*eng*

Article

# Techno-Economic Assessment of an Olive Mill Wastewater (OMWW) Biorefinery in the Context of Circular Bioeconomy

**Yannis Mouzakitis *** and **Emmanuel D. Adamides**

Department of Mechanical Engineering & Aeronautics, University of Patras, GR26504 Rio, Greece
* Correspondence: ymouzakitis@upatras.gr

**Abstract:** The concept of biorefinery constitutes a significant contributing factor to the emerging transition toward 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 on 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. Toward this end, adopting a systems perspective, the paper presents a structured and comprehensive framework, comprising the definition of the transformation process, business model development, techno-economic assessment, as well as strategic positioning and viability assessment, which may be employed to facilitate the engineering at large and launch 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 valorization of olive mill wastewater (a 'strong' and quite common industrial waste in the Mediterranean basin), and produces biopolymers (PHAs) and bioenergy ($H_2$).

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

check for updates

**Citation:** Mouzakitis, Y.; Adamides, E.D. Techno-Economic Assessment of an Olive Mill Wastewater (OMWW) Biorefinery in the Context of Circular Bioeconomy. *Eng* **2022**, *3*, 488–503. https://doi.org/10.3390/eng3040035

Academic Editors: Xuan Mu, Morgan Hawker and Feng Wang

Received: 19 October 2022
Accepted: 14 November 2022
Published: 18 November 2022



## 1. Introduction

Circular bioeconomy (CBE) is emerging in academia, industry, and policy-making as an important concept toward 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 [1–3]. In this direction, the 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) [4–6]. The concept of biorefinery [7,8], where biofuels, chemicals, and a wide spectrum of high value bioproducts are produced from biomass using several conversion technologies [9,10], constitutes a major step toward a CBE. Not surprisingly, in both CBE and biorefineries, which are associated with a wide range of agricultural products, the strategy of waste valorization, namely the biotechnological conversion of by-products and residues into valuable products, is highly valued [11–13].

So far, the literature on the 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 aforementioned 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 can be used in a variety of industrial symbiosis cases, wherein the wastes of processes can create value as raw materials or energy sources of different processes. It extends in four dimensions: process engineering, development of a 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 considered venture would process olive mill wastewater (OMWW), a quite typical agricultural waste and significant environmental burden in the Mediterranean region [14], and through a combination of bio-chemical and mechanical processes, would produce bioplastics (Polyhydroxyalkanoates or PHAs) and biogas, i.e., add value in the context of the circular economy [15]. The novelty of this paper lies in the integration of the four dimensions/tools of the framework, as well on the use of non-equilibrium economic modeling for the techno-economic assessment.

The remaining of this 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 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 [9].

Biorefineries appear in various forms, and Cherubin et al. [16] 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 [8,10]. 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 [17]. The afore-mentioned impacts largely depend 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 Wastewater (OMWW)

Olive oil is a liquid fat which is produced by pressing olives, a typical fruit of the Mediterranean basin. In the last 60 years, the production of olive oil has increased thrice, reaching 3.3 million tons in the 2019–2020 crop year [18]. The EU accounts for over 2 million tons of this output, with Spain (66%), Italy (15%), Greece (13%), and Portugal (5%) being the major producers [19].

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 to severe environmental issues [20,21], such as:

- Impacts on water bodies: intoxication, discoloration, eutrophication;
- Impacts on soil: changes in fertility, decrease in magnesium, soil porosity;
- Impacts on plants: fruit and leaf abscission, seeds germination, early growing stage.

**Table 1.** Quantity and properties of OMWW (based on [18,20,22].

| Quantity | Properties |
|---|---|
| – Olive growing area: 10.8 he (worldwide)<br>– Olive trees: 750 million (worldwide)<br>– Olive oil: 3 million tons (annual world production)<br>– OMWW: 6–30 million $m^3$ (annual world production)<br>– OMWW per 1 ton of processed olives: 1–1.6 $m^3$<br>– OMWW per 1 ton of olive oil: 4.7–7.6 $m^3$ | – Color: dark brown to black<br>– Smell: strong and offensive<br>– pH: acid (between 2 and 6)<br>– Solid matter and organic load: high<br>– Pollutants: polyphenols, flavonoids, phosphorus, potassium, tannins, reduced sugars, (acetic, formic and oleanolic) acids |

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.

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 valorization of OMWW [23–25] (. 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 this 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 [26]. 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 [27]. Bioplastics are gaining market share; in the last five years, they participated by around 2% in the world's total plastics production [28]. In a classification scheme presented by Gurunathan et al. [29], biopolymers can be distinguished into three groups:

1. Biomass products (polysaccharides and proteins), which are biopolymers derived from agro-resources;

2. Biotechnology products (polylactides and polyglycolides), which are synthesized from bio-derived polymers;
3. Micro-organism 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 [30]. They are biodegradable and highly deformable, presenting high heat resistance and achieving a sufficient balance between toughness and stiffness [31]. Not surprisingly, they have a growing number of applications in coating, packaging, prosthetics, etc. [31,32]. 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 [33].

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 [34], and PHAs [35]. Biohydrogen can be produced by several processes (biophotolysis, fermentation, hybrid bio-electrochemicals), each one having benefits and disadvantages [36,37]. Kotay and Das [38] 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 may be increased by tweaking the 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 [39].

## 3. Methodology

A biorefinery can be conceptualized as an anchor tenant [40,41] of an industrial symbiosis system [42]( 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 input OMWW from a number of olive mills (mainly local ones) and provides its outputs (the PHAs) to a number of plastic manufacturing facilities (not necessarily nearby ones).

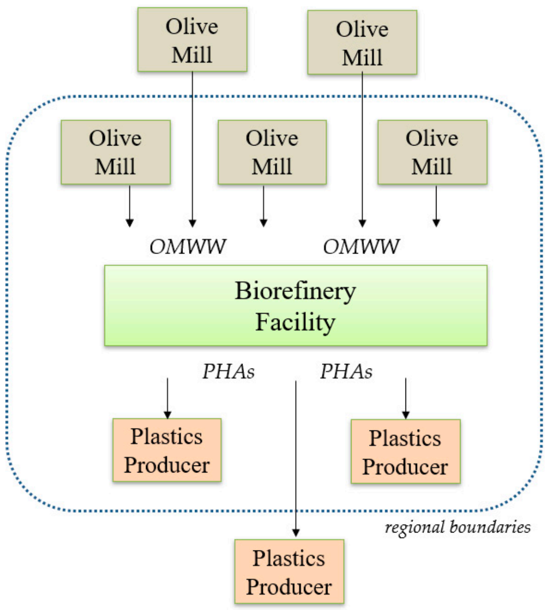



**Figure 1.** The biorefinery as an anchor tenant of an industrial symbiosis.

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

RQ1: How can 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, be assessed in a systematic and comprehensive way?

RQ2: How can the derived assessment framework (the answer of RQ1) 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 address 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 valorization of OMWW in the direction of PHAs and biogas [43–45], 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 [46] 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 on circular bioeconomy [6,47], while Business Model Canvas has been applied in similar cases of waste valorization in the olive oil sector [48,49].
3. In the following step, the economic viability of the planned venture is assessed by examining scenarios of different organizational configurations. In this direction, a techno-economic assessment can provide guidance for valuing the application of a specific technology, OMWW processing in our case. Various approaches to the techno-economic assessment of circular bioeconomic endeavors can be found in the literature [50–52]. 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 [53].
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 [54], which is a methodological tool that has already been applied in the context of circular bioeconomy [55,56]. A 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.

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 3271 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).

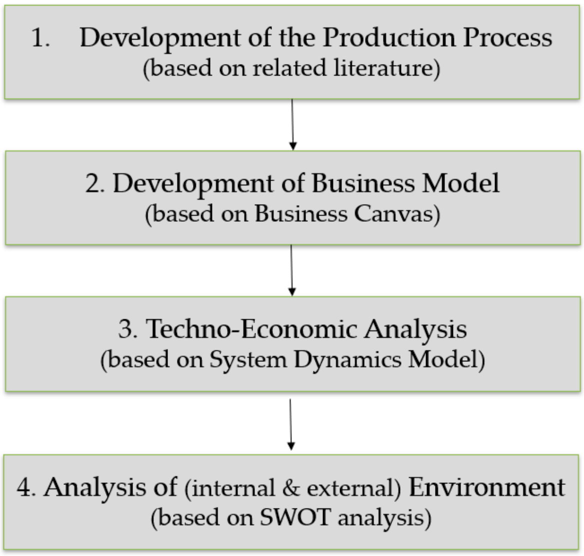



**Figure 2.** The 4-step framework of analysis.

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

| OMWW | PHAs |
| --- | --- |
| – Olive trees: 3.5 million<br>– Olive pressing facilities: 59 (mainly SMEs)<br>– Production of olive oil: 21,000 t/year<br>– Production of olive oil: 130,000 t/year | – Major plastic producers: 3 facilities<br>– The largest venture requires an input of plastic of 4.4 t/year |

## 4. Results and Discussion

Table 3 depicts the basic features of the planned biorefinery (platforms, products, feedstocks, processes) with respect to the classification scheme presented by Cherubini et al. [16]. In the following, in accordance with the afore-mentioned framework, we discuss the results of its application, concerning the production process (Section 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 [16]).

| Feature | Classification |
| --- | --- |
| Platforms | Oil and biogas |
| Products | Material products: biopolymers (PHAs)<br>Energy products: biogas |
| Feedstocks | Oil-based residues: OMWW (tertiary biomass) |
| Processes | Thermochemical: combustion<br>Biochemical: anaerobic digestion, aerobic conversion, enzymatic<br>Mechanical/physical: extraction, separation (filtering) |

### *4.1. The Production Process*

Drawing on Beccari et al., 2009; Ntaikou et al., 2009; and 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 and Storage of OMWW

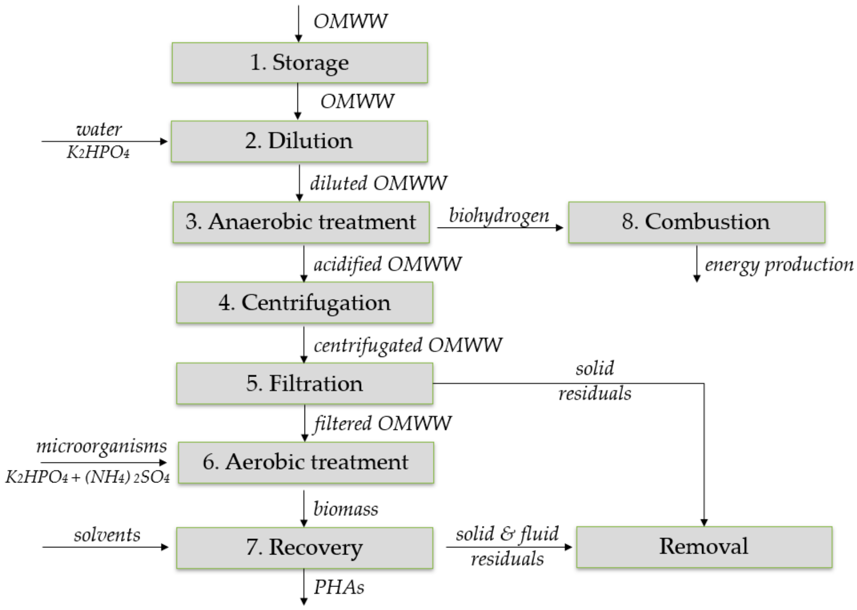



**Figure 3.** The 9 phases of the production process.

**Table 4.** The planned biorefinery: production process and technical infrastructure (equipment & supplementary materials).

| Phase | Equipment and Supplementary Materials |
|---|---|
| 1. Reception and 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 |

After its collection and reception, OMWW is stored in stainless steel tanks, bearing an external cooling cloak, with the aim of keeping their storage temperature at a level below 4 °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 [57].

Phase 2: Dilution of OMWW

Using a pump and stainless-steel ducts, the OMWW is driven into a tank, where dilution with tap water takes place. This is 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 is 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 °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 h.

Phases 4 and 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 the 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 being removed by a certified waste management organization.

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

### *4.2. The Business Model*

Clearly, the operation of the PHAs biorefinery can be considered through the lens of industrial symbiosis [42,58], 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 [59].

No matter whether materials are waste or byproducts, the purposeful transformation of materials 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. In the 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 the 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 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 [60].

Figure 4 below presents the Business Model Canvas for the afore-mentioned venture. The nine segments describe a venture that collects OMWW, thus shifting the burden of waste from olive mills, and produces biodegradable plastics and biogas using the technology described in Section 4.1. 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 the management of the olive mill's waste, as well as government subsidies for contributing to a cleaner environment and supporting local tourism. Finally, the venture's structure costs 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.

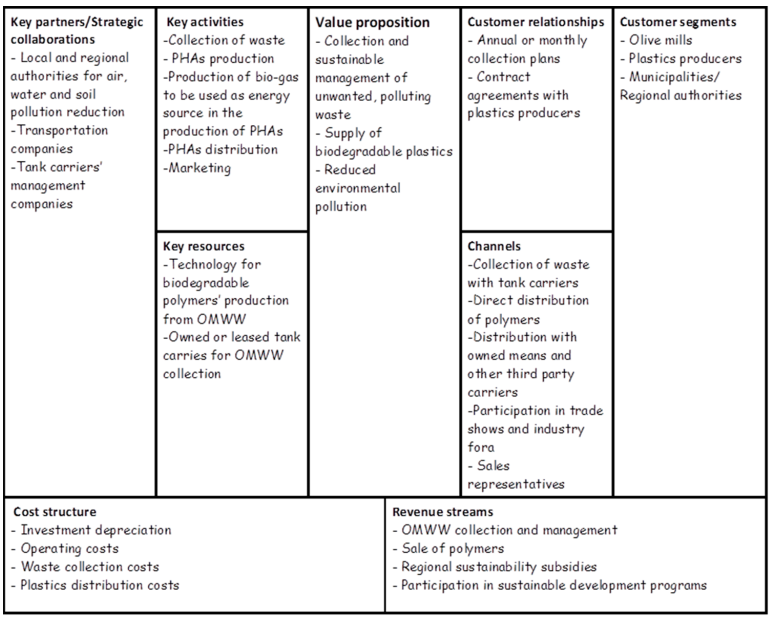



**Figure 4.** The Business Model Canvas of the planned biorefinery.

### *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 Figure 5. It is composed 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 [61,62].

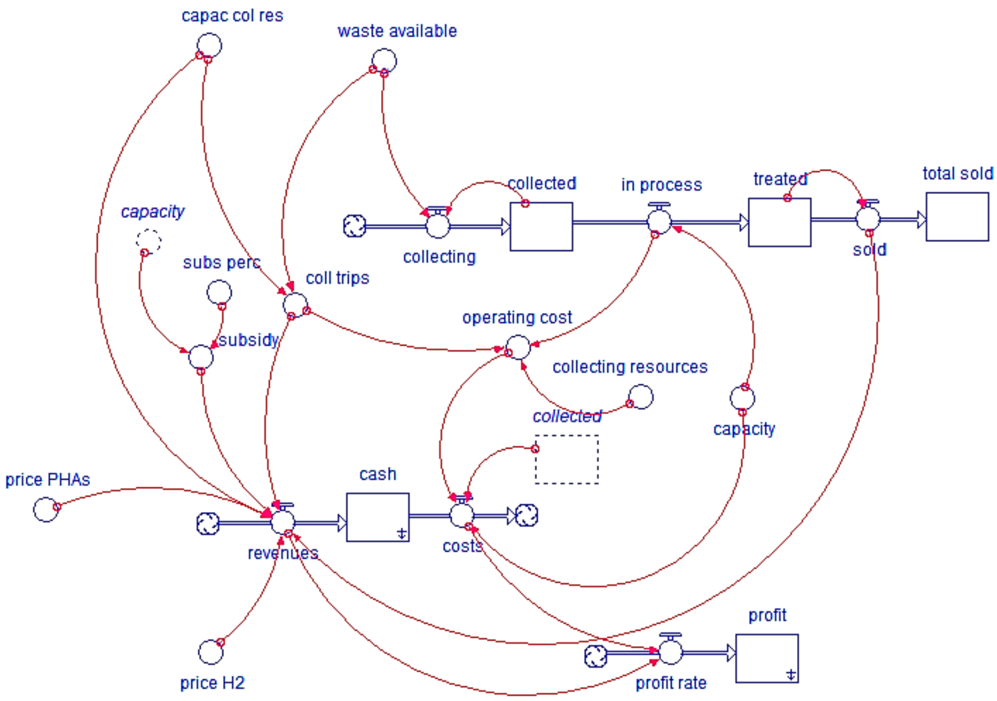



**Figure 5.** The system dynamics model of the techno-economic analysis.

**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 250 $m^3$ to 1250 $m^3$ per month in the 60-month period of the analysis) |
| cap_col_res | Constant | Capacity of collecting resources (default value = 20 $m^3$) |
| 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) |

**Table 5.** *Cont.*

| Variable | Type | Description |
|---|---|---|
| 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 $\leq$ 48 then capacity $\times$ 4 else 0) |
| revenues | Flow | Revenues = revenues from PHAs sold (quantity $\times$ 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 $\times$ price_PHAs + coll_trips $\times$ (150 + capac_col_res $\times$ 1.5) + price_H2 + subsidy) |
| subsidy | Auxiliary | Total subsidy based on operational capacity, operational costs, 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 (Σ[profit_rate]) |

**Table 6.** Assumptions and default values for model simulations.

| Assumptions | Default Values |
|---|---|
| Cost per trip (fuel)/month = 20 Euros<br>Cost of actual processing/$m^3$/month = 4 Euros<br>Cost of rent/lease of collecting resources/month = 500 Euros<br>Inventory cost/$m^3$/month = 3 Euros<br>Conversion coefficient of OMWW to PHAs (volume) = 0.42 | Capacity = 1000<br>subs perc = 0.5<br>collecting_ resources = 2 |

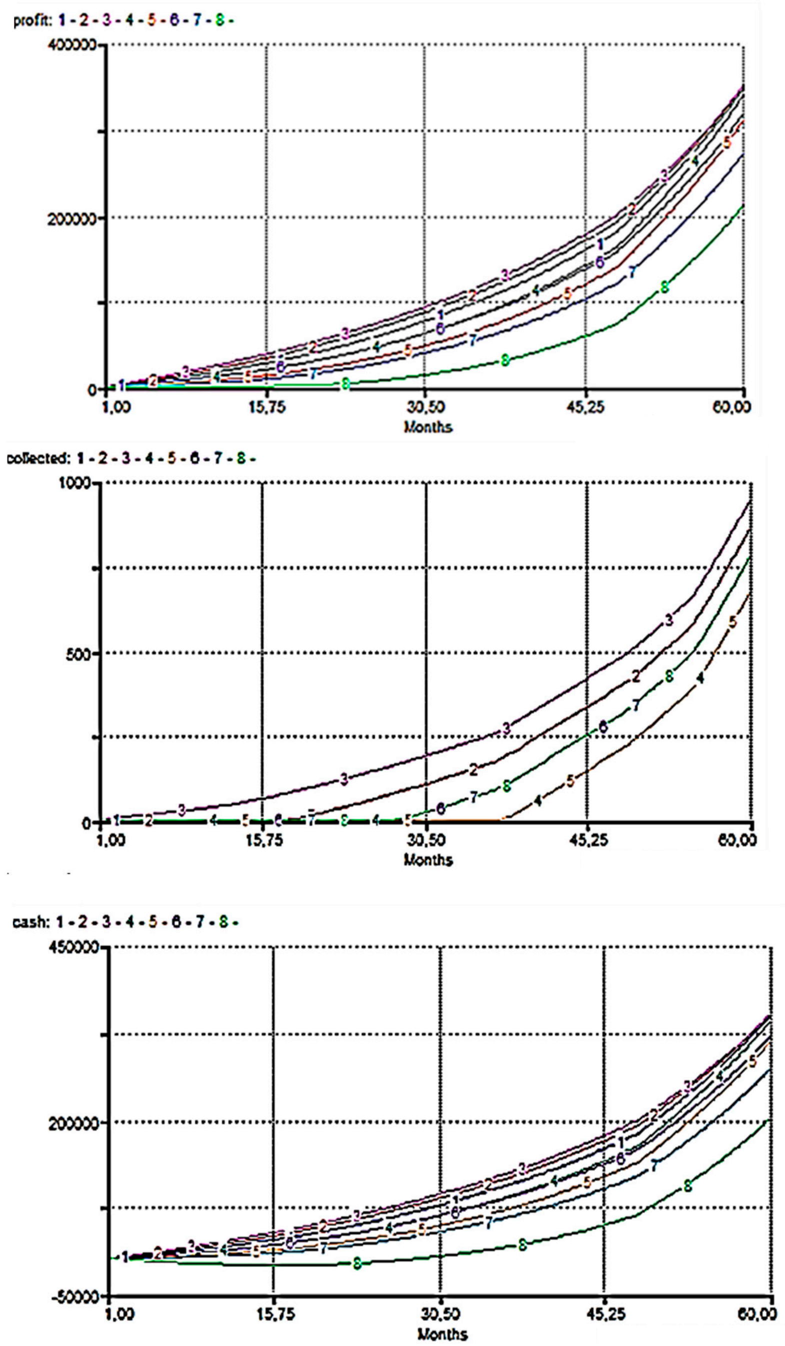
### 4.3.2. Simulations and Analysis

Using the *ithink* simulation environment, 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. The 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 | 1000 | 2 | 0.5 |
| 2 | 800 | 2 | 0.5 |
| 3 | 600 | 2 | 0.5 |
| 4 | 1250 | 2 | 0.5 |
| 5 | 1250 | 3 | 0.5 |
| 6 | 1000 | 3 | 0.5 |
| 7 | 1000 | 3 | 0.3 |
| 8 | 1000 | 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 significantly 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 collected 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.




(**a**)

(**b**)

(**c**)

**Figure 6.** Simulation results of the eight examined scenarios as produced by ithink. (**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 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) |
| Easy access to raw materials | Strategic collaboration with local (olive oil) cooperatives |
| Environmentally sound business | Technology acquisition from local University |
| | 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 and national subsidies) |
| | Consumer preference for bio-based products |
| | Geographical extension of symbiosis (olive mills, and/or other ventures from adjacent regions) |
| | Valorization 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 |
| Strong dependence on local olive mills | Economic instability and volatility in corresponding inputs and outputs prices |
| Focus on a single product | Impact of climate change on olive tree agriculture |
| | Industry reservations towards bio-based products as raw materials |

## 5. Conclusions

The concept of circular bioeconomy is reaching a tipping point, and biorefineries may have a significant contribution to the transition toward a sustainable and circular economy. In this paper, adopting a holistic perspective of technology as "configurations that work" [63], we presented the development of an OMWW treatment refinery in the context of industrial ecology. The disposal of OMWW is a significant environmental challenge due to 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.

Toward this objective, applying a holistic bottom-up approach to manage the complexity of the implementation 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 position of the venture in the specific implementation context in southern Greece, through an SWOT analysis. Overall, this holistic approach provides guidance for the implementation, or not, of the particular technology and the related business model in a particular socio-economic setting. Clearly, the framework presented here can be applied to different process technologies and diverse industries, supplemented by the Life Cycle Assessment (LCA) to explore the environmental impact of the entire production–consumption system.

**Author Contributions:** Conceptualization, Y.M. and E.D.A.; methodology, Y.M.; investigation, Y.M. and E.D.A.; visualization, Y.M.; writing—original draft preparation, Y.M. and E.D.A.; writing—review and editing, E.D.A. All authors have read and agreed to the published version of the manuscript.

**Funding:** This research received no external funding.

**Data Availability Statement:** Simulation output data are available from the authors.

**Conflicts of Interest:** The authors declare no conflict of interest.

## References


1. Carus, M.; Dammer, L. The circular bioeconomy—concepts, opportunities, and limitations. *Ind. Biotechnol.* **2018**, *14*, 83–91. [CrossRef]
2. Giampietro, M. On the circular bioeconomy and decoupling: Implications for sustainable growth. *Ecol. Econ.* **2019**, *162*, 143–156. [CrossRef]
3. Stegmann, P.; Londo, M.; Junginger, M. The circular bioeconomy: Its elements and role in European bioeconomy clusters. *Resour. Conserv. Recycl. X* **2020**, *6*, 100029. [CrossRef]
4. Mouzakitis, Y.; Tsoulfas, G.T. Fostering 'Bioeconomy Strategy' through synergies: Managerial implications from Interreg Europe. In the Proceedings of the 2nd International Conference on Management, Economics and Finance (ICMEF), Rotterda, The Netherlands, 15–17 November 2019.
5. Nizami, A.S.; Rehan, M.; Waqas, M.; Naqvi, M.; Ouda, O.K.; Shahzad, K.; Miandad, R.; Khan, M.Z.; Syamsiro, M.; Ismail, I.M.I.; et al. Waste biorefineries: Enabling circular economies in developing countries. *Bioresour. Technol.* **2017**, *241*, 1101–1117. [CrossRef]
6. Salvador, R.; Puglieri, F.N.; Halog, A.; de Andrade, F.G.; Piekarski, C.M.; Antonio, C. Key aspects for designing business models for a circular bioeconomy. *J. Clean. Prod.* **2021**, *278*, 124341. [CrossRef]
7. de Jong, E.; Higson, A.; Walsh, P.; Wellisch, M. *Bio-Based Chemicals: Value Added Products from Biorefineries*; Task42 Biorefinery; IEA Bioenergy: Rotorua, New Zealand, 2012.
8. Mohan, S.V.; Dahiya, S.; Amulya, K.; Katakojwala, R.; Vanitha, T.K. Can circular bioeconomy be fueled by waste biorefineries—A closer look. *Bioresour. Technol. Rep.* **2019**, *7*, 100277. [CrossRef]
9. Cherubini, F. The biorefinery concept: Using biomass instead of oil for producing energy and chemicals. *Energy Convers. Manag.* **2010**, *51*, 1412–1421. [CrossRef]
10. Mohan, S.V.; Nikhil, G.N.; Chiranjeevi, P.; Reddy, C.N.; Rohit, M.V.; Kumar, A.N.; Sarkar, O. Waste biorefinery models towards sustainable circular bioeconomy: Critical review and future perspectives. *Bioresour. Technol.* **2016**, *215*, 2–12. [CrossRef]
11. Liguori, R.; Amore, A.; Faraco, V. Waste valorization by biotechnological conversion into added value products. *Appl. Microbiol. Biotechnol.* **2013**, *97*, 6129–6147. [CrossRef]
12. Maina, S.; Kachrimanidou, V.; Koutinas, A. A roadmap towards a circular and sustainable bioeconomy through waste valorization. *Curr. Opin. Green Sustain. Chem.* **2017**, *8*, 18–23. [CrossRef]
13. Sun, Y.; Wang, T.; Sun, X.; Bai, L.; Han, C.; Zhang, P. The potential of biochar and lignin-based adsorbents for wastewater treatment: Comparison, mechanism, and application—A review. *Ind. Crops Prod.* **2021**, *166*, 113473. [CrossRef]
14. Delisi, R.; Saiano, F.; Pagliaro, M.; Ciriminna, R. Quick assessment of the economic value of olive mill waste water. *Chem. Cent. J.* **2016**, *10*, 1–5. [CrossRef] [PubMed]
15. Foti, P.; Romeo, F.V.; Russo, N.; Pino, A.; Vaccalluzzo, A.; Caggia, C.; Randazzo, C.L. Olive mill wastewater as renewable raw materials to generate high added-value ingredients for agro-food industries. *Appl. Sci.* **2021**, *11*, 7511. [CrossRef]
16. Cherubini, F.; Jungmeier, G.; Wellisch, M.; Willke, T.; Skiadas, I.; Van Ree, R.; de Jong, E. Toward a common classification approach for biorefinery systems. *Biofuels Bioprod. Biorefining* **2009**, *3*, 534–546. [CrossRef]
17. Uihlein, A.; Schebek, L. Environmental impacts of a lignocellulose feedstock biorefinery system: An assessment. *Biomass Bioenergy* **2009**, *33*, 793–802. [CrossRef]
18. International Olive Council. The World of Olive Oil. Available online: https://www.internationaloliveoil.org/the-world-of-olive-oil/ (accessed on 6 October 2022).
19. European Commission. Olive Oil. Available online: https://agriculture.ec.europa.eu/system/files/2020-03/factsheet-olive-oil_en_0.pdf (accessed on 6 October 2022).
20. Tsagaraki, E.; Lazarides, H.N.; Petrotos, K.B. Olive mill wastewater treatment. In *Utilization of By-products and Treatment of Waste in the Food Industry*; Springer: Boston, MA, USA, 2007; pp. 133–157.
21. Justino, C.I.; Pereira, R.; Freitas, A.C.; Rocha-Santos, T.A.; Panteleitchouk, T.S.; Duarte, A.C. Olive oil mill wastewaters before and after treatment: A critical review from the ecotoxicological point of view. *Ecotoxicology* **2012**, *21*, 615–629. [CrossRef] [PubMed]
22. Azbar, N.; Bayram, A.; Filibeli, A.; Muezzinoglu, A.; Sengul, F.; Ozer, A. A review of waste management options in olive oil production. *Crit. Rev. Environ. Sci. Technol.* **2004**, *34*, 209–247. [CrossRef]

23. Niaounakis, M.; Halvadakis, C.P. *Olive Processing Waste Management: Literature Review and Patent Survey*; Elsevier: Amsterdam, The Netherlands, 2006.
24. Jeguirim, M.; Chouchène, A.; Réguillon, A.F.; Trouvé, G.; Le Buzit, G. A new valorisation strategy of olive mill wastewater: Impregnation on sawdust and combustion. *Resour. Conserv. Recycl.* **2012**, *59*, 4–8. [CrossRef]
25. Ahmed, P.M.; Fernández, P.M.; Castellanos, L.I.; Pajot, H.F. Exploitation alternatives of olive mill wastewater: Production of value-added compounds useful for industry and agriculture. *Biofuel Res. J.* **2019**, *22*, 980–994. [CrossRef]
26. Vinod, A.; Sanjay, M.R.; Suchart, S.; Jyotishkumar, P. Renewable and sustainable biobased materials: An assessment on biofibers, biofilms, biopolymers and biocomposites. *J. Clean. Prod.* **2020**, *258*, 120978. [CrossRef]
27. Vert, M.; Doi, Y.; Hellwich, K.-H.; Hess, M.; Hodge, P.; Kubisa, P.; Rinaudo, M.; Schué, F. Terminology for biorelated polymers and applications (IUPAC Recommendations 2012). *Pure Appl. Chem.* **2012**, *84*, 377–410. [CrossRef]
28. Chinthapalli, R.; Skoczinski, P.; Carus, M.; Baltus, W.; de Guzman, D.; Käb, H.; Raschka, A.; Ravenstijn, J. Biobased building blocks and polymers—global capacities, production and trends, 2018–2023. *Ind. Biotechnol.* **2019**, *15*, 237–241. [CrossRef]
29. Gurunathan, T.; Mohanty, S.; Nayak, S.K. A review of the recent developments in biocomposites based on natural fibres and their application perspectives. *Compos. Part A Appl. Sci. Manuf.* **2015**, *77*, 1–25. [CrossRef]
30. Cataldi, P.; Steiner, P.; Raine, T.; Lin, K.; Kocabas, C.; Young, R.J.; Bissett, M.; Kinloch, I.A.; Papageorgiou, D.G. Multifunctional biocomposites based on polyhydroxyalkanoate and graphene/carbon nanofiber hybrids for electrical and thermal applications. *ACS Appl. Polym. Mater.* **2020**, *2*, 3525–3534. [CrossRef]
31. Poltronieri, P.; Kumar, P. Polyhydroxyalkanoates (PHAs) in industrial applications. In *Handbook of Ecomaterials*; Springer: Berlin/Heidelberg, Germany, 2017; Volume 4, pp. 2843–2872.
32. Adeleye, A.T.; Odoh, C.K.; Enudi, O.C.; Banjoko, O.O.; Osiboye, O.O.; Odediran, E.T.; Louis, H. Sustainable synthesis and applications of polyhydroxyalkanoates (PHAs) from biomass. *Process Biochem.* **2020**, *96*, 174–193. [CrossRef]
33. Anjum, A.; Zuber, M.; Zia, K.M.; Noreen, A.; Anjum, M.N.; Tabasum, S. Microbial production of polyhydroxyalkanoates (PHAs) and its copolymers: A review of recent advancements. *Int. J. Biol. Macromol.* **2016**, *89*, 161–174. [CrossRef] [PubMed]
34. Kaparaju, P.; Serrano, M.; Thomsen, A.B.; Kongjan, P.; Angelidaki, I. Bioethanol, biohydrogen and biogas production from wheat straw in a biorefinery concept. *Bioresour. Technol.* **2009**, *100*, 2562–2568. [CrossRef]
35. Sekoai, P.; Ezeokoli, O.; Yoro, K.; Eterigho-Ikelegbe, O.; Habimana, O.; Iwarere, S.; Daramola, M.; Ojumu, T. The production of polyhydroxyalkanoates using volatile fatty acids derived from the acidogenic biohydrogen effluents: An overview. *Bioresour. Technol. Rep.* **2022**, *18*, 101111. [CrossRef]
36. Azwar, M.Y.; Hussain, M.A.; Abdul-Wahab, A.K. Development of biohydrogen production by photobiological, fermentation and electrochemical processes: A review. *Renew. Sustain. Energy Rev.* **2014**, *31*, 158–173. [CrossRef]
37. Khan, I.U.; Othman, M.H.D.; Hashim, H.; Matsuura, T.; Ismail, A.F.; Rezaei-DashtArzhandi, M.; Azelee, I.W. Biogas as a renewable energy fuel–A review of biogas upgrading, utilisation and storage. *Energy Convers. Manag.* **2017**, *150*, 277–294. [CrossRef]
38. Kotay, S.M.; Das, D. Biohydrogen as a renewable energy resource—Prospects and potentials. *Int. J. Hydrogen Energy* **2008**, *33*, 258–263.
39. Asrul, M.A.M.; Atan, M.F.; Yun, H.A.H.; Lai, J.C.H. A review of advanced optimization strategies for fermentative biohydrogen production processes. *Int. J. Hydrogen Energy* **2022**, *47*, 16785–16804.
40. Korhonen, J.; Snakin, J.P. An anchor tenant approach to network management: Considering regional material and energy flow networks. *Int. J. Environ. Technol. Manag.* **2001**, *1*, 444–463. [CrossRef]
41. Topolski, K.; Lira-Barragán, L.F.; Panu, M.; Ponce-Ortega, J.M.; El-Halwagi, M.M. Integrating mass and energy through the anchor-tenant approach for the synthesis of carbon-hydrogen-oxygen symbiosis networks. *Ind. Eng. Chem. Res.* **2019**, *58*, 16761–16776. [CrossRef]
42. Boons, F.; Spekkink, W.; Mouzakitis, Y. The dynamics of industrial symbiosis: A proposal for a conceptual framework based upon a comprehensive literature review. *J. Clean. Prod.* **2011**, *19*, 905–911. [CrossRef]
43. Beccari, M.; Bertin, L.; Dionisi, D.; Fava, F.; Lampis, S.; Majone, M.; Valentino, F.; Vallini, G.; Villano, M. Exploiting olive oil mill effluents a renewable resource for production of biodegradable polymers through a combined anaerobic-aerobic process. *J. Chem. Technol. Biotechnol.* **2009**, *84*, 901–908. [CrossRef]
44. Ntaikou, I.; Kourmentza, C.; Koutrouli, E.; Stamatelatou, K.; Zampraka, A.; Kornaros, M.; Lyberatos, G. Exploitation of olive oil mill wastewater for combined biohydrogen and biopolymers production. *Biores. Technol.* **2009**, *100*, 3724–3737. [CrossRef]
45. Ntaikou, I.; Peroni, C.V.; Kourmentza, C.; Ilieva, V.; Morelli, A.; Chiellini, E.; Lyberatos, G. Microbial bio-based plastics from olive-mill wastewater: Generation and properties of polyhydroxyalkanoates from mixed cultures in a two-stages pilot scale system. *J. Biotech.* **2014**, *188*, 138–143. [CrossRef]
46. Osterwalder, A.; Pigneur, Y. *Business Model Generation: A Handbook for Visionaries, Game Changers, and Challengers*; John Wiley & Sons: Hoboken, NJ, USA, 2010.
47. Gatto, F.; Re, I. Circular bioeconomy business models to overcome the valley of death. A systematic statistical analysis of studies and projects in emerging bio-based technologies and trends linked to the SME instrument support. *Sustainability* **2021**, *13*, 1899. [CrossRef]
48. Donner, M.; Radić, I. Innovative circular business models in the olive oil sector for sustainable mediterranean agrifood systems. *Sustainability* **2021**, *13*, 2588. [CrossRef]

49. Donner, M.; Radić, I.; Erraach, Y.; El Hadad-Gauthier, F. Implementation of Circular Business Models for Olive Oil Waste and By-Product Valorization. *Resources* **2022**, *11*, 68. [CrossRef]
50. Anyaoha, K.E.; Zhang, L. Transition from fossil-fuel to renewable-energy-based smallholder bioeconomy: Techno-economic analyses of two oil palm production systems. *Chem. Eng. J. Adv.* **2022**, *10*, 100270. [CrossRef]
51. Gutiérrez, R.E.; Guerra, K.; Haro, P. Exploring the techno-economic feasibility of new bioeconomy concepts: Solar-assisted thermochemical biorefineries. *Appl. Energy* **2022**, *322*, 119535. [CrossRef]
52. Nematian, M.; Keske, C.; Ng'ombe, J.N. A techno-economic analysis of biochar production and the bioeconomy for orchard biomass. *Waste Manag.* **2021**, *135*, 467–477. [CrossRef]
53. Keen, S. *The New Economics: A Manifesto*; Polity: Cambridge, UK, 2022.
54. Helms, M.M.; Nixon, J. Exploring SWOT analysis–where are we now? A review of academic research from the last decade. *J. Strategy Manag.* **2010**, *3*, 215–251. [CrossRef]
55. Gomes, H.I.; Funari, V.; Ferrari, R. Bioleaching for resource recovery from low-grade wastes like fly and bottom ashes from municipal incinerators: A SWOT analysis. *Sci. Total Environ.* **2020**, *715*, 136945. [CrossRef] [PubMed]
56. Paes, L.A.B.; Bezerra, B.S.; Deus, R.M.; Jugend, D.; Battistelle, R.A.G. Organic solid waste management in a circular economy perspective–A systematic review and SWOT analysis. *J. Clean. Prod.* **2019**, *239*, 118086. [CrossRef]
57. Koutrouli, E. Biotechnological Exploitation of Olive Mill Wastes for Hydrogen Production. Ph.D. Thesis, University of Patras, Patras, Greece, 2008.
58. Chertow, M.; Ehrenfeld, J. Organizing self-organizing systems: Toward a theory of industrial symbiosis. *J. Ind. Ecol.* **2012**, *16*, 13–27. [CrossRef]
59. Adamides, E.D.; Mouzakitis, Y. Industrial ecosystems as technological niches. *J. Clean. Prod.* **2009**, *17*, 172–180. [CrossRef]
60. Gassmann, O.; Frankenberger, K.; Csik, M. *The Business Model Navigator: 55 Models that Will Revolutionise Your Business*; Pearson: London, UK, 2014.
61. Aminalragia-Giamini, R. Production of Bio-Polymers from Olive Mill Wastewater. Ph.D. Thesis, Department of Mechanical Engineering & Aeronautics, University of Patras, Patras, Greece, 2016. (In Greek)
62. Mouzakitis, Y.; Aminalragia-Giamini, R.; Adamides, E.D. From the treatment of olive mills wastewater to its valorization: Towards a bio-economic industrial symbiosis. In *Sustainable Design and Manufacturing 2017 (Smart Innovation, Systems and Technologies Series)*; Campana, G., Howlett, R., Setchi, R., Cimatti, B., Eds.; Springer: Berlin/Heidelberg, Germany, 2017; Volume 68, pp. 267–276.
63. Rip, A.; Kemp, R. Technological change. In *Human Choice and Climate Change*; Rayner, S., Malone, E.L., Eds.; Battelle Press: Columbus, OH, USA, 1998; Volume 2, pp. 327–399.