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Increasing Profits in Food Waste Biorefinery—A Techno-Economic Analysis

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Abstract: The present manuscript highlights the economic profit increase when combining organic waste anaerobic digestion with other mixed culture anaerobic fermentation technologies, e.g., lactic acid fermentation and dark fermentation. Here we consider the conversion of 50 tonnes/day of food waste into methane, power generation (from CHP of biomethane), lactic acid, polylactic acid, hydrogen, acetic acid and butyric acid. The economic assessment shows that the basic alternative, i.e., anaerobic digestion with methane selling to the grid, generates 19 USD/t_VS (3 USD/t_foodwaste) of profit. The highest profit is obtained by dark fermentation with separation and purification of acetic and butyric acids, i.e., 296 USD/t_VS (47 USD/t_foodwaste). The only alternative that presented losses is the power generation alternative, needing tipping fees and/or subsidy of 176 USD/t_VS (29 USD/t_foodwaste). The rest of the alternatives generate profit. From the return on investment (ROI) and payback time, the best scenario is the production of polylactic acid, with 98% ROI, and 7.8 years payback time. Production of butyric acid ROI and payback time was 74% and 9.1 years.

Keywords: food waste; anaerobic digestion; lactic acid fermentation; dark fermentation; poly-lactic acid; butyric acid

1. Introduction

Unlocking value from organic waste is a feasible idea, in contrast to the disposal of these organic wastes into landfills, that has an associated cost ranging from 40–400 USD/t [1–3]. Instead, the organic wastes (residues) can be converted into bio-products and/or bioenergy, creating economic value rather than costs, generating value and benefits for the society.

Based on the characteristics of organic wastes/residues, they can be characterized according to their saccharides, lignin, lipids and protein content [2]. The source of the waste is also classified into: agricultural waste, food waste, and municipal waste. Here we focus in the creations of economic value from complex organic wastes, e.g., food waste, by anaerobic digestion processes. The creation of value from non-complex residues, e.g., citrus peels, coffee spends, for the extraction of pigments has been reviewed elsewhere [2–4].

For the treatment of complex organic waste, anaerobic digestion has been historically the chosen technology. Anaerobic digestion converts the complex wastes into biogas, containing methane (bioenergy) and a digestate that can be valorize as soil improver. However, as noted by Pfaltzgraff et al. [3], the conversion of biomass to bulk chemicals is 3.5 to 7.5 times more profitable than its conversion to fuels/energy. This is the main motivation for this techno-economic analysis.

In recent years, several mixed culture anaerobic technologies, different from the conventional anaerobic digestion for biogas production, has emerged. Among these technologies are dark fermentation and mixed culture lactic acid fermentation. The interest in these "new" technologies is

their value products, with market prices more attractive than methane and digestate. Their average prices are 400 USD/t and 15 USD/t, respectively [5–12].

Figure 1 presents the market price range for the products yielded by anaerobic digestion, dark fermentation, and mixed culture lactic acid fermentation. Dark fermentation has been extensively reviewed for the production of value products [13–25]. Here it is presented the prices of hydrogen, acetic acid, ethanol, propionic acid, butyric acid, and caproic acid as dark fermentation products.

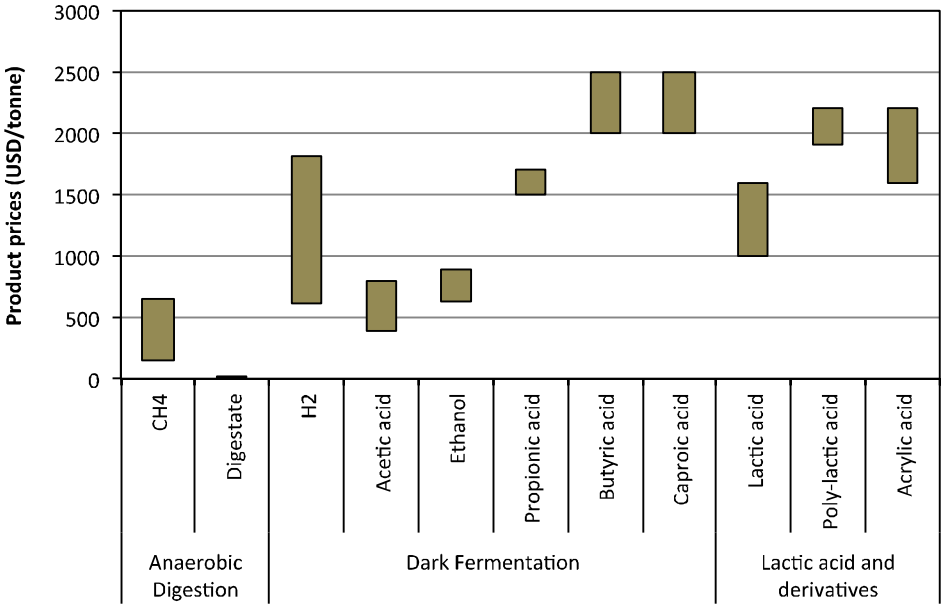

Figure 1. Market price ranges of main anaerobic-fermentation-based products.

Hydrogen price (600–1800 USD/t_H_2) is based on the production costs of hydrogen from natural gas. Hence, hydrogen price depends on natural gas market price. Here the hydrogen price was given when the natural price is in the range of 3–6 USD/GJ [26]. As described by Padro and Putsche [26], hydrogen production costs from natural gas are the cheapest when compare to other sources, i.e., coal, biomass, electrodialysis. To illustrate this, Clarke and Alibardi [7] reported a biomass-based bio-hydrogen price of 4700 USD/t_H_2.

Market price ranges for acetic acid [7,13] and ethanol [7,13,27] are closer to the methane price range, i.e., 400–900 USD/t, which makes it less attractive to spend effort trying to improve the production of either acetic acid and ethanol from organic wastes by anaerobic technologies. In contrast, price ranges for propionic acid, butyric acid and caproic acid [13], from 1500–2500 USD/t, are an incentive to optimize and improve the production of these organic acids by dark fermentation.

Lactic acid and polylactic acid relevance in this assessment is expressed in that that technology has been commercialized and has demonstrated its sustainability and profitability [2]. The conversion of food-waste into lactic acid by uncontrolled pH mixed culture fermentation, has been shown to be feasible [28–31], achieving lactic acid concentrations of 30 g/L with lactic acid selectivity of 93% (in COD base) over other organic acids [29,32]. Lactic acid market price range, 1000–1600 USD/t [13,27,33,34], and its derivatives, i.e., poly-lactic acid and acrylic acid, 1600–2200 USD/t [27,33,35] makes them attractive alternatives to biogas. Below is presented a techno-economic assessment of these three routes, i.e., anerobic digestion, mixed culture lactic acid fermentation, and dark fermentation, in order to compare their potential revenues, costs and profit.

2. Methodology

The present techno-economic assessment is based on relevant literature data, and using conservative assumptions. The assessment compares 3 main routes: anerobic digestion, mixed culture

lactic acid fermentation, and dark fermentation. Each route has been divided into two sub-routes: (A1) Anaerobic digestion where the produced and upgraded methane is sold to the grid; (A2) Methane is used to in-site power generation; (B1) Mixed culture lactic acid fermentation, where lactic acid is produced, separated and purified, and the residues from this process are converted into methane by anaerobic digestion; (B2) As in B1, adding a conversion of lactic acid to poly-lactic acid step; (C1) Dark fermentation producing an upgraded hydrogen stream sold to the grid, where the residues of this process are converted into methane by anaerobic digestion; (C2) Dark fermentation producing an upgraded hydrogen stream, and producing, separating and purifying acetic and butyric acid streams, where the residues are converted into methane by anaerobic digestion. Table 1 presents the capital and operational costs for each route/sub-route, considered in this techno-economic analysis. Capital and operational costs were obtained from literature [5,8,13,35–37]. For all the scenarios, it was considered a project time of 20 years, with an annual interest of 5%.

Figure 2 presents a scheme of the three main routes and sub-routes. The different assessed scenarios are as follow: Anaerobic digestion: (**A1**) methane (to the gas grid) and digestate; (**A2**) Electricity and digestate. Lactic acid fermentation combined with anaerobic digestion: (**B1**) lactic acid, methane, and digestate; (**B2**) Poly-lactic acid, methane, and digestate. Dark fermentation combined with anaerobic digestion: (**C1**) hydrogen, methane and digestate; (**C2**) hydrogen, acetic acid, butyric acid, methane and digestate. For the economic assessments, it was assumed a well segregated food waste, from the hospitality and catering sectors, and a biorefinery "valorization" plant of 50 t/day of food waste capacity, which is in the range of what has been reported in the anaerobic digestion economic assessment literature [5,6,12,36]. Segregated food waste is a realistic assumption where post-harvest activities, and processed food industries, e.g., breweries, fruit pulp/juice production, are additional sources of segregated food waste, avoiding the use of municipal organic solid waste (contaminated with plastics, glass, and metals). It was assumed a food waste composition (w/w) of 13% carbohydrates, 1% fats, 2% proteins, 3% ashes, with a total solids (TS) composition of 19% and a volatile solid (VS) of 16% [29,38]. Conversion yields, revenues and costs are based on tonnes of volatile solid content of food waste (t_VS_fw). The costs include investment and operational costs. The assessments are detailed below.

2.1. Anaerobic Digestion

For the assumed food waste composition, it was estimated a methane yield over the volatile solid content of food waste (VS_fw) after anaerobic digestion and biogas upgrading of 0.33 t/t_VS_fw, and a digestate (solid) yield of 0.25 t/t_VS_fw [39,40]. It was considered that the final treated digestate (sold as soil improver) has a moisture content of 55%. The price of methane sold to the grid was estimated at 207 USD/t [9], and 5 USD/t of digestate [5]. For the power generation by Combined Heat and Power (CHP) it was assumed a methane energy content of 10.35 kWh/m^3, 35% electricity generation efficiency and 65% heat production [40,41]. It was considered that 60% from the total electricity produced is sold as electricity surplus [40,41]. The selected price of electricity was 0.1 USD/kWh [10]. Heat was assumed to be used in the plant, with no market price as discussed by Gebrezgabher [6]. The investment and operational cost for the sub-route A1, production of methane (to the grid) and digestate as soil improver, were set as 53 USD/t_VS_fw [8]. For A2, power generation and digestate, was 280 USD/t_VS_fw [36].

Table 1. Capital and operational costs, obtained from literature, for the different assessed scenarios. All scenarios considered a project time of 20 years, with an annual interest of 5%, and a designed capacity of 50 t/day of food waste, with 16% volatile solids composition.

Route	Annualized Capital Cost (USD/t_VS_fw/year) *	Annual Operational Cost (USD/t_VS_fw/year)	Annualized Total Investment (USD/t_VS_fw/Year)	Capital Cost as Present Value (USD)	Total Investment as Present Value (USD)
(A1) Anaerobic digestion—methane sold to the grid	42 [a,b]	11 [a,b]	53	1,528,365	1,928,652
(A2) Anaerobic digestion—power generation	167 [c]	113 [c]	280	6,091,628	10,189,103
(B1) Mixed culture lactic acid fermentation	108 [a,b,d]	55 [a,b,d]	163	3,930,083	5,931,514
(B2) Polylactic acid production	114 [a,b,d]	59 [a,b,d]	173	4,148,421	6,295,410
(C1) Dark fermentation—hydrogen and methane sold to the grid	47 [a,b,d,e,f]	13 [a,b,d,e,f]	60	1,710,314	2,183,379
(C2) Dark Fermentation—Acetic and butyric acids purified	252 [a,b,d,e,f]	148 [a,b,d,e,f]	400	9,170,193	14,555,862

* t_VS_fw: tonnes of volatile solids of food waste, in this review it was used volatile solid composition of 16%. (A1) The costs considered an anaerobic digestion reactor, a digestate solid composting facility, and a methane upgrading facility; (A2) as in A1, plus a combined heat and power generator; (B1) Considers a mixed culture lactic acid reactor, a lactic acid separator and purification system, an anaerobic digestion reactor, a digestate solid composting facility, and a methane upgrading facility; (B2) as in B1, plus a lactic acid polymerization facility; (C1) Considers a dark fermentation reactor, a hydrogen upgrading facility, an anaerobic digestion reactor, a digestate solid composting facility, and a methane upgrading facility; (C2) as in C1, plus a acetic acid separation and purification facility, and a Butyric acid separation and purification facility. [a] Kim et al., 2016; [b] Whyte and Perry, 2001; [c] Moriarty, 2013; [d] Nampoothiri et al., 2010; [e] Bastidas-Oyanedel et al., 2015; [f] Bonk et al., 2015.

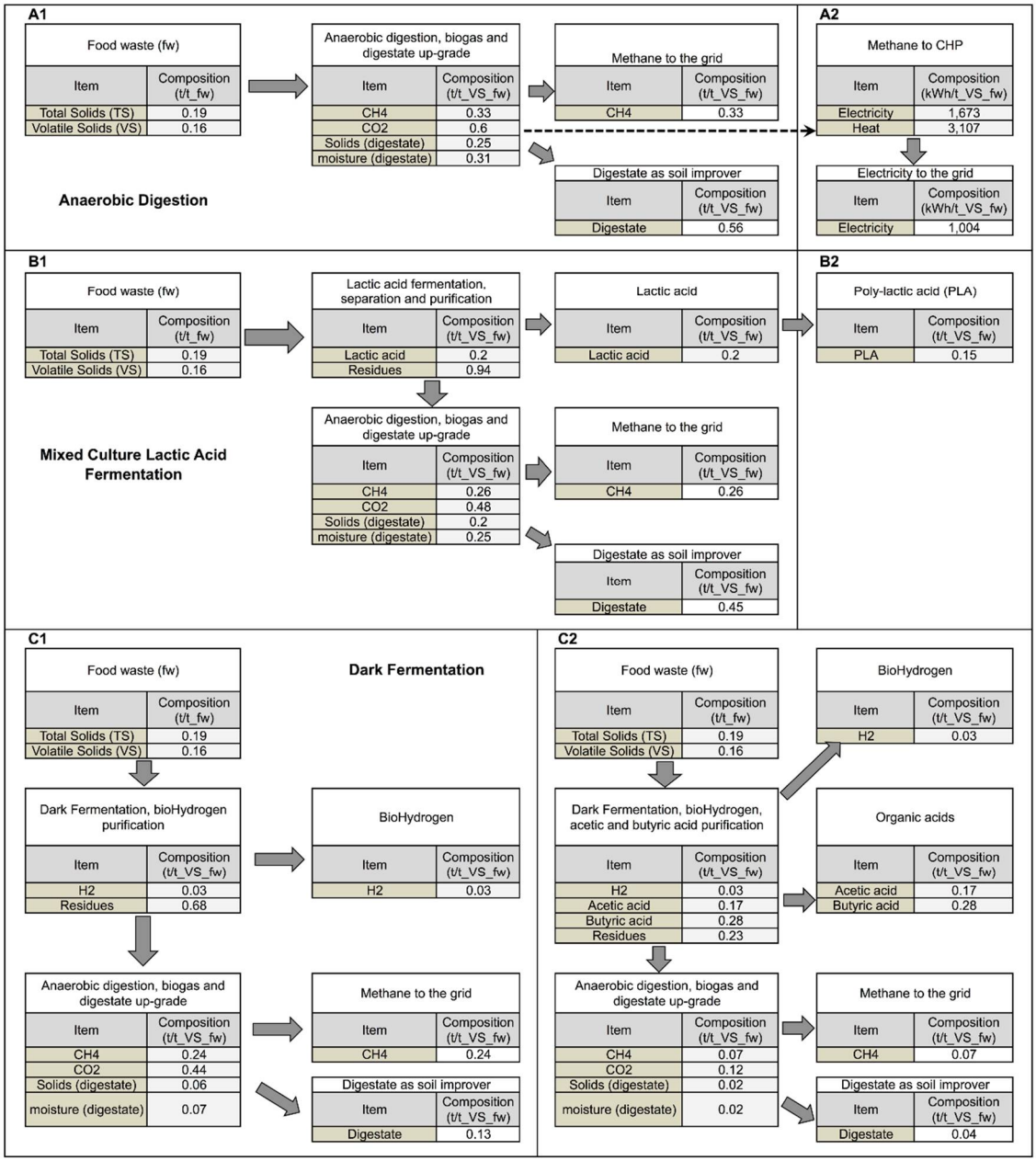

Figure 2. Mass flow diagram (t/t_VolatileSolid_foodwaste) for the different assessed scenarios. Anaerobic digestion: (**A1**) methane (to the gas grid) and digestate; (**A2**) Electricity and digestate. Lactic acid fermentation combined with anaerobic digestion: (**B1**) lactic acid, methane, and digestate; (**B2**) Poly-lactic acid, methane, and digestate. Dark fermentation combined with anaerobic digestion: (**C1**) hydrogen, methane and digestate; (**C2**) hydrogen, acetic acid, butyric acid, methane and digestate.

2.2. Mixed Culture Lactic Acid Fermentation

A yield of 0.2 t_lacticacid/t_VS_fw was used for the conversion, separation and purification of lactic acid [29,32,42–44]. This overall yield takes into account the fermentative production of lactic acid from food-waste [29,32], and the conventional downstream process-train, i.e., coarse separation of suspended solids from the broth, acidification of the broth with strong acid (H_2SO_4), removal of gypsum from the lactic acid solution, and distillation [42–44]. It was assumed that the residues of the lactic acid process were used to produce methane and digestate. Methane and digestate production and upgrading yield, from the lactic acid residue, were estimated as 0.2 and 0.45 t/t_VS_fw, respectively.

Poly-lactic acid (PLA) yield from the purified lactic acid was 0.75 t_PLA/t_LA [45,46]. In this process, purified lactic acid is first converted to lactide by a chemical process, and this molecule is further polymerized into PLA [45,46] Market prices for lactic acid and polylactic acid were assumed as 1000 and 1900 USD/t, respectively [33,35]. Prices for methane and digestate are as in Section 2.1. Cost for the production of lactic acid and anaerobic digestion of residues with methane and digestate as products was estimated as 163 USD/t_VS_fw and 173 USD/t_VS_fw for the scenario when lactic acid is converted to poly-lactic acid, converting the residues to methane and digestate [8,35]. These values are based on the targeted cost of lactic acid and polylactic acid reported by Nampoothiri et al. [35] of 0.55 USD/kg_LA and 0.8 USD/kg_PLA, respectively.

2.3. Dark Fermentation

Biohydrogen production and purification yield were assumed as 0.03 t/t_VS_fw [13,37], this is close to the maximum hydrogen yield. This was chosen, in order to discuss the huge effort in recent years regarding the biohydrogen production optimization from organic wastes by dark fermentation [16,47–52]. Purified hydrogen was assumed to be sold to the grid at a price of 1800 USD/t [26], to make it competitive versus natural gas-based hydrogen.

During the sub-route "hydrogen, methane and digestate" the residues from the biohydrogen production are converted to methane and digestate with 0.24 and 0.13 t/t_VS_fw yields, respectively. The cost of the dark fermentation and hydrogen upgrade was assumed to be 7.5 USD/t_VS_fw. This cost was based on the hydraulic retention time ratio of dark fermentation (2 days) [13] over anaerobic digestion (14 days) [17], i.e., the cost of dark fermentation was estimated as 1/7 the cost of the anaerobic digestion is as in Section 2.1, i.e., 53 USD/t_VS_fw [8]. The total cost for this sub-route was estimated as 60 USD/t_VS_fw.

The second sub-route "hydrogen, acetic acid, butyric acid, methane and digestate" assumed that acetic acid and butyric acid are separated and purified from the dark fermentation process. The combined production and purification yields of acetic and butyric acids used were 0.17 and 0.28 t/t_VS_fw, respectively [13,37,42–44]. These overall yields take into account the fermentative production of acetic and butyric acid from food waste [13,37], and the conventional downstream processing for other organic acid, i.e., lactic acid [42–44]. The residues are converted to methane and digestate by anaerobic digestion. Methane and digestate yields of 0.07 and 0.04 t/t_VS_fw were used. Prices for acetic and butyric acid considered were 400 and 2000 USD/t, respectively [13,37]. Cost for dark fermentation and anaerobic digestion are as in the previous sub-route. Separation and purification costs of 170 USD/t_VS_fw for acetic acid were assumed. The same cost was assumed for butyric acid. These values are based on the target production cost of polylactic acid [35], these costs can be decreased considerably for organic acids as discussed by Bonk et al. [37]. The total cost for this sub-route was estimated as 400 USD/t_VS_fw.

3. Results and Discussion

3.1. Economic Assessment Results

Figure 3 shows the revenues, cost and profit of the different assessed scenarios. For the first route, anaerobic digestion only, the food waste valorization plant, producing methane and digestate has profit of 19 USD/t_VS_fw. When considering the conversion into heat and power, the venues from electricity and digestate are close to 100 USD/t_VS_fw, but generating electricity at the assessed plant scale, i.e., 50 tonnes of food waste per day, considerably increases the total costs, 275 USD/t_VS_fw versus 50 USD/t_VS_fw when selling the methante to the grid. The conversion of methane into heat and power at the plant is only economically feasible when considering a minimum tipping fees and/or subsidies of 176 USD/t_VS_fw, i.e., 28 USD/t_foodwaste. This tipping-fees/subsidies are in the range of what has been reported in the literature for tipping fees, 40–60 USD/t_foodwaste [36], and considerable lower than the food waste landfilling costs, 40–400 USD/t_foodwaste [1–3].

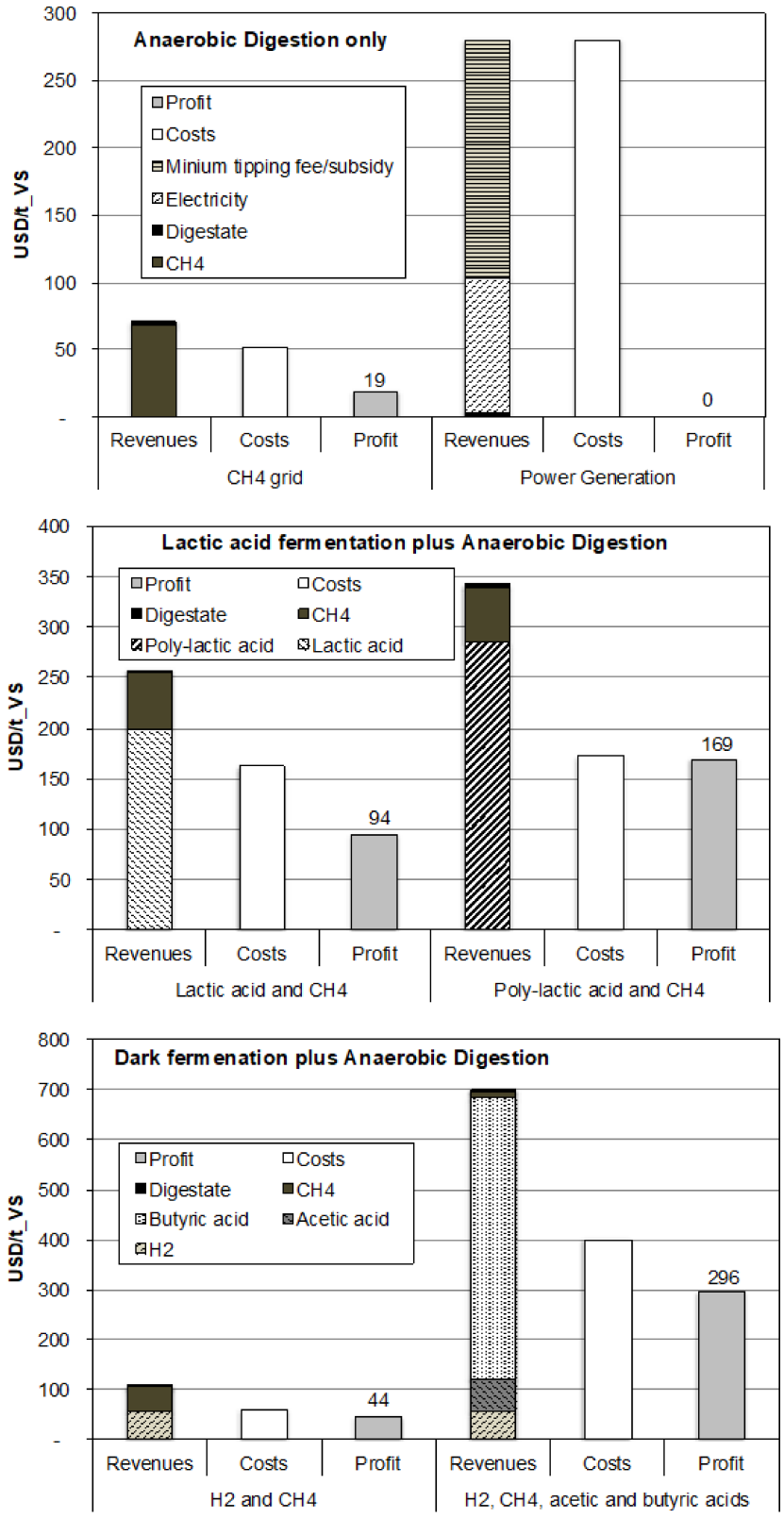

Figure 3. Economic assessment results for the different assessed scenarios.

The mixed culture lactic acid fermentation and anaerobic digestion scenario assessment resulted in higher profit, compared to the anaerobic digestion only scenario. Revenues for the production of

lactic acid, methane (to the grid) and digestate were estimated to be 94 USD/t_VS_fw, with total cost of 162 USD/t_VS_fw. The revenues for the production of poly-lactic acid, methane and digestate were 169 USD/t_VS_fw, with total cost of 172 USD/t_VS_fw. This implies an 80% revenues increase, with a 6% increase in the costs from lactic acid to poly-lactic acid.

The dark fermentation with production of hydrogen, methane and digestate resulted in total revenues of 95 USD/t_VS_fw, where hydrogen represented 57% of the revenues, followed by methane (42%) and digestate (0.3%). This sub-route generated a profit of 44 USD/t_VS_fw, with a cost of 60 USD/t_VS_fw. This profit is considerably increased by 570% to 296 USD/t_VS_fw when producing hydrogen, acetic acid, butyric acid, methane and digestate. The main source of revenues was butyric acid, 80% of the revenues, followed by acetic acid (10%), hydrogen (7%), methane (2%) and digestate (0.01%). This assessment suggests that the huge scientific effort toward biohydrogen production optimization from organic waste [16,47,48,53–55] may be re-focused into the production, separation, and purification of the organic acids produced during dark fermentation [13,19,21,56–58]. It should be noted that the cost of the organic acids sub-route has also increased by 570% to 400 USD/t_VS_fw, when compared to the 60 USD/t_VS_fw of the previous sub-route. This increase is due to the high acetic and butyric separation-purification costs assumed in this assessment, 170 USD/t_VS_fw for each of the organic acids.

As discussed before, the revenues/cost from the organic acids can be improved as the scientific effort could be (re)-directed into finding more environmentally friendly processes and lowering the cost of organic acid separation-purification [38,59]. In this regard, several techniques has been investigated for the recovery of organic acids from fermentation broths, including adsorption [60], solvent extraction [61], membrane-based solvent extraction [62], electro dialysis [63,64], and membrane separation [65].

In general, the conversion of food waste into valuable chemicals was more profitable than its conversion to fuels (methane and hydrogen), as noted by Pfaltzgraff et al. [3]. In our assessment the lactic and poly-lactic scenarios were 5 and 9 times more profitable than the methane (to the grid) scenario, respectively, while the acetic-butyric acid scenario was 16 times more profitable. Also, as has been discussed by Belasri et al. [66] fuel and energy generation from biomass, will not match the total requirements of the society.

Figure 4 presents a sensitivity analysis on profit variation for the assessed scenarios. The sensitivity analysis was performed using a 15% decrease/increase in selected parameters. In the case of scenarios (A1) biogas to grid, the parameters that strongly affect the profit variation, i.e., more than 20% variation, are capital cost, methane price, methane yield, methane upgrading yield, and volatile solid content. In the case of (A2) biogas to power, only the volatile solid content produces a variation over 20% in the minimum tipping fees/subsidy. For scenario (B1) lactic acid, lactic acid price, and combined lactic acid yield and separation efficiency generates profit variations above 20%. (B2) polylactic acid, the parameters that produce profit variations higher than 20% are polylactic acid price, polylactic acid yield, and combined lactic acid yield and separation efficienty. For scenario (C1) hydrogen and methane, none of the parameters produced variations higher than 20% on the profit. The parameters that produced at least 10% profit variation were capital cost, methane price, hydrogen price, combined methane yield and upgrade efficiency, combined hydrogen yield and upgrade efficiency. Case (C2) acetic and butyric acids, butyric acid price, and combined butyric acid yield separation efficiency produced more than 20% profit variation.

Figure 5 shows the return on investment (ROI) and the payback time for all the assessed scenarios. From the ROI perspective scenario (B2) polylactic acid, generates the highest ROI, 98%. From all the assessed scenarios, only (A2) biogas to power, does not generates ROI, assuming that tipping fees/subsidies are minimal. This is due to the high cost of the combined heat and power generator and the low prices for electricity and digestate sold as soil improver [36]. All the other scenarios present ROI higher than 30%.

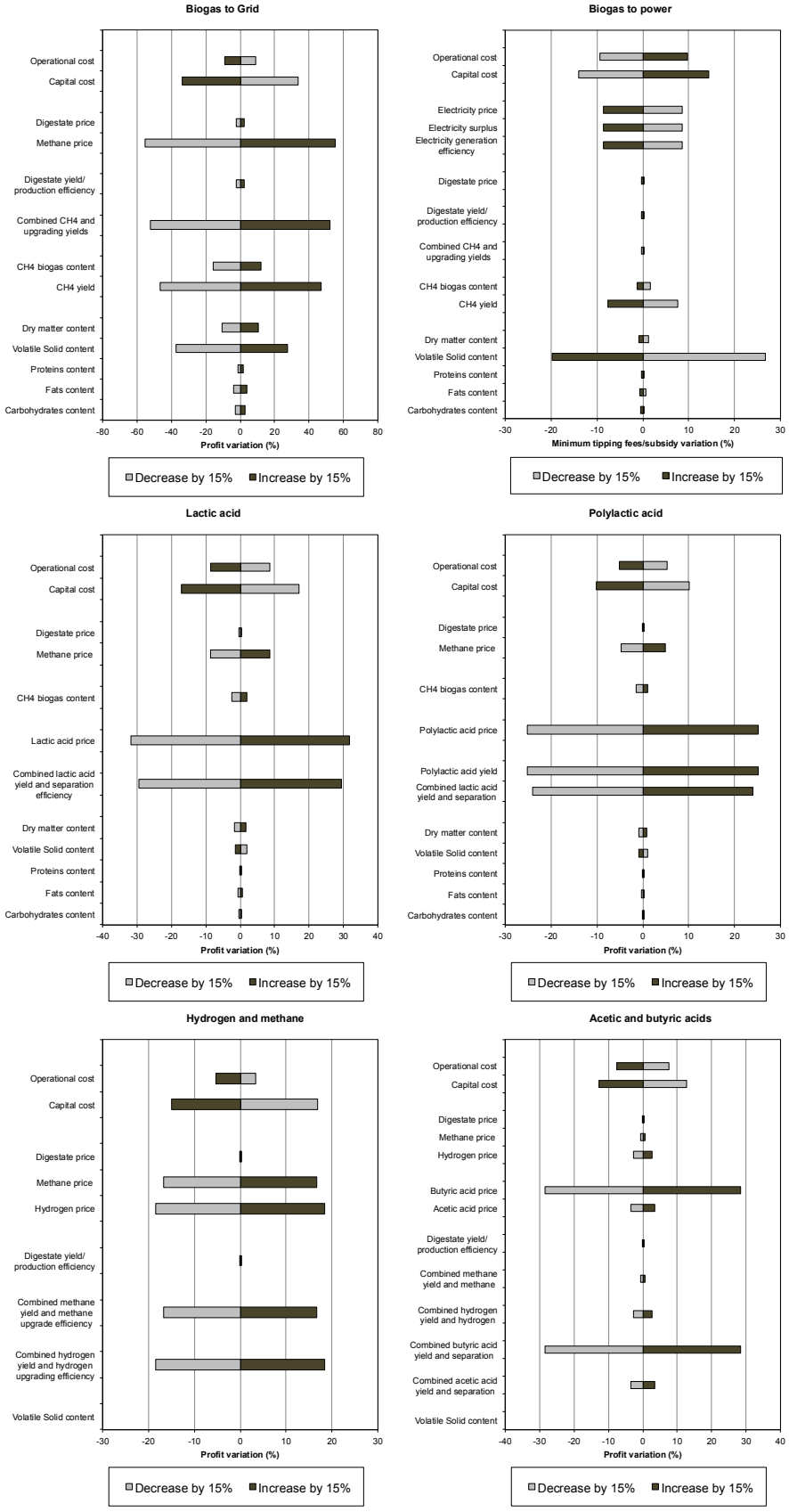

Figure 4. Economic sensitivity analysis results for the different assessed scenarios. All the scenarios where evaluated in a time frame of 20 years, with an annual interest of 5%. Costs include the capital cost, converted to annual, plus the annual operational cost.

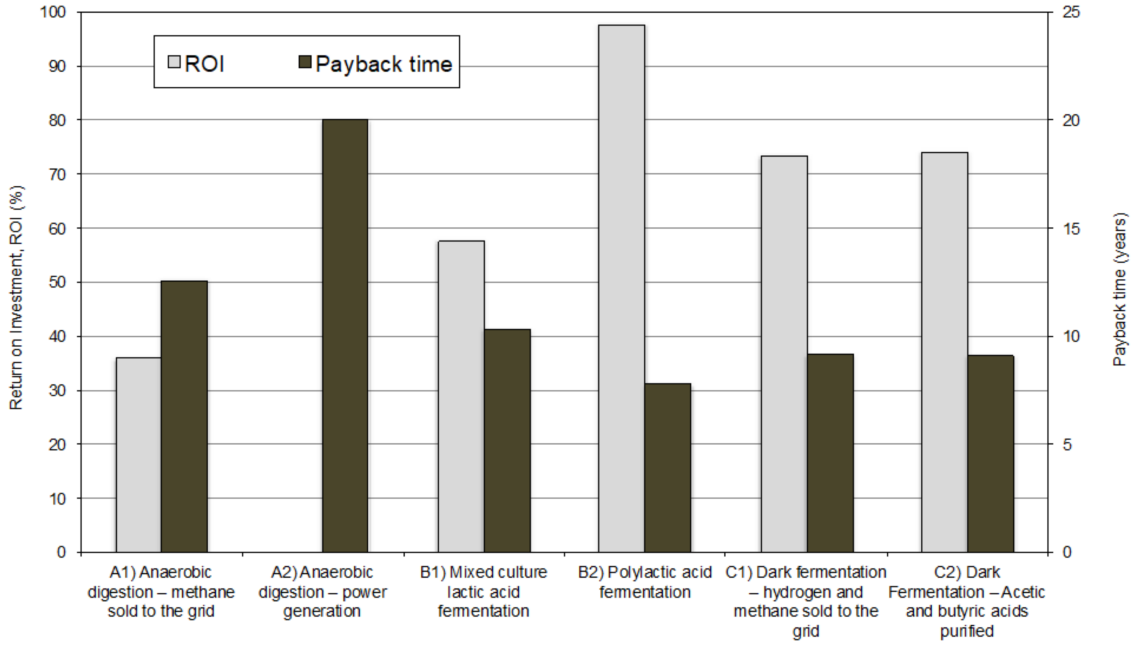

Figure 5. Return on investment (ROI) and payback time for the different assessed scenarios. All the scenarios where evaluated in a time frame of 20 years, with an annual interest of 5%.

The best pay back time was obtained for scenario (B2) polylactic acid, 7.8 years. Both scenarios (C1) hydrogen-methane and (C2) acetic-butyric acids, have payback times of 9.1 years. Scenarios (A1) biogas to grid and (B1) lactic acid, have payback times of 12.6 and 10.3 years, respectively.

3.2. Emerging Mixed Culture Technologies

The added benefits of mixed culture fermentation technologies, versus pure culture fermentations (where the feedstock has to be sterilized to prevent microbial contamination of the pure culture) has been partially discussed previously in the literature [13]. Here these benefits are expanded to: (1) use of a complex feedstock as food waste, (2) no feedstock sterilization, e.g., autoclaving, which reduces the process investment costs (no autoclave facilities are required) and operational costs (no energy is required for autoclaving). In the other hand, pure cultures are known for their high product selectivity, yielding higher product efficiency, and well controlled by environmental parameters [13]. However, new technologies in mixed culture dark fermentation are being developed to revert this trend. High product selectivity of one organic acid from the mixed culture dark fermentation has been reported for propionate using glycerol [56], propionate by controlling ammonium levels in the culture broth [57], or lactic acid using food waste in an uncontrolled pH mode [29,32]. High selectivity is pursued in order to make separation and purification a less complicated task. In this regard, elongation of carboxylic acids has been explored as an alternative to this issue. As an example, promoting the chain elongation of acetic and butyric acid can enhance caproic acid production [67–69]. Caproic acid solubility, 10.8 g/L in water [68] is low when compared to the miscibility of acetic and butyric acid [70]. Carboxilic acids esterification has been also reported to be improve separation, and reducing costs [71]. Electro-dialysis has been explored in order to increase carboxylic acid yield in dark fermentation [72–74], and for the separation of lactic acid from the culture broth [75]. In a complete different perspective, the production of carboxylic acids from syngas using anaerobic biofilms has been reported [76,77]. This is relevant, since anaerobic technologies can be used in combination to thermochemical processes for the valorization of plastics and lignocellulosic wastes, for the production of value chemicals.

4. Conclusions

The present techno-economic analysis has shown that profitability of food waste conversion to bulk chemicals, e.g., lactic acid or butyric acid, can be increased 5 to 16 times when compared to the base scenario, i.e., production of methane (sold to the grid). From the discussed scenarios, the highest profit is obtained by dark fermentation with separation and purification of butyric acid, 296 USD/t_VS (47 USD/t_foodwaste). From the return on investment (ROI) and payback time, the best scenario is the production of polylactic acid, with 98% ROI, and 7.8 years payback time. Production of butyric acid ROI and payback time was 74% and 9.1 years. From these profit, ROI, and payback time perspectives, the present techno-economic analysis suggests a change in focus from biogas/biohydrogen into butyric acid and polylactic acid production from food waste. These results suggest that industry may refocus effort on bulk chemicals, e.g., butyric acid and/or polylactic acid, rather than only focusing on biofuels, as H_2 and CH_4.

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