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Life cycle assessment of instant coffee production considering different energy sources

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ABSTRACT

Nowadays, coffee is a popular beverage globally and one of the largest traded commodities. Conventional instant coffee production requires energy and water, producing coffee bagasse (biomass) as an agro-industrial residue. This residue, spent coffee grounds (SCGs), in Ecuador is currently disposed of in the municipal landfills, losing the opportunity to recover energy and minerals. This paper studies the life cycle environmental impacts of instant coffee production using data from a coffee plant in Guayaquil, Ecuador. The study analyzes the impact of generating the required electricity by an internal combustion engine powered by fossil fuel, using the Ecuadorian power grid, or using a combined cooling, heat, and power (CCHP) trigeneration system powered by dried SCGs and natural gas. The results indicate that when SCGs is used to power auxiliary processes, the CO_2 emissions greatly decrease, helping to reduce fossil fuel dependence. The study also reveals that scenarios using electricity from the Ecuadorian power grid exhibit lower environmental indicators than those using internal combustion engines. The scenario that includes the CCHP records the lowest indicator in each category, reducing the GWP by 45.2 % compared to the base scenario, pointing out that using energy-efficient technologies lowers the carbon footprint, contributing to decarbonisation simultaneously.

1. Introduction

In developing regions like South America and the Caribbean, 16 % of world agricultural production is processed (Magalhães et al., 2019), representing 6.9 % of GDP (Banco Mundial and OCDE, 2021). The promotion of intensive agriculture (Ragauskaitė and Šlinkšienė, 2022) is substantially depleting natural resources and causing environmental deterioration due to the unsustainable use of water (Rahmah et al., 2022), excessive use of fertilizers (Poore and Nemecek, 2018), pesticides on crops (Steinfeld et al., 2009), and the occupation of large tracts of land (Poore and Nemecek, 2018). In addition, the agro-industrial sector generates high greenhouse gas emissions due to burning fossil fuel and agro-waste accumulation in landfills, which increase pathogenic bacteria and toxic degradation products (Freitas et al., 2021).

Among Latin America's most processed agricultural products are rice, coffee, fruits, and vegetables (America, 2019). The agro-industrial waste derived from these products mainly have lignocellulosic material, which means they have a high potential to be reused according to their energy and nutritional contribution (Freitas et al., 2021). The use of waste has environmental and economic benefits for being included again in the supply chain, promoting the circular economy (Vargas Corredor and Pérez Pérez, 2018). These residues can be used in the production of biofuels (Duan et al., 2020; Hiloidhari et al., 2019; Tait et al., 2021), to replace the use of fossil fuels (Freitas et al., 2021) Unfortunately, as these countries do not have viable alternatives for recovering potential energy and valuables components from their waste, these often end up being disposed of in landfills.

In the last ten years, spent coffee grounds (SCGs) or coffee bagasse

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has become an agro-industrial residue of great interest, as it is an alternative bioenergy resource to oil (Overturf et al., 2021). Without considering petroleum, coffee is the world's largest traded commodity and the favorite beverage globally (Tun et al., 2020). Between 2020 and 2021, according to the International Coffee Organization, world coffee production reached 9.9 billion kilograms (INTERNATIONAL COFFE ORGANIZATION (ICO), 2022). Conventional coffee production demands high amounts of energy, water, and land, generating high effluent discharges and requiring excessive use of fertilizers. Coffee production potentially impacts habitat destruction and fragmentation of native tropical biodiversity (Hassard et al., 2014), particularly due to the long and complex supply chain required to produce and transport coffee beans to market (Nab and Maslin, 2020; Cibelli et al., 2021). Gosalvitr et al. (Gosalvitr et al., 2023/06) carried out a comprehensive life cycle assessment for coffee production, identifying that the cultivation of green coffee beans contributes more than 84 % across all environmental impacts and costs. The agriculture impacts are usually associated with the use of fertilizers, in fact the main source of greenhouse gases from agriculture are N_2O associated with the use of nitrogen fertilizers.

Each ton of green coffee processed generates 650 kg of coffee bagasse (Atabani et al., 2019). SCGs are currently discarded in landfills or used as compost without exploiting their richness in minerals, oils, and antioxidants (Atabani et al., 2019). Previous studies show that SCGs are one of the best energetic potential resources to produce biofuels (Schmidt Rivera et al., 2020; Vardon et al., 2013; Kibret et al., 2021), power (Jang et al., 2015; Jin et al., 2018; Kang et al., 2017; Stylianou et al., 2018/12), and biocompounds (Zengin et al., 2020; Ingrao et al., 2022). Forcina et al. (2023) compare the environmental impact of dumping coffee bagasse in landfills with different reuse alternatives such as brick manufacturing, biodiesel, and composting. This study shows that these reuse alternatives reduce the emissions of gaseous pollutants into the air by up to 76 %. Although this article analyses the possibility of reusing SCG to produce other subproducts, it does not explore its use for reducing the required energy in the existing instant coffee manufacturing plant. The use of residual biomass has been proposed as basis for the development of a circular bioeconomy, that can support the reaching of several SDGs including SDG 13 "Taking urgent action to combat climate change and its impacts". (Duque-Acevedo et al., 2020). Furthermore, the development of circular systems in agroindustry can help the promotion of material and energy partial self-sufficiency in these systems (Fiallos-Cárdenas et al., 2022/03).

Moreover, using non-integrated systems based on fossil fuels has evolved into a serious economic and environmental situation (Rahnama Mobarakeh and Kienberger, 2022), especially for agroindustry processes that require high amounts of energy, such as coffee production (Cibelli et al., 2021). An alternative that reduces their environmental impact is cogeneration systems that produce electricity and heat from a fuel (CHP) and trigeneration systems or combined cooling, heat, and power (CCHP), which also generate chill water using the heat provided by the cogeneration system. CCHP systems generate power effectively by reducing energy losses, increasing overall efficiency compared to conventional systems (Su and Yang, 2022). In addition, trigeneration systems that use biofuel, such as biomass from agro-industrial waste, have been shown to achieve greater reduction in air emissions than fossil fuels (Tinoco Caicedo et al., 2023). Several studies have carried out life cycle analyses of trigeneration systems as a sustainable technology for energy production (Petrillo et al., 2021; Adams and McManus, 2014; Amores et al., 2013), finding that this technology improves fuel efficiency, reducing emissions per unit of useful energy. Considering the existing literature, no LCA studies have been found in the industrial-scale production process of instant coffee that reuses coffee bagasse as biofuel.

The main objective of the current study is to analyze the environmental impact associated with the production of instant coffee using different energy sources with data from a plant in Guayaquil, Ecuador. The study assesses the life cycle environmental impacts of the base case and five scenarios, considering different electricity sources such as the Ecuadorian power grid, the local production by internal combustion engines powered by diesel, and the use of a combined CCHP unit powered by dried SCG and natural gas; and evaluating the SCG wastes final destination, such as the disposal in the municipal landfill or the use of this sub-product as an energy source to produce steam, electricity, or both.

2. Material and methods

2.1. Scope definition

The current study uses LCA methodology, based on ISO standards 14040 (ISO 14040, 2006) and 14044 (ISO 14044, 2006). The scope of the instant coffee production study corresponds to an assessment from cradle to gate, including the agriculture, roasting, extraction, evaporation, and spray dryer stages.

2.2. Functional unit

The system functional unit for is "1 kg of instant coffee at the plant gate".

2.3. System boundaries

Figs. 1–4 show the system boundaries for the base case and the analyzed scenarios. The stages are grouped as agriculture, roasting, extraction, evaporation, and spray dryer.

Regarding *agriculture,* this activity includes: The orchard establishment phase includes tree nursery, soil cultivation, tree planting, installation of the trellis system (posts and wires), and irrigation. The productive phase of the orchard includes the operation of machines, corresponding infrastructure, fuel use, and sheds (Ecoinvent, 2020). This activity finalizes with delivering the final product, green coffee, to the world in jute sacks.

Roasting: Green coffee beans with initial moisture of 11.4 % arrive, is cleaned, and roasted at 232 °C with a residence time of 7 min using hot flue gases obtained from the combustion of diesel and air. Gases are sent to an afterburner to oxidize volatile organic compounds and carbon monoxide. Gases resulting from this process are released at a temperature of 283 °C to the environment. Roasted coffee beans result with an average moisture of 1 % at 360.1 °C. Roasted coffee beans are led to a cooling system in which a water stream decreases the beans' temperature to reach the ambient temperature. The beans that leave the cooling system have a moisture of 5.2 %. The roasted coffee beans pass through a mill to obtain grinding coffee. In addition, this process allows changes in the coffee beans, such as weight reduction, darkening, and development of important volatile aromatic compounds.

Extraction: In this process, the roasted coffee is passed through a grind and then fed to the extractor for the extraction process. The solid-liquid extraction occurs in a 6-countercurrent battery semi-continuous system between 200 and 500 kPa of pressure and a temperature between 118 °C and 120 °C. The spent coffee grounds are discarded to municipal landfill. The coffee extract is cooled in multiple heat exchangers until reaching a temperature of 12 °C. The cold extract is passed to a centrifuge to separate the insoluble solids and obtain coffee extract with soluble solids of 18 w/w%.

Evaporation: The coffee extract is preheated up to 50 °C by using steam and enters to the second effect evaporator and heated with the evaporated water of the first effect. A concentrated extract leaves the second effect and part of it is mixed with the heated extract and recirculated. The other part is sent to the first effect. The evaporated water enters the condenser where the temperature is reduced from 50 °C to 32 °C. The concentrated coffee that leaves the first effect evaporator reaches a concentration of 44 w/w% and then it is cooled from 66 °C to 11 °C in a heat exchanger of multiple flow, where cooling-tower water and chilled water are used (Tinoco-Caicedo et al., 2021a).

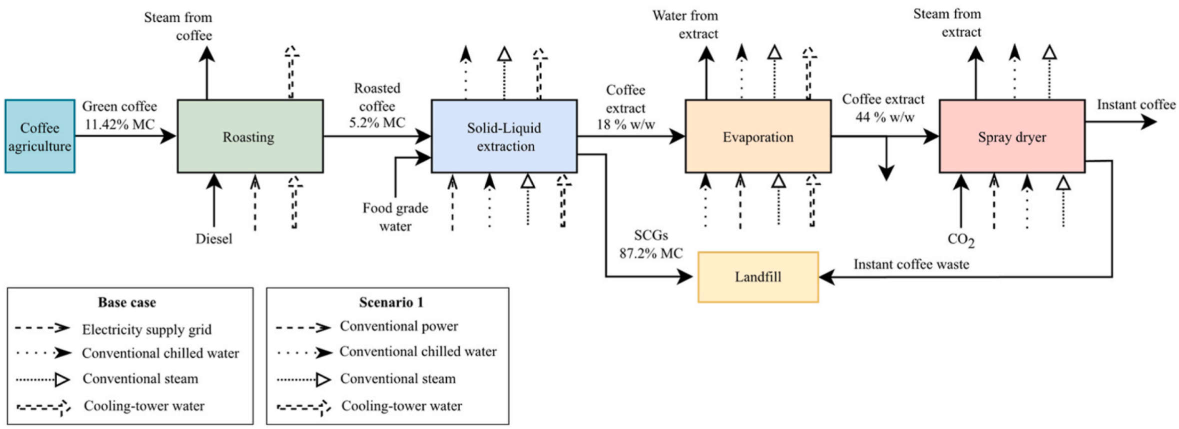

Fig. 1. System boundaries considered in Base Case and Scenario 1.

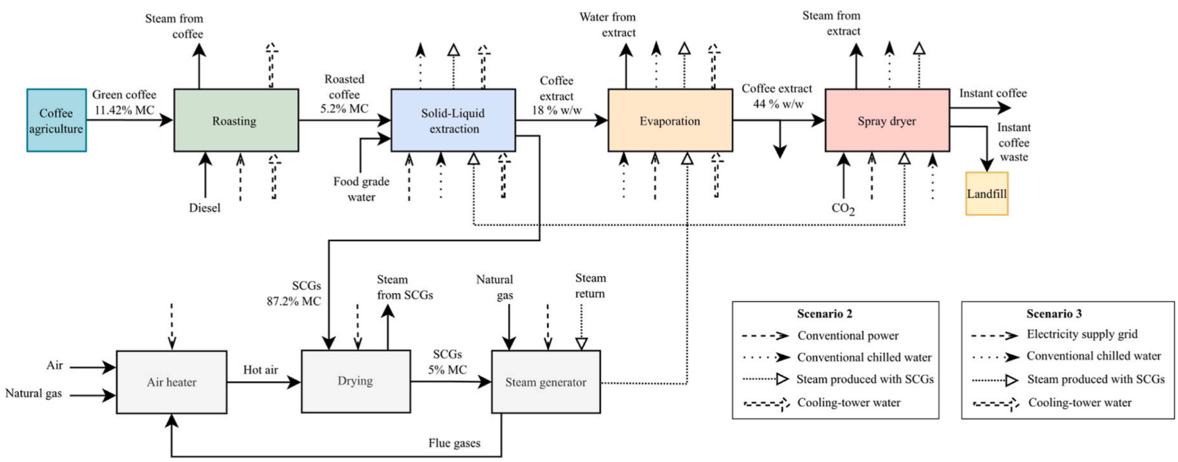

Fig. 2. System boundaries considered in Scenario 2 and 3.

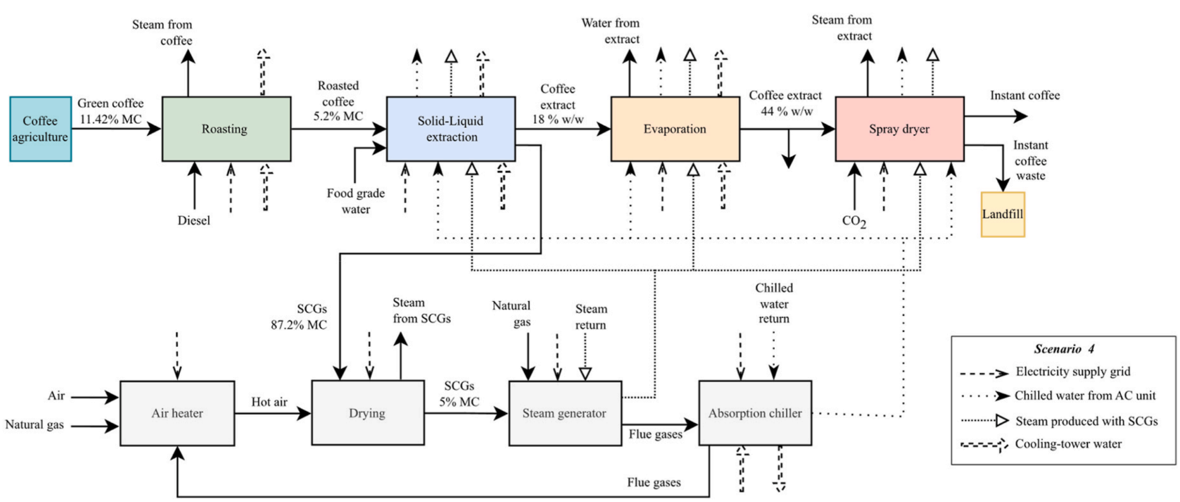

Fig. 3. System boundaries considered in the Scenario 4.

Spray Dryer: The concentrated coffee extract is pumped and mixed with carbon dioxide. The coffee extract is sprayed into the spray drying unit using a nozzle, which operates under vacuum pressure, and ambient air is heated using steam until it reaches a temperature of 180 °C. The resulting dried instant coffee, with a humidity of about 3 % m/m, is collected on a belt. Dehumidified air is used to gradually cool the coffee, preventing agglomeration. Subsequently, the instant coffee undergoes a vibratory screening process to achieve the required particle size. The fraction with the smallest particle size is recirculated into the process using dry air at 27 °C, while the larger particle size of instant coffee is considered waste and disposed of in a landfill (Tinoco-Caicedo et al., 2020).

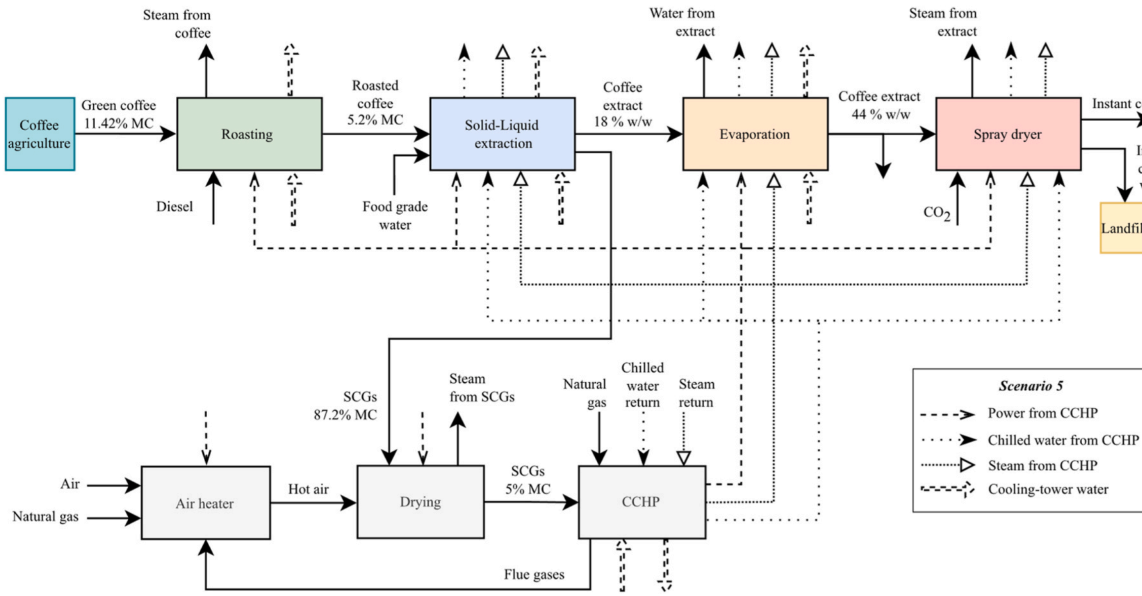

Fig. 4. System boundaries considered in Scenario 5.

2.4. Scenarios

This study proposes different scenarios within the production of instant coffee, taking advantage of the residual energy from treatment units and the recovery of SCGs from the extraction process. The proposed scenarios differ by obtaining: Electricity, steam, and chilled water, as well as the valuation given to the SCG (Table 1 and Figs. 1–4). A detail of each of the proposed scenarios is presented below:

- *Base case (EN-FO)*, considers the processes for instant coffee production; the Ecuadorian electricity supply grid provides the electricity required by all units. A steam generator is powered by Fuel Oil No. 6 and produces superheated steam at 190 °C and 12,500 kPa. A vapor-compression cycle is employed that includes the compression, condensation, expansion, and evaporation of the ammonia as refrigerant to produce chilled water. The non-integrated system used in the real process is presented in detail in a previous study by authors (Tinoco Caicedo et al., 2023). SCGs waste is disposed of in the municipal landfill. The chilled water, steam, and cooling tower water leaving instant coffee production returns to their respective production units.
- *Scenario 1 (ED-FO)*, this scenario considers the processes for instant coffee production; an internal combustion engine produces the electricity using diesel as fuel with an air/diesel ratio of 172.8. SCGs waste is disposed of in the municipal landfill. This situation is currently implemented in cases where there is an absence of an electricity supply grid at the plant.

In base case and scenario 1, there is no use of the SCGs remaining from the extraction of coffee and both are presented in Fig. 1.

- *Scenario 2 (ED-SCG + NG)*, this scenario considers the processes for instant coffee production; an internal combustion engine produces the electricity using diesel as fuel. A steam generator delivers the needed steam using the dried SCG left over from coffee extraction as fuel. The SCGs are dried with hot air, which is heated with the combustion gases obtained by the combustion of natural gas in the presence of air. The chilled water, steam, and cooling tower water leaving instant coffee production returns to their respective production units.
- *Scenario 3 (EN-SCG + NG)*, this scenario considers the processes for instant coffee production and the steam generator powered by dry SCGs, but unlike scenario 2, the electricity requirement is provided by the Ecuadorian electricity supply grid instead of an internal combustion engine. The chilled water, steam, and cooling tower water leaving instant coffee production returns to their respective production units. Scenarios 2 and 3 are similar; the only difference is the electricity source for the main processes, and both are presented in Fig. 2.

- *Scenario 4 (EN-ABS-SCG + NG)*, this scenario considers the processes for instant coffee production; the Ecuadorian power transmission grid provides the electricity required. A steam generator provides the needed steam using the dried SCG left over from coffee extraction as fuel. This case additionally considers an absorption chiller unit, which collects the residual heat from the steam generator to be used in the endothermic separation of water and lithium bromide. The process description of the proposed absorption chiller unit is presented in a previous study by authors (Tinoco Caicedo et al., 2023). The chilled water, steam, and cooling tower water leaving instant coffee production returns to their respective production units.

Table 1
Base case and scenarios description.

Scenario	Nomenclature	Electricity	Steam	Chiller water	SCG
Base case	EN-FO	Ecuador network	Ecuador network - FO - steam generator	Refrigeration	Landfill
1	ED-FO	Internal combustion engine	Internal combustion engine - FO - steam generator	Refrigeration	Landfill
2	ED-SCG + NG	Internal combustion engine	Drying - Steam generator	Refrigeration	Reuse in drying
3	EN-SCG + NG	Ecuador network	Drying - steam generator	Refrigeration	Reuse in drying
4	EN-ABS-SCG + NG	Ecuador network	Drying - steam generator	Absorption chiller	Reuse in drying
5	CCHP-SCG + NG-SCG + NG	CCHP - NG	Drying - CCHP	CCHP	Reuse in drying

- *Scenario 5 (CCHP-SCG + NG-SCG + NG)*, this scenario considers the processes for instant coffee production. Electricity, steam, and chilled water are obtained from a trigeneration system (CCHP) unit based on a biofuel-fueled gas turbine (GT) cycle, steam generator, and absorption chiller unit. It consists in the compression of natural gas and air to produce flue gases with high pressure to input into a turbine to produce power. The hot flue gases are used to produce superheated steam at 190 °C and 12,500 kPa. The exhaust flue gases are used in the absorption chiller unit that uses lithium bromide in solution as in the Scenario 4.

The CCHP systems based on biomass combustion led to better efficiencies, producing primary energy, reducing emissions, and improving the electricity supply to the network. The proposal and evaluation of the CCHP system to be implemented in the instant coffee factory is presented in a previous study by authors (Tinoco Caicedo et al., 2023). The chilled water, steam, and cooling tower water leaving instant coffee production returns to the CCHP process.

2.5. Life cycle inventory analysis

The technical staff of an instant coffee manufacturing company in Guayaquil provided the primary data for the inventory analysis. Subsequently, the material and the energy balance were carried out in each scenario based on the functional unit. Most of the product flows in the foreground system are engineering calculations based on primary data. The trigeneration process was simulated and validated in a previous study (Tinoco Caicedo et al., 2023). Additionally, Tinoco et al. (Tinoco-Caicedo et al., 2021b) previously simulated and analyzed the proposed SCGs treatment.

Annex 1 describes the inventory for each of the proposed scenarios. Fossil fuel (diesel and natural gas), tap water, final waste disposal, and green coffee bean agricultural production and processing data were taken from the Ecoinvent 3.1.7 database (Ecoinvent, 2020). The data is representative of the production of arabica green coffee beans in Colombia used for the export market. Electricity was derived from models developed in Ramirez et al. (2020). Ecuadorian electricity has an important hydropower penetration which results in a comparatively low carbon footprint electricity, however, this situation could change in the future, details of current and futures electricity mix can be found in Ramirez et al. (2020).

2.6. Life cycle impact assessment

The OpenLCA v1.10.3 software has been used to model the different scenarios of instant coffee production (Open Lca, 2021). The results of the environmental impact assessment indicator were calculated according to the hierarchical perspective of the ReCiPe v1.3 methodology (Goedkoop et al., 2009). The analysis includes the following impact categories: Global Warming Potential – GWP (kg CO_2-Eq), Fossil Depletion Potential - FDP (kg oil-Eq), Freshwater Eutrophication Potential - FEP (kg P-Eq), Marine Eutrophication Potential - MEP (kg N-Eq), Ozone Depletion Potential - ODP (kg CFC-11-Eq), Particulate Matter Formation - PMF (kg PM10-Eq), Photochemical Oxidant Formation Potential - POFP (kg NMVOC-Eq), Terrestrial Acidification Potential - TAP100 (kg SO_2-Eq). These categories have been selected as these are the essential ones associated with air pollution and fossil resources, which are relevant as this study is oriented towards the comparison of different energy sources.

3. Results and discussion

This section compares the environmental impacts of the base case and five scenarios proposed in instant coffee production, valuing the SCG as a source of electricity generation for various processes in this production chain. All the results are presented based on the functional unit of 1 kg of instant coffee at the plant gate.

3.1. Global warming potential (GWP100)

In this category, Fig. 5-a, the GWP ranges between 16.9 and 30.84 kg CO_2-Eq, being agriculture the most influential factor regarding all scenarios, representing 53 %–97 % of the GWP. The use of nitrogen fertilizers produces the greatest contribution to the process. In base case and scenario 1, the extraction represents 31 % and 33 %, respectively; this stage includes the treatment of the SCG toward the municipal landfill. Unlike the other scenarios, base case and scenario 1 do not give a valuation to this waste from the coffee extraction process, entailing environmental implications in the CO_2 emissions, representing a 23 % of the total contribution in both cases.

In scenario 2, the extraction and drying stages generate a considerable contribution of 17 % and 13 %, respectively; the steam generation required in the drying stage increases the climate change emissions. In the other scenarios, extraction represents less than 8 % because SCG is the energy source for other processes instead of being disposed of in landfills. Base case, scenarios 1 and 2 present the highest CO_2 emissions, with GWP indicator results of 27.08 kg CO_2-Eq, 30.84 kg CO_2-Eq, and 26.14 kg CO_2-Eq, respectively, noticing that case 1 is the most critical as it uses an internal combustion engine based only on fossil fuels as the energy source for producing the electricity and the steam required.

Scenarios 3 and 4 delivered similar GWP values: 19.58 and 20.32 kg CO_2-Eq, respectively, both use the same electricity arrangement, receiving it from the Ecuadorian electricity supply grid; however, scenario 4 uses more fossil fuel but less biomass (SCG) in its processes, unlike 3, which favors an increase in this category. The incorporation of the absorption chiller decreases the emissions in the extraction and drying stages.

It is important to remark that scenario 5 is the best scenario in this category, with an assessment of 16.90 kg CO_2-Eq, using SCG biomass (94 %) and fuels (6 %), the CCHP system reduces the emissions in all stages, excluding agriculture, which delivers the same indicator value in all the analyzed scenarios. It is also important to mention that using electricity from the Ecuadorian supply grid, as in base case and scenario 3, decreases emissions compared to using an internal combustion engine based on fossil fuels, as in scenarios 1 and 2.

3.2. Fossil depletion potential (FDP)

For all the reviewed scenarios, Fig. 5-b, the FDP range fluctuates between 3.00 and 6.11 kg of oil-Eq, delivering the lowest indicator result for scenario 5 and the highest for scenario 2. Like the GWP category, agriculture is the most important stage in all cases, accounting for an average value of 2.88 kg oil-Eq, followed by the extraction and drying stages of coffee production, where steam generation significantly contributes.

Scenarios 1 and 2 present the most critical FDP, as they require the highest fossil fuel consumption due to the internal combustion engine included in their processes. The base case, scenarios 3 and 4, which use electricity from the Ecuador electricity supply grid, present similar values between 4.0 and 4.6 kg oil-Eq; In scenario 4, although refrigeration does not contribute to FDP because of the adsorption chiller unit, it shows a higher indicator result. The main reason is that it has a higher value in the steam generation process, which is important in the extraction and drying stages. The greater the contribution in the steam generation process, the greater the total FDP, being the most critical of these three scenarios the case 4, followed by case 3 and base case, respectively. Steam generation represents 33.52 %, 27.66 %, and 22.40 % in scenarios 4, 3, and the base case, respectively.

Scenario 5, despite having a higher fuel consumption compared to the base case, scenarios 3 and 4, CCHP technology allows a reduction in emissions in the power generation, steam generation, and cooling, decreasing the FDP and obtaining a value of 3 kg oil-Eq, making this the

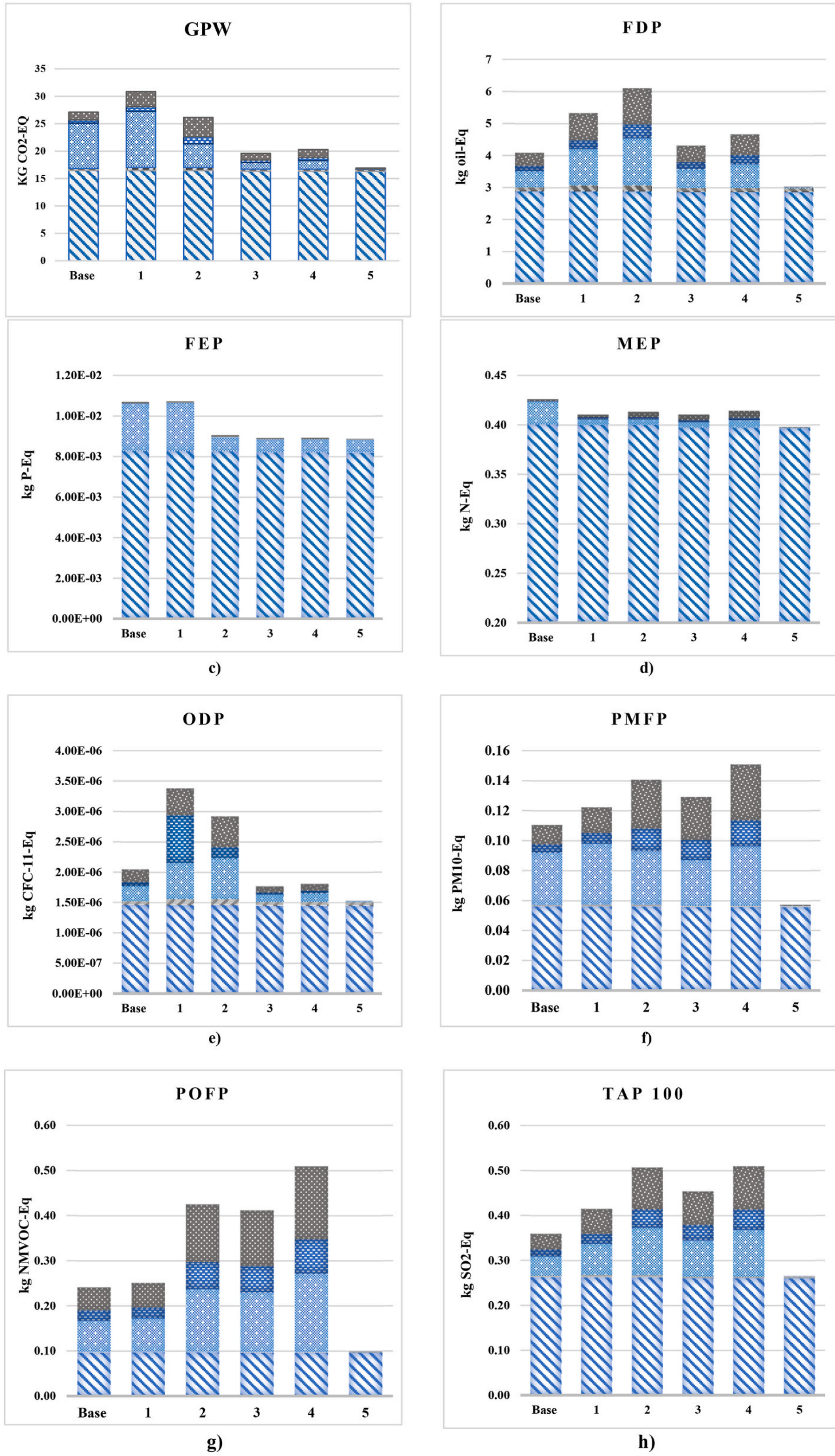

Fig. 5. Impact category indicator results with contribution analysis of a 1 kg Instant coffee in the base case and 5 scenarios. Base case (EN-FO Conventional case Electricity); Scenario 1: (ED-FO) Conventional case-power generation; Scenario 2 (ED-SCG + NG) Steam generation system – conventional power; Scenario 3 (EN-SCG + NG) Steam generation system - Electricity; Scenario 4 (EN-ABS-SCG + NG) Steam generation and absorption chiller system; Scenario 5 (CCHP-SCG + NG-SCG + NG) Combined cooling, heating, and power system.

(a) Global warming potential (GWP100); (b) Fossil depletion potential (FDP); (c) Freshwater eutrophication potential (FEP); (d) Marine eutrophication potential (MEP); (e) Ozone depletion potential (ODP); (f) Particulate Matter Formation (PMF); (g) Photochemical oxidation formation potential (POFP); (h) Terrestrial acidification potential (TAP100).

most attractive scenario.

3.3. Freshwater eutrophication potential (FEP)

According to Fig. 5-c, the indicator results of this category are very similar in all scenarios varying between 0.009 and 0,011 kg P-Eq. In cases 2, 3, 4, and 5, the value corresponds to 0.009 kg PO4-Eq; in the base case and scenario 1, it corresponds to 0.011 Kg P-Eq. The difference in the base case and scenario 1 concerning the rest of the scenarios is that in both cases, the disposal of SCG in municipal landfill increases the FEP by 16 % due to the decomposition of organic matter and nutrients in the waste. In all scenarios, the critical stage corresponds to agriculture, given the use of fertilizers in this activity.

3.4. Marine eutrophication potential (MEP)

Fig. 5-d shows that the range of this category fluctuates between 0.40 and 0.43 kg N-Eq for all scenarios, with the highest value being the base case and scenario 1. The greatest contribution in this category is the stage of agriculture, with a percentage greater than 93 % registered in all scenarios. Like the previous category, the difference between the base case and scenario 1 compared to the rest of the scenarios is that they have an additional contribution due to the disposal of SCG in municipal landfill, which increases the indicator by 5 %. The best scenario is case 5, with a value of 0.4 kg N-eq, almost completely produced by the agriculture stage.

3.5. Ozone depletion potential (ODP)

In this category, Fig. 5-e, agriculture is the most critical stage in instant coffee production, generating 1.46×10^{-6} kg CFC-11-Eq of the total indicator emissions for all scenarios, followed by the extraction and drying stages, where steam generation predominates. The ODP indicator varies between 1.52×10^{-6} kg and 2.92×10^{-6} kg CFC-11-Eq for all reviewed scenarios. Scenarios 1 and 2 present the highest indicator results. These are also the scenarios that demand the consumption of fossil fuels to generate electricity by using an internal combustion engine, increasing the indicator emissions. Scenario 2 has an ODP of 2.92×10^{-6} kg CFC-11-Eq, a higher indicator value than scenario 1 because it requires greater steam generation for the SCG drying process.

Base case and scenario 1 are similar, as these dispose of SCG in the landfill; considering both, the base case has a lower ODP as it uses electricity from the Ecuadorian electricity supply grid, reducing the indicator emissions by 25 %. Scenarios 3 and 4 present a similar indicator result, with a value of 1.76×10^{-6} kg CFC-11-Eq and 1.80×10^{-6} kg CFC-11-Eq, respectively. Although scenario 4 does not produce emissions in the refrigeration process since it has an absorption chiller, the ODP for the steam generation process is 39 % higher than in case 3. Scenario 5 presents the lowest indicator value of 1.52×10^{-6} kg CFC-11-Eq as it does not present contributions in its auxiliary services, having agriculture as the main input stage with 95 %.

3.6. Particulate matter formation potential (PMFP)

The results in this category (Fig. 5-f) for all reviewed scenarios are between 0.11 and 0.15 kg PM10-Eq, except for scenario 5, which presents a lower indicator result of 0.057 kg PM10-Eq. Agriculture is the critical stage in each scenario, making it the primary source of emissions, contributing between 40 % and 98 % of the total value. However, steam generation related to the drying and extraction stages is also an important source of emissions, representing up to 61 % of the total PMFP in the scenarios requiring high steam production, such as scenario 4, which is also the worst scenario regarding this indicator.

Scenario 2 has the second-highest PMFP; steam generation and power generation (internal combustion engine) are important in this case, contributing to 54 % and 3.5 % of the total PMFP, respectively. The main difference between cases 2 and 3 is that the latter uses electricity from the Ecuadorian electricity supply grid, decreasing the indicator result.

A similar situation occurs between the base case and scenario 1, where the use of the national electricity grid, in the base case, decreases its PMFP by 10 % compared to scenario 1, accounting for 0.110 kg PM10-Eq and 0.122 kg PM10-Eq, respectively. It is important to mention that in both scenarios, there is an additional contribution to the indicator emissions produced by the final disposal of SCG in landfills, representing an increase of 18 % and 20 %. Scenario 5 presents the lowest PMFP, having agriculture as the principal emission source, representing 98 % of the result.

3.7. Photochemical oxidation formation potential (POFP)

For this category, Fig. 5-g, scenarios 2, 3, and 4 record the highest values, ranging between 0.41 and 0.51 kg NMVOC-Eq, being the worst scenario 4, followed by scenarios 2 and 3, respectively. The main contribution occurs during agriculture, which represents 0.097 kg NMVOC-Eq for all scenarios; however, the extraction and spray drying stages, which involve the steam generation, also contribute significantly. In scenario 4, the steam generation represents 80 % of the total POFP; this scenario requires a high amount of steam for its processes, making this a critical activity. In scenario 3, steam generation represents 75 % of the POFP, which is why it has a lower value. POFP in scenario 3 is slightly higher than in scenario 2 because the latter also includes emissions from internal combustion engines to generate electricity. Regarding the base case and scenario 1, steam generation reduces its impact, representing only 52 % of the total POFP. Scenario 5 reports the lowest indicator results among all cases, having a value of 0.1 kg NMVOC-Eq; in this case, agriculture represents 97 % of the indicator emissions.

3.8. Terrestrial acidification potential (TAP100)

Fig. 5-h shows that agriculture is the main contributor to this category, representing 0.26 Kg of SO_2 in all scenarios; however, the steam generation processes required in the extraction and spray drying also significantly contribute to TAP 100. The indicator result fluctuates between 0.36 and 0.51 Kg of SO_2, except for scenario 5, which presents a result of less than 0.26 Kg of SO_2, a value related to the agriculture stage. This scenario has reported the lowest indicator values in the different categories analyzed.

Although scenario 4 requires a higher steam generation in its processes than scenario 2, they present an equal TAP100 value of 0.51 kg of SO_2 since the latter includes emissions from the electricity generation through the internal combustion engine. TAP100 in scenario 3 is 12 % lower than in scenario 2, as it uses electricity from the Ecuadorian power grid, reducing the emission values. A similar situation occurs in the base case and scenario 1, presenting values of 0.36 and 0.41 Kg of SO_2, respectively, reporting a reduction of 12 % in the TAP100 when using electricity from the Ecuadorian power grid.

3.9. Best scenario regarding energy source

Considering the previous discussion on each environmental indicator, scenario 5, which uses a trigeneration system (CCHP), has the best environmental performance among the different scenarios, reducing the GWP, FDP, FEP, MEP, ODP, PMFP, POFP, and TAP100 by 37.6 %, 25 %, 18.2 %, 7 %, 24 %, 48 %, 61 %, and 27.7 % respectively compared to the base case. It is also important to remark that in scenario 5, the emissions values correspond almost entirely to the agriculture stage, representing above 96 % in the different indicators. The CCHP unit takes advantage of the residual high-pressure flue gases to produce power, steam, and chiller water. This useful arrangement decreases environmental impact values in the roasting, extraction, evaporation, and spray dryer stages.

Biomass-based energy could have an essential role in the range of options to contribute to the decarbonisation and impulse the circularity of the industrial food sector. This study can serve as a basis for the instant coffee industry; however, other food chains may be able to evaluate and implement this type of system.

4. Conclusions

Reducing environmental emissions is essential to control global warming before it becomes a more threatening problem in the coming decades. Instant coffee production represents an important economic activity for some developing countries, such as Ecuador. This activity produces 65 % of coffee bagasse, which is currently disposed of in landfills without further use. This article analyzed the environmental emissions of instant coffee production by doing a comprehensive life cycle assessment of the base case and 5 scenarios considering different energy sources to produce electricity, steam, and chilled water, valuing the utilization of SCG as an energy source to power some process stages.

The LCA revealed that the agriculture stage has the greatest impact on the environmental indicators during nitrogen fertilization, contributing to more than 50 % of the entire process emissions. Therefore, options that reduce the application of fertilizers that supply such a nutrient should be sought. The final disposal of SCG greatly alters climate change emissions. Taking advantage of this sub-product as an energy source for steam and power generation significantly reduces CO_2 emissions compared to when it is disposed of in a municipal landfill without further use. In addition, using this residue reduces fuel fossil dependence.

Fuel fossil consumption is another important variable affecting indicators, reporting higher values in scenarios requiring electricity generation through an internal combustion engine than in scenarios that use electricity from the Ecuadorian power grid. In general, including the CCHP unit (scenario 5) greatly decreases emissions, reducing the GWP, FDP, FEP, MEP, ODP, PMFP, POFP, and TAP100 by 37.6 %, 25 %, 18.2 %, 7 %, 24 %, 48 %, 61 %, and 27.7 % respectively compared to the base case. The environmental emissions in this scenario are produced mainly during the agriculture stage, representing above 96 % of the values for each indicator impact. The emissions during the roasting, extraction, evaporation, and spray dryer stages are considerably decreased, demonstrating that using energy-efficient technologies lowers the values of the environmental indicators, making this the best scenario in terms of emissions.

CRediT authorship contribution statement

Mayra L. Pazmiño: Investigation, Methodology, Writing – original draft. **Medelyne Mero-Benavides:** Investigation, Methodology, Writing – original draft. **Daniel Aviles:** Investigation, Writing – original draft. **Ana María Blanco-Marigorta:** Investigation, Methodology, Supervision. **Diana L. Tinoco:** Conceptualization, Investigation, Supervision, Writing – review & editing. **Angel D. Ramirez:** Investigation, Methodology, Supervision, Writing – review & editing, Conceptualization.

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.

Data availability

No data was used for the research described in the article.

Appendix A

Table 2
Inputs and outputs of the processes in the base case and scenarios.

Process	United	Scenarios					
1. Roasting		Base case	1	2	3	4	5
Inputs							
Green coffee bean 11.42% MC	kg/h	1,08	1,08	1,08	1,08	1,08	1,08
Air	kg/h	$6{,}59x10^{-1}$	$6{,}59x10^{-1}$	$6{,}59x10^{-1}$	$6{,}59x10^{-1}$	$6{,}59x10^{-1}$	$6{,}59x10^{-1}$
Diesel	kg/h	$4{,}20x10^{-2}$	$4{,}20x10^{-2}$	$4{,}20x10^{-2}$	$4{,}20x10^{-2}$	$4{,}20x10^{-2}$	$4{,}20x10^{-2}$
Cooling-tower water	kg/h	$1{,}85x10^{-1}$	$1{,}85x10^{-1}$	$1{,}85x10^{-1}$	$1{,}85x10^{-1}$	$1{,}85x10^{-1}$	$1{,}85x10^{-1}$
Electricity	kW	$4{,}70x10^{-2}$	$4{,}70x10^{-2}$	$4{,}70x10^{-2}$	$4{,}70x10^{-2}$	$4{,}70x10^{-2}$	$4{,}70x10^{-2}$
Outputs							
Roasted coffee bean 5.2% MC	kg/h	1,00	1,00	1,00	1,00	1,00	1,00
Steam in flue gases from coffee	kg/h	$1{,}14x10^{-1}$	$1{,}14x10^{-1}$	$1{,}14x10^{-1}$	$1{,}14x10^{-1}$	$1{,}14x10^{-1}$	$1{,}14x10^{-1}$
Cooling-tower water	kg/h	$1{,}42x10^{-1}$	$1{,}42x10^{-1}$	$1{,}42x10^{-1}$	$1{,}42x10^{-1}$	$1{,}42x10^{-1}$	$1{,}42x10^{-1}$
N_2	kg/h	$4{,}90x10^{-1}$	$4{,}90x10^{-1}$	$4{,}90x10^{-1}$	$4{,}90x10^{-1}$	$4{,}90x10^{-1}$	$4{,}90x10^{-1}$
H_2O	kg/h	$7{,}91x10^{-2}$	$7{,}91x10^{-2}$	$7{,}91x10^{-2}$	$7{,}91x10^{-2}$	$7{,}91x10^{-2}$	$7{,}91x10^{-2}$
CO_2 from diesel	kg/h	$1{,}25x10^{-1}$	$1{,}25x10^{-1}$	$1{,}25x10^{-1}$	$1{,}25x10^{-1}$	$1{,}25x10^{-1}$	$1{,}25x10^{-1}$
CO_2 from SCG	kg/h	$4{,}42x10^{-6}$	$4{,}42x10^{-6}$	$4{,}42x10^{-6}$	$4{,}42x10^{-6}$	$4{,}42x10^{-6}$	$4{,}42x10^{-6}$
O_2	kg/h	$1{,}31x10^{-2}$	$1{,}31x10^{-2}$	$1{,}31x10^{-2}$	$1{,}31x10^{-2}$	$1{,}31x10^{-2}$	$1{,}31x10^{-2}$
H_2	kg/h	$1{,}48x10^{-3}$	$1{,}48x10^{-3}$	$1{,}48x10^{-3}$	$1{,}48x10^{-3}$	$1{,}48x10^{-3}$	$1{,}48x10^{-3}$
NO_x	kg/h	$8{,}35x10^{-9}$	$8{,}35x10^{-9}$	$8{,}35x10^{-9}$	$8{,}35x10^{-9}$	$8{,}35x10^{-9}$	$8{,}35x10^{-9}$
SO_x	kg/h	$1{,}12x10^{-3}$	$1{,}12x10^{-3}$	$1{,}12x10^{-3}$	$1{,}12x10^{-3}$	$1{,}12x10^{-3}$	$1{,}12x10^{-3}$
2. Extraction							
Inputs							
Roasted coffee bean 5.2% MC	kg/h	$3{,}57x10^{-1}$	$3{,}57x10^{-1}$	$3{,}57x10^{-1}$	$3{,}57x10^{-1}$	$3{,}57x10^{-1}$	$3{,}57x10^{-1}$
Food grade water for extraction	kg/h	2,03	2,03	2,03	2,03	2,03	2,03
Steam	kg/h	$7{,}96x10^{-1}$	$7{,}96x10^{-1}$	$7{,}96x10^{-1}$	$7{,}96x10^{-1}$	$7{,}96x10^{-1}$	$7{,}96x10^{-1}$
Chilled water	kg/h	2,25	2,25	2,25	2,25	2,25	2,25
Cooling-tower water	kg/h	$4{,}83x10^{1}$	$4{,}83x10^{1}$	$4{,}83x10^{1}$	$4{,}83x10^{1}$	$4{,}83x10^{1}$	$4{,}83x10^{1}$
Electricity	kW	$1{,}55x10^{-1}$	$1{,}55x10^{-1}$	$1{,}55x10^{-1}$	$1{,}55x10^{-1}$	$1{,}55x10^{-1}$	$1{,}55x10^{-1}$
Outputs							
Coffee extract 18% w/w	kg/h	1,00	1,00	1,00	1,00	1,00	1,00
SCG (kg/h) 87.2 % MC	kg/h	1,38	1,38	1,38	1,38	1,38	1,38
Steam	kg/h	$7{,}96x10^{-1}$	$7{,}96x10^{-1}$	$7{,}96x10^{-1}$	$7{,}96x10^{-1}$	$7{,}96x10^{-1}$	$7{,}96x10^{-1}$

(*continued on next page*)

Table 2 (*continued*)

Process	United	Scenarios					
1. Roasting		Base case	1	2	3	4	5
Chilled water	kg/h	2,25	2,25	2,25	2,25	2,25	2,25
Tower water (kg/h)	kg/h	4,83x10^{1}	4,83x10^{1}	4,83x10^{1}	4,83x10^{1}	4,83x10^{1}	4,83x10^{1}
Heat	kW	1,78x10^{-1}	1,78x10^{-1}	1,78x10^{-1}	1,78x10^{-1}	1,78x10^{-1}	1,78x10^{-1}
3. Evaporation							
Inputs							
Coffee extract (kg/h) 18 % w/w	kg/h	2,44	2,44	2,44	2,44	2,44	2,44
Steam	kg/h	8,76x10^{-1}	8,76x10^{-1}	8,76x10^{-1}	8,76x10^{-1}	8,76x10^{-1}	8,76x10^{-1}
Chilled water	kg/h	4,47	4,47	4,47	4,47	4,47	4,47
Cooling-tower water	kg/h	1,75x10^{2}	1,75x10^{2}	1,75x10^{2}	1,75x10^{2}	1,75x10^{2}	1,75x10^{2}
Electricity	kW	9,00x10^{-3}	9,00x10^{-3}	9,00x10^{-3}	9,00x10^{-3}	9,00x10^{-3}	9,00x10^{-3}
Outputs							
Coffee extract (kg/h) 44 % w/w	kg/h	3,00x10^{-1}	3,00x10^{-1}	3,00x10^{-1}	3,00x10^{-1}	3,00x10^{-1}	3,00x10^{-1}
Coffee extract (kg/h) 44 % w/w (Final product)	kg/h	7,00x10^{-1}	7,00x10^{-1}	7,00x10^{-1}	7,00x10^{-1}	7,00x10^{-1}	7,00x10^{-1}
Condensed water from extract	kg/h	1,44	1,44	1,44	1,44	1,44	1,44
Steam	kg/h	8,76x10^{-1}	8,76x10^{-1}	8,76x10^{-1}	8,76x10^{-1}	8,76x10^{-1}	8,76x10^{-1}
Chilled water	kg/h	4,47	4,47	4,47	4,47	4,47	4,47
Tower water	kg/h	1,75x10^{2}	1,75x10^{2}	1,75x10^{2}	1,75x10^{2}	1,75x10^{2}	1,75x10^{2}
Heat	kW	1,78x10^{-1}	1,78x10^{-1}	1,78x10^{-1}	1,78x10^{-1}	1,78x10^{-1}	1,78x10^{-1}
4. Spray dryer							
Inputs							
Coffee extract (kg/h) 44 % w/w	kg/h	2,64	2,64	2,64	2,64	2,64	2,64
Steam	kg/h	4,80	4,80	4,80	4,80	4,80	4,80
Chilled water	kg/h	1,27x10^{2}	1,27x10^{2}	1,27x10^{2}	1,27x10^{2}	1,27x10^{2}	1,27x10^{2}
Carbon dioxide (kg/h)	kg/h	3,70x10^{-2}	3,70x10^{-2}	3,70x10^{-2}	3,70x10^{-2}	3,70x10^{-2}	3,70x10^{-2}
Air	kg/h	6,96x10^{1}	6,96x10^{1}	6,96x10^{1}	6,96x10^{1}	6,96x10^{1}	6,96x10^{1}
Electricity	kW	3,67x10^{-1}	3,67x10^{-1}	3,67x10^{-1}	3,67x10^{-1}	3,67x10^{-1}	3,67x10^{-1}
Outputs							
Instant coffee	kg/h	1,00	1,00	1,00	1,00	1,00	1,00
Instant coffee waste	kg/h	1,62x10^{-1}	1,62x10^{-1}	1,62x10^{-1}	1,62x10^{-1}	1,62x10^{-1}	1,62x10^{-1}
Air	kg/h	6,96x10^{1}	6,96x10^{1}	6,96x10^{1}	6,96x10^{1}	6,96x10^{1}	6,96x10^{1}
Steam in air from extract	kg/h	1,48	1,48	1,48	1,48	1,48	1,48
Carbon dioxide in Air	kg/h	3,70x10^{-2}	3,70x10^{-2}	3,70x10^{-2}	3,70x10^{-2}	3,70x10^{-2}	3,70x10^{-2}
Steam	kg/h	4,80	4,80	4,80	4,80	4,80	4,80
Chilled water	kg/h	1,27x10^{2}	1,27x10^{2}	1,27x10^{2}	1,27x10^{2}	1,27x10^{2}	1,27x10^{2}
Heat	kW	6,57x10^{-1}	6,57x10^{-1}	6,57x10^{-1}	6,57x10^{-1}	6,57x10^{-1}	6,57x10^{-1}
5. Auxiliary Services							
5.1. Cooling tower							
Inputs							
Cooling-tower water return	kg/h	1,00	1,00	1,00	1,00	1,00	1,00
Make up water	kg/h	1,60x10^{-2}	1,60x10^{-2}	1,60x10^{-2}	1,60x10^{-2}	1,60x10^{-2}	1,60x10^{-2}
Air	kg/h	5,85x10^{-1}	5,85x10^{-1}	5,85x10^{-1}	5,85x10^{-1}	5,85x10^{-1}	5,85x10^{-1}
Electricity	kW	2,10x10^{-4}	2,10x10^{-4}	2,10x10^{-4}	2,10x10^{-4}	2,10x10^{-4}	2,10x10^{-4}
Outputs							
Cooling-tower water	kg/h	1,00	1,00	1,00	1,00	1,00	1,00
Air	kg/h	5,85x10^{-1}	5,85x10^{-1}	5,85x10^{-1}	5,85x10^{-1}	5,85x10^{-1}	5,85x10^{-1}
Water in Air	kg/h	1,60x10^{-2}	1,60x10^{-2}	1,60x10^{-2}	1,60x10^{-2}	1,60x10^{-2}	1,60x10^{-2}
5.2. Steam generator							
Inputs							
Fuel oil No. 6	kg/h	6,60x10^{-2}	6,60x10^{-2}	–	–	–	–
Water in Air	kg/h	1,00	1,00	–	–	–	–
Air	kg/h	1,06	1,06	1,64	1,64	3,36x10^{-1}	–
Electricity	kW	3,00x10^{-3}	3,00x10^{-3}	6,00x10^{-3}	6,00x10^{-3}	7,97x10^{-3}	–
SCG 5% MC	kg/h	–	–	1,37x10^{-1}	1,37x10^{-1}	1,37x10^{-1}	–
Steam return	kg/h	–	–	1,00	1,00	1,00	–
Air for SCG	kg/h	–	–	–	–	1,91	–
Natural gas	kg/h	–	–	–	–	1,85x10^{-2}	–
Outputs							
Steam	kg/h	1,00	1,00	1,00	1,00	1,00	–
N_2	kg/h	7,99x10^{-1}	7,99x10^{-1}	1,26	1,26	1,71	–
H_2O	kg/h	7,62x10^{-2}	7,62x10^{-2}	6,95x10^{-2}	6,95x10^{-2}	1,19x10^{-1}	–
CO_2 from Fuel oil N. 6	kg/h	2,09x10^{-1}	2,09x10^{-1}	–	–	–	–
O_2 from GN	kg/h	–	–	–	–	4,91x10^{-2}	–
CO_2 from SCG	kg/h	–	–	2,15x10^{-1}	2,15x10^{-1}	2,48x10^{-1}	–
O_2	kg/h	3,40x10^{-2}	3,40x10^{-2}	2,32x10^{-1}	2,32x10^{-1}	2,72x10^{-1}	–
NO_x	kg/h	6,05x10^{-3}	6,05x10^{-3}	3,70x10^{-3}	3,70x10^{-3}	1,01x10^{-2}	–
SO_x	kg/h	2,80x10^{-3}	2,80x10^{-3}	3,84x10^{-4}	3,84x10^{-4}	4,56x10^{-4}	–
5.3. Refrigeration system							
Inputs							
Chilled water return	kg/h	1,00	1,00	1,00	1,00	–	–
Cooling-tower water	kg/h	3,34	3,34	3,34	3,34	–	–
Electricity	kW	2,00x10^{-3}	2,00x10^{-3}	2,00x10^{-3}	2,00x10^{-3}	–	–
Outputs							
Chilled water	kg/h	1,00	1,00	1,00	1,00	–	–
Cooling-tower water	kg/h	3,34	3,34	3,34	3,34	–	–

(*continued on next page*)

Table 2 (*continued*)

Process	United	Scenarios					
1. Roasting		Base case	1	2	3	4	5
5.4. Power generator							
Inputs							
Diesel	kg/h	–	3,89x10^{-1}	3,89x10^{-1}	–	–	–
Air	kg/h	–	6,72x10^{1}	6,72x10^{1}	–	–	–
Electricity	kW	–	2,23x10^{-1}	1,99x10^{-1}	–	–	–
Outputs							
Electricity	kW	–	1,00	1,00	–	–	–
N_2	kg/h	–	5,16x10^{1}	5,16x10^{1}	–	–	–
H_2O	kg/h	–	4,76x10^{-1}	4,76x10^{-1}	–	–	–
CO_2	kg/h	–	1,21	1,21	–	–	–
O_2	kg/h	–	1,44x10^{1}	1,44x10^{1}	–	–	–
NO_x	kg/h		1,14x10^{-3}	1,14x10^{-3}	–	–	–
SO_x	kg/h	–	9,15x10^{-3}	9,15x10^{-3}	–	–	–
5.5. Air heater							
Inputs							
Air for drying	kg/h	–	–	1,00	1,00	1,00	1,00
Air for combustion	kg/h	–	–	4,14x10^{-2}	4,14x10^{-2}	3,06x10^{-2}	2,76x10^{-2}
Natural gas	kg/h	–	–	2,29x10^{-3}	2,29x10^{-3}	1,69x10^{-3}	1,52x10^{-3}
Flue gas from steam generation	kg/h	–	–	7,41x10^{-2}	7,41x10^{-2}	1,00x10^{-1}	1,23x10^{-1}
Electricity	kW	–	–	3,50x10^{-3}	3,50x10^{-3}	3,46x10^{-3}	3,45x10^{-3}
Outputs							
Air for drying	kg/h	–	–	1,00	1,00	1,00	1,00
N_2	kg/h	–	–	8,40x10^{-2}	8,40x10^{-2}	9,43x10^{-2}	1,09x10^{-1}
H_2O	kg/h	–	–	7,65x10^{-3}	7,65x10^{-3}	8,45x10^{-3}	1,06x10^{-2}
CO_2 from GN	kg/h	–	–	6,06x10^{-3}	6,06x10^{-3}	6,51x10^{-3}	9,31x10^{-3}
CO_2 from SCG	kg/h	–	–	8,95x10^{-3}	8,95x10^{-3}	1,03x10^{-2}	1,03x10^{-2}
O2	kg/h	–	–	1,03x10^{-2}	1,03x10^{-2}	1,18x10^{-2}	1,21x10^{-2}
NO_x	kg/h	–	–	8,78x10^{-4}	8,78x10^{-4}	9,56x10^{-4}	1,29x10^{-3}
SO_x	kg/h	–	–	1,77x10^{-5}	1,77x10^{-5}	2,02x10^{-5}	2,10x10^{-5}
5.6. SCG Dryer							
Inputs							
SCG 87.2 % MC	kg/h	–	–	7,42	7,42	7,42	7,42
Air	kg/h	–	–	1,75x10^{2}	1,75x10^{2}	1,75x10^{2}	1,75x10^{2}
Electricity	kW	–	–	5,88x10^{-1}	5,88x10^{-1}	5,88x10^{-1}	5,88x10^{-1}
Outputs							
SCG MC 5 %	kg/h	–	–	1,00	1,00	1,00	1,00
Steam in air	kg/h	–	–	6,42	6,42	6,42	6,42
Air	(kg/h)	–	–	1,75x10^{2}	1,75x10^{2}	1,75x10^{2}	1,75x10^{2}
5.7. Absorption chiller system							
Inputs							
Cooling-tower water	kg/h	–	–	–	–	2,00	–
Chilled water return	kg/h	–	–	–	–	1,00	–
Flue gases from steam generator	kg/h	–	–	–	–	3,41x10^{-1}	–
Electricity	kW	–	–	–	–	1,21x10^{-6}	–
Outputs							
Chilled water	kg/h	–	–	–	–	1,00	–
Cooling-tower water	kg/h	–	–	–	–	2,00	–
N_2	kg/h	–	–	–	–	2,42x10^{-1}	–
H_2O	kg/h	–	–	–	–	1,68x10^{-2}	–
CO_2 from GN	kg/h	–	–	–	–	6,97x10^{-3}	–
CO_2 from SCG	kg/h	–	–	–	–	3,51x10^{-2}	–
O_2	kg/h	–	–	–	–	3,86x10^{-2}	–
NO_x	kg/h	–	–	–	–	1,44x10^{-3}	–
SO_x	kg/h	–	–	–	–	6,47x10^{-5}	–
5.8. CCHP with biomass							
Inputs							
SCG MC 5 %	kg/h	–	–	–	–	–	1,94x10^{-1}
Air for SCG combustion	kg/h	–	–	–	–	–	2,71
Natural gas	kg/h	–	–	–	–	–	6,79x10^{-2}
Air for natural gas combustion	kg/h	–	–	–	–	–	1,23
Cooling-tower water	kg/h	–	–	–	–	–	2,00x10^{1}
Steam return	kg/h	–	–	–	–	–	1,42
Chilled water return	kg/h	–	–	–	–	–	1,00x10^{1}
Electricity	kW	–	–	–	–	–	5,39x10^{-1}
Outputs							
Electricity	kW	–	–	–	–	–	1,00
Chilled water	kg/h	–	–	–	–	–	1,00x10^{1}
Steam	kg/h	–	–	–	–	–	1,42
Cooling-tower water	kg/h	–	–	–	–	–	2,00x10^{1}
Heat	kW	–	–	–	–	–	9,33x10^{-2}
N_2	kg/h	–	–	–	–	–	2,99
H_2O	kg/h	–	–	–	–	–	2,55x10^{-1}
CO_2 from GN	kg/h	–	–	–	–	–	1,80x10^{-1}
CO_2 from SCG	kg/h	–	–	–	–	–	3,51x10^{-1}

(*continued on next page*)

Table 2 (*continued*)

Process	United	Scenarios					
1. Roasting		Base case	1	2	3	4	5
O_2	kg/h	–	–	–	–	–	$3{,}98 \times 10^{-1}$
NO_x	kg/h	–	–	–	–	–	$2{,}75 \times 10^{-2}$
SO_x	kg/h	–	–	–	–	–	$6{,}78 \times 10^{-4}$

*Note: (−) Does not apply.

References

Adams, P.W.R., McManus, M.C., 2014. Small-scale biomass gasification CHP utilisation in industry: energy and environmental evaluation. Sustain. Energy Technol. Assessments 6, 129–140. https://doi.org/10.1016/j.seta.2014.02.002.

America, L., 2019. a.

Amores, M.J., Mele, F.D., Jiménez, L., Castells, F., 2013. Life cycle assessment of fuel ethanol from sugarcane in Argentina. Int. J. Life Cycle Assess. 18 (7), 1344–1357. https://doi.org/10.1007/s11367-013-0584-2.

Atabani, A.E., et al., 2019. Valorization of spent coffee grounds into biofuels and value-added products: pathway towards integrated bio-refinery. Fuel 254 (February), 115640.

Banco Mundial and OCDE, 2021. Agricultura, valor agregado (% del PIB) - Latin America & Caribbean. https://datos.bancomundial.org/indicador/nv.agr.totl.zs?locations=ZJ.

Cibelli, M., Cimini, A., Cerchiara, G., Moresi, M., 2021. Carbon footprint of different methods of coffee preparation. Sustain. Prod. Consum. 27, 1614–1625. https://doi.org/10.1016/j.spc.2021.04.004.

Duan, Y., Pandey, A., Zhang, Z., Awasthi, M.K., Bhatia, S.K., Taherzadeh, M.J., 2020. Organic solid waste biorefinery: sustainable strategy for emerging circular bioeconomy in China. Ind. Crops Prod. 153 (March), 112568 https://doi.org/10.1016/j.indcrop.2020.112568.

Duque-Acevedo, M., Belmonte-Ureña, L.J., Cortés-García, F.J., Camacho-Ferre, F., 2020. Agricultural waste: review of the evolution, approaches and perspectives on alternative uses. Global Ecol. Cons. 22, e00902 https://doi.org/10.1016/j.gecco.2020.e00902, 2020/06/01.

Ecoinvent, 2020. Ecoinvent 3.7.1 Database.

Fiallos-Cárdenas, M., Pérez-Martínez, S., Ramirez, A.D., 2022. Prospectives for the development of a circular bioeconomy around the banana value chain. Sustain. Prod. Consum. 30, 541–555. https://doi.org/10.1016/j.spc.2021.12.014.

Forcina, A., Petrillo, A., Travaglioni, M., di Chiara, S., De Felice, F., 2023. A comparative life cycle assessment of different spent coffee ground reuse strategies and a sensitivity analysis for verifying the environmental convenience based on the location of sites. J. Clean. Prod. 385 (September 2022), 135727 https://doi.org/10.1016/j.jclepro.2022.135727.

Freitas, L.C., Barbosa, J.R., da Costa, A.L.C., Bezerra, F.W.F., Pinto, R.H.H., de Carvalho Junior, R.N., 2021. From waste to sustainable industry: how can agro-industrial wastes help in the development of new products? Resour. Conserv. Recycl. 169 (August 2020) https://doi.org/10.1016/j.resconrec.2021.105466.

Goedkoop, M., Heijungs, R., Huijbregts, M., De Schryver, A., Struijs, J., Van Zelm, R., 2009. ReCiPe 2008. May 2014.

Gosalvitr, P., Cuéllar-Franca, R.M., Smith, R., Azapagic, A., 2023. An environmental and economic sustainability assessment of coffee production in the UK. Chem. Eng. J. 465, 142793 https://doi.org/10.1016/j.cej.2023.142793, 2023/06/01.

Hassard, H.A., Couch, M.H., Techa-Erawan, T., Mclellan, B.C., 2014. Product carbon footprint and energy analysis of alternative coffee products in Japan. J. Clean. Prod. 73, 310–321. https://doi.org/10.1016/j.jclepro.2014.02.006.

Hiloidhari, M., et al., 2019. Agroindustry Wastes: Biofuels and Biomaterials Feedstocks for Sustainable Rural Development, No. 2005. Elsevier Inc.

Ingrao, C., Platnieks, O., Siracusa, V., Gaidukova, G., Paiano, A., Gaidukovs, S., 2022. Spent-coffee grounds as a zero-burden material blended with bio-based poly (butylene succinate) for production of bio-composites: findings from a Life Cycle Assessment application experience. Environ. Impact Assess. Rev. 97, 106919 https://doi.org/10.1016/j.eiar.2022.106919, 2022/11/01.

INTERNATIONAL COFFEE ORGANIZATION (ICO), 2022. Coffee Maket Report September 2022, pp. 1–11. September.

ISO 14040, 2006. Environmental Management- Life Cycle Assessment- Principles and Framework. International Organization for Standardization, Geneva, Switzerland.

ISO 14044, 2006. Environmental Management-Life Cycle Assessment-Requirements and Guidelines. International Organization for Standardization, Geneva, Switzerland.

Jang, H., Ocon, J.D., Lee, S., Lee, J.K., Lee, J., 2015. Direct power generation from waste coffee grounds in a biomass fuel cell. J. Power Sources 296, 433–439. https://doi.org/10.1016/j.jpowsour.2015.07.059.

Jin, L., Zhang, H., Ma, Z., 2018. Study on capacity of coffee grounds to be extracted oil, produce biodiesel and combust. Energy Proc. 152, 1296–1301.

Kang, S.B., Oh, H.Y., Kim, J.J., Choi, K.S., 2017. Characteristics of spent coffee ground as a fuel and combustion test in a small boiler (6.5 kW). Renew. Energy 113, 1208–1214.

Kibret, H.A., Kuo, Y.L., Ke, T.Y., Tseng, Y.H., 2021. Gasification of spent coffee grounds in a semi-fluidized bed reactor using steam and CO2 gasification medium. J. Taiwan Inst. Chem. Eng. 119, 115–127.

Magalhães, A.I., et al., 2019. Lignocellulosic biomass from agro-industrial residues in South America: current developments and perspectives. Biofuel. Bioprod. Biorefin. 13 (6), 1505–1519. https://doi.org/10.1002/bbb.2048.

Nab, C., Maslin, M., 2020. Life cycle assessment synthesis of the carbon footprint of Arabica coffee: case study of Brazil and Vietnam conventional and sustainable coffee production and export to the United Kingdom. Geo Geogr. Environ. 7 (2), 1–19. https://doi.org/10.1002/geo2.96.

Open Lca, 2021. https://www.openlca.org/.

Overturf, E., Pezzutto, S., Boschiero, M., Ravasio, N., Monegato, A., 2021. The circo (Circular coffee) project: a case study on valorization of coffee silverskin in the context of circular economy in Italy. Sustain. Times 13 (16). https://doi.org/10.3390/su13169069.

Petrillo, A., Travaglioni, M., Di Fraia, S., Vanoli, L., Cirillo, D., La Villetta, M., 2021. Experimental study and Life Cycle Assessment of biomass small-scale trigeneration plant. J. Clean. Prod. 326 (September), 129234 https://doi.org/10.1016/j.jclepro.2021.129234.

Poore, J., Nemecek, T., 2018. Reducing food's environmental impacts through producers and consumers. Science (80-) 360 (6392), 987–992. https://doi.org/10.1126/science.aaq0216.

Ragauskaitė, D., Šlinkšienė, R., 2022. Influence of urea on organic bulk fertilizer of spent coffee grounds and green algae chlorella sp. biomass. Sustain. Times 14 (3). https://doi.org/10.3390/su14031261.

Rahmah, D.M., Putra, A.S., Ishizaki, R., Noguchi, R., Ahamed, T., 2022. A life cycle assessment of organic and chemical fertilizers for coffee production to evaluate sustainability toward the energy–environment–economic nexus in Indonesia. Sustain. Times 14 (7), 1–28. https://doi.org/10.3390/su14073912.

Rahnama Mobarakeh, M., Kienberger, T., 2022. Climate neutrality strategies for energy-intensive industries: an Austrian case study. Clean. Eng. Technol. 10 https://doi.org/10.1016/j.clet.2022.100545.

Ramirez, A.D., Boero, A., Rivela, B., Melendres, A.M., Espinoza, S., Salas, D.A., 2020. Life cycle methods to analyze the environmental sustainability of electricity generation in Ecuador: is decarbonization the right path? Renew. Sustain. Energy Rev. 134, 110373 https://doi.org/10.1016/j.rser.2020.110373, 2020/12/01.

Schmidt Rivera, X.C., Gallego-Schmid, A., Najdanovic-Visak, V., Azapagic, A., 2020. Life cycle environmental sustainability of valorisation routes for spent coffee grounds: from waste to resources. Resour. Conserv. Recycl. 157 (February), 104751 https://doi.org/10.1016/j.resconrec.2020.104751.

Steinfeld, H., Gerber, P., Wassenaar, T., Castel, V., Rosales, M., de Haan, C., 2009. La larga sombra del ganado: problemas ambientales y opciones. FAO, Rome, Italy.

Stylianou, M., et al., 2018. Converting environmental risks to benefits by using spent coffee grounds (SCG) as a valuable resource. Environ. Sci. Pollut. Control Ser. 25 (36), 35776–35790. https://doi.org/10.1007/s11356-018-2359-6, 2018/12/01.

Su, Z., Yang, L., 2022. Energy management and life cycle assessment of efficient and flexible trigeneration system for coal-fired power plants. Appl. Therm. Eng. 217 (August), 119178 https://doi.org/10.1016/j.applthermaleng.2022.119178.

Tait, S., Harris, P.W., McCabe, B.K., 2021. Biogas recovery by anaerobic digestion of Australian agro-industry waste: a review. J. Clean. Prod. 299 https://doi.org/10.1016/j.jclepro.2021.126876.

Tinoco Caicedo, D.L., Santos Torres, M., Mero-Benavides, M., Patiño Lopez, O., Lozano Medina, A., Blanco Marigorta, A.M., 2023. Simulation and exergoeconomic analysis of a trigeneration system based on biofuels from spent coffee grounds. Energies 16 (4), 1–17. https://doi.org/10.3390/en16041816.

Tinoco-Caicedo, D.L., Lozano-Medina, A., Blanco-Marigorta, A.M., 2020. Conventional and advanced exergy and exergoeconomic analysis of a spray drying system: a case study of an instant coffee factory in Ecuador. Energies 13 (21). https://doi.org/10.3390/en13215622.

Tinoco-Caicedo, D.L., Feijoó-Villa, E., Calle-Murillo, J., Lozano-Medina, A., Blanco-Marigorta, A.M., 2021a. Advanced exergoeconomic analysis of a double effect evaporation process in an instant coffee plant. Comp. Aided Chem. Eng. 50, 353–358. https://doi.org/10.1016/B978-0-323-88506-5.50056-5.

Tinoco-Caicedo, D.L., Mero-Benavides, M., Santos-Torres, M., Lozano-Medina, A., Blanco-Marigorta, A.M., 2021b. Simulation and exergoeconomic analysis of the syngas and biodiesel production process from spent coffee grounds. Case Stud. Therm. Eng. 28, 101556 https://doi.org/10.1016/j.csite.2021.101556, 2021/12/01/.

Tun, M.M., et al., 2020. Spent coffee ground as renewable energy source: evaluation of the drying processes. J. Environ. Manag. 275 (August) https://doi.org/10.1016/j.jenvman.2020.111204.

Vardon, D.R., et al., 2013. Complete utilization of spent coffee grounds to produce biodiesel, bio-oil, and biochar. ACS Sustain. Chem. Eng. 1 (10), 1286–1294.
Vargas Corredor, Y.A., Pérez Pérez, L.I., 2018. Use of agro-industrial waste in improving the quality of the environment. Rev. la Fac. Ciencias Básicas 14 (1), 59–72.
Zengin, G., et al., 2020. Chemical composition, antioxidant and enzyme inhibitory properties of different extracts obtained from spent coffee ground and coffee silverskin. Foods 9 (6), 1–17.