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Feasibility Assessment of an Integrated Pyrolysis-Gasification Process Combined with a Solid Oxide Fuel Cell Towards Electricity and Crude Bio-oil Production

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The core aim of this study is the process simulation and techno-economic assessment of an integrated process for the co-generation of electricity and crude fuels. The process is based on a renewable energy feedstock (olive kernel residues) and includes the consequent stages of: a) the slow pyrolysis of the olive kernel, b) the (autothermal) gasification of biochar (derived from the slow pyrolysis) to syngas and c) the direct utilisation of the gasification syngas in a solid oxide fuel cell (SOFC) system. Through the additional exploitation of the excess process heat in a two-stage Rankine cycle steam turbine, the integrated system is able to co-generate more than 13.3 GWh and more than 26.8 kt of bio-oil (crude bio-fuel), annually. The combined process was simulated by using Aspen Plus software and was based on the experimental results of a previous study. Regarding the subsequent feasibility assessment, the total fixed capital investment and the total annual operating expenses (annual production costs) were estimated at 35 M€ and 8.2 M€, respectively. Based on these values, it was found that the levelized cost of electricity (LCOE) should range between 0.8 - 0.9 €/kWh in order for the process to be feasible in a 20 y period of operation. Based on a series of energy policies (e.g. variation of olive kernel cost, possibility of EU funding, and cost escalation of the expensive SOFC system), the results revealed that the LCOE can reach values of 0.25-0.6 €/kWh, which can be (potentially) compared with the increasing electricity prices due to the fluctuating conditions with crude oil and natural gas prices worldwide.

1. Introduction

Biomass is a cheap and geographically distributed renewable form of energy due to its carbon-neutral cycle. Agricultural and agro-industrial activities generate huge amounts of residual biomass, with the estimated quantity of the total agricultural wastes, co-products and by-products in the EU to be equal to ca. 18.4 Gt (Bedoić et al., 2019). Olive tree cultivation for olive oil production is a traditional agricultural activity in the Mediterranean region. Specifically, olive oil industry residues account for almost 40 % of the exploitable potential of agricultural (olive pruning and leaves) and agro-industrial (olive kernel, husk, stone/pits, pomace) residues in Greece (Vourdoubas, 2020). Moreover, Greece ranks among the five largest olive oil industries worldwide with an annual production of 300 kt/y (Vourdoubas, 2020), whereas the olive oil industry's supply chain produces a wide range of by-products, which are mainly dealt as wastes.

Currently, there are several studies in literature dealing with the technical and economic aspects of pyrolysis and gasification processes for a wide variety of biomass types. However, only a few studies have examined the integration of biomass pyrolysis-gasification schemes to simultaneously produce syngas and bio-oil from the olive kernel. Old efforts have focused on the exploitation of olive oil industry residues (pomace, kernel and husk) for power generation or fuels production through pyrolysis (Zabaniotou et al., 2015) or gasification (Aguado et al., 2022). In a similar study to ours, Gadsbøll et al. (2017) reported that the SOFC capital cost was the main barrier to commercialising biomass gasification integrated with SOFC systems. In the same trend, Fryda et al. (2008) have commented that a Gasification-SOFC-Gas Turbine system would probably not be economically

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feasible due to the high cost of the SOFC system. Besides the SOFC unit, the gas clean-up system has also been reported to account significantly for the overall major equipment cost or MEC (approximately 20 – 30 %) due to the fact that SOFC imposes stringent purification requirements, as compared to turbines or internal combustion engines (Nam et al., 2020).

In this context, the present work combines sequential biomass pyrolysis and pyrolytic bio-char gasification, incorporating a SOFC as the end-unit of the process. This novel alternative can promise high electric efficiency and confronts multiple challenges, such as thermal integration and stream recycling. These novel challenges are addressed in this study through the simulation of the complex processes of i) the slow pyrolysis towards gaseous, liquid and solid products, ii) bio-char gasification by using recirculation of the process combustion gases, iii) the SOFC operation for a highly efficient power generation and iv) the incorporation of a burner/boiler to provide the gasification agent and exploit excess heat into additional electrical power. The present study balances the critical assessment of the concept's economic viability by the estimation of the initial investment and the annual operating expenses in a series of energy policy scenarios. Summing up, the novelty of this study lies in a) the conceptual design of a process that is designed to serve towards the co-production of energy and fuels from the olive kernel (so far, only heat and energy production is derived in current state-of-the-art processes), b) the economic assessment of the integrated process and c) the step-up of the analysis by including a preliminary energy policy of the European Countries that could render the agriculture wastes as an important sector in Green Energy agendas.

2. Process system description and simulation results

The proposed concept of the integrated process is schematically illustrated in Figure 1 and is thoroughly based on literature research and an older group study (Lampropoulos et al., 2020) regarding the experimental operation of a pyrolyser. Wet olive kernel biomass (denoted as OK hereafter) is fed at a rate of 20 t/d and supplied to the slow-pyrolysis reactor. There, it is converted to crude bio-oil, an aqueous liquid phase, syngas and biochar. Crude bio-oil is considered a marketable crude product generated at a rate of 3.4 t/d. The biochar and the aqueous phase are subsequently fed to the gasification reactor for syngas production. This stream (rich in CO/H_2) is mixed with the pyrolysis syngas, cleaned in a module (built-up by a combination of gas filters and sorbent materials) and fed to the SOFC anode. The depleted air from the SOFC cathode and the unreacted fuel from the anode is supplied to an afterburner/boiler, which generates steam for the downstream steam turbines. The burner exhaust gases are split into a stream that serves as the gasification agent and a stream that serves as a heating medium for the SOFC anode (pure syngas), the SOFC cathode (ambient air) and the biomass feed to the pyrolyser. Exiting at the SOFC operation temperature (800 °C), the effluents of the anode and the cathode were sent to an after-burner, which was set to operate at a slightly higher temperature, operating as a boiler/superheater, generating superheated steam, which was supplied to the steam turbine to produce additional 215 kW_{el}.

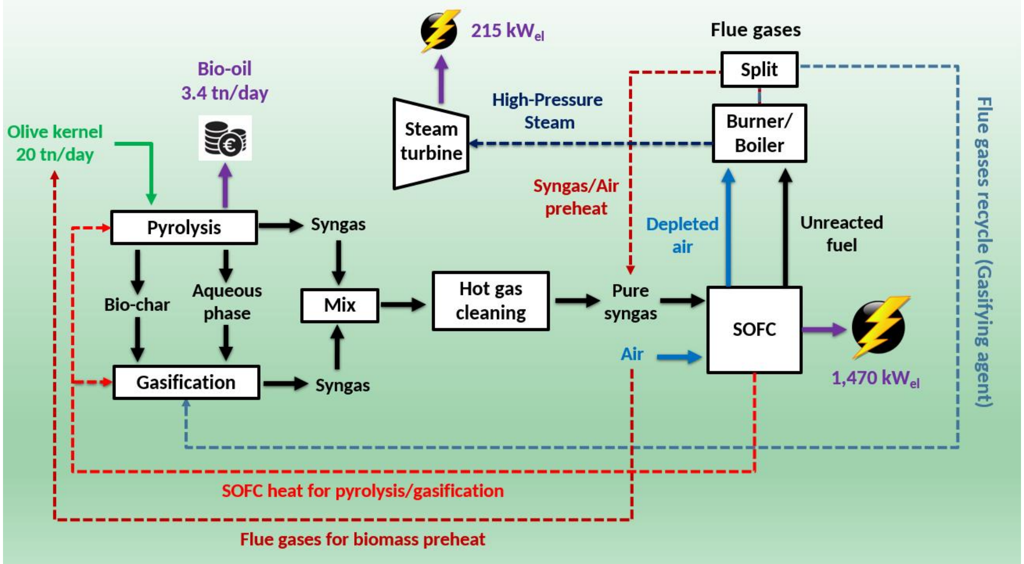

Figure 1: The concept of olive kernel slow-pyrolysis, bio-char gasification and power generation in a combined SOFC – steam turbine cycle

The molar flowrates of the involved streams, as provided in Figure 1, are shown in Table 1. In brief, the streams that matter the most refer to the i) bio-oil (ultra-rich in C/H content and low in O content), ii) biochar (>80 % rich in C content) and iii) the total syngas (rich in CO/H_2 content). The slow pyrolysis was set to the typical temperature of 500 °C in order to maximise liquid yield. For the purposes of this study, the heat requirements for the pyrolysis of OK have been assumed to be about 15 % of the HHV of the pristine biomass. The total syngas stream of the integrated process was further subjected to conditioning in a hot gas clean-up system, preheated at 800 °C and directly fed dry to the SOFC anode.

Table 1. Stream molar flowrates (kmol/h) of the integrated process

Cost Type	C	O_2	H_2	CO	CH_4	C_2H_6	CO_2	H_2O	N_2	Total
Olive kernel^1	32.08	9.66	22.46	-	-	-	-	3.65	0.19	68.05
Vapor/Gas	7.55	3.23	14.99	3.94	0.92	0.20	2.50	6.54	0.12	40.00
Tar-oil^2	7.55	3.23	13.16	-	-	-	-	6.54	0.12	30.61
Aqueous phase^2	0.76	2.44	6.58					5.61	0.02	15.41
Bio-oil^2	6.80	0.79	6.58	-	-	-	-	0.93	0.10	15.20
Pyrolysis syngas	-	-	1.83	3.94	0.92	0.20	2.50	0.00	-	9.39
Bio-char^1	16.76	0.51	2.17	-	-	-	-	-	0.07	19.51
Gasifier feedstock	17.52	2.95	8.75	-	-	-	-	5.61	0.09	34.93
Gasification syngas	-	-	14.57	17.97	0.10	-	1.65	1.22	17.52	53.04
Total syngas	-	-	16.40	21.91	1.01	0.20	4.15	1.22	17.52	62.43
Cathode air	-	51.94	-	-	-	-	-	-	195.39	247.33
Anode exhaust	-	-	3.33	5.43	0.20	0.04	21.77	16.35	17.52	64.65
Depleted air	-	34.80	-	-	-	-	-	-	195.39	230.19
Burner exhaust	-	30.08	-	--	-	-	27.48	20.22	212.91	290.71
Gasification agent	-	2.48	-	-	-	-	2.20	1.62	17.33	23.63
Process exhaust	-	27.68	-	-	-	-	25.28	18.61	195.88	267.45

^{1} *solid stream;* ^{2} *liquid stream*

3. Techno-economic analysis and results

As shown in Figure 2 and used from a previous study (Ipsakis et al., 2021), the process operating data and the established literature correlations regarding equipment cost and sizing form the basis for the techno-economic analysis. The MEC (shown in Figure 3) is then used to estimate direct (e.g., installation, piping, services), indirect (e.g., supervision, construction) and other (e.g., legal fees, contingencies) costs. Ultimately, these costs provide the total fixed capital investment (including the working capital).

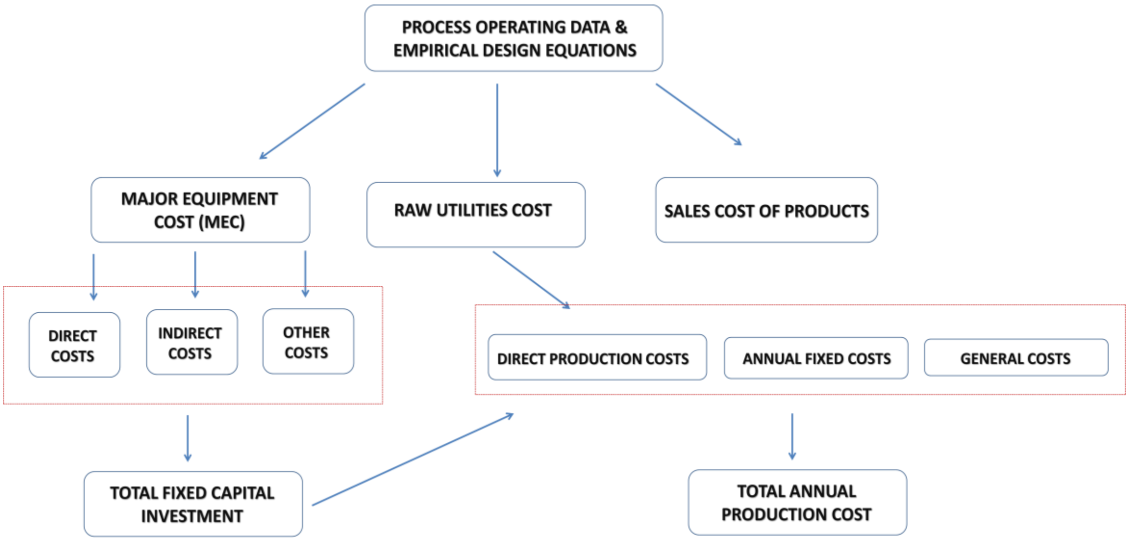

Figure 2: Step-by-step methodology for the techno-economic analysis (adapted from Ipsakis et al., 2021)

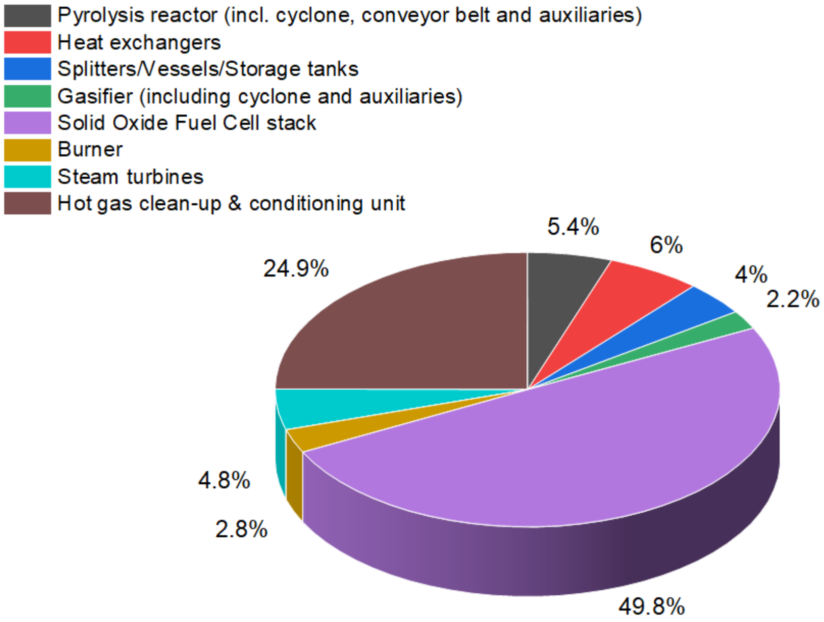

Figure 3: Percentage of Major Equipment Cost (%) based on the integrated process

Simultaneously, raw utilities cost (cooling needs, olive kernel etc.) that are based on current market values aid the estimation of direct production, and annual fixed and general costs (the olive kernel purchase cost was set at 40€/t that also includes the collection and transportation costs on-site). These three categories sum up to the total annual production cost. It is highlighted that cost escalation was accounted for through Marshall and Swift (M&S) indices for the last 2 y. In order to properly assess the profitability of the proposed venture, a list of indices is also included in the presented analysis. These indices provide an overview of the annual income and can lead to break-even prices: a) Gross Profit (R), b) Net Profit (P), c) Return on Investment (ROI) and d) Net Present Value (NPV). The useful life span of the project is assumed to be N = 20 y and with a plant operation factor of 90 %. As such, the depreciation and the capital recovery factors are assumed equal to 1/N or 5 %. The total income tax of 24 % on the net profit of the process plant is adapted throughout the yearly published economic performance calculations, while the risk factor and annual interest rate are equal to 8 % and 6 %. Table 2 summarises the overall results of the techno-economic analysis.

Table 2: Major equipment cost, total fixed capital investment and annual production expenditures for the coupled process systems in €.

Cost Type	Integrated System
Major Equipment Cost (see Fig.3)	5,905,539
Total Fixed Capital Investment	35,179,298
Direct Production Costs	3,147,886
Annual Fixed Costs	4,774,904
General Costs	361,060
Total Annual Production Cost	8,283,850

Table 3 presents the feasibility criteria for the LCOE (or break-even price) and for varying the bio-oil price. The base case scenario for the current market values of bio-oil and electricity is profoundly non-viable, leading to negative annual profits (either gross or net) and a severely negative return on the investment through the NPV. The electricity price for the venture's break-even point, i.e. for NPV = 0 throughout the investment's lifetime, was calculated at 0.915 €/kWh (for a bio-oil price of 400 €), which is considerably higher than the already subsidised bioelectricity price (0.175 €/kWh), assumed here and also based on the 2022 electricity prices (0.2 - 0.3 €/kWh, Greek Market Status, 2022). This break-even electricity price can be slightly dropped to 0.890 €/kWh for a higher bio-oil price of 700 €/tn. Table 3, break-even points, refer to the complete depreciation of the coupled Total Fixed Capital Investment and Annual Production Costs over the course of the 20 y, corresponding to Net Profits of 3.1 M€/y, leading to a ROI equal to 8.7 %.

Table 3: Economic indices and break-even prices for electricity and bio-oil for three scenarios

Cost Type	Base Case Scenario	Break-Even Point (electricity)	Break-Even Point (electricity+bio-oil)
Electricity, €/kWh	0.175	0.915	0.890
Bio-oil, €/t	400.0	400.0	700.0
R, M€/y	-5.58	4.03	4.03
P, M€/y	-3.24	3.07	3.07
ROI, %	-12.05	8.72	8.72
NPV, M€	-83.81	0.00	0.00

4. Sensitivity analysis and critical discussion

In order to assess the conditions under which the economic viability of the olive kernel pyrolysis/gasification/SOFC integrated plant could be feasible (for NPV = 0 at the end of the 20 y lifespan), the following maps were considered:

1. Reduction of the equipment cost for the SOFC and the gas clean-up, which would reduce Major Equipment Cost (MEC) and consequently the Total Fixed Capital Investment. This mapping is based on the fact that the combined SOFC and the gas clean-up units amount to 70-75 % of the total MEC, as shown in Figure 3.
2. Subsidization of the examined concept by European or national funding schemes. This mapping is based on the upcoming EU energy policy that will fund renewable solutions in the future.

Regarding the combined effect of both technologies cost reduction and capital investment subsidisation, Figure 4 illustrates the effect on the break-even electricity price (or, equivalently, the LCOE) of four different scenarios. In the first scenario of 20 % technology cost reduction combined with 50 % funding of the initial investment, the break-even electricity price was calculated to be equal to 0.63 €/kWh (i.e., reduced by 31.5 %, compared to 0.92 €/kWh in Table 3). For a further technology cost reduction by 50 %, the subsidisation rates of 50 % and 70 % lead to a reduction of the break-even electricity price at 0.43 and 0.39 €/kWh (by 53 and 57 %) in the second and third scenarios, respectively By considering a technology cost reduction of 70% and an equal amount of subsidisation, the break-even electricity price was lowered significantly to 0.27 €/kWh, which is only 57 % higher than the regarded 0.175 €/kWh electricity price of the base-case scenario (Table 3). Finally, a bio-oil selling price increase to 700 €/t (compared to the 400 €/t of the base case scenario) leads to an even lower break-even electricity price of 0.25 €/kWh. Overall, the foreseen major equipment cost reduction (primarily that of the SOFC unit and of the gas clean-up prior to entering the SOFC), coupled with enhanced subsidisation policies, could reduce the break-even electricity prices to levels comparable to the current bio-electricity prices of the base-case scenario.

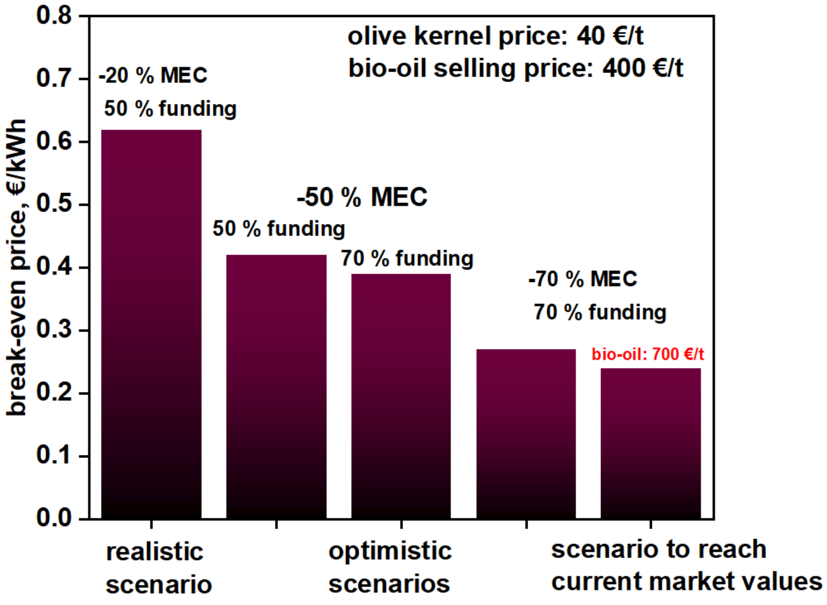

Figure 4: Break-even price for electricity as a function of MEC reduction and financing policies

5. Conclusions

In this study, an integrated biomass-fed power/bio-oil cogeneration plant was studied under the scope of process simulation and economic evaluation. The SOFC power output was accordingly set, within reasonable and state-of-the-art efficiency limits, so that the generated heat would cover the heat requirements of pyrolysis and gasification. Based upon the analytic calculation of total fixed capital investment cost and the annual production costs, the integrated power/bio-oil cogeneration plant was economically assessed by calculating the LCOE within different scenarios regarding the Major Equipment Cost and the potential subsidisation of the initial investment. It was found that the SOFC unit, along with the gas clean-up system, corresponded to 75 % of the initial investment and plays a major role in process economics. For the base-case scenario (current market values), employing the current technology costs, the break-even electricity price was 0.820 - 0.92 €/kWh, depending on bio-oil price and rendering the examined integrated plant financially non-feasible. Assuming the progressive reduction of the main equipment cost (up to 70 %) that shifts the fixed capital investment and the annual production costs to proportionally lower values, the break-even electricity price could be reduced to 0.25 €/kWh for increased bio-oil prices.

It is worth mentioning that the present study did not include any uncertainties during the simulation but included a simplified sensitivity analysis regarding the effect of certain variables (e.g. equipment cost variation, bio-oil price variation).

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References

Aguado R., Vera D., Jurado F., Beltrán G., 2022, An integrated gasification plant for electric power generation from wet biomass: toward a sustainable production in the olive oil industry, Biomass Conversion and Biorefinery, DOI:10.1007/s13399-021-02231-0

Bedoić R., Ćosić B., Duić N., 2019, Technical potential and geographic distribution of agricultural residues, co-products and by-products in the European Union, Science of the Total Environment, 686, 568–579.

Fryda L., Panopoulos K.D., Kakaras E., 2008, Integrated CHP with autothermal biomass gasification and SOFC-MGT, Energy Conversion and Management, 49, 281–290.

Gadsbøll R.Ø., Thomsen J., Bang-Møller C., 2017, Ahrenfeldt J., Henriksen U.B., Solid oxide fuel cells powered by biomass gasification for high efficiency power generation, Energy, 131, 198–206.

Ipsakis D., Varvoutis G., Lambropoulos A., Mandela E., Papaefthimiou S., Marnellos G.E., Konsolakis M., 2021, Circular approach to upgrade cement-based CO_2 and renewable H_2: techno-economic analysis of SNG production, Chemical Engineering Transactions, 88, 673-678.

Lampropoulos A., Kaklidis N., Athanasiou C., Montes-Morán M.A., Arenillas A., Menéndez J.A., Binas V.D., Konsolakis M., Marnellos G.E., 2020, Effect of olive kernel thermal treatment (torrefaction vs. slow pyrolysis) on the physicochemical characteristics and the CO_2 or H_2O gasification performance of as-prepared bio-chars, International Journal of Hydrogen Energy, 46, 29126-29141

Nam H., Ibano K., Konishi S., 2020, Cost analysis and energy return on investment of fuel cell and gas turbine integrated fusion-biomass hybrid system; application of a small scale conceptual fusion reactor GNOME, Energy, 203, 1-16

Vourdoubas J., 2020, Use of renewable energy sources for energy generation in rural areas in the island of Crete, Greece, European Journal of Environment and Earth Sciences, 1, 1–7.

Zabaniotou A., Rovas D., Libutti A., Monteleone M., 2015, Boosting circular economy and closing the loop in agriculture: Case study of a small-scale pyrolysis-biochar based system integrated in an olive farm in symbiosis with an olive mill, Environmental Development, 14, 22–36.