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Article

TECHNO-ECONOMIC ASSESSMENT OF AN OLIVE MILL WASTEWATER (OMWW) BIOREFINERY IN THE CONTEXT OF CIRCULAR BIO-ECONOMY

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Abstract: The concept of biorefinery constitutes a significant contributing factor to the emerging transition towards a sustainable bioeconomy. In such a context, replacing oil and petrochemicals by biomass may involve several feedstocks, platforms, processes, technologies, as well as final products. This paper concentrates in the complex process of transferring the concept of biorefinery from laboratory to industry, and sheds light on the techno-economic, and complexity management dimensions involved in this endeavor. Towards this end, adopting a systems perspective, the paper presents a structured and comprehensive framework, comprising of the definition of the transformation process, business model development, technoeconomic assessment and strategic positioning and viability assessment, which may be employed to facilitate the engineering at-large and launch of a biorefining venture in a circular bioeconomy context. The framework is applied in the context of a biorefinery plant in a specific region in Southern Greece, which is based on the valorisation of olive mill wastewater (a 'strong' and quite common industrial waste in Mediterranean Basin), and produces biopolymers (PHAs) and bioenergy (H_2).

Keywords: circular bioeconomy; biorefinery; waste valorisation; olive mill wastewater (OMWW), bioplastics; PHAs; business canvas; business model, SWOT analysis; industrial symbiosis

1. Introduction

Circular bioeconomy (CBE) is emerging in academia, industry and policy-making as an important concept towards sustainability. It extends across two fields: circular economy, and bioeconomy. In particular, it focuses on bio-based products and services, seeking to substitute the current linear material and energy flows with circular loops [Carus & Dammer, 2018; Giampetro, 2019; Stegman et al., 2020]. In this direction, CBE addresses several widely publicized sustainable development goals, and it has entered the agenda of policy plans in all continents, resulting in a growing number of initiatives implemented at different geographic levels (local, regional, national, and supranational) [Mouzakitis & Tsoulfas, 2019; Nizami et al., 2017; Salvador et al. 2022]. The concept of biorefinery (de Jong et al, 2012; Mohan et al. (2016), where biofuels, chemicals, and a wide spectrum of high value bioproducts are produced from biomass using several conversion technologies [Cherubini, 2010; Mohan et al. (2019)] constitutes a major step towards CBE. Not surprisingly, in both CBE and biorefineries, the strategy of waste valorisation, namely the biotechnological conversion of by-products and residues into valuable products, is highly valued [Liguori et al., 2013; Maina et al, 2017].

So far, the literature on CBE has taken two different but complementary directions: on the one hand, there is a growing number of publications with a clear bioengineering orientation, which provide evidence on the technical advances of the corresponding processes and technologies, while on the other, one may find scholars who adopt a techno-economic perspective, seeking to shed light on the processes of efficient implementation of the afore-mentioned technologies in real-world settings. This paper falls into the second category, as it takes a holistic engineering perspective and presents a methodological framework (and the corresponding results stemming from its application) which may be used to manage the complexity in the development of a biorefinery facility as a socially-conscious economic entity. The proposed framework extends in four dimensions: process engineering, development of business model for a venture to capitalize on the process, techno-economic assessment of the venture business model, assessment of venture viability in the specific implementation context, and is demonstrated through an exploratory case study in Greece, where the venture considered would process olive mill waste water (OMWW), a quite typical agricultural waste in the Mediterranean Region, and through a combination of bio-chemical and mechanical processes, would produce bioplastics (Polyhydroxyalkanoates or PHAs) and biogas.

The remaining of the paper has the following structure: Section 2 summarizes the related theoretical background on the four central elements and processes (biorefinery, OMWW, PHAs, biogas), and Section 3 outlines the Research Questions that the paper aims at answering, the proposed methodological framework, and the corresponding research tools. Then, in Section 3, we present and discuss our case study, covering four aspects of the planned venture: the production process, a related business model, the techno-economic assessment of the venture implementing the model, and an overall assessment of the intended implementation by means of a SWOT analysis. Finally, section 4 draws the conclusions, and outlines directions for future work.

2. Theoretical Background

2.1. Biorefineries

Similar to conventional oil refineries, which are industrial complexes where crude oil is being refined and transformed into consumer and industrial products (gasoline, asphalt base, lubricants, etc.), biorefineries are facilities which transform a variety of chemicals, after the fractionating of a raw material (biomass), into intermediates (carbohydrates, proteins, and triglycerides), which may then be further processed into value-added products [Cherubini, 2010].

Biorefineries appear in various forms, and Cherubini at al. (2009) proposed a four-group classification scheme consisting of:

1. *platforms*, which refer to the intermediates linking feedstocks and final products.
2. *products*, distinguished as energetic and non-energetic main products.
3. *feedstocks*, which may be either dedicated (such as grasses, sugar, starch, lignocellulosic or oil-based crops, etc.), or residual (organic, lignocellulosic, oil-based, etc.).
4. *processes*, which may be mechanical/physical (distillation, filtration, etc.), chemical (oxidation, hydrolysis, etc.), thermochemical (where the feedstock withstands changes in high pressure and temperature, with potential use of catalysts), or biochemical (changes occur under low temperature and pressure, using microorganism or enzymes) processes.

Biorefineries contribute to environmental sustainability, mainly because they facilitate fossil fuel decoupling, and the mitigation of climate change [Mohan et al., 2016; Mohan et al. 2019]. Nonetheless, one may find critiques of biorefining, largely due to their environmental impacts, such as changes in land use, eutrophication of water, use of pesticides [Uihlein and Schebek, 2009]. The afore-mentioned impacts depend largely on the origin of the feedstock, namely, whether the biomass is harvested from land (primary), consists of forest industry residues (secondary), or comes from municipal/industry wastes (tertiary). The feedstock considered here (OMWW) falls in the last category, and it should be underlined that besides the zero impacts (in terms of biomass production), there is a significant benefit stemming from the effective treatment of large volumes of waste.

2.2. Olive Mill Waste Water (OMWW)

Olive oil is a liquid fat which is produced by pressing olives, a typical fruit of Mediterranean Basin. In the last 60 years, the production of olive oil has increased by thrice, reaching 3,3 millions tonnes in the 2019–20 crop year (IOC, 2022). EU accounts for over 2 million tonnes of this output, with Spain (66%), Italy (15%), Greece (13%) and Portugal (5%) being the major producers.

The liquid waste which is generated during the extraction of olive oil is known as olive oil mill wastewater (OMWW), and it is considered as a strong industrial waste (see table 1). OMWW is related with severe enviromental issues, such as [Tsagaraki et al. 2007; Justino et al. 2012]:

- impacts on water bodies: intoxication, discoulouration, eytrophication.
- impacts on soil: changes in fertility, decrease in magnesium, soil porosity.
- impacts on plants: fruit and leaf amscission, seeds germination, early growing stage.

Clearly, the production of OMWW is not an uncontrollable process. There are several factors (extraction method, type of olive trees, type of soil and irrigation water, climatic conditions, use of pesticides/fertilizers, etc.) which have a significant impact on the quality (chemical synthesis and the corresponding polluting ingredients) and quantity of OMWW.

Table 1. Quantity & Properties of OMWW (based on Azbar et al. 2004; Tsagaraki et al. 2007; International Olive Council, 2022)

Quantity	Properties
	- colour: dark brown to black
- olive growing area: 10.8 he (worldwide)	- smell: strong and offensive
- olive trees: 750 million (worldwide)	- pH: acid (between 2 and 6)
- olive oil: 3 million tones (annual world production)	- solid matter and organic load: high
- OMWW: 6 - 30 million m^3 (annual world production)	- pollutants: polyphenols, flavonoids, phosphorus, potassium, tanins, reduced sugars, (acetic, formic and oleanolic) acids
- OMWW per 1 tn of processed olives: 1 - 1.6 m^3	
- OMWW per 1 tn of olive oil: 4.7 – 7.6 m^3	

Not surprisingly, there exist a large number of physical, physico-chemical, thermal, and biological methods, which can be used (stand alone or in combination) for the treatment and/or valorisation of OMWW [Niaounakis and Halvadakis, 2006; Jegirim et al. 2012; Ahmed et al. 2019). Selecting between different alternatives is a multi-parametric issue, and the corresponding decision depends on factors such as the technological know-how, the quantity and quality of the OMWW in hand, the financial affordability, the scattering and size of the involved olive mills, the proximity to human settlements, etc. In the paper, the proposed process for the facility under consideration, which is described in detail in section 4.1, is based mainly on microbiological treatment, and leads to the production of two valuable products: bioplastic (PHAs), and biogas (H_2).

2.3. Production of PHAs and biohydrogen

Biobased materials, such as biopolymers, biofibers, biofilms and biocomposites, are intended to replace synthetic ones, in an attempt to reduce the severe environmental impacts caused by the latter [Vinod at al., 2020]. Contrary to conventional petro-based plastics which are produced from oil or natural gas, bioplastics (biobased polymers) are produced from renewable biomass (seed fats and oils, straw, wood waste, etc.). Although a major benefit of biobased polymers is the decoupling from fossil fuels, in fact, bioplastics are not necessarily environmentally superior to petro-based ones [Vert et al., 2012]. Bioplastics are gaining market share, as in the last five years, they participated by around 2% in the world's total plastics production [Chinthapalli et al., 2019]. In a classification scheme presented by Gurunathan et al. (2015), biopolymers can be distinguished in three groups:

1. biomass products (polysaccharides and proteins), which are biopolymers derived from agro-resources,
2. biotechnology products (polylactides & polyglycolides), which are synthesized from bio-derived polymers, and
3. micro-organisms products (polyhydroxyalkonates-PHAs), which are micro-organism-based products.

PHAs are thermoplastic polymers, which may be processed with conventional machinery, and similarly to other biopolymers, they present different properties with respect to their specific chemical synthesis [Cataldi et al., 2020]. They are biodegradable and highly deformable, presenting high heat resistance and achieving a sufficient balance between toughness and stiffness [Poltronieri & Kumar, 2019]. Not surprisingly, they have a growing number of applications in coating, packaging, prosthetics, etc.[Poltronieri & Kumar, 2019; Wand and Chen, 2017]. Overall, despite their relatively high production cost with respect to other plastics, they constitute a promising area of biomaterials with a growing market and high value functionalities [Anjum et al., 2016].

The second product of the OMWW valorization, which can be derived from the planned biorefinery, is biohydrogen, a gas which is associated with both the biorefinery [Kaparaju et al, 2009], and PHAs [Sekoai et al., 2022]. Biohydrogen can be produced by several processes (biophotolysis, fermentation, hybrid bio-electrochemical), each one having benefits and disadvantages [Azwar et al., 2014]. Kotay and Das (2008) underline that biohydrogen is highly convenient for small-scale decentralized energy production systems, which are integrated within agricultural, industrial and waste-treatment facilities. They also argue that process engineering, associated with the design and operating conditions of bioreactors, is one of the key elements affecting the efficiency of hydrogen conversion. More specifically, this efficiency might be increased by tweaking reactor design and operational parameters including pH, hydraulic retention time, and temperature. In this vein, given the complexity of the corresponding reactor, the use of artificial intelligence, which may take into account the non-linear interactions between the inputs of the process, is highly recommended (Asrul et al., 2022).

3. Methodology

A biorefinery can be conceptualised as an anchor tenant [Korhonen and Snakin, 2001; Topolski et al., 2019], of an industrial symbiosis system [Boons et al. 2011], where wastes or byproducts of one industrial process constitute the raw material for another. More specifically, and in the context of the presented study, we consider the biorefinery as the "heart" of symbiosis (see Figure 1). In such a position, it takes as inputs the OMWW from olive mills (mainly local ones), and provides its outputs (the PHAs) to plastic manufacturing facilities (not necessarily nearby ones).

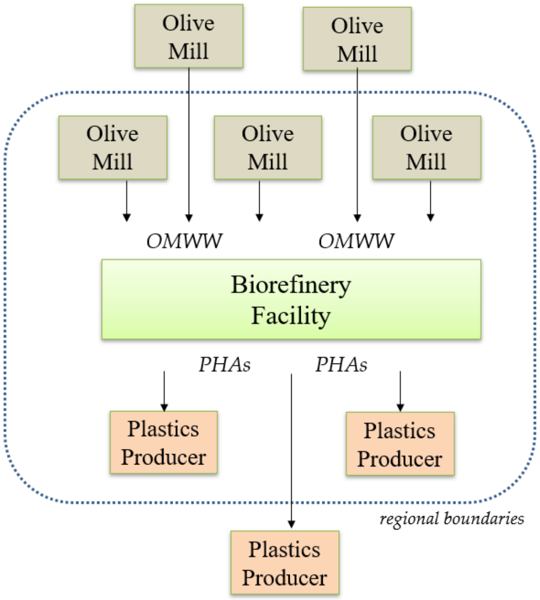

Figure 1. The biorefinery as an anchor tenant of an industrial symbiosis.

In this paper, we focus on the anchor tenant (biorefinery level), aiming to provide answers to the following research questions (RQ):

RQ1: How the potential of the actual implementation in a specific real-word context of a biorefinery based on novel biotechnologies, which have been developed and tested in vitro, can be assessed in a systematic and comprehensive way?

RQ2: How the derived assessment framework (the answer of RQ1) can be used in a specific case-study in a region in Greece, where the planned biorefinery has a feedstock of OMWW and produces PHAs and biogas?

In order to deal with the above research questions, we have developed and applied a four step process (see Figure 2):

1. Relying on the literature which focuses on the valorisation of OMWW in the direction of PHAs and biogas (e.g. Beccari et al. 2009, Ntaikou et al. 2009, Ntaikou et al. 2014), we present the production process of the facility. The publications mentioned above adopt a bio-engineering perspective and provide evidence on the exploitation of OMWW for bio-polymers and bio-energy production through a combination of both anaerobic and aerobic processes.
2. Then, we use the Business Model Canvas [Osterwalder et al., 2010] to develop the corresponding business model. Business Model Canvas is a tool that provides a detailed structured template for developing and communicating business models, by means of nine elements: value proposition, market/customer segments, (market) channels, customer relationships, key resources/assets, key activities, key partners/collaborators, cost structure, and revenue streams. The importance of novel business models has been underlined in the literature of circular bioeconomy [Salvador et al,2021], while Business Model Canvas has been applied in similar cases of waste valorisation in the olive-oil sector [Donner & Radić, 2021; Donner et al., 2022].
3. In the step following, the economic viability of planned venture is assessed by examining scenarios of different organizational configurations. Various approaches to techno-economic assessment of circular bioeconomic endeavours can be found in the literature (Anyaoha & Zhang, 2022; Gutiérrez et al. 2022; Nematian, et al. 2021]. Our method of analysis is novel, in that it is based on a non-equilibrium system dynamics model calibrated using cost-price data specific to the region of the case study (see below). In addition, such an approach incorporates the endogenous investment dynamics and assesses outcomes in operational - rather than correlational - terms (Keen, 2022).
4. Finally, using input from the previous stages, we carry out an analysis of the internal and external environment of the planned facility, based on the strategic management technique of SWOT analysis [Helms & Nixon, 2011], which is a methodological tool already been applied in the context of circular bioeconomy [Gomes et al., 2020; Paes et al., 2019]. SWOT analysis can be employed to identify internal and external environmental elements, factors and characteristic, which may act as positive or negative catalysts in the development of a specific venture.

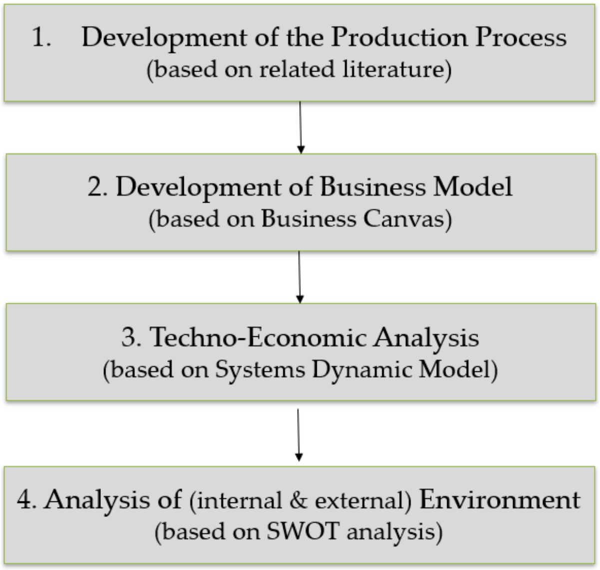

Figure 2. The 4-step framework of analysis.

The above process was applied for the development of an OMWW biorefinery in Achaia, the largest prefecture in Western Greece which has a population of roughly 300,000 people, and an area of 3,271 km^2 . In the area, the service sector accounts for 70% of the local economy's Gross Domestic Product, while the rest of the GDP is made up of manufacturing (about 20%), and agriculture (10%). Achaia was chosen as the subject of the case study because, apart from a significant production and demand for the planned venture (see Table 2), its capital (Patras) hosts a high-ranking engineering school with significant related research, which could make a positive contribution to the project (see Section 4.4).

Table 2. Prefecture of Achaia: Data on OMWW supply and PHAs demand

OMWW	PHAs
- olive trees: 3.5 million	- major plastic producers: 3 facilities
- olive pressing facilities: 59 (mainly SMEs)	- the largest venture requires an input of plastic of 4.4 tns/year
- production of olive oil: 21,000 tns / year	
- production of olive oil: 130,000 tns / year	

4. Results & Discussion

Table 3 depicts the basic features of the planned biorefinery (platforms, products, feedstocks, processes) with respect to the classification scheme presented by Cherubini at al. (2009). Following, in accordance with the aforementioned framework, we discuss the results of its application, concerning the production process (section

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4.1), the business model (section 4.2), the techno-economic assessment (section 4.3), and the SWOT analysis (section 4.4).

Table 3. Classification of the planned biorefinery [based on Cherubini at al. (2009)]

feature	classification
platforms	oil & biogas
products	material products: biopolymers (PHAs) energy products: biogas
feedstocks	oil-based residues: OMWW (tertiary biomass)
processes	thermochemical: combustion biochemical: anaerobic digestion, aerobic conversion, enzymatic mechanical/physical: extraction, separation (filtering)

4.1. The production process

Drawing on [Beccari et al. 2009, Ntaikou et al. 2009, Ntaikou et al. 2014), the PHAs production process of the OMWW treatment plant is given in Figure 3. The technical infrastructure required is depicted in Table 4. More specifically, the process is constituted by the following phases:

Phase 1: Reception & Storage of OMWW

After their collection and reception, OMWW are stored in stainless steel tanks, bearing an external cooling cloak, with the aim of keeping their storage temperature at a level below 4^{o}C. This is considered necessary as it has been shown that close to this temperature, the concentration of carbohydrates is reduced (possibly due to microbial activity), thus affecting their performance during anaerobic fermentation. In addition, monitoring the temperature of OMWW is crucial in order to control their flow to the anaerobic bioreactor with the appropriate rate [Koutrouli, 2008].

Phase 2 : Dilution of OMWW

Using a pump and stainless-steel ducts, OMWW is driven into a tank, where dilution with tap water takes place. This is a necessary as the anaerobic hydrogen production process is hampered when undiluted liquid oil mill waste is used as a substrate, whereas this is not the case when diluted waste is used as a substrate in the ratio of 1:4 to 1:2. In addition, K_2HPO_4 is added to the dilution tank, in a ratio of 1 g/lt, as a phosphorus source.

Phase 3 : Anaerobic treatment of OMWW

The diluted OMWW are led into a stainless continuous stirred-tank reactor (CSTR). The reactor has double cylindrical walls (heating mantle) between which water flows at a temperature of 1-2

^{0} C higher than the desired temperature of 35 °C inside the reactor, so that there are no losses and ensures its operation in the mesophile conditions. The heating of the liquid is achieved by an external system. Inside the reactor there is a stirring system, while at its top there is a device for collecting the biogas produced. In addition, one may find two receptacles, one for taking a gaseous sample and one for taking a liquid sample. The feeding of the anaerobic reactor with diluted OMWW takes place through a peristaltic pump, which is appropriately adjusted to feed the reactor with a specific amount of diluted waste at regular intervals depending on the hydraulic residence time (HRT). This is chosen to be 14,5 hours.

Phases 4 & 5: Mechanical treatment of OMWW

After the anaerobic treatment, the acidified OMWW undergoes centrifugation and filtration in order to remove the solids. The centrifugated and filtrated OMWW is led to an aerobic reactor.

Phase 6: Aerobic treatment of OSH

An enriched mixed culture is added to the aerobic reactor as a 20% inoculant. The mixture is enriched with K_2HPO_4, at a ratio of 3 g/L feed, as a source of phosphorus, but also in order to adjust the pH, and with $(NH_4)_2SO_4$ as a source of nitrogen. The reactor operates at ambient temperature, it is equipped with aeration, agitation and exhaust systems, and operates periodically and automatically, completing each treatment cycle in 2.5 days. The reactor is equipped with an automatic system which by receiving data on the quantity and quality of OMWW flowing into the plant, automatically adjusts the operation of the unit by adjusting the times and sequence of operation of all pumps, aerators, agitators and electrovalves.

Phase 7: Recovery of PHAs

With the aid of solvents the PHAs are recovered from the biomass, which has been produced by the aerobic reactor.

Phase 8: Collection and combustion of biogas

The biogas produced in the anaerobic reactor (Phase 3) is extracted through a pipeline in a storage tank. The expected hydrogen production is 233 ml/lt of diluted OMWW, and the corresponding combustion is used for energy production.

Phase 9: Removal of residuals

The solid and fluid residuals produced in Phases 5 and 7 are collected and stored, before removed by a certified waste management organisation.

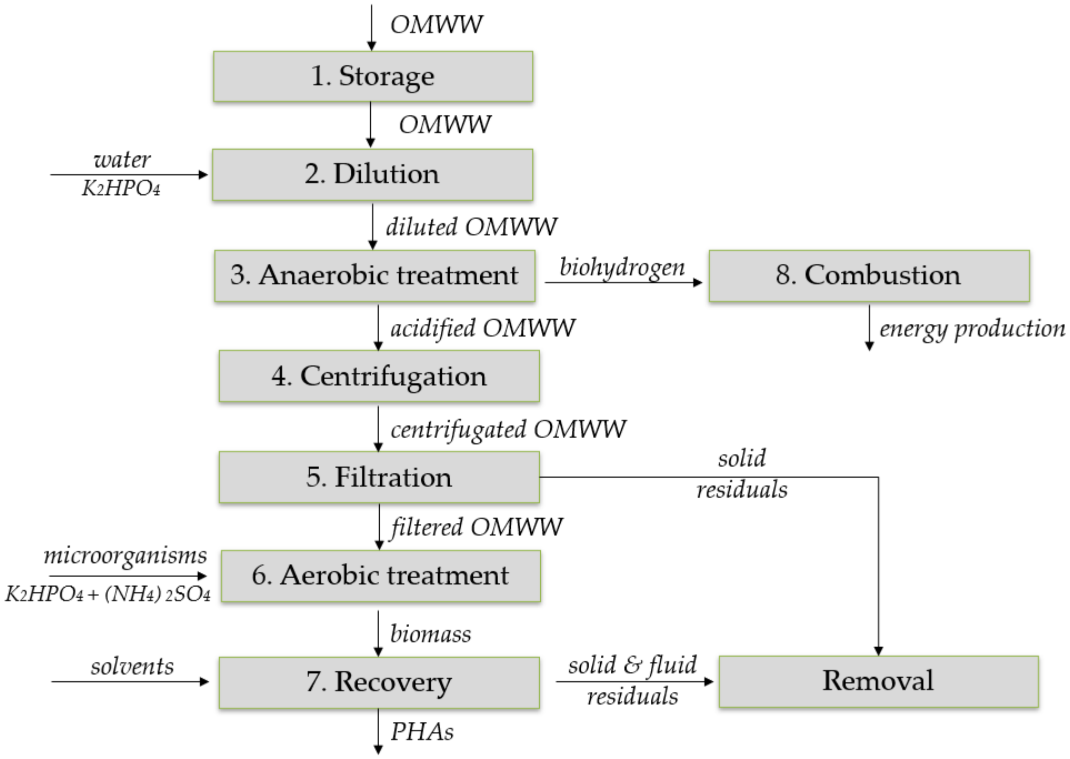


Figure 3. The 9 phases of the production process.

Overall, and according to the aforementioned literature, the ramp-up period until the process reaches a level of satisfactory operation, where the biogas and biomass production rates stabilize, is expected to be a period in the range of 150-180 days.

Table 4. The planned biorefinery: production process & technical infrastructure

Phase	Equipment (supplementary supplies)
1. reception & storage	storage tanks with cooling coats , pumps, ducts
2. dilution	dilution tank (water + K_2HPO_4)
3. anaerobic treatment	anaerobic reactor
4. centrifugation	centrifuge
5. filtration	filtration filters
6. aerobic treatment	aerobic reactor (microorganisms + K_2HPO_4 + $(NH_4)_2SO_4$
7. recovery	chemical solvents
8. combustion	storage tank, peristaltic pump
9. removal	storage tank

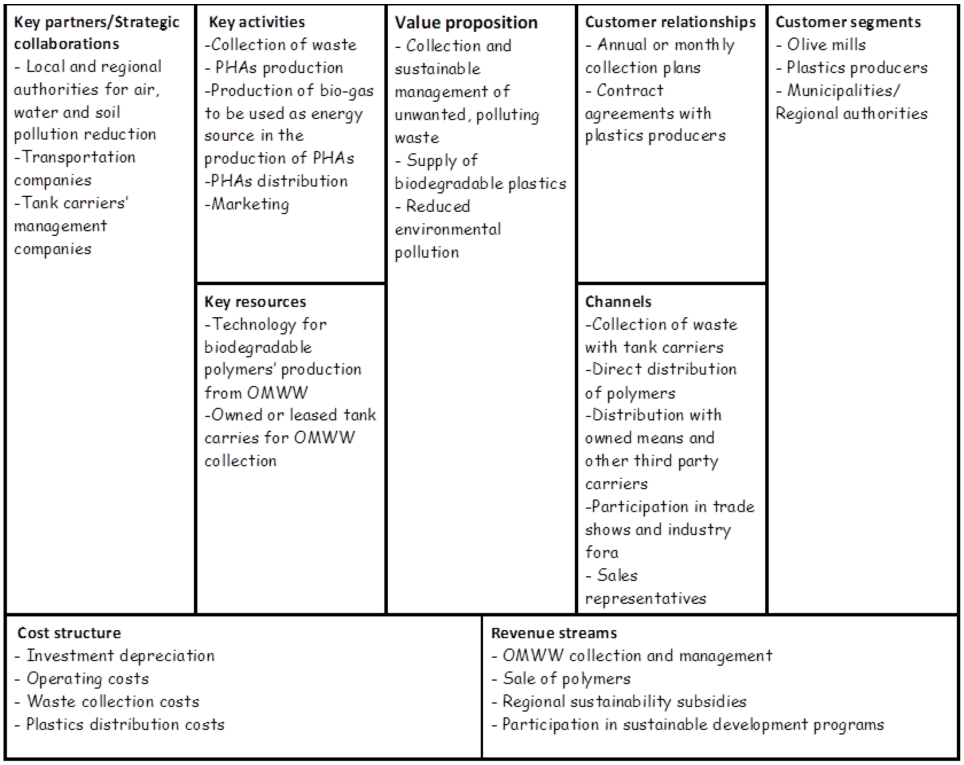
4.2. The Business Model

Clearly, the operation of the PHAs biorefinery can be considered through the lens of industrial symbiosis [Boons et al, 2011; Chertow and Ehrenfeld, 2012], which, as it was already indicated, refers to the feeding of an industrial (or service) process with the waste or byproducts of another process. Feeding may concern the raw materials or the energy requirements of the process. In most cases, industrial symbiosis requires the transformation of waste and byproducts to a form that is usable by the receiving process. In systems of industrial symbiosis (industrial ecosystems) different transformations (e.g. waste to raw material, waste to energy source, etc.) at different points in the processes network (e.g. at the end of a process or at the materials receiving point, etc.) may take place (Adamides and Mouzakitis, 2009).

No matter whether materials are waste or byproducts, on purpose materials transformation is a value-adding activity whose productivity and effectiveness can benefit from innovative technologies and/or engineering systems solutions. Hence, innovative entrepreneurial ventures are usually built around transformation technologies contributing to the wider acceptance and use of these technologies. These ventures are built on the basis of business models contingent to the national and regional economies that they are associated with. Following we present a business model suitable for a venture implementing the OMWW treatment technology in a peripheral European economy in the Mediterranean region (Greece).

As we described in Section 3, a PHAs production from OMWW venture can be described by means of the Business Model Canvas template and its related logic. A technology-based firm's business model is a description of how a venture built around a technology creates and appropriates value. More specifically a business model describes where value lies, i.e. what is the value proposition (e.g. for industrial customers, cost-saving, design, burden-taking, etc.), who is the recipient of value (customer(s)), how the value proposition is created (value chain), and why the particular business model creates profits (Gassmann et al, 2014).

Figure 4 below presents the Business Model Canvas for the aforementioned venture. The nine segments describe a venture that collects OMWW, thus shifting the burden of waste from olive mills, and produces biodegradable plastics ad biogas using the technology described in Sections XXX. The company operates as a multi-sided platform addressing the needs of olive mills by managing their waste, of plastics produces by supplying raw material with ecological properties, as well as those of local and regional authorities that are interested in providing a clean environment to their citizens. The implementation of the OMWW transformation technology and the necessary means of transportation are the venture's key resources. The collection of OMWW will take place according to a predetermined schedule, so that the collection is fast and efficient, both in economic and environmental terms (one vehicle round can serve many olive mills). The supply of PHAs will take place in accordance with signed agreements with the plastics manufacturers. The marketing of the services will be through industry trade shows as well as through service representatives. The revenue streams, in addition to the sales of plastics raw material, will include revenues from that management of the olive mills' waste, as well as government subsidies for contributing to a cleaner environment and supporting local tourism. Finally, the venture's costs structure will be constituted by the collection and distribution costs, in addition to operation and capital costs related to the development and installation of the waste transformation technology.



Key partners/Strategic collaborations
- Local and regional authorities for air, water and soil pollution reduction
-Transportation companies
-Tank carriers' management companies

Key activities
-Collection of waste
- PHAs production
-Production of bio-gas to be used as energy source in the production of PHAs
-PHAs distribution
-Marketing

Key resources
-Technology for biodegradable polymers' production from OMWW
-Owned or leased tank carries for OMWW collection

Value proposition
- Collection and sustainable management of unwanted, polluting waste
- Supply of biodegradable plastics
- Reduced environmental pollution

Customer relationships
- Annual or monthly collection plans
- Contract agreements with plastics producers

Channels
-Collection of waste with tank carriers
-Direct distribution of polymers
-Distribution with owned means and other third party carriers
-Participation in trade shows and industry fora
- Sales representatives

Customer segments
- Olive mills
- Plastics producers
- Municipalities/ Regional authorities

Cost structure
- Investment depreciation
- Operating costs
- Waste collection costs
- Plastics distribution costs

Revenue streams
- OMWW collection and management
- Sale of polymers
- Regional sustainability subsidies
- Participation in sustainable development programs

Figure 4. The Business Model Canvas of the planned biorefinery.

4.3. *Techno-economic analysis*

4.3.1. Simulation-based techno-economic analysis

For assessing the utility of the implementation of the biorefinery technology, and for ensuring the viability of the related venture for different collecting and processing capacities, a techno-economic analysis is necessary. As it was already mentioned in Section 3, the techno-economic analysis of the planned facility is based on a non-equilibrium system dynamics model calibrated using cost and price data specific to the region of the case study (Peloponnese, in Southern Greece). System dynamics models are constructed using stock (accumulation), flow (rate) and constant/auxiliary variable elements. The model used for the analysis is shown in Fig. 5. It is comprised of two main sectors: the upper part models the value chain from waste collection through PHAs and gas production to selling, whereas the lower part denotes the dynamics of cost, revenue and profit accumulation. Table 5 lists the model variables accompanied by short descriptions of their role in the model, while Table 6 presents the assumptions and default values for the corresponding simulations. The total purchasing cost of production resources was estimated in the region of 190,000 Euros (Aminalrgia-Giamini, 2016).

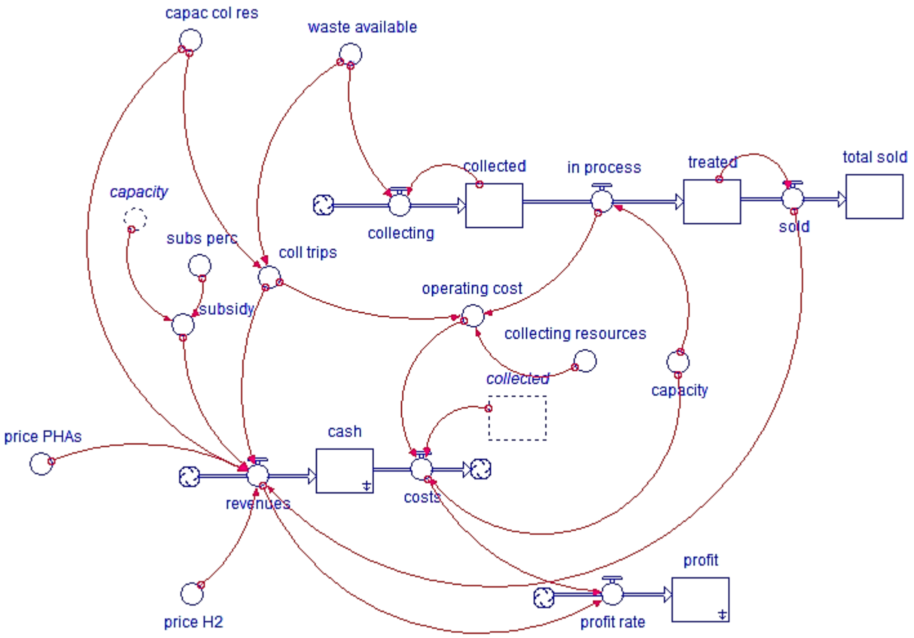


Figure 5. The system dynamics model of the techno-economic analysis.

Table 5. System dynamics model variables and their explanation

Variable	Type	Description
waste_available	Auxiliary (graphical function)	OMWW available for processing-work load/demand per month (increases from $250m^3$ to 1,250 m^3 per month in the 60 month period of the analysis)
cap_col_res	Constant	Capacity of collecting resources (default value = $20m^3$)
coll_trips	Auxiliary	Total number of trips for collecting OMWW per month [coll_trips =waste_available/cap_col_res]
collecting_ resources	Constant	Number of collecting resources

operating_cost	Auxiliary	Cost of process operation [operating_cost = in_process*3.3+(coll_trips*20)+collecting_resources*500] – cost per m^3 processed (3.3 Euros) was initially calculated in annual basis and then allocated monthly
capacity	Constant	Available process capacity (m^3/month)
collecting	Flow	OMWW collected per month (m^3)
collected	Stock	Intermediate storage of collected before being processed (incoming inventory)
in_process	Flow	Volume of OMWW processed per month (m^3)
treated	Stock	Intermediate storage of treated before being sold
sold	Flow	Volume of treated (m^3) sold per month
costs	Flow	costs = operating cost + capacity depreciation cost over a specific period (no of months)+inventory cost (collected) - calculated monthly in Euros [costs = operating_cost+(if time <=48 then capacity*4 else 0]
revenues	Flow	revenues = revenues from PHAs sold (quantity*price)+revenues from collection services (150 Euros per collection trip + revenues depending on the volume collected) + revenues from selling hydrogen produced + government subsidy depending on the operational capacity and the related operational cost (all in Euros) [revenues=sold*price_PHAs+coll_trips*(150+capac_col_res* 1.5)+ price_H2 +subsidy]
subsidy	Auxiliary	Total subsidy based on operational capacity, operational cost and subs_perc coefficient
subs perc	Constant	Percentage of operational cost subsidized
price_PHAs	Constant	Price of PHAs per m^3 (in Euros)
price_H2	Constant	Price of H_2 per m^3 (in Euros)
cash	Stock	cash=revenues – costs
profit_rate	Flow	Profit rate per month [profit_rate= revenues – costs]
profit	Stock	Total profit in 60 months ($\sum$[profit_rate])

Table 6. Assumptions and default values for model simulations

Assumptions	Default Values
Cost per trip (fuel)/month = 20 Euros	Capacity = 1,000
Cost of actual processing/m^3/month = 4 Euros	subs perc = 0.5
Cost of rent/lease of collecting resources/month = 500 Euros	collecting_ resources = 2
Inventory cost/m^3/month= 3 Euros	
Conversion coeffieint of OMWW to PHAs (volums) =0,42	

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4.3.2. Simulations and analysis

Exploratory simulations were executed with the default variable values indicated above, with the exception of those mentioned explicitly in the scenarios examined. Overall, eight scenarios were examined as depicted in table 7. Scenarios examined the effect of processing capacity, number of collecting resources and subsidy percentage on the size and timing of profitability.

Table 7. The eight (8) scenarios examined

No	Processing capacity (m^3)	No of collecting resources (#)	Percentage of subsidy (%)
1	1,000	2	0.5
2	800	2	0.5
3	600	2	0.5
4	1,250	2	0.5
5	1,250	3	0.5
6	1,000	3	0.5
7	1,000	3	0.3
8	1,000	3	ø

Figure 6a below shows the evolution of profit over the 60-month period for the eight scenarios. The most profitable scenarios are scenarios 1, 2, 3 and 4 (total profit around 350,000 Euros in 60 months). In these, lower capacities (scenarios 2 and 3) show better profitability as the operating costs, which contribute a lot to the total cost and depend on capacity size, are lower. The tradeoff in performance of increased inventories is depicted in Figure 6b. Increasing the number of collecting resources results in lower profitability (comparison of scenarios 1 and 6) as the monthly cost of collecting resources is relatively high. As it was expected, subsidies play an important role in the overall viability of the venture, and the absence of subsidies produces the worst performance, requiring the injection of additional cash for some time as Figure 6c indicates.

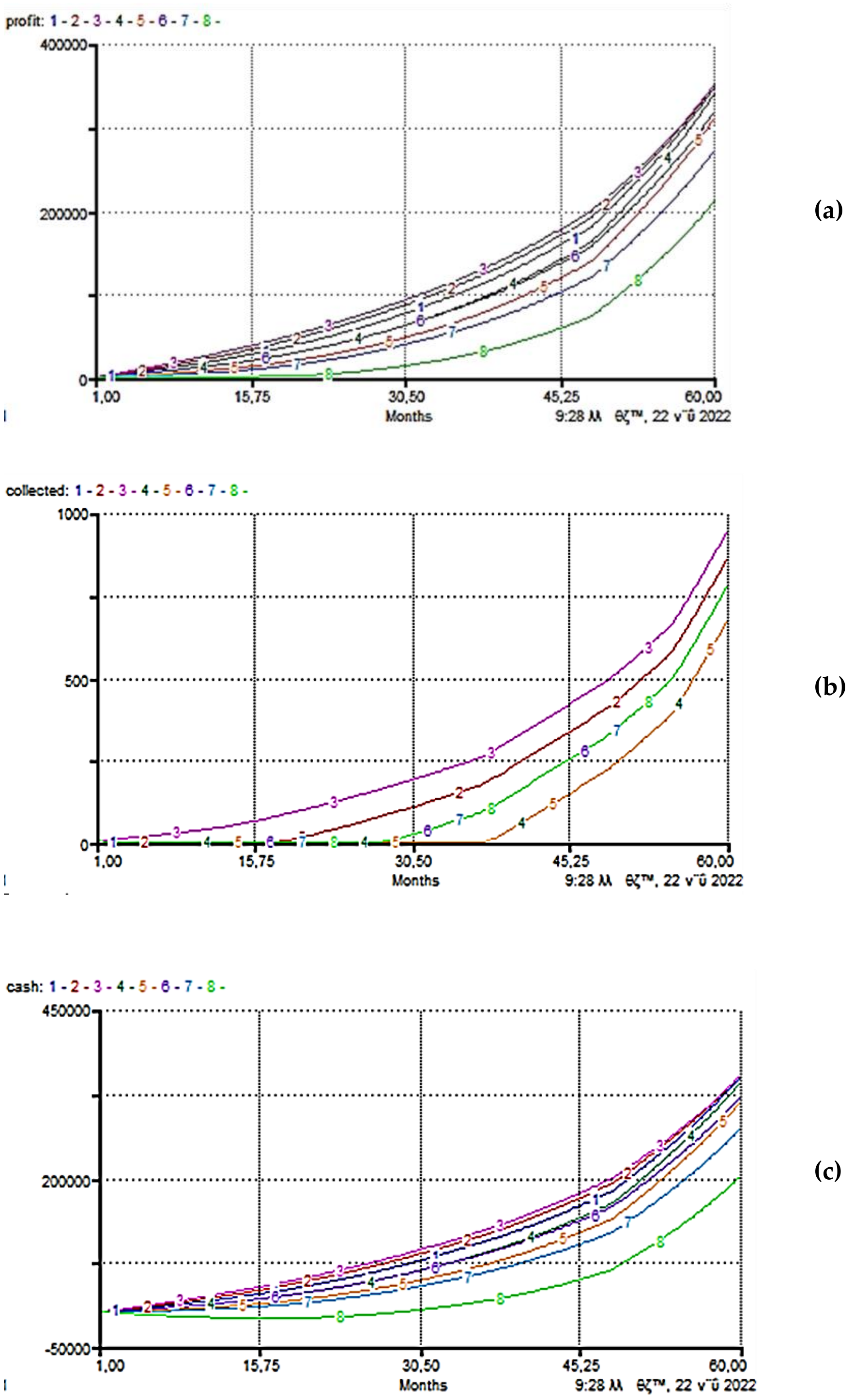

Figure 6. Simulation results of the eight examined scenarios. **(a)** Evolution of profitability; **(b)** Evolution of currying inventories (collected); **(c)** Cash flow in the eight scenarios

It should be noted that the evolution of the OMWW collected inventories is indicative of the average *real* inventory as the collection and processing of OMWW is a seasonal activity. In the model this activity was "spread" over the entire 12-month year.

In summary, the economic analysis indicated that a venture implementing the OMWW processing technology in the business model described above needs to balance the investment and operational costs of large capacity (collection and processing) with the potential of increased revenues from plastics volume sales. As the operation matures and costs and revenues increase, the differences in profitability and cash availability between scenarios become marginal. Of course, it must be noted that these observations are meaningful for the specific case and its assumptions.

4.4. The SWOT analysis

Launching and developing a new venture is a complex process, and one may find a significant number of (endogenous and exogenous) 'catalysts', which may enhance or act as a deterrents to the success and viability of the project. In this vein, the results of the SWOT analysis (Table 8) provide a structured and comprehensive mapping of both positive and negative influencing factors, originating from both the internal and the external environment of the planned biorefinery and its operational business model.

Table 8. The SWOT analysis of the planned facility

Internal Environment	External Environment
Strengths	*Opportunities*
Provision of a novel service (market creation)	Local potential customers (plastic production ventures) Strategic collaboration with local (olive-oil) cooperatives
Easy access to raw materials	Technology acquisition from local University
Environmentally sound business	Tightening up and monitoring existing regulations for OMWW Campaigns for the promotion of bioplastics through national policy, and/or business strategies Available funding schemes (EU grants & national subsidies) Consumer preference of bio-based products Geographical extension of symbiosis (olive mills, and/or other ventures from adjacent regions) Valorisation of similar (and locally-produced) wastes (e.g. dairy industry)
Weaknesses	*Threats*
Seasonality of feedstocks	Possible failure/shutdown of basic suppliers
Feedstocks of varying quality	Changes in legislation (restrictions in waste transportation/treatment)
Use of novel not sufficiently tested technology	Threat of new competitor(s) entering the market Economic instability & volatility in corresponding inputs and outputs prices
Strong dependence on local olive-mills	Impact of climate change on olive tree agriculture
Focus on a single product	Industry reservations towards bio-based products as raw materials

5. Conclusions

Circular Bioeconomy is reaching a tipping point, and biorefineries may have a significant contribution to the transition towards a sustainable and circular economy. In this paper adopting a holistic perspective of technology as configuration that work (Rip and Kemp, 1998), we presented the development of an OMWW treatment refinery in the context of industrial ecology. The disposal of OMWW is a significant environmental challenge because of the quantity and unique chemical properties of the produced wastewater. Therefore, its treatment is extremely valuable, especially when it additionally results in tangible economic benefits, as in the case of the production of PHAs and biogas described in this paper.

Towards this objective, applying a holistic bottom-up approach to manage the complexity of the implementaion of the associated biorefinery process as a venture in an industrial symbiosis setting, we first described the engineering of the process, then the development of a business model for a venture to capitalize on the process, followed by a techno-economic assessment of the venture's business model, and an assessment of the competitive posistiion of the venture in the specific implementation context in Southern Greece, through SWOT analysis. Clearly, the framework presented can be applied to diffent process technologies and diverse industries, supplemented by LCA analysis to explore the environmental impact of the entire production-consumption system.

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