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Evaluation of the economic and energy performance of advanced biofuels from OFMSW in a demonstration-scale biorefinery

Konstantinos Passadis [a,*], Dimosthenis Asimakopoulos [b], Dimitris Malamis [c]

[a] National Technical University of Athens, School of Chemical Enegineering, Unit of Environmental Science and Technology, 9 Iroon Polytechniou, Zografos, 15772, Athens, Greece

[b] National and Kapodistrian University of Athens, Laboratory for the Measurements of the Indoor Environment, Faculty of Physics, Building Physics 5, University Campus, 157 84, Athens, Greece

[c] Department of Civil and Environmental Engineering, College of Engineering, Design & Physical Sciences, Brunel University of London, London, UB8 3PH, United Kingdom

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ABSTRACT

This study presents a comprehensive economic and energy performance assessment of a demonstration scale, energy driven biorefinery plant, highlighting the innovative valorization of the organic fraction of municipal solid waste as a feedstock for advanced liquid biofuel production. A gate-to-gate mass and energy balance were conducted, leading to both a cost assessment and an Energy Return on Investment (EROI) analysis. The results for this specific plant underline the drying process as the most energy intensive stage, contributing 80 % and 49 % to the total energy demand for bio-oils and bioethanol production, respectively. By employing a high-efficiency dryer, characterized by specific energy consumption equal to 0.25 kWh per kilogram of water evaporated, bio-oils and bioethanol production costs decreased significantly, reaching 0.44 and 0.86 €/kg. For the best-case scenario, EROI values of 1.76 for bio-oil and 0.8 for bioethanol were estimated, with biogas contribution leading to a final biorefinery EROI of 1.36, indicating energy viability (as total EROI >1). The integration of a high efficiency distillation process could further increase the plant EROI to almost 2. This study reveals the significant dual role of the system as both an energy production plant and a waste treatment solution. The integration of such biorefinery plants with existing industries where waste heat is available is suggested as a critical strategy to secure both economic and energy viability. As a real data driven assessment, this study provides reliable and useful insights that can enforce the current literature about the feasibility of advanced liquid biofuel production.

Abbreviations

AD	Anaerobic Digestion
CAPEX	Capital Expenditures
CHP	Combined Heat and Power
CSTR	Continuous Stirred-Tank Reactor
$C_{bio-oil}$:	Cost of bio-oil
$C_{bioethanol}$:	Cost of bioethanol
$C_{E.thermal}$:	Total cost of thermal energy
$C_{E.electrical}$:	Total cost of electrical energy
$C_{hex.loss}$:	Total cost of hexane losses
$C_{enzymes}$:	Total cost of enzymes
C_{yeast}:	Total cost of yeast
EHD	Electrohydrodynamic
EROI	Energy Return on Investment
EU	European Union

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LHV	Low Heating Value
LTCP	Lavrion Technological and Cultural Park
MS	Member States
$m_{bio-oils}$:	Total mass of bio-oils
$m_{bioethanol}$:	Total mass of bioethanol
NTUA	National Technical University of Athens
OFMSW	Organic Fraction of Municipal Solid Waste
OPEX	Operational Expenditure
PFR	Plug Flow Reactor
RED	Renewable Energy Directive
SEC	Specific Energy Consumption
SSF	Simultaneous Saccharification and Fermentation
UCO	Used Cooking Oils
UEST	Unit of Environmental Science and Technology
VVV	Vari Voula Vouliagmeni

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* Corresponding author.
E-mail address: kpassadis@mail.ntua.gr (K. Passadis).

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$\sum E$:	Total energy requirements
$\sum m_{H_2O}$:	Total mass of water evaporated

1. Introduction

To succeed in the global climate and energy goals, based on the principles of circular economy, bioeconomy is recognized as a vital instrument that enables the valorization of renewable biological resources to produce bio-based products and energy. Specifically, exploitation of the organic fraction of municipal solid waste (OFMSW) is a key priority for sustainable resource management. OFMSW constitutes a feedstock with high availability and significant exploitation potential. The conversion of the waste biomass into biofuels combines circular economy and bioeconomy objectives, while highlighting the synergy between waste management and renewable energy sector. This interaction offers the dual benefit of valorizing organic waste while producing low-carbon renewable fuels. In this framework, the development of energy-driven biorefineries capable of processing biowaste constitutes an ambitious and strategically significant solution for enhancing resource efficiency, energy resilience and achieving European Union (EU) climate targets [1,2].

The EU supports this pathway through key legislative frameworks. The revised Waste Framework Directive (2018/851) mandates the source-separation collection of biowaste for all Member States (MS) and encourages their valorization through sustainable methods. Moreover, the Renewable Energy Directives (RED II and RED III) promote the production of advanced biofuels guided by strict sustainability criteria and derived from specific feedstock categories included in ANNEX IX. To ensure the adoption of its strategy, the EU sets a binding target for all MS requiring that advanced biofuels (correspond to Annex IX Part A) contribute at least 5.5 % to the energy share used in transport by 2030 [3–5].

Based on the current strategy, composting units remain the most widely used method for treating municipal biowaste. In addition, Anaerobic Digestion (AD) has emerged as the most technologically advanced treatment process that is commonly implemented. Besides these conventional treatment methods, various innovative and emerging technologies are being developed that aim to transform biowaste into valuable products or energy sources. The Unit of Environmental Science and Technology (UEST) in National Technical University of Athens (NTUA), has been actively engaged for many years in the research for biowaste management [6–8]. As part of this ongoing effort, UEST has successfully established an innovative demonstration biorefinery plant dedicated to the production of advanced biofuels from biowaste. This was done within the framework of the CIRCforBIO project [9]. The novelty of this system is the coproduction of advanced liquid biofuels and biogas, derived from OFMSW, instead of the conventional treatment method of solely AD where biogas is the only product. In this study, the fats and oils extracted from OFMSW are referred to as bio-oil, which is raw material for liquid biofuel production.

Based on literature, the bioethanol production potential from the OFMSW has been investigated via process modeling, reporting a minimum feasible selling price of 0.66 $ per liter [10–12]. On the other hand, many studies based on experimental procedures focus mainly on process yields, without examining either economic viability or energy performance [13–15]. There is a notable gap in literature about the cost assessment of fats and oils extraction from OFMSW, with limited data. For example, Gaeta Bernardi et al. [16] and Musharavati et al. [17], conducted technoeconomic assessments based on theoretical or lab-scale data, reporting total investment costs related to final products. However, they did not isolate the extraction cost of bio-oils, which serve as intermediate feedstock for subsequent conversion processes, thus limiting the use of their results. To address this, the present study performs a cost analysis of extraction stage of bio-oils driven by real data from demonstration-scale operations. Moreover, despite the large amount of literature on the topic of EROI associated with biofuels in general, a research gap remains regarding EROI assessments for biofuels derived from OFMSW [18,19]. In particular, C. Rachid-Casnati et al. [20], conducted one of the few studies on the existing literature related to EROI assessment of 2nd generation biorefineries finding an EROI of 2.3. As reported by Papagianni et al. [18], only 5 % of the 150 reviewed case studies in literature are based on pilot or demonstration plants. However, OFMSW has not been the primary focus of most existing studies on waste-to-biofuel conversion. The present study addresses this gap by utilizing real-world data from pilot and demonstration-scale operations processing 0.05 and 1 tonne per day of wet OFMSW, respectively, thereby ensuring realistic and reliable results. In both cases, the processing capacity is mainly constrained by the drying unit, which constitutes the first stage of the system.

The primary objective of this study is to assess the energy and economic performance of a real demonstration-scale biorefinery that valorizes the OFMSW into advanced liquid biofuels. It focuses mainly on liquid biofuels production, considering biogas production as a mature and commercially established technology. By analyzing detailed mass and energy balances, alongside a cost analysis and EROI evaluation, this work aims to quantify the viability of such a biorefinery system under both current and optimized technological configurations. The broader goal of this study is to promote the sustainable integration of waste management and renewable energy systems within a circular economy framework. It provides researchers with detailed performance and energy efficiency data, particularly through cost analysis and energy return on investment (EROI) analysis that can inform future studies and support the development of more refined models. For industry stakeholders, the study offers practical insights into the technical and economic feasibility of converting the OFMSW into liquid biofuels, including key bottlenecks, cost-driving stages, and realistic production cost estimates for bioethanol and bio-oils based on rarely published demonstration-scale data. By revealing the potential of this widely available feedstock and highlighting areas for technological and economic optimization, the study serves as a decision-support tool for both academic and industrial actors. Finally, it outlines a strategic and innovative pathway for OFMSW valorization, while clearly identifying the barriers that must be addressed for successful large-scale implementation.

2. Methodology

2.1. Feedstock description

In the framework of this study, source separated household food waste produced in Vari-Voula-Vouliagmeni (VVV) Municipality in Attika, Greece, was evaluated for its economic viability and technical suitability as a feedstock for advanced biofuel production. The biowaste was delivered to the premises of UEST, located at the Lavrion Technological and Cultural Park (LTCP) where a demonstration scale biorefinery plant has been established. For this study, OFMSW is also referred as "food waste" as the feedstock was almost solely household source separated food waste.

Municipal food waste has been thoroughly investigated in previous studies, focusing on its valorization for advanced biofuels production [17,21–23]. The study conducted by Salimi et al. [24], assessed the potential of biofuel production from restaurant food waste showing an innovative pathway of valorization. Tsafara et al. [7], performed an extensive study on the impact of seasonality on the structural components of source-separated biowaste collected from the municipality of VVV. In particular, almost 3 tonnes of biowaste were collected and analyzed across 23 distinct batches, providing holistic insights into variations in biowaste composition.

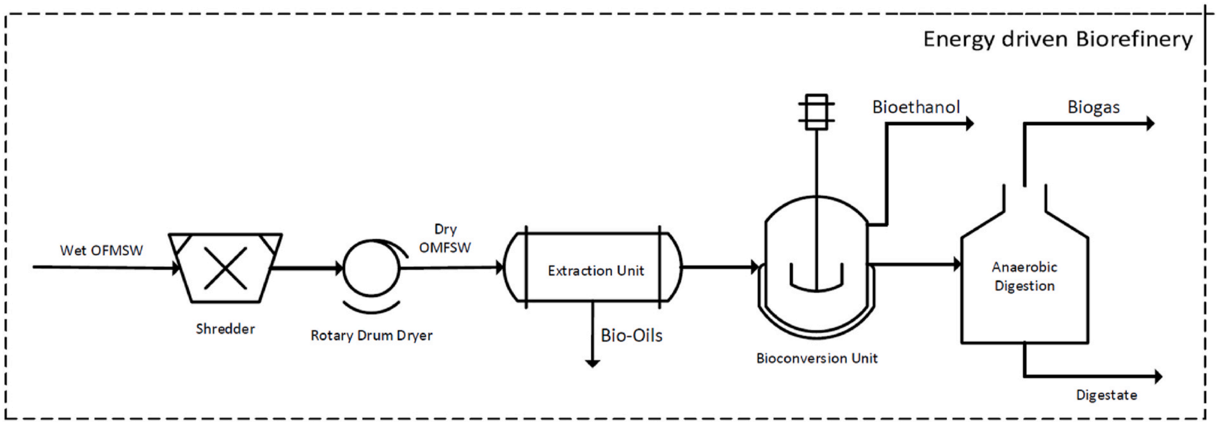

Fig. 1. Process flow diagram of the established CIRCforBIO demonstration plant.

2.2. System configuration and biorefinery process description

The analysis conducted is based on a multi-feedstock demonstration scale biorefinery plant in order to produce advanced biofuels (Fig. 1). The facility consists of four main units: (i) a drying unit for moisture removal and thermal pretreatment, ii) an extraction unit for bio-oils recovery, iii) a bioconversion unit for bioethanol production, and v) an AD unit for biogas and digestate production. This system was designed in the context of circular economy principles, aiming at the optimal exploitation of biowaste through a cascading conversion approach that maximizes liquid biofuel production and minimizes residual outputs [25,26]. Design schematics, P&IDs, and key equipment specifications for each major processing unit are provided in the supplementary file to support technical transparency and reproducibility.

2.2.1. Drying unit

The process starts with a conventional rotary drum dryer with a capacity of 1 tonne per day, where food waste is subjected to thermal drying in order to reduce its initial moisture content. The main part of the unit is a cylindrical rotating drum, slightly inclined through the horizontal axis, ensuring gravity-assisted movement of the material. The drum is internally equipped with lifting flights to enhance contact between the hot air and the material, achieving efficient drying. The unit operates in direct convection mode, where exhaust gases with hot air are inserted in the starting point of the feed and flows co-currently with the material. The system is powered by a biomass burner securing inlet air temperature in the range of 350–500 °C. The food waste is fed into the drum with an initial moisture content of 76 % on a wet basis and discharged at a final moisture content of below 10 % on a wet basis. The Specific Energy Consumption (SEC) of the system is equal to 1.2 kWh per kg of water evaporated.

2.2.2. Extraction unit

The extraction unit of the plant includes an integrated solid-liquid extraction process combined with a solvent recovery system designed for oil recovery using hexane as a solvent [17,24]. The dried food waste is transferred to a primary extraction tank where the solids come into contact with hexane in ambient conditions. Subsequently, the resulting mixture of hexane-oils, known as miscella, is separated from the solid material via thermal distillation and transferred to a distillation tank for solvent recovery and oil discharge. The vaporized hexane passes through a shell-and-tube heat exchanger condensing back to two dedicated storage tanks and is reused in the next extraction cycle. The system's thermal energy requirements are covered by a centralized steam boiler supplying saturated steam. This closed loop system minimizes solvent losses, achieves high efficiency and supports the sustainability of the process through solvent recovery and reuse.

2.2.3. Bioconversion unit

The bioconversion unit consists of two primary components which are a bioreactor and a heat exchanger. The bioreactor has a total volume of 2.0 m^3, with a working volume of approximately 1.5 m^3. It is equipped with a double-jacketed wall for indirect heating or cooling via hot or cold water. Hot water is supplied by a biomass burner while cold water is provided by a heat pump, respectively. The reactor is also configured with a vertical mechanical agitator to ensure the appropriate mixing of the substrate. Last, a shell-and-tube heat exchanger is also integrated to the reactor designed to condense ethanol-water vapors produced during the distillation process.

The process of bioethanol production is based on Simultaneous Saccharification and Fermentation (SSF) [6,7], which combines enzymatic hydrolysis and anaerobic microbial fermentation in a single step. The combination of these two processes not only reduces processing time but also enhances the bioethanol yield. Several experimental studies conducted have verified the high efficiency of SSF for various types of biowaste, particularly those with low lignin [27–30]. The optimized conditions verified and employed in this study are a solid loading of 25 %, a temperature of 35 ^{O}C, and an operating time equal to 18 h. The bioconversion process employed commercial yeast such as the *Saccharomyces cerevisiae* as the fermentation microorganism, supplemented with also commercial enzymes such as CellicCTec3 cellulase and Spirizyme Excel HS amylase. Further information can be found in the supplementary file accompanying this study.

2.2.4. Anaerobic digestion unit

The AD process was carried out in a Plug Flow Reactor (PFR) with a total volume of 5 m^3. The bioreactor, internally integrated with a heat exchanger, is thermally insulated and heated to maintain mesophilic conditions at nearly 40 °C. A horizontal agitation mechanism secures partial mixing without disrupting the plug flow behavior. Compared to the conventional systems of continuous stirred-tank reactors (CSTRs), the PFR configuration provides various advantages such as a higher conversion of organic matter and thus, higher biogas yields [31,32]. The key specifications of the AD unit are a total solid content of 10–15 %, an organic loading rate of 5–10 kg COD/m^3/d and a hydraulic retention time of 12–15 days.

2.3. Data sources and assumptions

The presented analysis is based on a combination of experimental data, pilot-scale and demonstration scale trials. Complementary literature sources were included in order to ensure an accurate assessment of the operational performance of an integrated energy driven biorefinery [26]. It is important to highlight that this study focuses on evaluating the operational performance of a demonstration scale biorefinery, with

Table 1
Specific energy consumption (SEC) of drying technologies.

Drying Technology	SEC, kWh kg^{-1}_{H2O}	Source
Thermal		
Direct-heat rotary drying	1.20	Actual dryer
Conveyor drying	1.06	[34]
Fluidized bed drying	1.36	[34]
Agitated contact drying	0.80	[34]
Non thermal		
Electrohydrodynamic (EHD)	0.03–0.25	[33]

specific emphasis on estimating the production cost of advanced liquid biofuels through a detailed assessment of operational expenses, excluding capital expenditures.

2.3.1. Drying unit

Operational data regarding the drying unit were derived from demonstration scale experimental trials. As it was impossible to feed continuously food waste at large scale due to unforeseen circumstances, drying trials were also conducted using industrial biowaste streams with similar composition and physicochemical characteristics such as the initial high moisture content. This approach enabled the acquisition of more reliable data related mainly to thermal consumption.

The drying unit of the plant does not reflect the performance of optimized drying technologies and innovative systems. The energy balance was performed utilizing both experimental data from the proposed system and literature-reported consumption values for advanced dryers appropriate for high moisture feedstocks and similar scale capacity [26,33]. These optimized systems present improved SEC as shown in Table 1. SEC is defined as the amount of energy required (thermal, electrical, etc.) to evaporate a specific amount of water, expressed in kWh per kilogram of water evaporated (Equation (1)) [34]. The energy consumption due to the drying process was equally allocated between the bio-oils and bioethanol production step. This is due to the drying unit not producing a final product but serving as a preparatory step common to both processes.

$$SEC = \sum E \Big/ \sum m_{H_2O} \qquad \text{Equation 1}$$

2.3.2. Extraction unit

The extraction unit's operational data was based on demonstration scale trials [26]. Data related to oil yields and energy inputs were obtained during the operation of the extraction process and were utilized to evaluate the process performance. Note that the product of this process was fats and oils referred to as bio-oil, which serves as an intermediate energy carrier and can be further valorized for the production of either biodiesel or sustainable aviation fuels. In this work, bio-oil is included under the umbrella of advanced biofuels for simplicity reasons.

2.3.3. Bioconversion unit

Data for the bioconversion unit were gathered from several trials conducted using source separated food waste from VVV. These experiments provided information on operating parameters such as temperature, pH, enzyme dosage, hydrolysis, fermentation efficiency and ethanol yields. Given technical constraints and the limited representativeness of the thermal system at demonstration scale, the energy demand of downstream processing, particularly for bioethanol distillation, was estimated using a computational method based on a process model developed in Aspen Plus. The thermodynamic properties were calculated using the UNIQUAC activity coefficient method. The vapor-liquid equilibrium parameters were retrieved from APV120 VLE-IG databank. The simulation was developed with the assumption that a liquid stream containing water-ethanol mixture, obtained from the fermentation process, was directed to the distillation column. An equilibrium model using the RadFrac block was developed to simulate the operating parameters, and energy demands of the process. Energy optimization was conducted through sensitivity analysis on the heat duty of the Kettle reboiler with a set constraint of the product's purity at 95 v/v %. This approach was implemented as the results from on-site distillation were not representative of real working conditions at full scale. Moreover, an innovative distillation technology, known as Pass-Through Distillation (PTD) [35], was employed exclusively during the EROI assessment to evaluate the potential enhancement of the system's energy performance.

Table 2
Overall specifications and assumptions associated with mass and energy balance assessment.

	Value	Source
Bio-oils (kg/m^3)	940	Actual data
	920–940	[37]
Bioethanol density (20 °C) (kg/m^3)	791	Actual data
	789	[38]
Biogas density (60 % of methane) (kg/m^3)	1.215	[39]
Distillation energy consumption (kWh/kg bioethanol)	6.34	Computational data from this study
CHP Electric. Efficiency (%)	37	[36]
CHP Thermal. Efficiency (%)	49	[36]
AD heat requirements (% of biogas energy content)	30	[40]

2.3.4. Anaerobic digestion unit

Regarding the AD plant, data were collected from bench, pilot and demonstration trials. For the purposes of this assessment, the digestate produced simultaneously with the biogas production, was not included in this analysis. Its potential impacts – either beneficial as a biofertilizer or as a challenge requiring further treatment-were excluded focusing on the evaluation solely on the energy and cost performance of the advanced biofuels production line. Specific assumptions regarding the end use of biogas were adapted as a Combined Heat and Power (CHP) system was not established in the demonstration plant. Therefore, the energy recovery from the AD plant was evaluated assuming a CHP system with overall efficiency of 86 %, operating at an electrical efficiency of 37 % and a thermal efficiency of 49 %. These values are in accordance with the performance data in literature and reported for biogas CHP applications [36]. The recovered excess heat energy was considered to be utilized in the drying process, reducing the total heat input requirement and securing the energy efficiency of the total plant. The basic specifications and assumptions used for this assessment presented in Table 2.

2.4. Mass and energy balance

The mass and energy balance of the analyzed biorefinery plant and all computations were normalized to a functional unit of one tonne of food waste. The system boundaries were defined as gate-to-gate containing all the conversion processes to produce bioethanol, bio-oil and biogas, excluding upstream collection and downstream fuel distribution. Mass and energy flows for each process unit were calculated primarily based on experimental data wherever feasible. In cases where measurements could not be performed or where experimental results were considered unrepresentative due to scale or process limitations, validated literature data and engineering assumptions were applied. This approach is consistent with the methodological framework proposed by Imtiaz et al. [41], which supports the integration of reliable literature and analogous technological data in lieu of direct measurements under such conditions. The utilization of validated literature data and information derived from similar technologies is considered appropriate when direct experimental data measurements cannot be conducted or evaluated as unrepresentative.

The mass balance was developed setting an initial input of one tonne of wet food waste, reflecting the as-received condition of the feedstock at

Table 3
Energy content of biofuels and biogas based on its LHV.

	LHV (kWh/kg)	Source
Bio-oils	10.3	[4]
Bioethanol	7.5	[4]
Biogas[a]	4.9	[42]

[a] This calculation assumes density 1.215 kg/m^3 [39].

Table 4
General assumptions related to cost assessment.

	Value	Source
Electricity Cost (€/kW$_e$h)	0.10	Greek Energy Market[a]
Thermal Cost (€/kW$_{th}$h)	0.06	Actual data[b]
Enzyme Cellulase Cost (€/L)	1.00	[45]
Enzyme Amylase Cost (€/L)	1.00	[45]
Yeast Cost (€/kg)	1.20	[45]
Hexane Price (€/m^3)	760	Current European Market[c]
Water Cost (€/m^3)	1.00	EYDAP[d]

[a] RAAEY: Regulatory Authority for Energy, Waste and Water, Greece.
[b] Based on actual market price, olive stones were procured for the plant at a price of 220 €/tn.
[c] Based on current European Market prices of hexane.
[d] Based on the most recent data of the relevant Greek authority for water supply (EYDAP).

the plant. Results and data for all major processes for the demonstration scale are reported with detailed information [26]. As the drying process is a part of the biorefinery and within the system boundaries, the wet basis was selected as a starting reference point for the integrated biorefinery. However, for transparency and broader applicability, process yields are also presented on a dry matter basis. This facilitates comparison with alternative system configurations where drying may occur upstream or outside of the defined boundaries.

The energy balance was calculated simultaneously with mass balances to quantify the external energy inputs required for each unit and the energy outputs related to the energy content of produced biofuels based on their Low Heating Value (LHV) (Table 3). The analysis considered electric and thermal energy needs associated with each production phase. Energy inputs, similar to the previously mentioned mass flows, were determined based on experimental data and were supplemented by validated process modeling or literature data in instances where direct measurements were unavailable.

2.5. Cost analysis framework

The presented cost analysis of this study was focused solely on the production of liquid advanced biofuels, as the AD unit at this scale does not provide representative data for precise estimation of biogas production cost. Moreover, since AD process is well-established and widely commercialized technology, the biogas production cost has been extensively studied and reported in literature [43,44]. Therefore, the boundaries of biogas analysis in this study are limited to its energy contribution and overall efficiency of the proposed system, as described in section 3.6.

The cost analysis conducted in this study includes only the operational expenditures (OPEX) associated exclusively with the production line of advanced liquid biofuels. This includes energy consumption (electrical and thermal) and materials consumption such as enzymes, yeast, chemicals and water. It should be noted that neither transportation costs nor additional pre-treatment steps beyond thermal drying were included in this analysis. The feedstock—OFMSW—is assumed to be delivered as part of existing municipal waste services, where a gate fee is typically received rather than paid, and no chemical or mechanical pre-treatment was applied beyond drying. General assumptions regarding the values of these costs are presented in Table 4, which

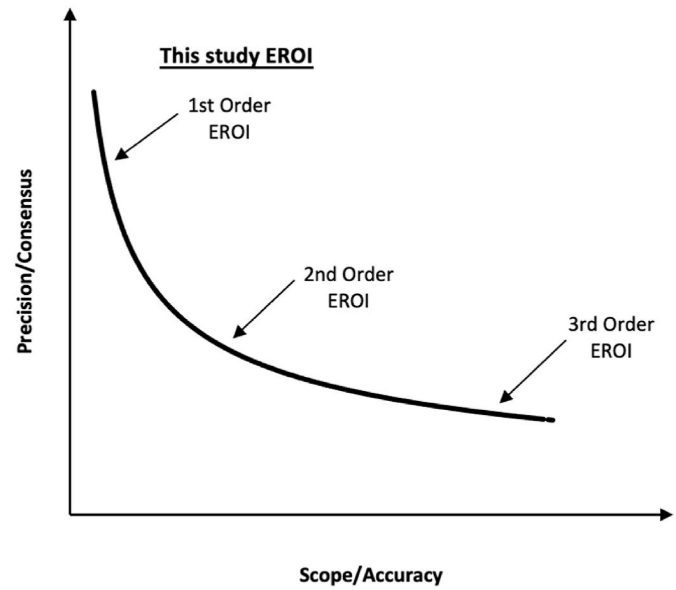

Fig. 2. Relationship between EROI scope, accuracy, level of precision and general acceptance [53].

related to a Mediterranean country such as Greece. OPEX related to labor costs and similar expenses along with the capital expenditures (CAPEX) related to equipment procurement and the required infrastructure are excluded from this assessment.

This approach aims to isolate and highlight the variable production cost of advanced biofuels under relevant working conditions, providing a clear baseline for evaluating their economic performance.

In order to evaluate the impact of the energy intensive process of drying on overall production costs, two scenarios were applied. The first, considers the energy consumption of the existing dryer, which has low energy efficiency. The second scenario assumes an innovative efficient dryer, in accordance with literature, to assess an optimized process configuration. Finally, a sensitivity analysis was conducted while the other processing parameters are kept constant. This comparison shows the potential cost reduction achievable through the implementation of innovative, highly efficient dryers. The results were then compared with the competitive market prices. The relevant equations associated with the cost assessment are presented below:

$$C_{bio-oil}\ (€ / kg) = \frac{C_{E.thermal} + C_{E.electrical} + C_{hex,loss}}{m_{bio-oils}} \quad \text{Equation 2}$$

$$C_{bioethanol}\ (€ / kg) = \frac{C_{E.thermal} + C_{E.electrical} + C_{enzymes} + C_{yeast} + C_{water}}{m_{bioethanol}} \quad \text{Equation 3}$$

2.6. Energy Return on investment (EROI)

This section evaluates the energy performance of the proposed biorefinery system through the computation of the Energy Return on Investment (EROI). As reported by C. Hall et al. [46], a supplementary alternative to a conventional economic analysis is the net energy analysis, which is represented clearly by the EROI. This indicator is critical to assess energy efficiency and sustainability, reflecting the ratio between the useful energy output gained in the form of advanced liquid biofuels (bio-oils and bioethanol) and biogas, and the total energy input required to produce them.

A critical question discussed and analyzed in literature, is related to the minimum EROI required to sustain modern complex societies. The rationale is that if the EROI is insufficiently high while the energy demands of the energy sector itself are substantial, other sectors cannot be

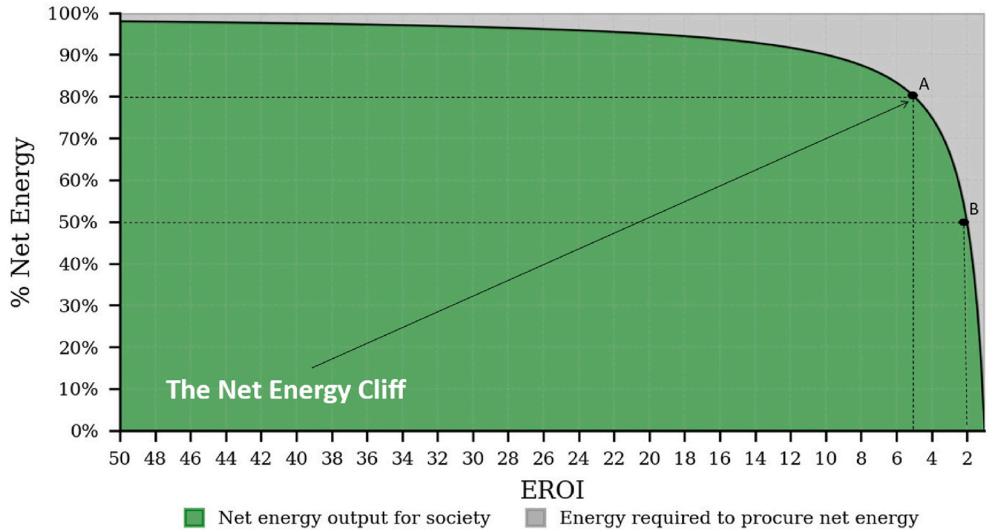

Fig. 3. The Net Energy Cliff ([52]).

developed appropriately or sustainably to meet societal needs [47–50]. Specifically, a minimum $EROI_{st}$ of 3:1 for oil products is required in order to sustain transportation, without any discretionary surplus for all other aspects needed to support the industrial and modern civilization [51]. $EROI_{st}$ (or EROI standard) includes the energy which is required for the products and systems that are eventually used on site, in order to obtain energy. This approach of estimating EROI is similar with this study's methodology where EROI is calculated based on equation (4).

One of the most significant problems related to the transparent and representative estimation of EROI is the boundaries of its calculation, as reported by several studies [52,53]. Mulder K. et al. [53], developed a framework of EROI methodologies highlighting three different levels of analysis as shown in Fig. 2. This figure illustrates that as EROI assessment becomes more comprehensive in scope and more accurate -progressing from first to third order-the level of its precision and the degree of consensus among researchers tend to decline. Consequently, this study adopts a first-order EROI approach, as it offers greater methodological precision and aligns more closely with the prevailing scientific consensus in the existing literature.

Therefore, the EROI was calculated based on the following equation [53]:

$$EROI = \frac{Eoutput}{Einput} \qquad \text{Equation 4}$$

Where:

- E_{output} represents the energy content of biofuels produced, based on their lower heating values (LHV)
- E_{input} includes all thermal and electrical energy demands associated with the operation of the biorefinery.

To evaluate the impact of drying energy demand on overall system performance, the EROI was assessed under two distinct scenarios for the drying unit. The first represents the real measured energy consumption of the existing dryer while the second assumes the use of a commercially suitable high energy-efficient dryer based on literature. These same configurations were also considered in the cost analysis to ensure a consistent evaluation of the influence of drying technology on both economic and energy performance. As Murphy & Hall [52] reported, EROI constitutes a valuable decision-making tool prior to the initiation of the exploitation of an energy source or when formulating policy. They highlight that the "energy break-even" point appears when the EROI falls below 1, indicating that more energy is consumed in the process than is produced, resulting in net energy loss for society.

An additional approach selected in this study to illustrate the interpretation of EROI is the calculation of the net energy supplied to society as a percentage of the total energy content of the biofuels delivered. The metric reflects the portion of energy that remains available for end use after excluding the energy consumed during the production process. This net energy for society is calculated using equation (5) and is presented in Fig. 3 [52]:

$$Net\ Energy\ for\ Society\ (\%) = \frac{Net\ Energy}{Total\ energy\ content\ of\ delivered\ fuels} = \frac{(EROI - 1)}{EROI} x\ 100$$

Equation 5

Investigating EROI from this perspective shows how declining energy returns significantly reduce the amount of net energy that can be delivered to society. As shown in Fig. 3, the relationship is non-linear, and a sharp reduction in net energy becomes evident as EROI approaches lower values. This phenomenon, referred to as the "Net Energy Cliff", is particularly observed near point A (EROI = 5), where minus reductions in EROI result in disproportionate losses in net energy output. At point B (EROI = 2), only 50 % of the gross energy yield of the delivered fuel remains available for end use, highlighting the potential inefficiency of energy systems operating below this threshold. This behavior illustrates the importance of maintaining EROI values beyond critical limits in order to ensure meaningful energy contribution to society.

Table 5
Feedstock composition.

	Moisture (%)	Fats and Oils (% d.b)	Cellulose (% d.b)	Starch (% d.b)	Hemicellulose (%.d.b)	VS (% d.b)	Source
Food waste	75.9 ± 2.2	11.2 ± 2.7	14.6 ± 3.6	7.7 ± 3.4	9.4 ± 4.9	90.5 ± 2.5	This study [26]
OFMSW Greece	75.7–78.9	9.2–11.9	3.2–18.3	16.0–26.0	3.0–11.0	81.5–97.8	[54]

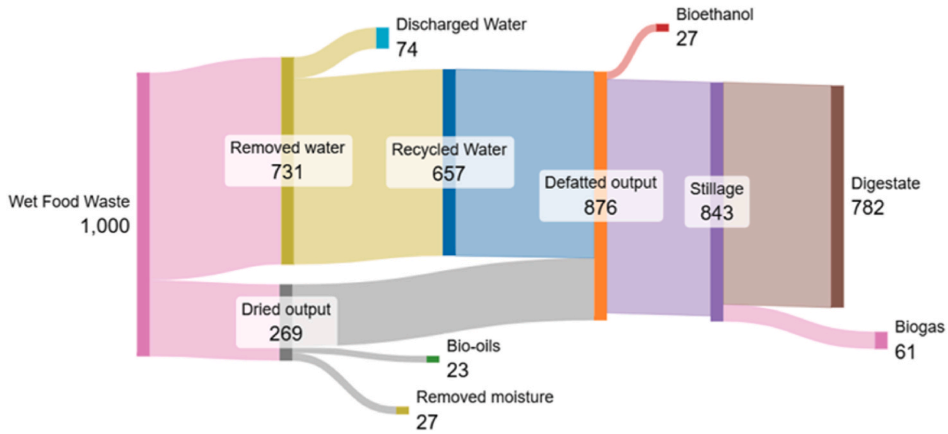

Fig. 4. Primary mass flows related to 1000 kg processing wet Food Waste.

Table 6
Core mass flows and yields of the biorefinery.

	Drying Unit	Extraction Unit		Bioconversion Unit		AD unit	
Mass balance							
Wet Input (kg)	1000	Dried Input (kg)	269	Defatted Input (kg)	219	Input (kg)	823
Dried Output (kg)	269	Defatted Output (kg)	219	Water Input (kg)	657	Digestate (kg)	782
Evap. Water (kg)	731	Removed moisture (kg)	27	Stillage (kg)	823	Produced biogas (m^3)	50
		Produced Bio-oils (kg)	23	Produced Bioethanol (kg)	27		
Yields							
		23 Kg bio-oils/tn wet F.W.		27 Kg bioethanol/tn wet F.W.		50 m^3 biogas/tn wet F.W.	
		95 Kg bio-oils/tn dry F.W.		122 Kg bioethanol/tn dry F.W.		299 m^3 biogas/tn dry F.W.	
						333 m^3 biogas/tn V.S. F.W.	
Performance/Efficiency							
		Extraction Efficiency (%)	85	Starch Hydrolysis (%)	95	VS degradation (%)	93
				Cellulose Hydrolysis (%)	85		
				Ferment. Efficiency (%)	96		

3. Results and discussion

3.1. Feedstock analysis

Food waste comprises one of the most complicated feedstocks to characterize, due to its highly variable composition. In order to define this range of composition and study the impact of seasonality, at least 3 tonnes were collected by VVV consisting of 23 batches. This process ensures that the proposed composition is reliable and representative [7]. Food waste is considered the main component of OFMSW and as shown in Table 5, its composition is in the range reported by literature [54]. It is noteworthy that only the considered starch of this study is out of this range. However, this underscores the importance of this study, as it is among the few that investigate real, source separated household food waste. In contrast, the majority of literature relies on simulated food waste or samples collected from specific sources such as restaurants and institutional kitchens where starch content is much higher [21,23,55,56].

3.2. Mass balance results

The mass balance assessment was developed based on the processing of one tonne of wet source-separated household food waste, following the system configuration analyzed in section 3.2 and presented in Fig. 4. The examined food waste presented an average moisture content of nearly 75.9 %, resulting in a dry matter content of 241 kg.

In the drying unit, the majority of moisture was removed, resulting in 269 kg of dried biomass and 731 kg of evaporated water. Subsequent solid-liquid extraction of lipids produced 23 kg of bio-oils, with the remaining 219 kg (27 kg moisture content was also removed) directed to bioconversion unit. The processed fraction resulted in the production of approximately 27 kg of bioethanol, meaning 40.8 g/L ethanol concentration, and 820 kg of stillage, which was further processed in the anaerobic digestion unit producing almost 50 m^3 of biogas and 780 kg of digestate [26].

The presented mass flows across units reflects the efficiency of substrate utilization and the effective conversion of food waste into the targeted biofuels. As stated in section 3.4, while the system input is defined on a wet basis (1 tonne of food waste), process yields are also expressed on a dry matter basis. Almost 155 L of advanced bioethanol is produced per tonne of dried food waste while the highest yield has been reported is equal to 315 L/tn of feedstock [57]. This dual reporting facilitates more meaningful interpretation and enhances comparability with other studies or feedstocks, specifically in cases where the initial moisture content differs, or the drying process is performed upstream. The core mass flows and yields associated with one tonne wet feedstock are presented in Table 6.

A comparable ethanol concentration was reported by Mosquera-Toscano et al., who achieved 43.4 g/L ethanol using the organic fraction of municipal solid waste (OFMSW) as feedstock under high-solids loading conditions (29 %) [58]. Their study demonstrated the feasibility of reaching ethanol levels similar to ours (40.8 g/L), albeit under more concentrated substrate conditions, which typically require enhanced process control and pretreatment strategies. In another relevant study, Gupte et al. achieved even higher ethanol concentrations (~60 g/L), but this was obtained using a mixed feedstock, combining OFMSW with starch-rich rice waste, which significantly enhanced fermentable sugar availability [22]. While their approach yields higher ethanol concentration, the use of co-substrates such as rice waste introduces additional supply chain and sustainability considerations not present in our single feedstock approach. Carmona-Cabello et al. [59], reported lipid contents averaging around 29 wt% in restaurant food

Table 7
Energy balances of the actual biorefinery (capacity of 1 t wet FW) configuration with low efficient conventional drying technology.

	Drying	Extraction unit	Bioconversion unit	AD unit	Total system Energy Balance
Thermal Energy Consumption	1.20 $kW_{th}h/kgH_2O$	3.04 $kW_{th}h$/kg bio-oil	6.34 $kW_{th}h$/kg bioethanol	-[a]	
Electrical Energy Consumption	0.04 kW_eh/kgH_2O	0.43 kW_eh/kg bio-oil	0.94 kW_eh/kg bioethanol	0.40 kW_eh/kg biogas	
Total Energy Input	1.24 kWh/kgH_2O	3.47 kWh/kg bio-oil	7.28 kWh/kg bioethanol	0.40 kWh/kg biogas	
Final Energy Consumption	Allocation[b] of drying energy	*19*.68 kWh/kg bio-oil	16.92 kWh/kg bioethanol	0.40 kWh/kg biogas	
Total Energy Input (1 t capacity) (kWh)	804[c]	80	195	20	1205
Total Energy Output (1 t capacity) (KWh)		236	203	110	549

[a] AD thermal demand is met by heat from CHP.
[b] As clearly stated in section 3.4, drying energy consumption was allocated to bio-oils and bioethanol.
[c] On this calculation excess heat (almost 103 KWh) produced by CHP unit of AD plant was subtracted from the total energy requirements of drying.

Table 8
Energy balances of the proposed system (capacity of 1 t wet FW) based on SEC of an optimized drying technology of EHD.

	Drying	Extraction unit	Bioconversion unit	AD unit	Total
Thermal Energy Consumption	0.25 $kW_{th}h/kgH_2O$	3.04 $kW_{th}h$/kg bio-oil	6.34 $kW_{th}h$/kg bioethanol		–
Electrical Energy Consumption	0.04 $kW_{th}h/kgH_2O$	0.43 kW_eh/kg bio-oil	0.94 kW_eh/kg bioethanol	0.40 kW_eh/kg biogas	
Total Energy Input	*0.29* $kW_{th}h/kgH_2O$	*3*.47 kWh/kg bio-oil	*7*.28 kWh/kg bioethanol	0.40 kWh/kg biogas	
Final Energy Consumption	Allocation[a] of drying energy	*4*.60 kWh/kg bio-oil	3.96 kWh/kg bioethanol	0.4 kWh/kg biogas	
Total Energy Input (1 t capacity) (kWh)	110	80	195	20	404
Total Energy Output (1 t capacity) (KWh)		236	203	110	549

[a] As clearly stated in section 3.4, drying energy consumption was allocated to bio-oils and bioethanol.

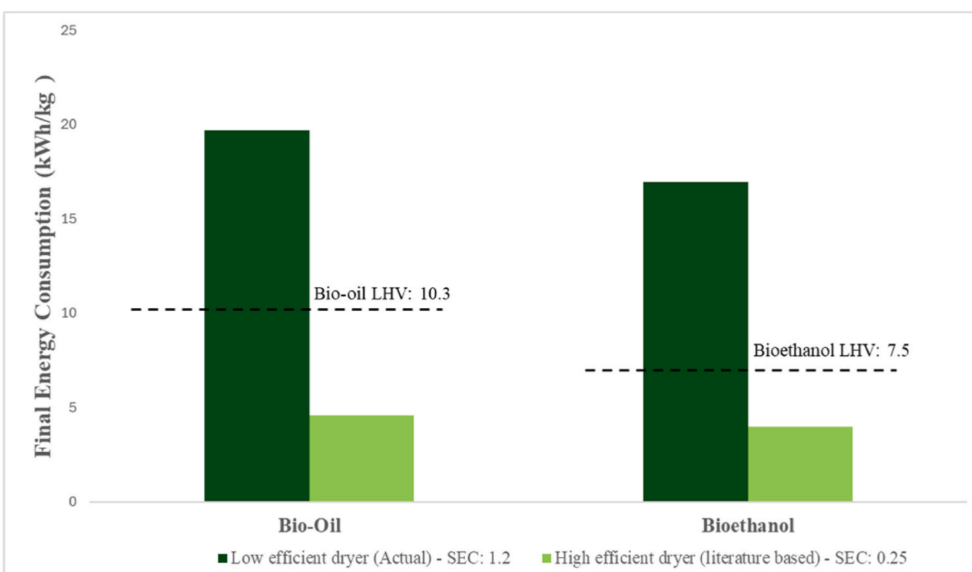

Fig. 5. Comparison of final energy consumption and LHV for advanced biofuels under low-efficiency and high efficiency drying technologies.

waste, corresponding to an oil yield of approximately 252 kg per dry ton using a hexane/ether extraction method. In comparison, our process yielded 95 kg of bio-oils per dry tonne of OFMSW. Similarly, Yang et al. [60], investigated lipid extraction from instant noodle waste using n-hexane and recovered 5 g of oil per 100 g of feedstock—equivalent to 50 kg per ton. While these feedstocks also represent real-world waste streams, they are typically more homogeneous and inherently richer in lipids than OFMSW. In contrast, the organic fraction of municipal solid waste is not only more heterogeneous and contaminated, but also characterized by lower intrinsic lipid content, making efficient oil recovery significantly more challenging. These comparisons underscore the need to critically assess the viability of OFMSW for lipid-based valorization, considering both its limited lipid content and the complexities associated with its composition and handling.

3.3. Energy balances results

The energy balance results of the system associated with the proposed biorefinery configuration are summarized in Tables 7 and 8. Table 7 reflects the actual experimental data obtained from the demonstration plant, while Table 8 corresponds to a scenario based on literature values for an optimized drying technology with SEC equal to

Table 9
Overview of production cost of bio-oils and bioethanol.

		Bio-oils	*Bioethanol*
Drying cost (€/kg)	SEC: 0.25	0.17	0.11
	SEC: 1.20	1.06	0.72
Extraction cost (€/kg)		0.27	–
Bioconversion cost (€/kg)		–	0.75
Total production cost (€/kg)	SEC: 0.25	0.44	0.86
	SEC: 1.20	1.33	1.46

0.25 kWh/kg H_2O. The comparison of these results highlights the impact of the drying process on total energy requirements, given its highly intensive thermal energy demand and the high-water content of the feedstock. While the process flow remains the same in both cases, the implementation of a highly efficient dryer with low SEC value indicates the potential efficiency advancement of the system. This approach provides a more precise representation of the energy cost related to advanced biofuels production, even in the absence of an optimized dryer in the established biorefinery demonstration plant. However, given the intensive thermal needs of the plant, the integration of the biorefinery with external industrial sources of waste heat could sufficiently compensate for the lack of a highly efficient dryer.

Fig. 5 above, provides an overview of the final energy consumption required to produce advanced biofuels, considering both low and high efficiency drying technologies. The addition of the fuels' LHVs as benchmark lines allows the comparison of process energy demand relative to the energy output. This assessment highlights the significance of energy-efficient drying systems in advancing the sustainability and overall viability of advanced biofuels production pathways.

3.4. Cost analysis results

The cost analysis results related to this study focus on the production cost of bio-oils and bioethanol derived from food waste. Table 9 summarizes the cost of extraction and bioconversion process including drying process evaluating two different scenarios: one based on the currently installed low-efficiency dryer (SEC: 1.20 kWh/kg H_2O) and another representing an optimized configuration utilizing a high-efficiency drying technology (SEC:0.25 kWh/kg H_2O) [33]. The latter scenario reflects a theoretical assumption grounded in literature-reported performance levels and is included to explore the potential economic improvements achievable through advanced drying technologies [33]. The cost assessment verified that reducing the SEC to 0.25 kWh/kg H_2O significantly decreased the production cost of bio-oil from 1.33 to 0.44 €/kg, and that of bioethanol from 1.46 to 0.86 €/kg. This approach clarifies the costs associated with the main processes,

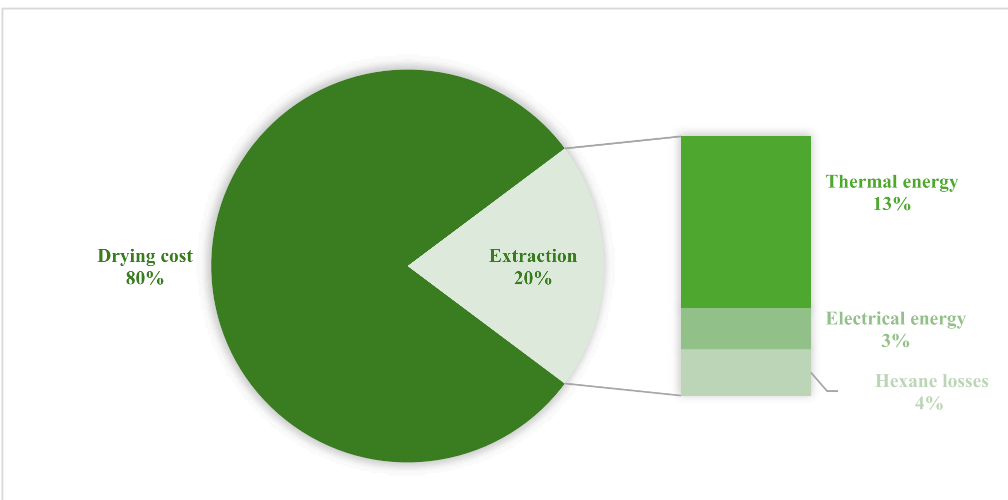

Fig. 6. Breakdown of bio-oil production cost (more details in Table S4).

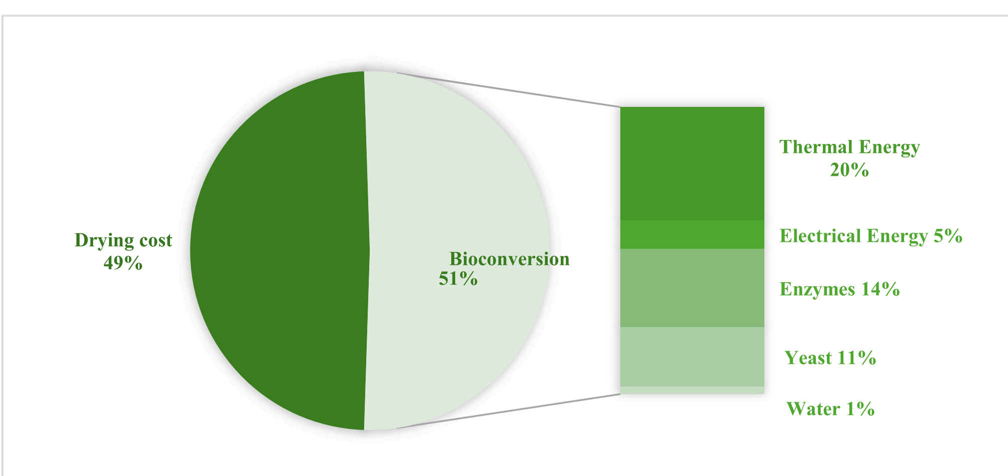

Fig. 7. Breakdown of bioethanol production cost (more details in Table S7).

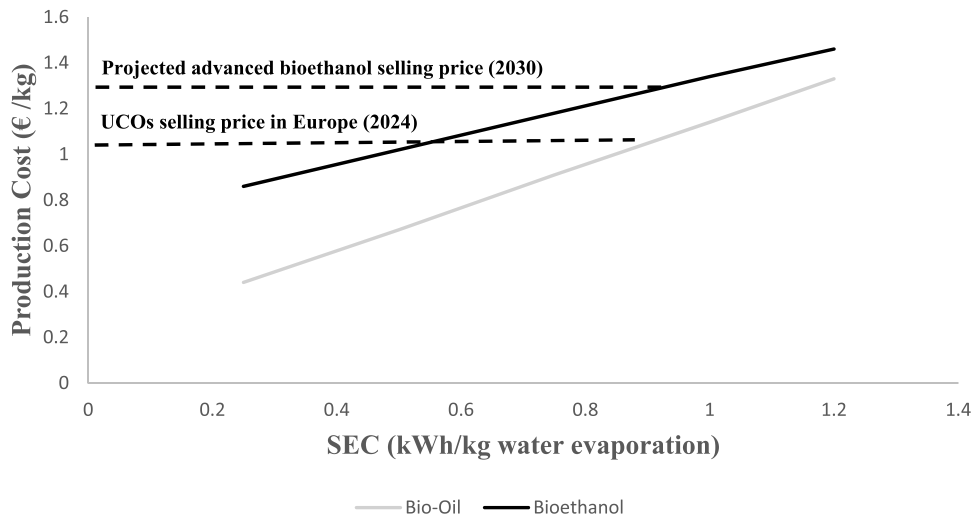

Fig. 8. Influence of SEC of drying technology in the production cost of advanced liquid biofuels.

including the drying process, which serves as an auxiliary treatment.

Figs. 6 and 7, provide the breakdown of production costs for bio-oil and bioethanol, respectively. These illustrations offer insights into the economic contribution of each stage, thereby identifying key cost drivers in overall process. The results presented are based on the actual data of the current low efficient drying technology with a SEC equal to 1.20 kWh/kg H_2O.

As shown in Fig. 6, given a SEC equal to 1.20 kWh/kg H_2O, the drying phase comprises the main cost of recovery of bio-oils, accounting for 80 % of the total cost. The remaining 20 % of extraction process is compartmentalized between thermal/electrical energy and hexane losses for each process cycle. Nonetheless, with a highly efficient dryer of SEC equal to 0.25 kWh/kg H_2O the respective contribution of drying could be reduced approximately to 38 %.

Fig. 7 shows that bioethanol is characterized by a more balanced cost distribution, as the drying and bioconversion process share is almost equal. Regarding the bioconversion process, high energy demands which are associated with distillation process are evident. For bioethanol, an innovative dryer (SEC:0.25 kWh/kg H_2O) reduces the drying contribution to 13 %, highlighting the influence of distillation and the use of enzymes to the overall production cost. These observations align with existing studies highlighting the energy and cost intensive nature of ethanol distillation [61–63]. Given the prominent influence of drying on the cost of both products, Fig. 8 presents the impact of SEC in total production cost of these two advanced liquid biofuels.

In the absence of similar cost assessments dedicated to the recovery of bio-oils from food waste, a comparative analysis is presented based on used cooking oils (UCOs) market prices in Europe. This approach is justified by the fact that bio-oils derived from food waste and UCOs present similar physicochemical characteristics which influence their processing requirements and refining costs [64]. Hence, UCO prices serve as a relevant benchmark for estimating the economic potential of bio-oil recovery from food waste. As reported by Prykhodko [65], UCO prices in Europe (December 2024), was almost 1.18 €/kg. It's important to highlight that the quality of the produced bio-oils, in terms of free fatty acids content, is much higher than UCO's, indicating a potentially higher market value [26].

In this study, the calculated production cost of bio-oils derived from food waste ranged from 1.33 €/kg under current drying conditions (SEC = 1.2 kWh/kg H_2O) to 0.44 €/kg under an optimized scenario (SEC = 0.25 kWh/kg H_2O). The latter value is significantly lower than current UCO market prices, suggesting strong economic viability under energy-efficient configurations. Even the higher-end estimate remains within a comparable range, particularly considering that the recovered bio-oils from OFMSW demonstrate high quality, with lower free fatty acid content than UCOs [26]. This quality advantage may justify a higher market value, reinforcing the economic attractiveness of this valorization pathway.

With regard to bioethanol, several techno-economic assessments of second-generation biofuels using various lignocellulosic feedstocks—such as switchgrass, barley straw, eucalyptus residues, and corn stover—report production costs ranging from 0.86 €/kg to 1.90 €/kg [66–68]. Moreover, the European Court of Auditors [69], estimates the typical production cost of advanced bioethanol between 0.75 and 1.20 €/kg, while the European Commission projects an average selling price of to1.30 €/kg up to 2030 [69]. These values serve as practical benchmarks for assessing the economic competitiveness of OFMSW-derived ethanol. In this study, the calculated production cost of bioethanol was 1.46 €/kg under current demonstration conditions, which include a relatively high SEC of 1.2 kWh/kg of water evaporated during the drying stage. Although this cost exceeds average market prices, it aligns with the upper range of reported values for second-generation systems. Furthermore, if SEC is reduced to 0.25 kWh/kg—through either high-efficiency drying or integration with waste heat sources—the production cost decreases significantly, reaching 0.86 €/kg, which matches the most competitive values reported in the literature. This clearly demonstrates the potential for economic viability of OFMSW-derived ethanol under optimized energy configurations. Moreover, considering the European Commission's projected average selling price of 1.30 €/kg by 2030, it becomes evident that even relatively high production costs—such as the 1.46 €/kg calculated under current demonstration conditions—may still be commercially feasible. This reinforces the importance of improving energy efficiency in pre-treatment stages, particularly drying, to enhance competitiveness and align production costs with market expectations.

To ensure that the production costs of both advanced biofuels remain within economically viable limits, the drying process which is the major contributor to thermal energy demand must achieve a SEC below 1.0 kWh/kg of water evaporated. This can be achieved either through the implementation of high-efficiency drying technologies or by integrating the system with external sources of waste heat. Given that the drying and distillation processes are the most thermally intensive stages of the biorefinery, industrial symbiosis with waste heat-supplying facilities is identified as a strategic pathway to improve energy efficiency and reduce production costs.

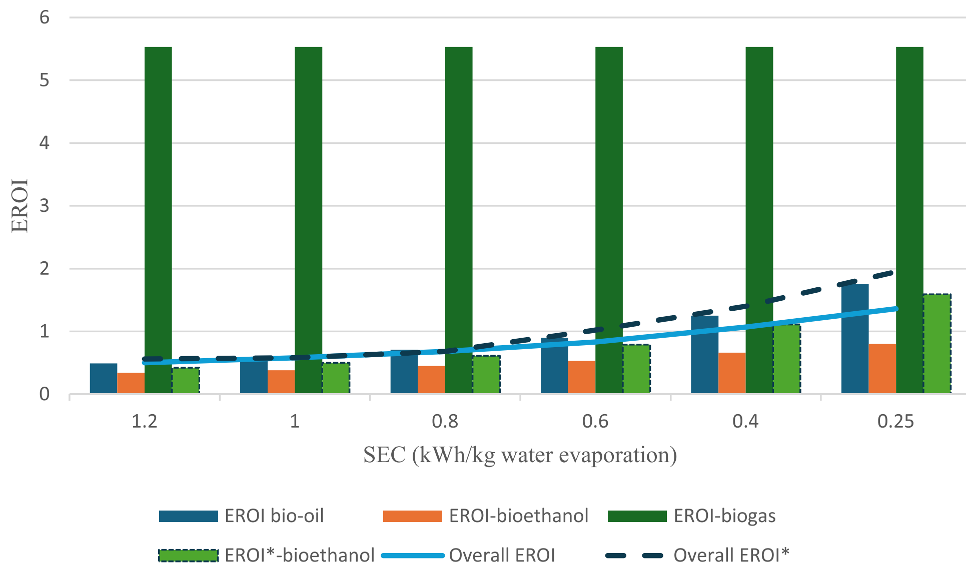

Fig. 9. Influence of drying technology (SEC) to EROI of the system.

3.5. EROI results

The initial EROI values calculated for the demonstration-scale biorefinery system are based on current operating conditions. As shown in Figs. 6 and 7, drying and distillation stages represent the most energy-intensive operations, significantly affecting overall energy efficiency. This is consistent with findings in the literature, which identify drying and distillation as among the most energy-demanding stages in biofuel production processes due to their high thermal requirements [62,70].

Under current conditions, biogas achieves a high EROI of 5.53 due to its low energy input requirements, whereas **bioethanol** and **bio-oils** yield significantly lower EROIs of 0.34 and 0.49, respectively. The overall EROI of the biorefinery plant is approximately 0.5, which falls below the commonly accepted sustainability threshold (EROI = 1) [53], indicating that the system consumes more energy than it produces. These values underscore the considerable energy demands of thermal processes—particularly drying and distillation—which act as critical bottlenecks to the energy performance of liquid biofuels derived from OFMSW. In light of these findings, a theoretical assessment was conducted to explore whether improving the efficiency of these two most energy-intensive processes based on values reported in the literature, could enhance the overall EROI of the system to sustainable levels and render the biorefinery energetically viable.

Fig. 9 presents a theoretical assessment of how variations in drying technology—expressed as SEC—affect the EROI of each individual biofuel and the overall biorefinery system. When an optimized SEC of 0.25 kWh/kg is applied, the EROI of bio-oils increases to 1.76, while bioethanol reaches 0.80. Although bioethanol remains below the sustainability threshold (EROI = 1), the strong contribution of biogas (EROI = 5.53), which is unaffected by drying, raises the overall system EROI to 1.36—surpassing the energy break-even point. In this context, it was also observed that to achieve an EROI above unity, the SEC for bio-oil production must remain below 0.5 kWh/kg. These findings highlight the critical role of drying efficiency in the energy performance of liquid biofuels.

Building on this analysis and recognizing that bioethanol remains energy-deficient even under optimized drying conditions, a second theoretical scenario was considered focusing on the distillation stage. In particular, the use of an advanced distillation technology,known as PTD [35], was assessed for its potential to enhance the EROI of ethanol production. PTD is reported to achieve significantly lower thermal energy requirements, approximately 1.723 kWh/kg of ethanol recovered [35]. Therefore, regarding bioethanol, further studies about potential innovative distillation processes were conducted to assess whether could enhance its EROI. Notably, this approach was assessed solely for energy performance and not included in the cost analysis to avoid incorporating additional assumptions. As illustrated in Fig. 9 (in light green bars), the implementation of PTD in combination with a high efficiency dryer could increase the EROI* of bioethanol to almost 1.60, while the overall EROI of the integrated system to approximately 2.0. This assessment was based solely on energy performance and excluded from the cost analysis to avoid introducing additional assumptions.

To contextualize these findings, several EROI values from the literature were considered. Chiriboga et al. [71], reported EROIs of 1.797 for sugarcane-derived ethanol, 1.040 for corn, and 0.739 for wood. These results highlight that even first-generation bioethanol pathways typically operate near the EROI break-even point. Other studies, such as Felix et al. [72], estimated a maximum EROI of 2.62:1 for switchgrass-based ethanol, while Papagianni et al. [18], reported a much higher value of 25:1 for the same feedstock. However, it is important to clarify that the latter figure originates from a study that evaluates the EROI of the feedstock itself rather than the final bioethanol product. This distinction highlights a common issue in EROI literature: inconsistencies in the definition of system boundaries. Such variations often lead to incomparable values across studies, particularly when methodological assumptions are not explicitly aligned. The generally low EROI values of bioethanol have been discussed in a dedicated chapter provided by Friedemann AJ et al. [73], where the lack of transparency and boundary standardization are emphasized as major limitations in energy return assessments.

Although biogas production requires the lowest energy input and achieves the highest EROI among the biofuels examined in this study, liquid biofuels remain essential for decarbonizing sectors where electrification is not yet feasible—such as aviation, shipping, and heavy transport. In this context, food waste emerges as a promising feedstock for the sustainable production of advanced liquid biofuels, provided that overall energy efficiency is sufficiently optimized. Our results suggest that an EROI above unity can be achieved through the adoption of high-efficiency technologies, particularly in energy-intensive stages such as drying and distillation. Moreover, as previously discussed in Section 4.4, integration of the biorefinery into industrial ecosystems capable of supplying waste heat could serve as an alternative—or

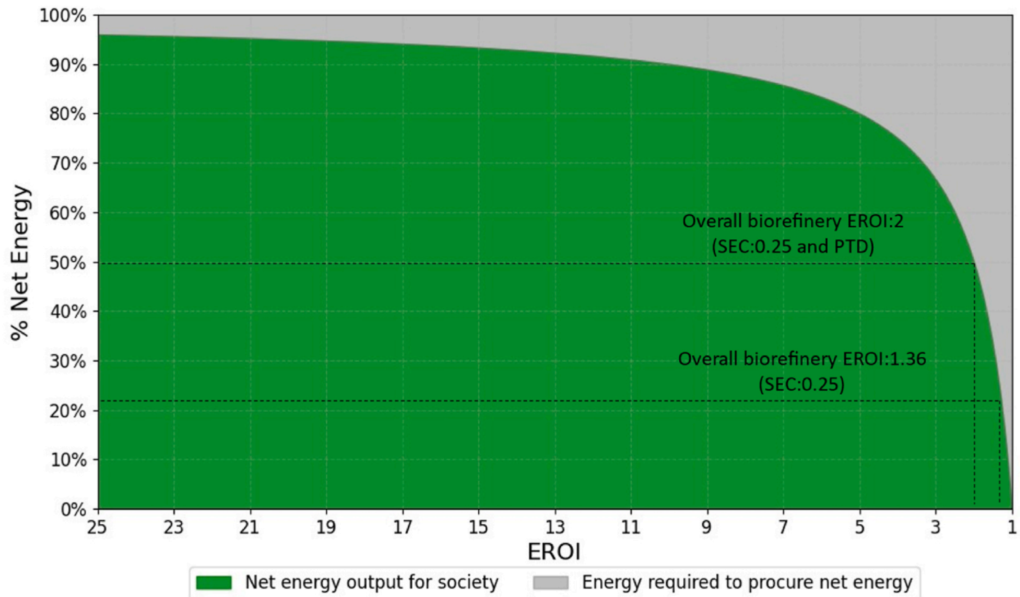

Fig. 10. Potential net energy for society for different biorefinery configurations.

complementary—strategy to reduce energy demand. The combination of advanced technologies with industrial symbiosis has the potential to further enhance system performance.

As shown in Fig. 10, the implementation of these optimizations can significantly increase the net energy contribution of the system. Specifically, the overall EROI improves from below 1.0 under current demonstration conditions to 1.36 with advanced drying alone, and up to 2.0 when both advanced drying and distillation are applied. These values correspond to net energy contributions of approximately 26 % and 49 %, respectively. While the current demonstration setup falls short of the energy sustainability threshold (EROI = 1), this analysis highlights that, with innovative and advanced available technologies, OFMSW can be transformed into a high-value resource for producing advanced liquid biofuels that contribute positively to societal energy balances.

As previously emphasized, an EROI value greater than 1 is generally considered the minimum threshold for energy sustainability, ensuring that a system produces more energy than it consumes. However, Hall et al. [46], argue that an EROI of at least 3 is necessary for an energy system to contribute meaningfully to society beyond its own operational needs—supporting infrastructure, distribution, and broader economic functions. In this context, even with the implementation of innovative drying and distillation technologies, the proposed biorefinery configuration does not achieve this higher benchmark.

This finding reinforces a key conclusion: to meet stricter sustainability criteria such as those outlined by Hall et al., the integration of waste heat sources via industrial symbiosis becomes not only beneficial but potentially essential. It is important to note, however, that the system under study serves a dual function: it is not solely a biofuel production facility, but also a municipal solid waste management unit. Given this broader environmental and societal role, evaluating its performance strictly by the EROI ≥3 threshold which typically is applied to dedicated fuel production systems may not fully capture its value. Nonetheless, improving energy efficiency through strategic integration remains critical for enhancing both the economic and environmental sustainability of such biorefineries.

3.6. *Concluding remarks*

This study presents a real-data-based evaluation of a demonstration-scale biorefinery that converts the OFMSW into advanced liquid biofuels. The findings highlight the crucial impact of integrating high-efficiency drying and distillation technologies on improving both economic and energy performance. With such enhancements, production costs of bio-oil and bioethanol become competitive, and the system's overall EROI approaches 2.0. Embedding such biorefineries within existing industrial infrastructures—particularly those providing waste heat—can further increase their feasibility.

Beyond energy recovery, the biorefinery system serves a dual role by offering an effective waste management solution, thus aligning with EU objectives on circular economy and climate neutrality. This dual-function approach demonstrates that food waste can be a strategic feedstock for sustainable biofuel production, supporting decarbonization, energy security, and waste valorization. The study offers actionable insights for advancing urban biorefineries as scalable, resource-efficient systems within a low-carbon future.

CRediT authorship contribution statement

Konstantinos Passadis: Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Dimosthenis Asimakopoulos:** Writing – review & editing, Supervision. **Dimitris Malamis:** Writing – review & editing, Supervision, Project administration, Funding acquisition, Conceptualization.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.biombioe.2025.108279.

Data availability

Data will be made available on request.

References

[1] European Commission, A New Circular Economy Action Plan: for a Cleaner and More Competitive Europe, European Commission, 2020.
[2] N. Scarlat, J.-F. Dallemand, F. Monforti-Ferrario, V. Nita, The role of biomass and bioenergy in a future bioeconomy: policies and facts, Environ. Dev. 15 (2015) 3–34, https://doi.org/10.1016/j.envdev.2015.03.006.
[3] European Parliament and Council, Directive (EU) 2018/851 of the European Parliament and of the Council of 30 May 2018 Amending Directive 2008/98/EC on Waste, European Union, 2018.
[4] European Parliament and Council, Directive (EU) 2018/2001 of the European Parliament and of the Council of 11 December 2018 on the Promotion of the Use of Energy from Renewable Sources, European Union, 2018.
[5] European Parliament and Council, Directive (EU) 2023/2413 of the European Parliament and of the Council of 18 October 2023 on the Promotion of the Use of Energy from Renewable Sources (Recast), European Union, 2023.
[6] K. Passadis, D. Christianides, D. Malamis, E.M. Barampouti, S. Mai, Valorisation of source-separated food waste to bioethanol: pilot-scale demonstration, Biomass Convers. Biorefinery 12 (2022) 4599–4609, https://doi.org/10.1007/s13399-022-02732-6.
[7] P. Tsafara, K. Passadis, D. Christianides, E. Chatziangelakis, I. Bousoulas, D. Malamis, et al., Advanced bioethanol production from source-separated bio-waste in pilot scale, Sustainability 14 (2022) 12127, https://doi.org/10.3390/su141912127.
[8] E.M. Barampouti, S. Mai, D. Malamis, K. Moustakas, M. Loizidou, Liquid biofuels from the organic fraction of municipal solid waste: a review, Renew. Sustain. Energy Rev. 110 (2019) 298–314, https://doi.org/10.1016/j.rser.2019.04.005.
[9] CIRCforBIO. Circforbio. https://circforbio.eu/, 2024. (Accessed 7 April 2025).
[10] B. Gegić, D. Vučurović, S. Dodić, B. Bajić, Process modelling of integrated bioethanol and biogas production from organic municipal waste, Energies 17 (2024) 4286, https://doi.org/10.3390/en17174286.
[11] F. Meng, A. Dornau, S.J. Mcqueen Mason, G.H. Thomas, A. Conradie, J. McKechnie, Bioethanol from autoclaved municipal solid waste: assessment of environmental and financial viability under policy contexts, Appl. Energy 298 (2021) 117118, https://doi.org/10.1016/j.apenergy.2021.117118.
[12] J. Rocha-Rios, A. Pérez-Roman, T. Lopez-Arenas, M. Sales-Cruz, Simulation of the biofuel production process from organic fraction of municipal solid waste (OFMSW), in: Comput. Aided Chem. Eng., vol. 50, Elsevier, 2021, pp. 1943–1948, https://doi.org/10.1016/B978-0-323-88506-5.50301-6.
[13] A.D. Moreno, J.A. Magdalena, J.M. Oliva, S. Greses, C. Coll Lozano, M. Latorre-Sánchez, et al., Sequential bioethanol and methane production from municipal solid waste: an integrated biorefinery strategy towards cost-effectiveness, Process Saf. Environ. Prot. 146 (2021) 424–431, https://doi.org/10.1016/j.psep.2020.09.022.
[14] S. Karimi, K. Karimi, Efficient ethanol production from kitchen and garden wastes and biogas from the residues, J. Clean. Prod. 187 (2018) 37–45, https://doi.org/10.1016/j.jclepro.2018.03.172.
[15] H. Onyeaka, R.F. Mansa, C.M.V.L. Wong, T. Miri, Bioconversion of starch base food waste into bioethanol, Sustainability 14 (2022) 11401, https://doi.org/10.3390/su141811401.
[16] A. Gaeta-Bernardi, V. Parente, Organic municipal solid waste (MSW) as feedstock for biodiesel production: a financial feasibility analysis, Renew. Energy 86 (2016) 1422–1432, https://doi.org/10.1016/j.renene.2015.08.025.
[17] F. Musharavati, A. Ahmad, M.H. Javed, K. Sajid, M. Naqvi, Sustainability assessment of biofuel and value-added product from organic fraction of municipal solid waste, Environ. Res. 246 (2024) 118121, https://doi.org/10.1016/j.envres.2024.118121.
[18] S. Papagianni, I. Capellán-Pérez, A. Adam, A. Pastor, Review and meta-analysis of energy return on investment and environmental indicators of biofuels, Renew. Sustain. Energy Rev. 203 (2024) 114737, https://doi.org/10.1016/j.rser.2024.114737.
[19] W. Prananta, I. Kubiszewski, Assessment of Indonesia's future renewable energy plan: a meta-analysis of biofuel Energy Return on Investment (EROI), Energies 14 (2021) 2803, https://doi.org/10.3390/en14102803.
[20] C. Rachid-Casnati, F. Resquin, L. Carrasco-Letelier, Availability and environmental performance of wood for a second-generation biorefinery, Forests 12 (2021) 1609, https://doi.org/10.3390/f12111609.
[21] H. Kazemi Shariat Panahi, M. Dehhaghi, G.J. Guillemin, V.K. Gupta, S.S. Lam, M. Aghbashlo, et al., Bioethanol production from food wastes rich in carbohydrates, Curr. Opin. Food Sci. 43 (2022) 71–81, https://doi.org/10.1016/j.cofs.2021.11.001.
[22] A.P. Gupte, N. Di Vita, M.W. Myburgh, R.A. Cripwell, M. Basaglia, W.H. van Zyl, et al., Consolidated bioprocessing of the organic fraction of municipal solid waste into bioethanol, Energy Convers. Manag. 302 (2024) 118105, https://doi.org/10.1016/j.enconman.2024.118105.
[23] Y.-F. Yang, G.-B. Ye, H.-J. Wang, H.-Y. Li, C.S.K. Lin, X.-F. Zheng, et al., Utilization of lipidic food waste as low-cost nutrients for enhancing the potentiality of biofuel production from engineered diatom under temperature variations, Bioresour. Technol. 387 (2023) 129611, https://doi.org/10.1016/j.biortech.2023.129611.
[24] E. Salimi, M.E. Taheri, K. Passadis, J. Novacovic, E.M. Barampouti, S. Mai, et al., Valorisation of restaurant food waste under the concept of a biorefinery, Biomass Convers. Biorefinery 11 (2021) 661–671, https://doi.org/10.1007/s13399-020-00613-4.
[25] LIFE CIRCforBIO, Deliverable C.1.1: Facility Operation and Maintenance Manual, CIRCforBIO, 2024.
[26] LIFE CIRCforBIO, Deliverable C.2.2: Report on the Test Operation and Optimization of the Biorefinery System, LIFE CIRCforBIO, 2024.
[27] M. Nikolaou, C. Stavraki, I. Bousoulas, D. Malamis, M. Loizidou, S. Mai, et al., Valorisation of bakery waste via the bioethanol pathway, Energy 280 (2023) 128185, https://doi.org/10.1016/j.energy.2023.128185.
[28] M. Bibra, D. Samanta, N.K. Sharma, G. Singh, G.R. Johnson, R.K. Sani, Food waste to bioethanol: opportunities and challenges, Fermentation 9 (2023) 8, https://doi.org/10.3390/fermentation9010008.
[29] R. Verhe, S. Varghese, J.M. Thevelein, J.H. Nikroo, M. Lambrecht, E. Redant, et al., Production of bio-ethanol from the organic fraction of municipal solid waste and refuse-derived fuel, Biomass 2 (2022) 224–236, https://doi.org/10.3390/biomass2040015.
[30] A. Singh, R.R. Singhania, S. Soam, C.-W. Chen, D. Haldar, S. Varjani, et al., Production of bioethanol from food waste: status and perspectives, Bioresour. Technol. 360 (2022) 127651, https://doi.org/10.1016/j.biortech.2022.127651.
[31] F. Calise, F.L. Cappiello, L. Cimmino, M. Napolitano, M. Vicidomini, Analysis of the influence of temperature on the anaerobic digestion process in a plug flow reactor, Thermo 2 (2022) 92–106, https://doi.org/10.3390/thermo2020009.
[32] R. Shoshaa, S. Ghanimeh, F. Almomani, Recent advances in plug flow reactors for anaerobic digestion and in-depth evaluation of mixing approaches: a review, Fuel 377 (2024) 132711, https://doi.org/10.1016/j.fuel.2024.132711.
[33] I. Bashkir, A. Martynenko, Optimization of multiple-emitter discharge electrode for electrohydrodynamic (EHD) drying, J. Food Eng. 305 (2021) 110611, https://doi.org/10.1016/j.jfoodeng.2021.110611.
[34] A. Alex Martynenko, G.N.A. Vieira, Sustainability of drying technologies: system analysis, Sustain. Food Technol. 1 (2023) 629–640, https://doi.org/10.1039/D3FB00080J.
[35] T. Janković, A.J.J. Straathof, I.R. McGregor, A.A. Kiss, Bioethanol separation by a new pass-through distillation process, Sep. Purif. Technol. 336 (2024) 126292, https://doi.org/10.1016/j.seppur.2024.126292.
[36] J. Ciuła, A. Generowicz, K. Gaska, A. Gronba-Chyła, Efficiency analysis of the generation of energy in a biogas CHP system and its management in a waste landfill – case study, J. Ecol. Eng. 23 (2022) 143–156, https://doi.org/10.12911/22998993/149609.
[37] L.T. Thanh, K. Okitsu, L.V. Boi, Y. Maeda, Catalytic technologies for biodiesel fuel production and utilization of glycerol: a review, Catalysts 2 (2012) 191–222, https://doi.org/10.3390/catal2010191.
[38] W.M. Haynes (Ed.), CRC Handbook of Chemistry and Physics: a ready-reference Book of Chemical and Physical Data, 95th ed., CRC Press, Boca Raton, 2014.
[39] S.E. Hosseini, G. Bagheri, M. Khaleghi, M. Abdul Wahid, Combustion of biogas released from Palm oil Mill effluent and the effects of hydrogen enrichment on the characteristics of the biogas flame, J. Combust. 2015 (2015) 1–12, https://doi.org/10.1155/2015/612341.
[40] D. Deublein (Ed.), Biogas from Waste and Renewable Resources: an Introduction. 3. Nachdr, Wiley-VCH-Verl, Weinheim, 2010.
[41] H.F. Imtiaz, A framework for upscaling of emerging chemical processes based on thermodynamic process modeling and simulation, ChemEngineering 8 (2024) 46, https://doi.org/10.3390/chemengineering8030046.
[42] World Bioenergy Association, Factsheet: Biogas, 2013.
[43] A. Rosati, P. Camps, C. Sebastiani, Overview of the Greek Market Condition, AzzeroCO2, 2023.
[44] N. Primmer, Biogas: Pathways to 2030, World Biogas Association, 2021.
[45] V. Felekis, C. Stavraki, D. Malamis, S. Mai, E.M. Barampouti, Optimisation of bioethanol production in a potato processing industry, Fermentation 9 (2023) 103, https://doi.org/10.3390/fermentation9020103.
[46] C. Hall, S. Balogh, D. Murphy, What is the minimum EROI that a sustainable society must have? Energies 2 (2009) https://doi.org/10.3390/en20100025.
[47] I. Capellán-Pérez, C. De Castro, L.J. Miguel González, Dynamic Energy Return on Energy Investment (EROI) and material requirements in scenarios of global transition to renewable energies, Energy Strategy Rev. 26 (2019) 100399, https://doi.org/10.1016/j.esr.2019.100399.
[48] A.R. Brandt, How does energy resource depletion affect prosperity? Mathematics of a minimum Energy Return on Investment (EROI), Biophys. Econ. Resour. Qual. 2 (2017) 2, https://doi.org/10.1007/s41247-017-0019-y.
[49] F. Fizaine, V. Court, Energy expenditure, economic growth, and the minimum EROI of society, Energy Policy 95 (2016) 172–186, https://doi.org/10.1016/j.enpol.2016.04.039.
[50] J.G. Lambert, C.A.S. Hall, S. Balogh, A. Gupta, M. Arnold, Energy, EROI and quality of life, Energy Policy 64 (2014) 153–167, https://doi.org/10.1016/j.enpol.2013.07.001.
[51] C.A.S. Hall, S. Balogh, D.J.R. Murphy, What is the minimum EROI that a sustainable society must have? Energies 2 (2009) 25–47, https://doi.org/10.3390/en20100025.
[52] D.J. Murphy, C.A.S. Hall, Year in review–EROI or energy return on (energy) invested, Ann. N. Y. Acad. Sci. 1185 (2010) 102–118, https://doi.org/10.1111/j.1749-6632.2009.05282.x.
[53] K. Mulder, N.J. Hagens, Energy return on investment: toward a consistent framework, AMBIO A J. Hum. Environ. 37 (2008) 74–79, https://doi.org/10.1579/0044-7447(2008)37[74:EROITA]2.0.CO;2.
[54] E.M. Barampouti, S. Mai, K. Moustakas, D. Malamis, M. Loizidou, K. Passadis, et al., Advanced bioethanol production from biowaste streams. Recent Adv. Renew. Energy Technol, Elsevier, 2022, pp. 77–154, https://doi.org/10.1016/B978-0-12-823532-4.00006-9.
[55] B. Motavaf, R.A. Dean, J. Nicolas, P.E. Savage, Hydrothermal carbonization of simulated food waste for recovery of fatty acids and nutrients, Bioresour. Technol. 341 (2021) 125872, https://doi.org/10.1016/j.biortech.2021.125872.

[56] W. Anaya Menacho, A.M. Mazid, N. Das, Modelling and analysis for biogas production process simulation of food waste using Aspen plus, Fuel 309 (2022) 122058, https://doi.org/10.1016/j.fuel.2021.122058.
[57] S. Jain, S. Kumar, A comprehensive review of bioethanol production from diverse feedstocks: current advancements and economic perspectives, Energy 296 (2024) 131130, https://doi.org/10.1016/j.energy.2024.131130.
[58] H.G. Mosquera-Toscano, O. González-Barceló, I. Valdez-Vazquez, A. Durán-Moreno, Ethanol and methane production from the organic fraction of municipal solid waste in a two-stage process, BioEnergy Res. 17 (2024) 634–645, https://doi.org/10.1007/s12155-023-10610-w.
[59] M. Carmona-Cabello, D. Leiva-Candia, J.L. Castro-Cantarero, S. Pinzi, M.P. Dorado, Valorization of food waste from restaurants by transesterification of the lipid fraction, Fuel 215 (2018) 492–498, https://doi.org/10.1016/j.fuel.2017.11.096.
[60] X. Yang, S.J. Lee, H.Y. Yoo, H.S. Choi, C. Park, S.W. Kim, Biorefinery of instant noodle waste to biofuels, Bioresour. Technol. 159 (2014) 17–23, https://doi.org/10.1016/j.biortech.2014.02.068.
[61] C.D. Scown, N.R. Baral, M. Yang, N. Vora, T. Huntington, Technoeconomic analysis for biofuels and bioproducts, Curr. Opin. Biotechnol. 67 (2021) 58–64, https://doi.org/10.1016/j.copbio.2021.01.002.
[62] E. Gnansounou, A. Dauriat, Techno-economic analysis of lignocellulosic ethanol: a review, Bioresour. Technol. 101 (2010) 4980–4991, https://doi.org/10.1016/j.biortech.2010.02.009.
[63] D. Humbird, R. Davis, L. Tao, C. Kinchin, D. Hsu, A. Aden, et al., Process design and economics for biochemical conversion of lignocellulosic biomass to ethanol: dilute-acid pretreatment and enzymatic hydrolysis of corn stover. https://doi.org/10.2172/1013269, 2011.
[64] ISCC Waste and Residue Guidance Document, ISCC System Gmbh, 2025.
[65] V. Prykhodko, UCO prices reach two-year high in 2024, increases to continue in 2025 amid demand, Fastmarkets (2025). https://www.fastmarkets.com/insights/uco-prices-reach-two-year-high-in-2024-increases-to-continue-in-2025-amid-demand/. (Accessed 23 April 2025).
[66] Olughu O. Onu, L.G. Tabil, T. Dumonceaux, E. Mupondwa, D. Cree, X. Li, Technoeconomic analysis of a fungal pretreatment-based cellulosic ethanol production, Results Eng. 19 (2023) 101259, https://doi.org/10.1016/j.rineng.2023.101259.
[67] S. Kuittinen, J. Hietaharju, I. Bhattarai, MdK. Hassan, L. Kupiainen, J. Kangas, et al., Technoeconomic analysis and environmental sustainability estimation of bioalcohol production from barley straw, Biocatal. Agric. Biotechnol. 43 (2022) 102427, https://doi.org/10.1016/j.bcab.2022.102427.
[68] B. Correia, H.A. Matos, T.F. Lopes, S. Marques, F. Gírio, Sustainability assessment of 2G bioethanol production from residual lignocellulosic biomass, Processes 12 (2024) 987, https://doi.org/10.3390/pr12050987.
[69] European Commission. Directorate General for Research and Innovation., Exergia., E3Modelling., Wageningen University & Research., BEST., BTG., Development of Outlook for the Necessary Means to Build Industrial Capacity for drop-in Advanced Biofuels: Final Report, LU: Publications Office, 2024 et-al.
[70] C. Cardonaalzate, O. Sancheztoro, Energy consumption analysis of integrated flowsheets for production of fuel ethanol from lignocellulosic biomass, Energy 31 (2006) 2447–2459, https://doi.org/10.1016/j.energy.2005.10.020.
[71] G. Chiriboga, A. De La Rosa, C. Molina, S. Velarde, C.G. Carvajal, Energy Return on Investment (EROI) and Life Cycle Analysis (LCA) of biofuels in Ecuador, Heliyon 6 (2020) e04213, https://doi.org/10.1016/j.heliyon.2020.e04213.
[72] E. Felix, D.R. Tilley, Integrated energy, environmental and financial analysis of ethanol production from cellulosic switchgrass, Energy 34 (2009) 410–436, https://doi.org/10.1016/j.energy.2008.10.013.
[73] A.J. Friedemann, Ethanol and Energy Return on Investment (EROI), in: A. J. Friedemann (Ed.), Life Foss. Fuels Real. Check Altern. Energy, Springer International Publishing, Cham, 2021, pp. 125–130, https://doi.org/10.1007/978-3-030-70335-6_22.