plot Q and Molesieve. The carrier gas was Helium. The temperature profile of the gas chromatograph was isothermal, at 40 °C. The standard gas mixture used for the calibration of the method contained CO, CO_2, H_2, CH_4, C_2H_4 and C_2H_6 1% (v/v) balanced in Helium. The GC system comprised two detectors, where thermal conductivity detector (TCD) used for CO, CO_2, H_2, CH_4, C_2H_4 and C_2H_6 analysis, and the flame ion detector (FID) for CH_4, C_2H_4 and C_2H_6, (Ktori et al., 2017).

4. Results from the experimental study and discussion

The pyrolysis experiments performed at a temperature range of 400–750 °C, under a heating rate of 50 °C/s, that defines the process as intermediate pyrolysis.

4.1. Temperature effect on the pyrolysis product yields

The composition and yield of slow pyrolysis products depend on the characteristics of the SCG and on the pyrolysis conditions. One of the most important parameters affecting the products yield was the pyrolysis temperature. The product yields obtained, after calculation and quantification by weight are depicted in Fig. 1. Figs. 2, 5, 6 depict each product evolution with pyrolysis temperature (gas-oil-char).

The production of the pyrolysis gas was favored at high temperatures. An increase in gas yield can be observed with the temperature rise. It reached the yields of 20% at high temperature ($T = 700$ °C), (Fig. 2). The produced pyrolysis gas composed mainly by CO, CO_2, CH_4, and less by light hydrocarbons (C_2H_4 and C_2H_6) (Fig. 3). Since the produced gas contains in addition to the gases resulting from the pyrolysis process, the Helium entering the reactor to achieve an inert atmosphere, the results in Fig. 3 are normalized, by subtracting the Helium.

As Fig. 3 shows, the main components of the pyrolysis gas are carbon monoxide (CO) and carbon dioxide (CO_2) as their values reach >70% v/v. The methane (CH_4), ethane (C_2H_6) and ethene (C_2H_4) concentrations are at low levels (<20% v/v). The energy density of the gas measured by its low heating value (LHV) which is a very important thermodynamic indicator for the pyrolysis gas (Fig. 4). LHV exhibits a slight increase with the rise in pyrolysis temperature. The LHV primarily influenced by the carbon monoxide content of the gas (CO) and secondarily by methane (CH_4) and light hydrocarbons (C_2H_4, C_2H_6). It was calculated using the following Eq. (2) (Chen et al., 2006):

$$LHV = (30 * CO\% + 25.7 * H_2\% + 85.4 * CH_4\% + 151.3 * C_nH_m\%) * 4.2 * 10^{-3} \quad (2)$$

The yield of bio-oil increased with the increase of the pyrolysis temperature approaching a maximum at $T = 600$ °C (Fig. 5) and then at higher pyrolysis temperature it decreased. Bio-oil produced from SCG exhibits increased carbon density and lower oxygen content compared to the raw SCG.

Char yield decreased with temperature rise (Fig. 6). Two samples of char were selected for analysis of their characteristics, one produced at 500 °C and the other at 600 °C, because the pyrolysis temperature $T =$ 500–600 °C were considered to be the optimal process temperature where the gas showed a good LHV and char exhibited a good yield. Analysis of the char has shown that the char produced at 600 °C exhibits a higher HHV, higher C content but lower H, N, O content, compared to that produced at 500 °C. The effect of temperature on the composition of the produced char is shown in Table 2.

4.2. Comparisons of SCG pyrolysis with other food and agricultural wastes

The results of this study compared with the results reported in the international literature, related to different food waste and agricultural waste pyrolysis (Table 3). The aim of the comparison was to bring insights on the effect of the type of waste, pyrolysis and reactor to the products' yields. Comparison of the obtained results with other raw materials and pyrolysis techniques is of great importance for the evaluation of the results.

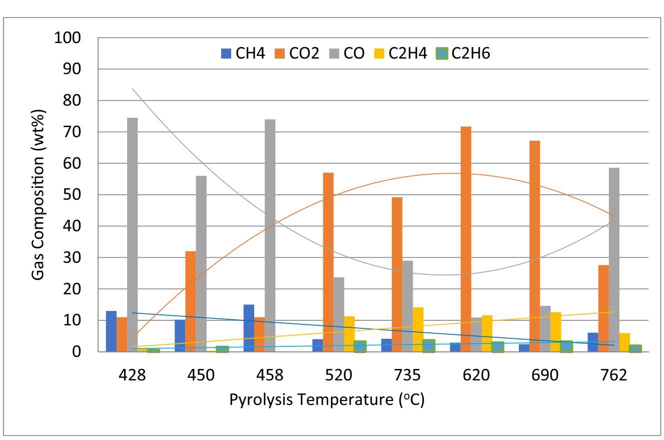

Fig. 3. Effect of temperature on gas composition (wt%).

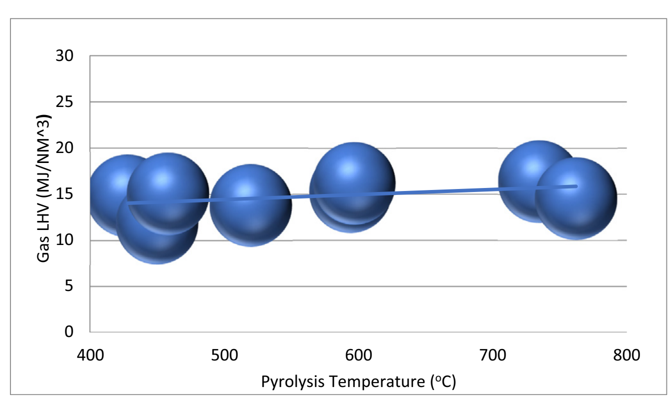

Fig. 4. Effect of temperature on bio-oil yield (wt%).

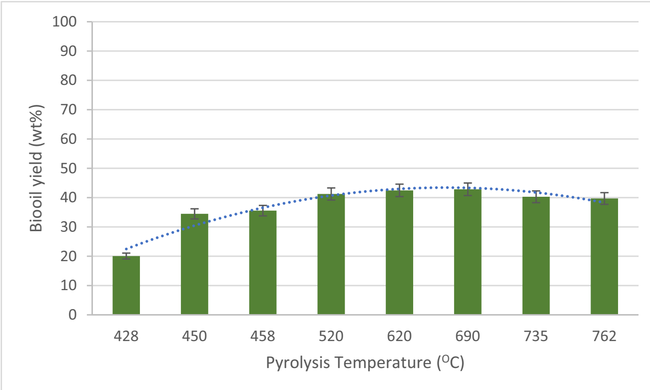

Fig. 5. Effect of temperature on char yield (wt%).

In addition, another comparison made, between the results obtained in this study where polyphenols/polysaccharides-extracted SCG were used as pyrolysis with the results of raw SCG (as received pyrolysis) (Table 3). The aim was to investigate the effect of polyphenols/polysaccharides on the pyrolysis products' yield. From this comparison, it can be concluded that the extraction of polyphenols/polysaccharides from the SCG mainly affects the yields of bio-oil and char, and less gas's yield. Raw SCG pyrolysis gives higher char yields compared with the pyrolysis of polyphenols/polysaccharides-extracted SCG. This is in accordance with the finding of other researchers (Lin et al., 2015).

5. Techno-economic study

An economic evaluation of a standalone circular economy pyrolysis plant conducted for the pyrolysis of SCG produced in the city of Larissa, in Greece, that has a population of around 150,000.

5.1. Hypotheses of the study

The transportation costs of SCG were not included in this preliminary study, hypothesizing that the owners of the coffee shops will pay for their waste transportation.

The scenario also suggests pyrochar use as biochar (soil amendment), offering carbon sequestration, and mitigating climate change mitigation.

The city of Larissa was chosen in this study for two reasons:

a) It is the city with the largest number of coffee shops per capita in Greece, and
b) SCG collection data are available.

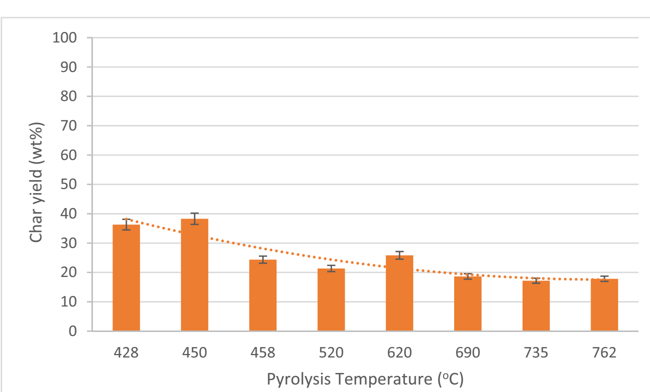

Fig. 6. Effect of temperature on gas low heating value (LHV).

Table 2
Ultimate analysis and high heating value (HHV) of chars obtained at two pyrolysis temperature.

T (°C)	Ultimate analysis (%wt)				HHV (MJ/kg)
	C	H	N	O	
500	70.69	2.85	3.2	23.26	25.56
600	72.92	2.59	2.59	21.90	26.18

Another hypothesis of the study is that SCG is a zero-cost feedstock. The scenario studied, includes SCG collection from the various coffee shops of Larissa city, with special collection vehicles, storage in silos, and later transportation to a standalone pyrolysis unit, to be installed in close proximity to the city in order to have reduced transport costs. The SCG collection and pyrolysis circular economy scenario's graphical representation is depicted in Fig. 7.

5.2. Pyrolysis technology description

The scaled up pyrolysis technology that was used in this study, is a rotary kiln slow pyrolysis that developed at Aristotle University of Thessaloniki, within the framework of the DEPOTEC project, funded by EU LIFE+ program (Antoniou and Zabaniotou, 2018). The DEPOTEC unit can process up to 100 kg/h SCG. High-purity stainless steel (SS) was used to construct the rotary kiln intermediate to slow pyrolysis reactor. The rotary kiln reactor shows advantages including high heat transfer, ease of handling, and an affordable cost. The process is continuous (Antoniou and Zabaniotou, 2018). Fig. 8 shows the flow diagram of the pyrolysis prototype.

From the experimental study, the optimal temperature for the pyrolysis found to be $T = 550$ °C. This temperature selected for the operation of the pyrolysis unit because it optimizes the results.

The annual amount of SCG produced from the city of Larissa calculated to 2,566,315 kg.

The unit considered to operate 300 days annually, for 24 h/d.

The mass flow calculated to 324 kg/h.

The unit's energy requirements calculated at 167KW/h.

5.3. Expected products

Three products can be produced from the proposed pyrolysis plant:

a) The gas product, which can be recycled and used for the pyrolysis endothermic reaction needs in energy, reducing unit's energy requirements, closing the energy cycle.
b) The char product that can be sold for soil amendment, thus closing material cycle.
c) The bio-oil that need to be initially upgraded and then be sold.

5.4. Costs estimation

For the economic evaluation of the standalone pyrolysis plant in the Larissa city, that will process the amount of SCG produced in the coffee shops of the city, analyses of the capital and operational costs were conducted, followed by the calculation of the net profit of the unit and the economic indicators ROI and POT.

5.4.1. Capital cost

The analysis of the capital cost for the pyrolysis unit is shown in Table 4. The purchase price of the electricity in Greece was provided by the *Public Power Corporation S.A-Hellas* (PPC, 2018).

The following assumptions and data used:

Table 3
Comparison of spend coffee grounds (SCG) pyrolysis with other food waste and agricultural waste-based pyrolysis.

Raw material	Pyrolysis type	Reactor type	Pyrolysis temperature (°C)	Bio-oil (% wt)	Char (% wt)	Gas (% wt)	Reference
Agricultural waste							
Rice husks	Fast	–	500	36	48	16	(Kahhat et al., 2017)
Hazelnut shell	Slow	Fixed-bed tubular reactor	400	20	48	19	(Pütün et al., 1999)
			700	45	38	27	
Rapeseed	Flash	–	500	71	16	8	(Kockar and Onay, 2003)
			600	73	15	8	
			700	67	13	15	
Rice straw	Intermediate	Heat-carrier-free-rotating bed reactor	400	33	40	25	(Ba et al., 2017)
			500	38	39	27	
			600	35	38	28	
Maize straw	Intermediate	Heat-carrier-free-rotating bed reactor	400	32	40	27	(Ba et al., 2017)
			500	36	35	29	
			600	34	33	31	
Wheat straw	Intermediate	Heat-carrier-free-rotating bed reactor	400	35	39	24	(Ba et al., 2017)
			500	37	32	26	
			600	38	31	25	
Olive kernel	Intermediate	Batch	350	30	60	10	(Antoniou et al., 2019)
			450	37	34	29	
			550	51	31	18	
Mallee	Fast	Fluidized-bed reactor	700	62	21	12	(Bok et al., 2012)
			800	57	14	17	
Food waste							
Sweet sorghum	Fast	Fluidized-bed reactor	700	59	25	13	(Bok et al., 2012)
			800	55	18	22	
Orange bagasse	Intermediate	Semi-batch	400	16	50	25	(Bhattacharjee and Biswas, 2019)
			500	25	35	30	
			600	26	28	39	
SCG							
SCG	Fast	Fluidized-bed reactor	700	44	34	11	(Bok et al., 2012)
			800	53	20	15	
SCG	Intermediate	Batch	450	33	38	8	(Ktori et al., 2017)
			550	38	30	10	
			650	27	25	16	
SCG polyphenols-polysaccharides extracted	Intermediate	Batch	450	30	33	9	This study
			550	40	23	13	
			650	43	20	16	
			750	39	19	20	

- Raw materials' cost is zero.
- The purchase price of the electricity is 0,059 €/KWh, (https://dei.gr/el)
- The occupational costs calculated using the Wessels method (Peters and Timmerhaus, 2003).

The fixed capital calculated by using the following equation:

$$I_F = I - I_W = 497,690 - 76,020 = 421,670€ \quad (3)$$

5.4.2. Operational cost

Table 5 shows the operational costs analysis of the SCG pyrolysis unit. The market price for bio-oil was found to be 0.75 €/lt (https://www.btg-btl.com/en/company/services/shop) and for the char 250 €/tn (Baranick et al., 2011).

The revenue from the sale of bio-oil was calculated to 846,890 €/yr, while the char revenue was estimated to 131,530 €/yr. The unit's revenue (S) estimated at 978,420 €/yr. Gross profit (R) was calculated at 242,600 €/yr, by using the type:

$$R = S - C \quad (4)$$

The assumptions for the calculation of the net profit of the unit were:

- The economic life of this unit is $N = 10$ years.
- The depreciation is linear.
- The flat tax rate is $t = 0.4$.
- The depreciation coefficient for tax purposes is $d = 1/N = 0.1$
- The depreciation coefficient of the fixed investment is e=d
- The net profit of the unit is calculated based on the above assumptions by using the following type (Peters and Timmerhaus, 2003):

$$P = R - eI_f - (R - dI_f)t = 120,260 \text{ €}/yr \quad (5)$$

5.4.3. Economic indicators

The economic indicators ROI (return of investment) and POT (pay-out time) selected as the profitability criteria (Peters and Timmerhaus, 2003). Although they do not take into account the time value of money and the risk of investment, they are satisfactory efficient criteria for our limited data.

$$ROI = \frac{P}{I} = 0,24 \quad (6)$$

$$POT = \frac{I_f}{P + e \cdot I_f} = 2,6 \quad (7)$$

The technical and economic characteristics of the unit are summarized in Table 6.

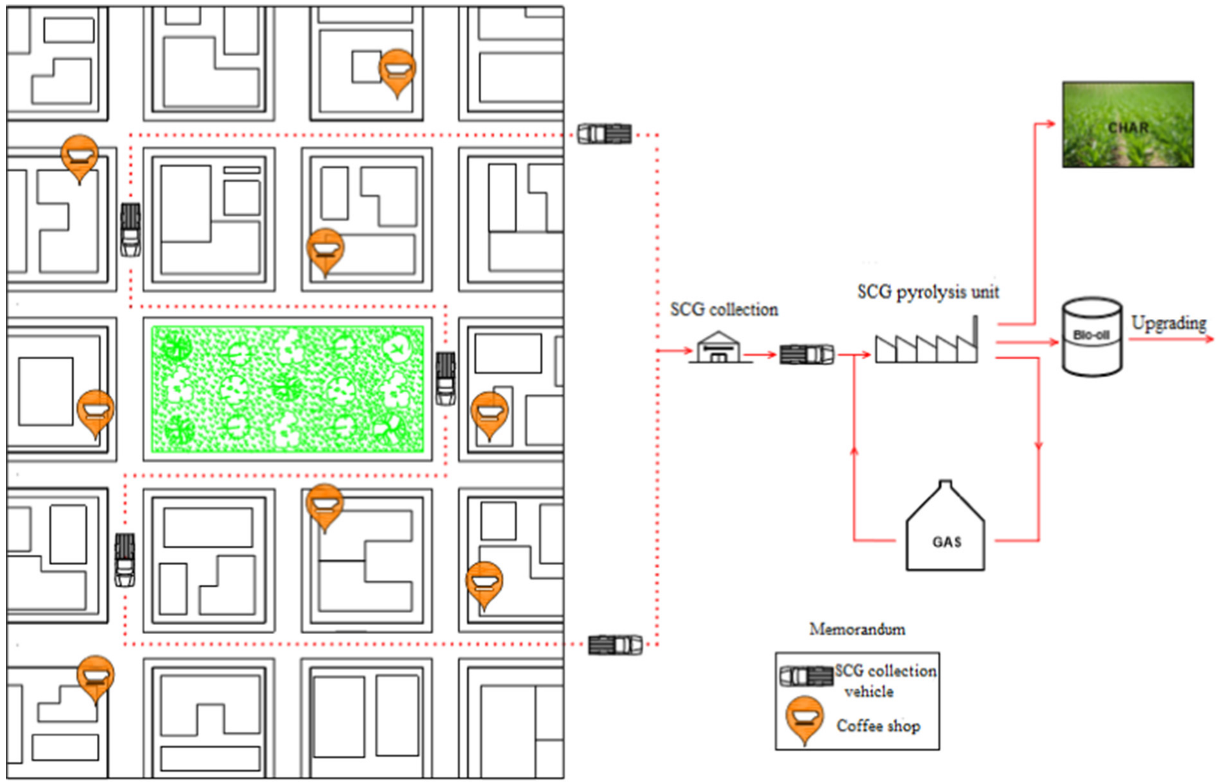

Fig. 7. SCG collection and pyrolysis graphical representation.

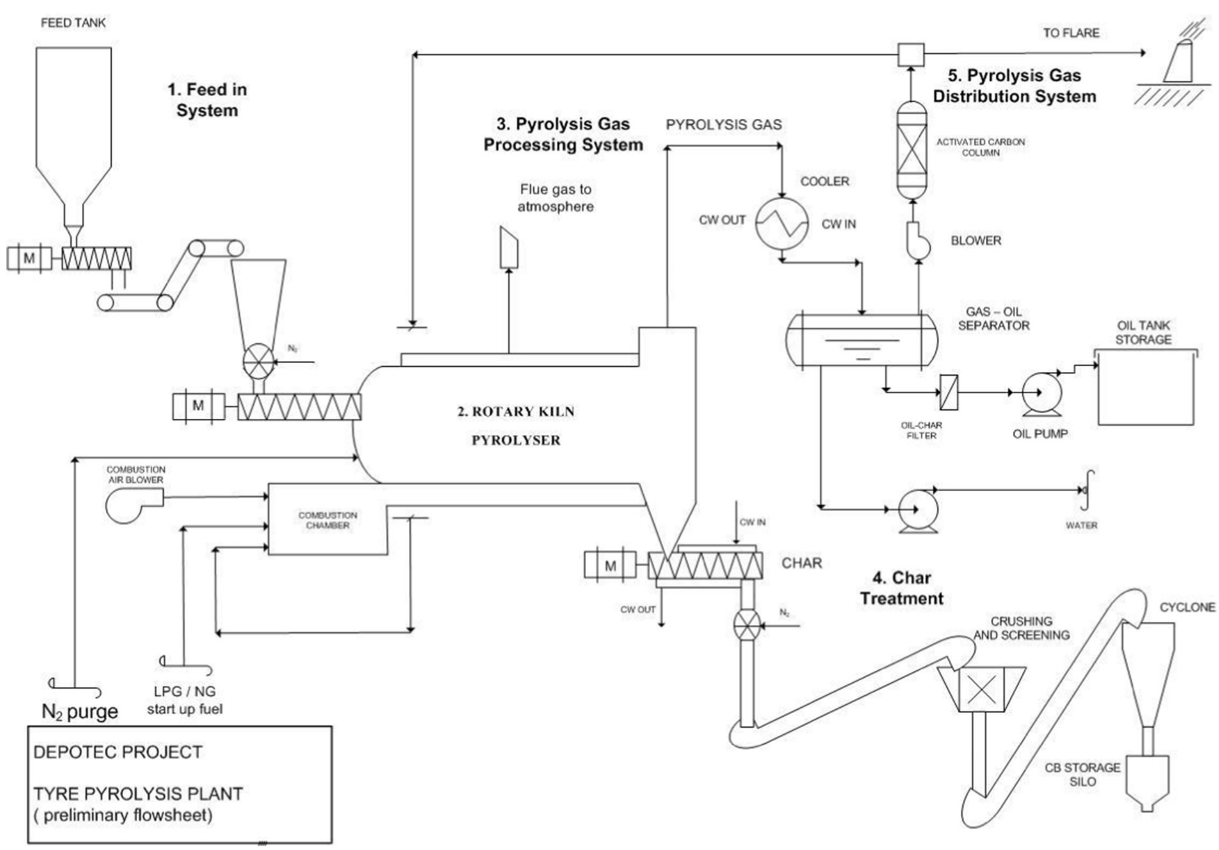

Fig. 8. Flow diagram of the rotary kiln pyrolysis prototype (Antoniou and Zabaniotou, 2018).

Table 4
Capital cost analysis of a pyrolysis plant with capacity of 2566 t/yr spend coffee grounds (SCG).

Cost type	Percentage of machinery value	value (€)
I. Direct costs		
i. Machinery value	100	88,400
ii. Machinery installation	47	41,550
iii. Control systems	18	15,910
iv. Pipelines	66	58,340
v. Electronics	11	9720
vi. Buildings	18	15,910
vii. Land improvement	10	8840
viii. Services	70	61,880
Total direct investment costs	340	300,560
II. Indirect costs		
i. Supervision	33	29,170
ii. Construction	41	36,240
Total direct and indirect investment costs	414	365,980
iii. Contractor payment	21	18,560
iv. Contingencies	42	37,130
III. Fixed capital I + II	477	421,670
IV. Working capital Iw	86	76,020
Total investment cost I	563	497,690

6. Reflections and discussion

A growing number of food companies and consumers understand the challenge and want to forge a new direction that is consistent with human health and planetary survival. All companies in the food sector, both producers and distributors, should adopt clear guidelines, metrics, and reporting standards to align with the Sustainable Development Goals and the Paris Climate agreement (Sachs and Riccaboni, 2019).

To move towards a more ecologically sound and prosperous society, it is important to promote specific areas of innovations, that address environmental problems, energy and resource efficiencies, while promoting sustainable economic activity and achieving a decoupling of economic growth from environmental impacts. This type of innovation is referred to as eco-innovation (https://www.oecd.org/innovation/inno/49537036.pdf).

Table 5
Operational cost analysis of a pyrolysis plant with capacity of 2566 t/yr spend coffee grounds (SCG).

Cost type	Cost estimation	€/yr
I. Production costs		
A. Direct costs		
i. Raw materials		0
ii. Occupational costs		95,240
iii. Supervision	15% A(ii)	14,290
iv. Utilities		57,750
v. Maintenance / Repairs	5% If	21,080
vi. Materials	0.75% If	3160
vii. Lab costs	10% A(ii)	9520
B. Permanent costs		
i. Insurance	1% If	4220
ii. Taxes	1% If	6320
iii. Depreciation	10% If	42,170
Γ. Additional costs	60% [A(ii) + A(iii) + A(v)]	78,370
Total operational costs		332,110
II. General costs		
A. Administrative expenses	5% If	21,080
B. Distribution/sales costs	4% (I + II)	14,720
Total general costs		35,800
III. Total operational costs I + II:		367,910
i. Contingencies	2.5% III	9200
IV. Total		735,820

Table 6
Technical and economic characteristics of the pyrolysis plant with capacity of 2566 t/yr of spend coffee grounds (SCG).

Capacity (tn SCG/yr)	2566
Operational costs (€/yr)	735,820
Gross profit (€/yr)	242,600
Net profit (€/yr)	120,260
ROI	0,24
POT	2,60
Net profit per ton (€/tn)	47

Scholars made a distinction between types of innovations:

- ✓ *Incremental innovation*, which concerns the innovation in industry, aiming at modifying and improving existing technologies or processes (Scrase et al., 2009).
- ✓ *Disruptive innovation*, which aims to change how things are done without necessarily changing the technological regime itself (Scrase et al., 2009).
- ✓ *Eco-innovation* that aims to improve products, processes, methods, structures, leading to environmental improvements, reducing the use of resources and decreases the pollution, across the whole lifecycle (Scrase et al., 2009).
- ✓ *Radical innovation* is more likely a non-technological change mobilizing diverse actors and it involves a shift in the technological regime (Scrase et al., 2009).
- ✓ *Eco-social innovations* are referred to social innovations with a strong ecological orientation, experimented within a context with less pressure from the mainstream society and market towards creating new pathways and pilots in participatory processes, aiming to promote sustainability transition, and interconnect environmental and human issues (Matthies et al., 2019).

Taking in consideration the waste management, this has undergone a radical change. It has shifted to recovering the valuable materials and energy from waste, involving an assessment of the energy, emissions and innovations needed to recycle or reuse the waste via waste reduction projects that often show small payback periods.

The present study showed that SCG, waste from coffee extraction, contains nutrients that via pyrolysis will move to the solid product, the char, to be used as biochar enabling plant growth. The study also showed that a pyrolysis plant fueled with SCG from many coffee shops of a city, towards producing biochar with parallel energy recycling, is economically beneficial, with a POT = 2,6 years.

The present study provides an innovation, which is *eco-innovation*. Eco-innovation represents an opportunity for many SMEs to increase their competitiveness and is about creating business models that are both competitive and respect the environment, by reducing resource intensity of products and services (https://www.eco-innovation.eu/).

SCG pyrolysis is environmentally sound because it provides a management practice to recover valuable materials from SCG. The study provides also a *social innovation* solution because it provides a pathway and pilot in a participatory process, aiming to promote sustainability transition, interconnect environmental and human issues. If the proposed pyrolysis plant could be managed by a social enterprise to provide biochar for the societal needs, for example city gardening or other public used, and the collection of SCG could be done by social stakeholders, then this endeavor can be a successful eco-social innovation.

If radical innovations, as discussed in the OECD report (https://www.oecd.org/innovation/inno/49537036.pdf) could include not only the breakthrough technologies but also closing the loop from resource input to waste output, then the present study provides a *radical innovation*, as well.

The study wishes to inspire businesses in the coffee shop industry, and consumers to engage in the circular economy, for sustainable economies and societies.

7. Conclusions

SCG is an important food waste, as it is produced in huge quantities worldwide. Rotary kiln pyrolysis is a circular economy option that can be used for SCG added-value management, with eco-socio-economic benefits.

The results of the experimental pyrolysis study showed that the utilization of SCG leads to the formation of three valuable products that can be sold or used in situ or off-site, closing energy and material loops:

- ➢ Biogas with a low calorific value of 14 MJ/Nm3, clearly lower than that of natural gas (38 MJ/Nm3), but still good as fuel to be used in situ for the needs of the plant, closing the energy loop.
- ➢ Biooil which is of low quality and needs further to be upgraded before any sale, although, its properties make it a rather satisfactory fuel that can be fed smoothly to existing combustion systems, in situ, closing energy loops.
- ➢ Biochar which can be used as soil amendment or fertilizer for the city's gardening needs, closing the material loop.

The study proposes a circular economy solution that is SCG pyrolysis to biochar and energy, that is eco-social innovative. It proposes a standalone pyrolysis plant to be built in a logistically efficient location, to serve many customers, in this case the coffee bars of a city like the case of Larisa city in Greece, by collecting their coffee-drink residues at a zero price. The capacity of the pyrolysis plant was estimated at approximately 2566 tons of SCG per year, which rends the endeavor economically profitable, with a net profit at 47€ per ton of treated SCG.

The study provides experimental and economic feasibility data that can serve for broadening this concept with more city and country specific contexts. An appropriate collection system must be further studied, being of great importance for the continuous SCG flow to the pyrolysis plant.

The findings of this study could be useful to the coffee shops sector, recycling sector, waste management authorities, regional and city leaders, of other cities and countries, undergoing circular economy transition. Although the economic results are preliminary, yet, they provide positive and realistic indicators for a successful implementation.

Finally, endeavoring to integrate circular economy waste recovery applications into society should be a priority. A key advantage for establishing an eco-social innovative SCG pyrolysis plant is the zero cost of raw materials and the use of biochar for the city's gardening needs. In addition, this solution actively contributes to the reduction of the carbon dioxide by avoiding the deposition of SCG in landfills.

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.

Acknowledgements

The authors would like to acknowledge Mrs. Paraskevi Kamaterou, PhD student, for the support to the experimental study.

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