Techno-economic analysis and life cycle assessment (LCA) of biomass gasification for power generation

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Abstract

Environmentally friendly alternatives are under investigation because of the rising negative consequences of climate change, which are caused, among other things, by greenhouse gas (GHG) emissions from fossil fuel-based electricity production. Biomass gasification is a promising technology for fossil fuel phase-out due to biomass diversity, accessibility and dispatchability. Through a Life Cycle Assessment (LCA) and Techno-economic analysis (TEA), this study evaluates the environmental impact, economic viability, and technical challenges of the gasification process of various biomass feedstocks and utilization of produced syngas for power generation based on experimental data.

The study investigated three biomasses gasification (olive pomace, miscanthus and pine) under two reactor types (fixed bed and fluidized bed). Among analysed biomasses, the olive pomace is the best feedstock. It is not only the least harmful but also the most economically attractive and contributes to waste stream mitigation from the olive oil industry. However, the Levelized Cost of Electricity (LCOE) is higher than alternative renewable solutions on the market. Moreover, there are still a few challenges to large-scale implementation, and more research needs to be done in this direction.

Keywords: Life Cycle Assessment (LCA); Techno-economic analysis (TEA); Biomass Gasification; Olive pomace; Miscanthus; Pine.

1. Introduction

The critical threat to humanity is climate change driven by greenhouse gas (GHG) emissions associated among others with power generation. It has already changed the environment in which people live [1] and it continues to do so, by degrading water quality and causing extreme weather events such as catastrophic flooding, droughts, and rising sea levels. Climate change puts the world's food supply at risk since crops are sensitive to climate fluctuations, which give lower yields and variability in agricultural production [2]. In response, global initiatives like the Paris Agreement and the EU's 2030 climate and energy framework aim to combat climate change, setting targets for emissions reduction, energy efficiency, and renewable energy adoption [3],[4].

The four main categories of renewable energy sources are solar, wind, hydropower, and biomass [5]. Regarding diversity, accessibility, and sustainability, biomass is one of the most important renewable energy sources [6]. Biomass can benefit the overall operation of the energy system by providing stable, dispatchable power that complements the high levels of output from variable sources like solar PV and wind [7]. However, due to the inconvenient form of biomass [8] it is usually converted through physicochemical, biochemical, or thermochemical processes [6]. Biomass gasification has gained significant attention due to its advantages, positioning it as a key player in global energy and industrial markets, particularly in clean power generation [9],[10]. This process involves high-temperature interactions between a gasifying agent and feedstock in a gasifier. yielding syngas (CO, CH_4, H_2, and other hydrocarbons) with impurities like untreated charcoal, fly ash, sulphides, alkali metals, and heavy carbon compounds [10].

However, the gasification process is complex and depends on the biomass characteristics, the operating parameters, the oxidizing agent, and the gasifier type and design [11]. Biomass with elevated carbon and oxygen content yields a greater percentage of combustibles [12], while high ash content can impede gasification, causing slagging and feed blockage [13]. Maintaining feedstock moisture below 15% is recommended to ensure proper reactor performance [14]. Smaller particle sizes increase the hydrogen content of the syngas generated and reduce tar creation [15], but the reduction process consumes much energy, so the particles should not be smaller than required [16]. Larger-sized particles reduce pretreatment energy expenditures but have difficulties with feeding, devolatilization, decomposition performance and more char are created due to the incomplete decomposition [16],[17]. High working pressure minimize char and tar yield but poses economic challenges for small-scale plants [18]. Air is a cost-effective gasifying agent but dilutes syngas heating value due to nitrogen[19]. Oxygen-based gasification yields syngas with the highest heating value, but pure O_2 induces high operational costs. Steam as a gasifying agent enhances H_2 production but increases energy requirements [19]. Catalyst is not obligatory but eliminates tars, enhances syngas yield and heating value [8],[20].

The fixed bed is one of the oldest and simplest gasification technologies, with feedstock coming down through the gasifier. Due to its uncomplicated design and operational ease, it is the most widely employed gasifier commercially. Those gasifiers are the most cost-effective and ideal for small-scale gasification for heat and power generation applications but are also commonly used for thermal large-scale systems. The most common fixed bed gasifier types are updraft and downdraft gasifiers [21],[22].

Fluidized bed gasifiers, operating on the fluidization principle, ensure temperature homogeneity, yielding high efficiency and conversion rates through rapid biomass decomposition [50]. Bed materials, like silica or alternatives such as sand, olivine, dolomite, and limestone with catalytic properties, address tar-related challenges. In-bed additives like kaolin, calcium oxide, or carbonite and bauxite effectively mitigate tar agglomeration. Fluidized bed reactors are classified as bubbling or circulating fluidized bed reactors [17],[21].

Comprehensive analyses covering technical, economic, and environmental aspects are essential for developing a sustainable energy system. The Life Cycle Assessment (LCA) is a globally recognized approach for evaluating environmental impacts [9]. To assess technical and economic feasibility, industries commonly use Techno-economic analysis (TEA) [13],[15].

The objective of this study is to assess, through Life Cycle Assessment (LCA), the potential environmental impacts of three types of biomasses through gasification within two different reactors for electricity generation and through Techno-econimic analysis (TEA) their economic feasibility based on the experimental data acquired with the collaboration of of Valoriza of Instituto Politécnico de Portalegre (IPP).

2. Methodology

The present workis primarily based on the data acquired under the collaboration with Valoriza at Politécnico de Portalegre (IPP). The data consists of biomass characteristics, the gasification process energy consumptions, and the yields and compositions of obtained products. Within retrieved data, the Ecoinvent 3 database and assumptions, the Life Cycle Assesment (LCA) and Techno-economic analysis (TCA) have been performed.

2.1. Data Collection

Biomass Description

The gasification process performed by IPP utilized pellets of olive pomace, miscanthus, and pine. Initial steps involved drying, milling, and pelletizing the raw biomass. Olive pomace, due to its small pieces after the olive oil extraction process, did not require milling.

Gasification Process and Results:

Measurements utilized a 15 kWe downdraft fixed bed gasifier (laboratory-scale) and an 85 kWe bubbling fluidized bed gasifier (pilot-scale). Syngas samples, collected in polypropylene bags upon stabilization, facilitated system comparison after normalizing data to a 100 kg/h feed rate. Results, detailed in Table 1, shows lower Cold Gas Efficiency (CGE) and syngas yield in fluidized bed gasification of miscanthus and pine due to reported clogging issues.

2.1. Life Cycle Assessment

Life Cycle Assessment (LCA) study carried out according to the ISO 14040:2006 with the use of SimaPro 9.1 software, which proved to be the most chosen LCA software in the scientific world due to its robust database, user-friendly interface, advanced modelling capabilities, compliance with international standards.

Goal and scope definition

The LCA study aims to investigate and compare the environmental impact of the gasification process for power generation using biomasses of three different origins in two types of reactors (fixed bed, fluidized bed) with each other and with natural gas power plant. The mentioned origins of biomasses include Agriculture (Olive pomace), Energetic crops (Miscanthus) and Forest (Pine).

Functional unit (FU) and system boundary

The functional unit (FU) is specified as the production of 1 MWh of electricity.

The LCA carried in the study includes the cultivation, harvesting, pretreatment (drying, milling, pelletizing), gasification and power generation in the biomass supply chain. On Figure 1 has presented system boundary and process schemes for olive pomace, miscanthus, and pine cases. The LCA analysis is evaluated within assumptions that the gasification plant is in Portugal, co-located with the biomass source, omitting biomass transportation. Olive pomace is treated as a byproduct of olive oil production. Therefore, emissions and energy need from olive cultivation and processing are not accounted for in the olive pomace case. The already shredded olive pomace from extraction olive oil eliminates milling needs in biomass pretreatment.

Life Cycle Inventory (LCI)

Within the Life Cycle Inventory (LCI) phase, an inventory of input and output data for the studied fulfil predefined objectives, is conducted.

The primary data, such as electricity usage and feedstock amount requirements for pretreatment and gasification were retrieved from a gasification plant located at Instituto Politécnico de Portalegre,

Table 1. Results of biomass gasification (normalized to feed rate of 100kg/h).

Parameter	Unit	Fixed bed			Fluidized bed		
		Olive pomace	Miscanthus	Pine	Olive pomace	Miscanthus	Pine
CO_2	%	8.52	11.59	11.52	16.21	15.70	17.20
C_2H_4	%	0.47	0.57	0.73	2.76	0.30	2.87
C_2H_6	%	0.09	0.14	0.19	0.14	0.00	0.30
C_2H_2	%	0.02	0.02	0.04	0.10	0.10	0.00
H_2S	%	0.05	0.04	0.00	0.00	0.00	0.00
N_2	%	55.01	54.80	54.87	52.15	50.70	50.80
CH_4	%	2.04	2.01	3.35	4.42	3.80	4.40
CO	%	19.91	18.45	15.87	11.50	13.20	16.30
H_2	%	13.56	12.32	13.21	12.7	16.2	8.13
LHV	MJ/Nm^3	4.82	4.59	4.95	5.90	4.76	6.10
Tars flow rate	Nm^3/h	0.003	0.004	0.002	0.020	0.010	0.010
Char mass rate	kg/h	6.1	3.4	3.0	4.9	3.7	5.3
Syngas flow rate	Nm^3/h	282.4	249.8	264.7	230.3	172.5	150.2
Cold gas Efficiency (CGE)	%	73.6	70.3	80.1	73.3	50.3	56.0

Portugal, where laboratory measurements utilizing all three specified biomasses in downdraft fixed bed and bubbling fluidized bed reactors were done. Supplementary data regarding miscanthus and pine stages of cultivation and harvesting, the emissions associated with the use of electricity (Portugal energy mix) sourced from Ecoinvent 3 - allocation, cut-off by classification database. Table 2 and Table 3 contains the material and energy inputs, as well as the various outputs, including electricity, char, and emissions for analysed biomass feedstocks pretreatment and gasification with power generation for fixed bed and fluidized bed gasifiers.

Life Cycle Impact Assessment (LCIA)

Environmental impacts are evaluated using midpoint and endpoint methods, each offering a distinct approach. Midpoint and endpoint methods, complement each other due to different approaches of calculating impacts. Midpoint methods work on intermediate indicators establishing links between emissions and environmental stressors, whereas endpoint methods directly link environmental impacts and real damages [23]. The chosen midpoint method is CML-IA Baseline V3.05 / EU25. CML-IA methodology is a midpoint impact assessment method developed by Leiden University, focuses on the European context and is widely accepted [24], [25], [26]. It comprehensively assesses categories: abiotic depletion, global warming, ozone layer depletion (ODP), human toxicity, freshwater aquatic ecotoxicity, marine aquatic ecotoxicity terrestrial ecotoxicity, photochemical oxidation, acidification, and eutrophication [27]. Whereas as endpoint impact method has chosen IMPACT (MPact Assessment of Chemical Toxics) developed by the Swiss Federal Institute of Technology – Lausanne (EPFL), which contains human health, ecosystem quality, climate change and resources impact categories [28]:

Techno-economic analysis

Data and assumptions

The economic analysis was carried under assumption and based on data from various literature, which are in Table 4.

Gasification unit is located near wood, miscanthus, or olive oil facilities in Portugal. Transportation cost is negligible in such case therefore price of pine and miscanthus based on the lower value of the price ranges reported in the literature. In the case of olive pomace price, literature reported the price of 30 €/ton [29], [30] but due to the oversupply of olive pomace in Portugal [31] has assumed a price of 15 €/ton of olive pomace. Additionally assumed 1 month in year off duty for plant maintenance, no bank loan, no inflation, and no salvage value.

3. Results and Discussion

3.1. Life Cycle Assessment

As stated previously in the LCIA methodology and within the study's scope, the environmental impacts associated with power generation from three distinct biomass sources, employing the two types of reactors, have been computed across eleven midpoint and four endpoint categories (Figure 2).

Abiotic depletion

Pine and miscanthus have the greatest impact on this category due to land cultivation, involving flora cutting, soil mineral extraction, and fertilizer use. Pine's slower growth can be reason for higher abiotic depletion than miscanthus. Olive pomace, due to assumptions, has a lower impact (1.5%). Natural gas power plants minimally affect abiotic depletion (0.3%). Among gasifiers in the miscanthus and pine case fluidized bed has a larger impact than the fixed bed by 23% and 30%, respectively, due to lower efficiency and higher feedstock consumption. Olive pomace in both gasifiers shows a significantly lower impact at $1.2\cdot10^{-6}$ kg Sb eq./MWh, attributed to cultivation differences, compared to literature's $9.5\cdot10^{-3}$ kg Sb eq./MWh [25].

Abiotic depletion (fossil fuels)

In this category, the natural gas power plant has the highest impact on abiotic depletion of fossil fuels, as expected due to its extraction. Other biomasses contribute due to partial reliance on fossil fuels in various life cycle stages.

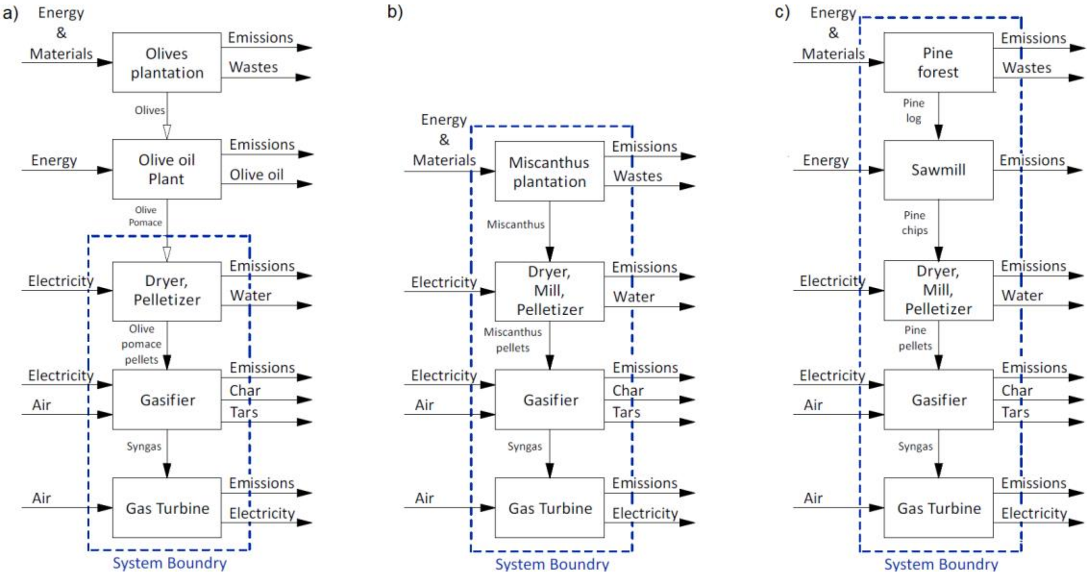

Figure 1. System boundaries and processes of feedstocks. a) Olive pomace, b) Miscanthus, c) Pine.

Pine has a greater impact than miscanthus due to more processing, while olive pomace, per the study's assumption, has the least impact (7.5% for fixed bed and 7.1% for fluidized bed). Among gasifiers, the fluidized bed has impact higher of 4.6% and 5.6% than the fixed bed in miscanthus and pine likely due to process efficiency. Comparing with literature both fixed bed (860 MJ/MWh) and fluidized bed (808 MJ/MWh) olive pomace gasification show lower values but are not distinctly different from Ozturk et al.'s study of 1161 MJ/MWh [25]. For miscanthus, the study reports results of 1290 MJ/MWh for fixed bed and 1810 MJ/MWh for fluidized bed. The fixed bed value is higher but comparable to Jeswani et al. at 1151 MJ/MWh [41], and much higher than Balcioglu et al.'s 879 MJ/MWh [43]. For pine, the study reveals fixed bed and fluidized bed gasification results of 1490 MJ/MWh and 2130 MJ/MWh, notably diverging from Jeswani et al.'s findings of 868 MJ/MWh [41].

Global warming,

All biomasses have over 70% lower impact than natural gas, due to the short carbon cycle of biomass. Olive pomace, regardless of gasifier type, has the best results at 66 kg CO_2 eq./MWh, which is 9.4% of natural gas and is lower compared to literature's 112 kg CO_2 eq./MWh [25]. Miscanthus, in fixed bed gasification, shows 124 kg CO_2 eq./MWh being 17.5%, and in fluidized bed, it is 173 kg CO_2 eq./MWh, which corresponds to 24.5%. Such result falls between literature findings of 296 kg CO_2 eq./MWh [42] and 110 kg CO_2 eq./MWh [41], [43]. For pine, the fixed bed and fluidized bed gasification results are 132 kg CO_2 eq./MWh and 189 kg CO_2 eq./MWh, respectively, being close to reported value of 203 kg CO2 eq./MW [44], but much higher than waste wood (70 kg CO2 eq./MWh) [41].

Ozone layer depletion (ODP)

Natural gas has the highest impact due to extraction and processing. Olive pomace gasification in both fixed bed and fluidized bed cases shows values of $3.8\cdot10^{-7}$ kg CFC11 eq./MWh which corresponds to 0.4% of maximal impact in this category. It is also much smaller compared to $8.8\cdot10^{-6}$ kg CFC11 eq./MWh in literature [25]. For miscanthus, the study reports results of $1.2\cdot10^{-6}$ kg CFC11 eq./MWh and $1.7\cdot10^{-6}$ kg CFC11 eq./MWh for fixed bed and fluidized bed which corresponds to 1.4% and 1.9% of maximum, it also differs from literature values of 1.0·10-5 kg CFC11 eq./MWh [43] and $1.8\cdot10^{-5}$ kg CFC11 eq./MWh [41]. Literature's ozone layer depletion for pine result of $2.9\cdot10^{-6}$ kg CFC11 eq./MWh [44], which is lower than fixed bed ($5.4\cdot10^{-6}$ kg CFC11 eq./MWh) and fluidized bed ($7.7\cdot10^{-6}$ kg CFC11 eq./MWh) pine gasification corresponding to 6.0% and 8.6% respectively. Waste wood in Jeswani et al.'s findings has the highest value of $1.4\cdot10^{-5}$ kg CFC11 eq./MWh [41].

Human toxicity

Pine and miscanthus gasification have the greatest human toxicity impact, with olive pomace and natural gas having smaller impacts of about 11% and 6% of the maximal impact in this category. The absence of burdens from olive cultivation significantly lowers olive pomace's impact. Pine and miscanthus have a direct impact during cultivation and harvesting, with pine being about 20-30% more harmful than miscanthus, depending on the gasifier. Fixed bed gasification has a lower impact than fluidized bed due to process efficiency. In olive pomace, literature reports 821 kg 1,4-DCB eq./MWh [25], while this study found values of 3.5 kg 1,4-DCB eq /MWh for fixed bed and 3.4 kg 1,4-DCB eq /MWh for fluidized bed. Miscanthus impacts are 15.7 kg 1,4-DCB eq /MWh for fixed bed and 21.8 kg 1,4-DCB eq /MWh for fluidized bed, with the fixed bed value similar to literature at 12.0 kg 1,4-DCB eq /MWh [41]. Balcioglu et al. reported a notably lower impact at 4.1 kg 1,4-DCB eq /MWh [43].

Table 2. Feedstock pretreatment inputs and outputs (per functional unit).

Parameter	Unit	Fixed bed			Fluidized bed		
		Olive pomace	Miscanthus	Pine	Olive pomace	Miscanthus	Pine
Input							
Feedstock$_{dry}$	kg	938	949	1163	941	1325	1662
Electricity	kWh	16	22	21	16	31	30
Output							
Feedstock (pellets)	kg	725	860	753	727	1202	1077
Emissions to air							
H_2O	kg	214	89	409	214	124	585

Table 3. Feedstock pellets gasification with power generation inputs and outputs (per functional unit).

Parameter	Unit	Fixed bed			Fluidized bed		
		Olive pomace	Miscanthus	Pine	Olive pomace	Miscanthus	Pine
Input							
Feedstock (pellets)	kg	725	860	753	727	1202	1077
Oxidizing agent (air)	kg	1564	1640	1499	1417	1334	1058
Electricity	kWh	112	112	116	112	185	166
Output							
Electricity	kWh	1000	1000	1000	1000	1000	1000
Char	kg	44	29	22	36	44	57
Tars	kg	25	44	21	185	156	135
Emissions to air							
$CO_{2,\ biogenic}$	kg	638	710	642	629	685	705
SO_2	kg	0.78	0.65	-	-	-	-
H_2O	kg	112	107	106	86	135	53

Table 4. Assumptions and data used in economic evaluation.

Name	Unit	Value	Reference
Feedstock capacity	kg/h	100	-
Operating hours	h/year	8035	-
Lifetime	years	20	-
Biochar price (sell)	€/kg	0.2093	[32], [33]
Electricity price (sell)	€/kWh	0.1132	[34], [35]
Electricity price (buy)	€/kWh	0.1397	[36]
Feedstock price			
Olive pomace	€/t	15	[29], [30]
Miscanthus	€/t	40	[37], [38]
Pine	€/t	44	[9]
CAPEX			
Fixed bed	€/kW	2 500	[39], [40], [34]
Fluidized bed	€/kW	3 750	[39], [40], [34]
OPEX			
Variable	€/kW	0.0031	[40]
Fixed	% of CAPEX	4	[40]
Discount rate	%	7	-

Pine evaluations show higher impacts, with fixed bed gasification at 21.4 kg 1,4-DCB eq /MWh and fluidized bed at 30.5 kg 1,4-DCB eq /MWh, compared to waste wood (12.3 kg 1,4-DCB eq /MWh [41]) and the lowest reported value by Zang et al. at 4.1 kg 1,4-DCB eq /MWh [44].

Freshwater aquatic ecotoxicity,

Pine shows the highest impact within fluidized bed and fixed bed gasification, with a difference of 30% between reactors. Miscanthus has a much lesser impact (13%-18%), while natural gas and olive pomace have marginal impacts, being 1.7% and 0.6% respectively. Pine's higher impact could be due to clearcutting practices leading to soil disturbance and erosion, impacting water quality. Miscanthus, requiring less fertilizers and pesticides, leading to a lower risk of soil and groundwater contamination than pine. In olive pomace gasification, literature reports 5.2 kg 1,4-DCB eq./MWh [25], while this study finds 0.1 kg 1,4-DCB eq /MWh for both fixed bed and fluidized bed. Miscanthus gasification results are 1.5 kg 1,4-DCB eq /MWh and 2.1 kg 1,4-DCB eq /MWh for fixed bed and fluidized bed, comparable to literature values of 1.4 kg 1,4-DCB eq /MWh [41] and 1.7 kg 1,4-DCB eq /MWh [43]. Pine gasification in this study indicates higher impacts, with fixed bed and fluidized bed at 7.9 kg 1,4-DCB eq /MWh and 11.3 kg 1,4-DCB eq /MWh, respectively, contrasting with waste wood at 1.00 kg 1,4-DCB eq /MWh [41].

Marine aquatic ecotoxicity

In marine aquatic ecotoxicity, pine and miscanthus show the higher percentage, with olive pomace having less influence (5.2%) and natural gas being negligible (0.7%). The magnitudes are significant in all cases, and as in previous impact categories, the fixed bed shows about a 30% lower impact for pine and miscanthus compared to the fluidized bed due to process efficiency. Ozturk et al. reported a high impact of 55079 kg 1,4-DCB eq /MWh [25] for olive pomace, while this study found 8670 kg 1,4-DCB eq /MWh for fixed bed and 8690 kg 1,4-DCB eq /MWh for fluidized bed. For miscanthus, this study's values are significantly higher, with fixed bed gasification at 120000 kg 1,4-DCB eq /MWh and fluidized bed at 167000 kg 1,4-DCB eq /MWh, contrasting with literature values of 2.1 kg 1,4-DCB eq /MWh [41] and 2.8 kg 1,4-DCB eq /MWh [43]. Pine gasification results in significant impacts, with fixed bed and fluidized bed at 117000 kg 1,4-DCB eq /MWh and 167000 kg 1,4-DCB eq /MWh, respectively, in contrast to waste wood at 1.5 kg 1,4-DCB eq /MWh [41].

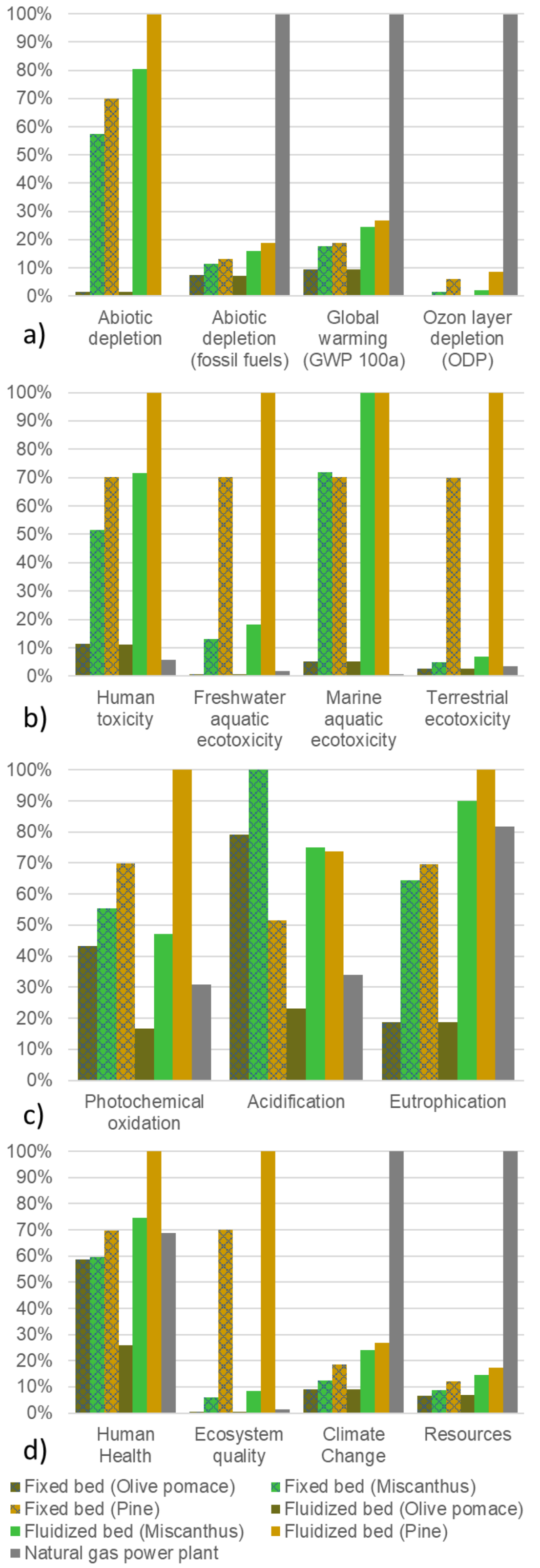

Figure 2. Impact categories comparison among cases. midpoint – a), b), c); endpoint d)

Terrestrial ecotoxicity,

In the terrestrial ecotoxicity impact category, a similar trend to freshwater aquatic ecotoxicity is observed, with pine being the most influential. Miscanthus, olive pomace, and natural gas have impacts below 10% compared to pine, owing to the same reasons as freshwater aquatic ecotoxicity, although with smaller magnitudes. For olive pomace gasification, both fixed bed and fluidized bed have results of 0.02 kg 1,4-DCB eq /MWh, contrasting with the literature value of 9200 kg 1,4-DCB eq /MWh [25]. In miscanthus, the study's results are smaller, with 0.04 kg 1,4-DCB eq /MWh for fixed bed and 0.06 kg 1,4-DCB eq /MWh for fluidized bed, compared to literature values of 0.16 kg 1,4-DCB eq /MWh [41] and 0.21 kg 1,4-DCB eq /MWh [43]. Pine has higher impacts in the study, with fixed bed and fluidized bed pine gasification at 0.61 kg 1,4-DCB eq /MWh and 0.878 kg 1,4-DCB eq /MWh, respectively, while literature values for waste wood are 0.15 kg 1,4-DCB eq /MWh [41].

Photochemical oxidation

In this category, pine contributes the most due to fertilizer and machinery used during cultivation, releasing NO_x into the atmosphere, a key compound for photochemical oxidation. Unlike previous categories, fixed bed gasification of miscanthus and olive pomace has higher impacts than fluidized bed by about 8.5% and 26.5%, respectively, likely due to H_2S in syngas, leading to SO_2 release and contributing to photochemical oxidation and acidification. Fluidized bed olive pomace gasification, lacking H_2S, has the lowest impact of 16.7%, while natural gas is the second least harmful (30.8%). For olive pomace, fixed bed gasification is higher at 0.06 kg C_2H_4 eq./MWh compared to literature's 0.04 kg C_2H_4 eq./MWh [25], while fluidized bed gasification is lower at 0.02 kg C_2H_4 eq./MWh.

Acidification

In this category, the cases with H_2S in the syngas show the highest impact. Fixed bed gasification of miscanthus and olive pomace significantly contributes to acidification due to H_2S, leading to SO_2 release during combustion. The lowest impact is in fluidized bed olive pomace gasification (23.0%), followed by natural gas (34.0%). Despite no H_2S in syngas for fluidized bed pine and miscanthus, they have a higher impact due to a less efficient process. For olive pomace gasification, the fixed bed has 1.33 kg SO_2 eq./MWh, slightly higher than the reported 1.29 kg SO_2 eq./MWh [25]. On the other hand, fluidized bed olive pomace gasification has a smaller impact of 0.39 kg SO_2 eq./MWh. Comparing the results of miscanthus align with the literature, fixed bed at 1.68 kg SO_2 eq./MWh and fluidized bed at 1.26 kg SO_2 eq./MWh, compared to 1.05 kg SO_2 eq./MWh [43] and 1.60 kg SO_2 eq./MWh [42]. For pine, fixed bed and fluidized bed are over twice as high, 0.87 kg SO_2 eq./MWh and 1.24 kg SO_2 eq./MWh, respectively, compared to literature 0.42 kg SO_2 eq./MWh [44].

Eutrophication

In eutrophication, regardless of the reactor, olive pomace gasification has the lowest impact at 18.7%, compared to the highest impact of fluidized bed pine. The next most harmful are fluidized bed miscanthus gasification (90.0%), along with natural gas power plants (81.8%). However, fixed bed gasification of miscanthus and pine has a lower impact than natural gas power plants by about 17% and 12% respectively. For olive pomace, fixed bed, and fluidized bed gasification exhibit values of 0.02 kg PO_4 eq./MWh each, compared to the higher 0.624 kg PO_4 eq./MWh [25]. Miscanthus has 0.08 kg PO_4 eq./MWh and 0.11 kg PO_4 eq./MWh for fixed bed and fluidized bed, respectively, compared to literature reports of 7.8 kg PO_4 eq./MWh [41]. Pine, in fixed bed and fluidized bed, has higher impacts (0.08 kg PO_4 eq./MWh and 0.12 kg PO_4 eq./MWh, respectively) than literature values of 0.03 kg PO_4 eq./MWh [44].

Human health

Fluidized bed pine gasification has the highest impact of $1.31\cdot10^{-4}$ DALY, influenced by extensive pine processing, reliance on fossil fuels, higher fertilizer and pesticide use, and low gasification process efficiency leading to increased NO_x emissions. Fluidized bed gasification of miscanthus is the second most harmful ($9.76\cdot10^{-5}$ DALY) due to similar reasons but with lower need of fertilizer and pesticide use. Fixed bed pine ($9.14\cdot10^{-5}$ DALY) and natural gas ($9.03\cdot10^{-5}$ DALY) have almost identical impacts, differing by only 0.84%, likely due to higher NO_x emissions, which is major contributor to respiratory and health issues for humans. In contrast, fluidized bed olive pomace gasification has the lowest impact of $3.14\cdot10^{-5}$ DALY, which corresponds to 26.0%, due to lack of H_2S content in syngas, which is crucial in mitigating severe effects on respiratory, cardiovascular, and nervous systems caused by SO_2 emissions.

Ecosystem quality

Pine is the most harmful with result of 415 PDF·m^2*yr/MWh, regardless of the gasifier used, with a difference of about 30% between reactors and even higher compared to other biomasses. This outcome is attributed to land changes disrupting local ecosystems, cutting trees, and causing biodiversity loss. Pesticide usage for pine trees also affects insects and birds [45]. Miscanthus has a lower impact 35.6 PDF·m^2*yr/MWh and 25.2 PDF·m^2*yr/MWh for fluidized bed and fixed bed, respectively. Olive pomace has a negligible effect on ecosystems (2.52 PDF·m^2*yr/MWh and 1.7 PDF·m^2*yr/MWh for fluidized bed and fixed bed, respectively), by being a byproduct of olive oil production with no land-use changes. Natural gas has about 0.9% higher impact than fixed bed olive pomace.

Climate change

In this category the pattern mirrors that of the midpoint global warming category. All biomasses, benefiting from carbon sequestration, have a much lower impact than natural gas (680 kg CO_2 eq./MWh). Olive pomace, with approximately 9.0% impact compared to natural gas, shows the smallest impact, influenced by the type of gasifier. The choice between fixed bed and fluidized bed gasification affects miscanthus (84 kg CO_2 eq./MWh and 164 kg CO_2 eq./MWh) and pine (127 kg CO_2 eq./MWh and 182 kg CO_2 eq./MWh) cases, with both biomasses having less impact in a fixed bed due to the cold gas efficiency.

Resources impact

Natural gas power plant has the highest resources impact (12700 MJ primary/MWh), as expected, being a non-renewable fossil resource. Biomasses, relying on fossils during their life cycle, follow, with fluidized bed pine (17.4%) and miscanthus (14.7%) gasification being the next most impactful due to low process efficiency. Olive pomace has the lowest impact in this category, approximately 6.8%, regardless of the reactor.

3.2. Techno-economic analysis

The key economic indicators of economic analysis have presented in Table 5.

Overall olive pomace is the most economically viable biomass feedstock. The usage of fixed bed gasifiers gives better results than fluidised bed gasifiers with NPV of 507 864 € and 240 445 €, respectively. Despite similar yields, the fluidised bed gasifier is more expensive. The cases of fluidised bed gasification of miscanthus and pine show economic infeasibility, characterised by negative NPVs after 20 years. This outcome proves the importance of process efficiency, as low efficiency contributes to higher operating and feedstock costs, surpasses potential revenues.

The LCOE results align with Timilsin & Govind's [46] biomass power generation database range (50-164 €/MWh), Fixed bed olive pomace falls slightly below the range (-5.0%), while fluidized bed is at the lower end (+1.7%). Fixed bed pine and miscanthus exceed the lowest reported value by 4.7% and 6.6%, respectively. Fluidized bed gasification of these biomasses is within the range, at 20.6% and 22.4%. However, even the cheapest fixed bed olive pomace LCOE is nearly twice as expensive as utility-scale PV (21€/MWh), currently the most cost-effective technology.

Table 5. Key economic indicators calculated within techno-economic analysis.

Indicator	Unit	Fixed bed			Fluidized bed		
		Olive pomace	Miscanthus	Pine	Olive pomace	Miscanthus	Pine
Net Present Value (NPV) (20 years)	€	507 864	43 595	89 729	240 445	-285 089	-257 530
Return on Investment (ROI)	-	2.47	1.15	1.27	1.47	0.09	0.26
Discounted Payback Period (DPP)	years	5.27	15.30	12.95	10.42	-	-
Levelized Cost of Electricity (LCOE)	€/MWh	42	61	58	53	87	84

Sensitivity analysis

As the data and assumptions used within the economic analysis have a direct impact on the results, the sensitivity analysis addresses the uncertainties of market fluctuations. The sensitivity analysis covered price changes within +/- 30% of the originally assumed. In all cases the selling price of electricity is the most significantly influencing factor on the NPV after 20 years. Second most impacting is feedstock price, but not in the case of olive pomace due to low starting value. In the context of olive pomace gasification in a fixed bed gasifier the NPV after 20 years is always positive in this framework.

For fixed bed miscanthus gasification decreasing the electricity sell price by -10% or increasing the feedstock price by +10% would lead to a negative NPV after 20 years, it is also the case for CAPEX, electricity purchase price, and the combined fixed and variable costs if increased by +30%. Similar is in the case of the gasification of pine in a fixed bed gasifier, decreasing the electricity sell price by -10% or increasing the feedstock price by +20% or CAPEX by +30% would lead to a negative NPV after 20 years.

When considering a fluidized bed, for olive pomace if the electricity sales price would drop by -20%, the project would not be profitable. In the case of the miscanthus fluidized bed, any price change within the +/- 30% framework does not make the project profitable. The electricity sales price would have to exceed +37% to break through an NPV equal to 0 after 20 years, while in the fluidized pine case, with the electricity buys price change of +30% would result in a break even after 20 years, while other factors do not.

Technical challenges in biomass gasification

Large-scale adoption faces challenges related to feedstock supply, handling complexity, technological obstacles, and market uncertainty.

A crucial factor dictating the success of biomass-based projects is the availability of biomass. Larger power plants, requiring a substantial biomass source, face the challenge of its potential unavailability or substitution with other, sometimes more expensive feedstock [47]. Biomass properties, including density and mineral variations, affect plant efficiency and logistics [48] [49]. Low bulk density requires larger, costlier handling equipment and increases operational costs and emissions [50].

Maintaining optimal temperature is crucial but challenging due to feedstock fluctuations [51]. Safety procedures are vital for high-temperature and pressure handling [52]. Tar compounds pose technical and financial issues, with ongoing research exploring mitigation methods with the use of catalysts [53], [54]. The syngas resulting from biomass gasification may contain ultrafine particles, known as soot, which can obstruct ducts and compromise process efficiency. Effectively controlling soot levels is essential for both commercialization and process stability. Studies have looked at methods such as torrefaction and leaching of raw biomass [55]. Furthermore, studies indicate that the use of porous particles in fluidised bed gasifiers can lead to soot-free synthesis gas [56]. All those factors interfere the stability of gasifiers above 500 kW [57].

Uncertain biomass prices impact electricity tariffs, creating investment risks and investor reluctance toward large-scale gas technology adoption [58]. Approved manufacturers of biomass gas generators remain limited, with many barriers including regulatory constraints, limited access to biomass raw materials, significant initial investment requirements, adherence to pollution standards, licensing policies, and strict product testing for market survival [21]. From a commercial point of view, the main barriers are high-risk investment and limited revenue generation [59] as it was also proved within economic assessment of this study, with the electricity price determining project success.

4. Conclusions

This study assesses the environmental impact and economic feasibility with technical challenges through a life cycle assessment (LCA) and techno-economic analysis (TEA) of the gasification process of different biomass feedstocks and utilization of produced syngas for power generation based on experimental data. Olive pomace proved to be the most environmentally friendly and economically attractive option, showing a quick return on investment and lower risk while also being waste treatment, contributing to decreasing the waste stream problem created during olive oil production. In comparison, pine and miscanthus include a trade-off. Pine gasification has the highest environmental impact among studied biomasses, especially within ecosystem quality, about 11 times more than miscanthus, but its economics is twice better than miscanthus within a fixed bed, whereas in the case of a fluidised bed, both biomasses are not economical. However, in countries where olives are not grown, miscanthus can be an environmentally friendly option, but economics is something to look at and find ways to improve. The LCOE shows the competitiveness of other renewables, especially solar PV. Nevertheless, these systems are weather-dependent, so diversification of energy sources is necessary as part of the phase-out of fossil fuels. Gasification technology faces many challenges influencing the development of this solution on a large scale, one of them being proper operation conditions. This study also highlighted the significance of gasification process efficiency by demonstrating that low-efficiency build-up issues with higher costs and emissions, along with lower revenue streams. Additionally, the study showed the harmful impacts of SO_2 emissions, which underlined the importance of proper gas cleaning.

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