



Fermentative production of butyric acid from wheat straw: Economic evaluation

Baroi, G. N.; Gavala, Hariklia N.; Westermann, P.; Skiadas, Ioannis

Published in:
Industrial Crops and Products

Link to article, DOI:
[10.1016/j.indcrop.2017.04.008](https://doi.org/10.1016/j.indcrop.2017.04.008)

Publication date:
2017

Document Version
Peer reviewed version

[Link back to DTU Orbit](#)

Citation (APA):
Baroi, G. N., Gavala, H. N., Westermann, P., & Skiadas, I. (2017). Fermentative production of butyric acid from wheat straw: Economic evaluation. *Industrial Crops and Products*, 104, 68-80.
<https://doi.org/10.1016/j.indcrop.2017.04.008>

General rights

Copyright and moral rights for the publications made accessible in the public portal are retained by the authors and/or other copyright owners and it is a condition of accessing publications that users recognise and abide by the legal requirements associated with these rights.

- Users may download and print one copy of any publication from the public portal for the purpose of private study or research.
- You may not further distribute the material or use it for any profit-making activity or commercial gain
- You may freely distribute the URL identifying the publication in the public portal

If you believe that this document breaches copyright please contact us providing details, and we will remove access to the work immediately and investigate your claim.

Manuscript Number: INDCRO-D-16-03637R2

Title: Fermentative production of butyric acid from wheat straw: economic evaluation

Article Type: Research Paper

Section/Category: Biorefinery, valorization of byproducts

Keywords: Economic analysis;
Wheat straw;
Butyric acid;
Fermentation;
C. tyrobutyricum;
Electrodialysis

Corresponding Author: Dr. Ioannis V. Skiadas, PhD

Corresponding Author's Institution: Technical University of Denmark

First Author: George Baroi

Order of Authors: George Baroi; Hariklia Gavala; Peter Westermann;
Ioannis V. Skiadas, PhD

Abstract: The economic feasibility of biochemical conversion of wheat straw to butyric acid was studied in this work. Basic process steps included physicochemical pretreatment, enzymatic hydrolysis and saccharification, fermentation with in-situ acids separation by electrodialysis and product purification. Two scenarios (S1 and S2) were examined assuming a plant with an annual capacity of 10,000 tonnes of product installed in India (due to significantly lower feedstock prices). S1 resulted in a product of 89% butyric acid mixed with acetic acid and S2 produced butyric acid of 99% purity. Unit production cost was estimated at 2.75 and 3.31 \$ per kg product for S1 and S2 respectively. The main part of production cost was attributed to steam for the purification step and electricity for the in-situ acids separation. This unit production cost combined with an estimated butyric acid selling price (year 2014) at 3.50 and 3.95 \$ per kg product (for S1 and S2 respectively) and a plant capacity of 10,000 tonnes indicated an internal rate of return of 14.92% and 12.42 % and payback time of 4.28 and 4.70 years for S1 and S2 respectively. Sensitivity analysis showed that under the assumptions of the present study the optimum plant capacity would lie between 10,000 and 15,000 tonnes of product per year.

- High yield of butyrate (0.45 g g^{-1} sugar) can be achieved from fermentation of wheat straw
- In-situ acids separation by electro dialysis is necessary to secure high yields
- Butyrate production from straw is economically viable for big enough plant capacities
- The optimum plant capacity lies between 10 and 15 million kg of product per year
- Estimated unit production cost is around 3 \$/kg and payback time less than 5 years

1 Fermentative production of butyric acid from wheat straw: economic evaluation

2
3 G.N. Baroi^a, H.N. Gavala^b, P. Westermann^a and I.V.Skiadas^{b,*}

4
5 ^aAalborg University, Department of Chemistry and Bioscience, A C Meyers Vænge 15, DK
6 2450 Copenhagen SV, Denmark

7 ^bTechnical University of Denmark, Department of Chemical and Biochemical Engineering,
8 Søltofts Plads Bldg 228, 2800 Kgs. Lyngby, Denmark

9 *Corresponding author: e-mail: ivsk@kt.dtu.dk & ioannis_sk@yahoo.co.uk, tel: +4545252729.

10 11 **Abstract:**

12 The economic feasibility of biochemical conversion of wheat straw to butyric acid was
13 studied in this work. Basic process steps included physicochemical pretreatment, enzymatic
14 hydrolysis and saccharification, fermentation with in-situ acids separation by electrodialysis
15 and product purification. Two scenarios (S1 and S2) were examined assuming a plant with an
16 annual capacity of 10,000 tonnes of product installed in India (due to significantly lower
17 feedstock prices). S1 resulted in a product of 89% butyric acid mixed with acetic acid and S2
18 produced butyric acid of 99% purity. Unit production cost was estimated at 2.75 and 3.31 \$
19 per kg product for S1 and S2 respectively. The main part of production cost was attributed to
20 steam for the purification step and electricity for the in-situ acids separation. This unit
21 production cost combined with an estimated butyric acid selling price (year 2014) at 3.50 and
22 3.95 \$ per kg product (for S1 and S2 respectively) and a plant capacity of 10,000 tonnes
23 indicated an internal rate of return of 14.92% and 12.42 % and payback time of 4.28 and 4.70
24 years for S1 and S2 respectively. Sensitivity analysis showed that under the assumptions of
25 the present study the optimum plant capacity would lie between 10,000 and 15,000 tonnes of
26 product per year.

27
28
29 **Key words:** Economic analysis, Wheat straw, Butyric acid, Fermentation, *C. tyrobutyricum*,
30 Electrodialysis

31 32 **1. Introduction**

1 Butyric acid is a four carbon fatty acid, which is commonly found in milk and milk products
2 such as butter and has diverse applications in food and feed, chemical and pharmaceutical
3 industries (Dwidar et al., 2012). In the chemical industry, the primary application of butyric
4 acid is plastic production (e.g. cellulose-acetate-butyrate) (Cao et al., 2011). Previous research
5 has also shown that butyric acid can be converted to butanol in a two steps fermentation
6 process where sugars are converted to butyric acid in the first step by *C. tyrobutyricum* and in
7 the second (solventogenic) step, butyric acid is converted to butanol by *C. acetobutylicum*
8 (Ramey, 1998). The current annual production of butyric acid is estimated to be around
9 50,000 tonnes (Sauer et al., 2008) and it is mainly produced by oxidation of butyraldehyde
10 (obtained from propylene derived from crude oil by oxosynthesis). Currently, the chemical
11 synthesis of butyric acid is preferred mainly because of its lower production cost and the
12 availability of the starting materials (Dwidar et al., 2012). Due to the increasing petroleum
13 prices (in the long term), the concerns about greenhouse gas emission and global warming and
14 the customers' preferences, butyric acid production from renewable resources is receiving
15 growing interest from the scientific community and the industry (Zhang et al., 2009; Zigova
16 and Sturdik, 2000) . However, biological production of butyric acid (e.g. from lignocellulosic
17 biomasses) is relatively costly (Dwidar et al., 2012) and petroleum based production cannot
18 be economically outcompeted by the renewable alternatives so far.

19 Wheat straw is the most abundant agricultural biomass in the world after rice
20 straw (Kim and Dale, 2004) with, approximately, 600 million tonnes of wheat straw produced
21 globally in 2009 (estimation based on FAO grain production data) (Bakker et al., 2013).
22 Agricultural biomass is extensively exploited for production of power and biofuels.
23 Particularly, in India, agricultural residues (e.g. rice husk, small wood chips, rice husks,
24 cotton stalks, and other agro-residues) are used for grid power generation but the major

1 portion of agricultural biomass (e.g straw) is currently left in the fields (Mangaraj and
2 Kulkarni, 2011). However, recent actions encouraged by the governmental policy supporting
3 a low-carbon growth path increased potential exploitation of agricultural biomass (Purohit and
4 Fischer, 2014).

5 Typical process for biological production of butyric acid from lignocellulosic
6 biomasses such as wheat straw comprises pre-treatment, saccharification, fermentation,
7 extraction and purification. Pre-treatment and enzymatic hydrolysis (saccharification), in
8 general, is similar to 2G ethanol production process (Kazi et al., 2010) with weak acid
9 hydrolysis being one of the most common pretreatment methods also for fermentative butyric
10 acid production (Jha et al., 2014). Fermentation and acids extraction processes have been
11 discussed in several review articles where different in-situ extraction strategies including
12 solvent extraction and electrodialysis were suggested (Dwidar et al., 2012; Zhang et al.,
13 2009; Zigova and Sturdik, 2000). Typical solvent extraction methods tested so far include
14 physical extraction, reactive extraction or pertraction using different solvents such as decanol,
15 and alamine 336/oleyl-alcohol with the main disadvantage being their inhibitory effect on the
16 fermentation process. Recently, Baroi et al. (2015) reported promising results from a butyric
17 acid production method based on the fermentation of pre-treated and enzymatically
18 hydrolyzed wheat straw (PHWS), which was successfully tested in laboratory as well as in
19 pilot scale. In this method, a single strain (*C. tyrobutyricum*, which cannot hydrolyse cellulose
20 or hemicellulose) fermentation process was applied in combination with in-situ acids
21 separation by Reverse Electro Enhanced Dialysis (REED). This resulted at a high butyric acid
22 productivity, yield and selectivity ($1.30 \text{ g L}^{-1} \text{ h}^{-1}$, 0.45 g g^{-1} sugar, and 0.88 g g^{-1} acids
23 respectively) which was accompanied by significantly smaller (but not negligible) acetic acid
24 production. One possibility to eliminate acetic acid in the fermentation step is using a co-

1 culture of symbiotic microbial species (methanogens), which are able to convert acetic acid
2 and hydrogen (released by butyric acid producing bacteria) to methane but are not able to
3 consume butyric acid and have similar growth requirements with *C. tyrobutyricum*. This
4 microbial symbiotic relationship is very common and naturally occurs in anaerobic digestion
5 processes (Batstone et al., 2002). Methanogens such as *Methanosarcina sp* and *Methanosaeta*
6 *sp.* can catabolize H₂-CO₂ and acetic acid, respectively (Stams et al., 2003). It is expected that
7 a co-culture of *C. tyrobutyricum* with methanogens will obviously have the advantage of
8 resulting in a fermentation broth containing only butyric acid and (practically) no acetic acid
9 with additional production of methane (which could be used as fuel for the process). On the
10 other hand, the fermentation step will have to be designed for a longer hydraulic retention
11 time in order to avoid washing out of the methanogens which grow slower than *C.*
12 *tyrobutyricum*(Khanal, 2008).

13 To our knowledge, the above mentioned butyric acid efficiency is the highest
14 observed so far in suspended growth fermentation systems and therefore, it is worthy to
15 further examine possibilities for upscaling and commercial exploitation. Techno-economic
16 analysis is a fundamental tool for studying the feasibility of new processes and estimating
17 their economic viability and performance. A representative software package which is
18 commercially available and can be used for simulation and techno-economic analysis of
19 processes is SuperPro Designer®. SuperPro Designer® has among others been used for the
20 techno-economic analysis of bioethanol production (Kazi et al., 2010; Wooley et al., 2002),
21 bio-diesel production (Marchetti et al., 2008) and biopharmaceutical process optimization
22 (Petrides et al., 2014) by estimating mass and energy balances as well as economic
23 parameters. Furthermore, SuperPro Designer® can provide the distribution of cost over
24 different process sections and perform cash flow analysis.

1 In the present study, a complete plant is envisaged where wheat straw is
2 pretreated, enzymatically hydrolyzed and fermented to butyric acid, which is subsequently
3 separated by applying the process developed by Baroi et al. (2015). The plant, which is
4 assumed to have a production capacity of around 10,000 tonnes purified acids as main product
5 (MP) from wheat straw, is analyzed and simulated by SuperPro Designer®, technoeconomic
6 analysis is performed and its economic feasibility is evaluated.

7

8 **2. Methods**

9 *2.1 Description of the process model*

10 The process model includes five major process steps: feedstock handling, pretreatment,
11 saccharification, fermentation and extraction and purification (see figure 1). The detailed
12 process model, developed by using SuperPro Designer® V9.0, is shown in figure 2. In
13 addition to the five sections, the model includes heat and power generation units where by-
14 products such as solids and biogas are used for steam and power generation. Feedstock
15 handling includes size reduction, which in combination with pretreatment facilitates the
16 disintegration of the lignocellulosic structure of the biomass and thus increases the release of
17 sugar monomers in the saccharification step. The liquid fraction of the latter step is then used
18 for butyric acid fermentation. Organic acids produced in the fermentation step are extracted
19 by distillation in the final purification step.

20 **Figure 1 here**

21 In most of the single strain fermentation processes developed so far for butyric acid
22 production acetic acid is a side product even after genetic modification (Zhu et al., 2005).
23 Acetic acid is also produced during the pretreatment. Butyric acid purification technologies
24 after extraction are not yet fully developed and often butyric acid is produced as a mixture

1 (Zigova and Ernest, S, Vandak D, 1999). Acetic acid (boiling point 117.95 °C) has an almost
2 similar pKa value as butyric acid (boiling point 164.85 °C) and both acids form azeotropic
3 mixtures with water making the purification energy demanding. Hence, two scenarios (S1 and
4 S2) were investigated in this study. S1 is based on the fermentation process developed by
5 Baroi et al. (2015) where a mixture of butyric acid with acetic acid is the main product (MP).
6 S2 is based on the same bacterium used in S1 (*C. tyrobutyricum*) in coculture with
7 methanogens, which are able to convert acetic acid to methane and thus butyric acid is the
8 MP. Each of the scenarios is modelled in SuperPro Designer where materials and energy
9 balances are developed and then used for the economic evaluation of the processes.

10 **Figure 2 here**

11

12 *2.1.1 Feed stock*

13 Composition, availability and thus prices of wheat straw can vary significantly depending on
14 the climate, soil and harvesting time as well as local market conditions (Molinuevo-Salces et
15 al., 2013). As a result, unit production costs can be affected by these parameters when wheat
16 straw is used as feedstock. In 2009-2010, wheat and rice straw production in India reached
17 186 million tonnes and 75% of this was either burnt or wasted (Mangaraj and Kulkarni,
18 2011). Furthermore, prices of wheat straw in India (0.0125 \$/kg (Mangaraj and Kulkarni,
19 2011)) are considerably lower than in Denmark and Sweden (0.0724 \$/kg (Statistik, 2014)
20 and 0.108 \$/kg (Horváth et al., 2013)) Due to large availability and very low prices of straw it
21 is assumed that the plant for butyric acid production from wheat straw considered in the
22 present study will be located in India. Hence, this study considers India as a potential ground
23 for this process.

1 Major constituents of wheat straw are cellulose, hemicellulose and lignin as shown in
2 table 1. Furthermore, wheat straw contains silica as 13% to 18% of ash content
3 (Antongiovanni and Sargentini, 1991; Halvarsson et al., 2010) and 8 to 14% water (Bauer et
4 al., 2009; Larsen et al., 2012) . The chemical composition of wheat straw used in this study
5 was assumed to be cellulose 39.7%, hemicellulose 23.9%, lignin 20.5% and ash 5.7% as
6 averages of the respective values presented in table 1.

7 **Table 1 here**

8

9 *2.1.2 Feedstock handling and pre-treatment*

10 Feedstock handling includes wheat straw washing and size reduction. Fresh water
11 requirement in this process is assumed to be minimal since water generated in downstream
12 purification steps is used in the washing step. Washed straw is passed through a grinder for
13 size reduction down to 2-3 mm increasing the surface area, which facilitates the subsequent
14 physicochemical pre-treatment step (Njoku et al., 2012). Storage cost is not taken into account
15 for the estimation of unit production cost in this study.

16 The primary objective of the pretreatment is to make the carbohydrates, imbedded in
17 lignocellulosic biomass, accessible for enzymatic hydrolysis (saccharification) (Galbe and
18 Zacchi, 2002; Taherzadeh and Karimi, 2008). In the process considered in the present study,
19 washed and grinded straw is transferred to the pretreatment reactor where it undergoes wet
20 explosion (reactions outlined in table 2) followed by pressure release and temperature drop to
21 1 bar and 32 °C respectively in a flash tank. Wet explosion is carried out at 150 °C, retention
22 time of 15 min, H₂SO₄ concentration of 0.3% (w/w), total solids (TS) content of 12-13% and
23 a pressure of 6 bar (Biswas et al., 2013; Njoku et al., 2012). Heat released in this step is
24 recycled to preheat the biomass feeding stream to the pretreatment reactor. The pretreated

1 straw is transferred from the flash tank to the saccharification step. For the purpose of the
2 present study and in order to avoid the modelling of very complex commercial scale
3 pretreatment reactor design, for which there is not enough information available (Kumar and
4 Murthy, 2011), the pretreatment step is assumed to be one piece of equipment shown in figure
5 2 (pretreatment reactor grouping together a series of equipment such as screw conveyors,
6 tanks, reactor, flash tank etc.)

7 **Table 2 here**

8

9 *2.1.3 Saccharification*

10 The slurry, produced after the pretreatment, has a very low pH (<5.0) and therefore, prior to
11 enzymatic hydrolysis, pH is adjusted to 5 by adding NaOH. Enzyme complex dose (Cellic
12 CTec2), reaction temperature, and residence time are 50 g/kg cellulose, 30⁰C and 24 hours
13 respectively (Öhrman et al., 2013). Reactions and conversion efficiency used in
14 saccharification modeling are shown in table 2. After saccharification, the remaining solids
15 are separated by a belt-filter as suggested by Wooley et al. (2002). During this filtration step,
16 water is used for washing purposes at so small quantities that it may be assumed as negligible
17 without introducing significant error in the overall process modelling and calculations. The
18 separated solid fraction, usually called ‘cake’, is characterized by a moisture content of 50%
19 and is used for heat and power generation. The remaining liquid stream is utilized as the
20 substrate for the following fermentation step.

21

22 *2.1.4 Fermentation coupled with extraction*

23 Prior to fermentation, the liquid is neutralized with potassium hydroxide, and urea and
24 K₂HPO₄ are added at a concentration of 4.5 g/L and 0.64 g/L respectively. The mixture is then

1 sterilized at a temperature of 140 °C and pumped into the fermentation tank. For both
2 scenarios (S1 and S2) examined in this study the fermentation is carried out at a temperature
3 of 37 °C and pH 7 following the fermentation stoichiometry and conversion efficiencies
4 presented in table 2. The hydraulic retention time (HRT) is not assumed the same in the two
5 scenarios. As demonstrated by Baroi et al., (2015), recommended HRT for scenario S1 is 1.28
6 d. However, the maximum specific growth rate for methanogens is between 0.25 and 0.5 d⁻¹
7 (Gavala et al., 2003) which corresponds to a minimum HRT between 2 and 4 d for the
8 methanogens to grow fast enough and not being washed out. Thus the HRT for scenario S2 is
9 assumed to be 2 d. *C. tyrobutyricum*, which is assumed in this study, has previously been well
10 adapted to the fermentation medium (wheat straw hydrolysate) (Baroi et al., 2015; Baroi et
11 al., 2015a) and therefore, is not expected to be affected by any inhibition. On the other hand,
12 methanogens may be inhibited by compounds in wheat straw hydrolysate (Shanmugam et al.,
13 2014). Based on literature data, it is assumed here that this inhibition effect is not severe and
14 also that adaptation of the methanogens will take place and thus the longer hydraulic retention
15 time used in S2 will be sufficient to maintaining a healthy methanogens population in the
16 fermentation system (Rivard and Grohmann, 1991).

17 For both S1 and S2 scenarios the fermentor is connected with a membrane system for
18 in-situ separation of butyric acid. Specifically, the fermentation broth flows through a REED
19 anion-exchange membrane unit where organic acid anions (e.g. CH₃(CH₂)COO⁻) are removed
20 from the broth facilitated by an electric field and replaced by OH⁻ coming from a NaOH
21 solution flowing at the opposite side of the membrane. The organic acid anions are then
22 combined with the remaining Na⁺ and the formed salt solution is passed through an EDBM
23 (electrodialysis with bipolar membrane) unit which regenerates the NaOH and releases a
24 water solution of the organic acids as demonstrated by (Garde, 2002; Wang et al., 2013). In

1 this process, there is a loss of a small part of NaOH, which is replenished by an external
2 addition of a NaOH solution. Butyric acid and acetic acid recovery efficiencies for the REED
3 unit are 90% and 91% respectively as reported by Baroi et al. (2015). Organic acids recovery
4 efficiency of EDBM is assumed to be 100% which is similar to that used by Garde (2002) for
5 lactic acid production. Based on estimations made by Jurag Separation A/S, the providers of
6 REED/EDBM technology, the butyric acid content of the acid solution generated by the
7 EDBM unit was expected to be around 5.5%. In the present study, the REED/EDBM units are
8 modeled as one unit for simplification purposes. Detailed operational parameters and
9 technical characteristics of REED/EDBM are presented in table 3. Finally, the effluent from
10 the fermentation tank (from which organic acids have been removed and recovered) is
11 assumed to be wastewater that requires proper treatment and disposal.

12 **Table 3 here**

13

14 *2.1.5 Purification*

15 The purification steps include storage, extraction and distillation units. 1-octanol (as a
16 representative model solvent) was selected for the extraction of organic acids from the water
17 phase coming from the REED/EDBM unit. The partition co-efficient (PC) of butyric acid in
18 octanol was 6.17 and the PC of acetic acid was 0.68. The solubility or entrainment of water in
19 octanol or octanol in water was assumed 0.01 g/L. After extraction, the octanol phase that
20 contains the organic acids is distilled. The organic acids (butyric and acetic acids for S1 or
21 only butyric acid for S2), which are more volatile than octanol are collected from the top of
22 the distillation column as the main product while octanol leaves from the bottom of the
23 distillation vat and is recycled back to the extraction unit after replenishment of the octanol
24 losses. Detailed operational parameters and technical characteristics of extraction and

1 distillation units are presented in table 3. The distillation processes were modelled in
2 SuperPro Designer® using a semi-empirical shortcut method (Fenske-Underwood-Gilliland).
3 The distillation column is operated at a reflux ratio of 41 and 48 for S1 and S2 respectively.
4 Heat recovered from the distillation effluent streams is used for pre-heating the feed stream.
5 The water phase from the bottom of the extraction unit is used as washing water in the straw
6 washing unit and finally ends up as wastewater that requires proper treatment and disposal.

7

8 *2.1.6 Combined heat and power (CHP) generation*

9 The filter cake, which is produced during belt filtration of hydrolyzed straw as well as the
10 biogas from the fermentation unit are combusted for heat and power production where well
11 water is used for steam generation. It is assumed that the steam and electricity produced in
12 this step are fully consumed by the modelled enterprise to cover energy needs of the rest of
13 the process steps. Detail operating parameters for CHP are presented in table 3, There is a
14 possibility to tune parameter in SuperproDesigner® to get different pressure steam in order to
15 satisfy the needs of the production process. However, default values were chosen for steam
16 generator.

17

18 *2.2 Economic analysis*

19 The economic evaluation of butyric acid production from wheat straw studied in the present
20 work involved the estimation of capital cost, variable and fixed operating costs as well as
21 profitability. SuperPro Designer® was used in order to model and simulate the production
22 process. The calculated material and energy balances were then used for equipment sizing and
23 cost estimation. The purchase costs for some of the equipment (such as belt filtration,
24 sterilization unit, extraction, distillation unit, steam generation unit, heat exchangers and

1 coolers) were obtained from SuperPro Designer® existing databases combined with the build-
2 in scaling law (equation 1) while for others (such as washing table, shredder, pretreatment
3 vessel, flush tank, enzymatic hydrolysis, fermentation reactor, storage tanks, REED and
4 EDBM) the purchase costs calculations were based on the simulated equipment sizes and the
5 application of scaling law with specific equipment index taken from previous reports (Aden et
6 al., 2002; Garde, 2002).

$$8 \quad New \text{ Cost} = \text{Original Cost} \left(\frac{New \text{ Size}}{Original \text{ Size}} \right)^n \quad (1)$$

9 Where n=specific equipment index

10

11 Additionally, SuperPro Designer® accounted for the cost of secondary equipment, which was
12 not listed for model simplification purposes. The purchase cost of this unlisted equipment was
13 estimated to be 20% of the purchase cost of listed equipment. Finally and as recommended by
14 SuperPro Designer®, maintenance cost was assumed to be 10% of the total equipment
15 purchase cost. Equipment, raw materials and labor purchase costs which are subject to
16 changes with time due to inflation and other parameters influencing market conditions were
17 estimated by equation 2, where specific indexes are used to estimate the purchase cost for the
18 desired year (Cost2) when the cost is known for a previous year (Cost 1):

19

$$20 \quad Cost2 = Cost1 \frac{Index_2}{Index_1} \quad (2)$$

21

22 The necessary parameters for the estimation of the total capital investment cost and operating
23 cost of the process were obtained from literature (Humbird et al., 2011; Ou et al., 2014). Thus,
24 the project life and the depreciation period were taken as 20 and 10 years respectively while

1 the salvage value, the construction and start-up period and the inflation rate were 5%, 30
2 months, 6 months and 4% respectively.

3

4 2.2.1 *Raw materials, consumables, utilities, labor and waste disposal costs*

5 The prices of raw materials used in the present process modeling and economic evaluation are
6 shown in table 4. Where necessary, the prices have been adjusted by indexing them to year
7 2014 as suggested by Aden et al. (Aden et al., 2002). The price of wheat straw used as
8 feedstock in this study was 0.0125 \$/kg (see also section 2.1.1 Feedstock). Octanol price
9 varied from 1.65-1.83 \$/kg but an average value of 1.7 \$/kg was used in this study. Also, it
10 was assumed that the enzyme prices would remain stable during the years included in the
11 evaluation even though one can expect lowering prices due to future technological
12 development. Prices of consumables such as membranes used for REED (198 \$/m²) and
13 EDBM (1567 \$/m²) were taken from Garde (2002) and adjusted for the year 2014 using
14 equation 2. Purchase costs of utilities such as water (0.203 \$/tonne), electricity (0.07 \$/kWh)
15 and steam (115⁰C , 60.95 \$/tonne) as well as labor price (basic 2.5 \$/h) are taken from
16 literature (Burkley, 2014; Sikder et al., 2012) and, where necessary, they were adjusted for the
17 year 2014. It is remarkable though, that steam price in India seemed several times higher
18 compared to what has been reported in other similar studies for ethanol production (17.08
19 \$/tonne (year 2006 price) (Kwiatkowski et al., 2006)) or biogas production (4.05 \$/tonne (
20 year 2013 price) (Shafiei et al., 2013)). The above are the buy-in prices of energy utilities, if
21 the CHP does not satisfy demand.

22 The cost for wastewater treatment and disposal can vary significantly depending
23 on its organic load (BOD or COD content). Harrison et al. (2013) reported a disposal fee of
24 0.2 \$/m³ to 0.5 \$/m³ for waste water having a BOD content less than 1000 mg/L which was

1 the expected organic load of the effluent from wheat straw wash unit. However, the
2 wastewater mixture generated during the present butyric acid production process, that is the
3 fermentation effluent mixed with the effluent from straw wash unit, was expected to have
4 significantly higher organic load. Buyukkamaci and Koken, (2010) estimated a cost of 0.7-
5 2.35 $\$/\text{m}^3$ for the treatment of high strength (10 g COD/L and 5 g/L suspended solids) paper
6 and pulp industry wastewater. Garde (2002) used a cost of 2.36 $\$/\text{m}^3$ for the treatment of
7 wastewater from a fermentative lactic acid production process. The cost for wastewater (both
8 fermentation effluent and washing water) treatment assumed in this study was 2 $\$/\text{m}^3$. Finally,
9 the cost for the disposal of the ash generated in the heat and power section was assumed to be
10 at 0.0041 $\$/\text{kg}$ (Wooley et al., 2002). The costs of the waste/wastewater treatment and
11 disposal are not necessarily representative of those in India. These costs are bound to vary
12 considerably across municipalities, and even more so across continents. However, these costs
13 are usually a very small portion of the total operating cost and it is assumed in the present
14 study that they cannot influence significantly the economics of the examined production
15 process. This assumption is confirmed from the results of the present study presented below
16 in section 3.2. Furthermore, the used costs are representative of North Europe and North
17 America which (due to very strict environmental regulations) present the highest costs
18 compared to other geographical areas and thus the economic evaluation results of the present
19 study cannot be influenced negatively by locating the production unit in India.

20 **Table 4 here**

21

22 *2.2.2 Product price*

23 Current market price of butyric acid was not possible to be recovered from public databases.

24 However, butyric acid price can be estimated from the price of n-butyraldehyde, which is the

1 raw material used during the chemical synthesis of butyric acid. Zidwick et. al. (2013)
2 reported a butyric acid price of 1.5 \$/kg in year 1982 based on the market price of n-
3 butyraldehyde. Since then, there has been a considerable increase of oil price, which has
4 resulted to significant increases of butyric acid price reported by producers such as
5 EASTMAN (www.eastman.com) or OXEA (www.oxea-chemicals.com). Recently, OXEA
6 has reported a list price of n-butyraldehyde at 3.95 \$/kg (OXEA, 2014) and thus list price of
7 butyric acid can be be 4.78\$/kg (production cost factor of 1.21 was calculated based on the
8 data reported by Zidwick et al. (2013)). However, due to the uncertainties with the above
9 price estimations it has been chosen a minimum price for butyric acid of 3.95 \$/kg being the
10 same with that of n-butyraldehyde. Thus the economic evaluation was performed on a worst
11 case scenario where the price of butyric acid produced through chemical synthesis will be so
12 low as this of n-butyraldehyde. The purity of the commercially available butyric acid varies
13 from 99 to 99.5%. In order to perform cash flow analysis in this study the price of butyric acid
14 (purity >99%) was assumed to be 3.95 \$/kg. The main product resulting from scenario S1 is a
15 mixture of butyric acid and acetic acid. Butyric acid content in this mixture is 89%. Based on
16 a 89% purity of butyric acid, the price of the product from S1 was assumed to be 3.50 \$/kg,
17 calculated proportionally from the price used for the product with 99 % purity. The product
18 from S2 was assumed to be pure (99%) butyric acid.

19

20 *2.3 Parameters for Sensitivity analysis*

21 Depending on local conditions and their yearly variation, such as climate, yield of crops,
22 and feedstock availability versus demand, the price of feedstock (wheat straw) may have a
23 large variation and thus affect substantially the unit production cost. In order to demonstrate
24 the effect of wheat straw price as well as that of plant size (capacity) and selling price of main

1 product on the profitability of the whole enterprise, a sensitivity analysis was performed
2 (single parameter at a time) by using SuperPro Designer® Component Object Model (COM)
3 interface in combination with Microsoft Excel® interface.

4 5 **3. Results and Discussion:**

6 *3.1 Economic summary of the scenario S1 and S2*

7 The economic results for plant product capacity of 10,000 tonnes per year after simulation of
8 both S1 and S2 scenarios are presented in tables 5 and 6. Based on a market price (year 2014)
9 estimation for butyric acid at 3.95 \$/kg (purity 99%) both scenarios showed encouraging
10 results. Unit production cost was estimated at 2.75 \$/kg product and 3.31 \$/kg product for S1
11 and S2 respectively. For the plant capacity examined in this study (10,000 tonnes of product
12 per year) this reveals a very efficient investment with Internal Rate of Return (after tax) of
13 14.92% and 12.42 % and payback time of 4.28 and 4.7 years for S1 and S2 respectively.

14 Total Lang factors (Peters and Timmerhaus, 1991) of 5.07 and 5.10 were used for S1 and
15 S2 respectively to estimate total capital investment based on equipment purchase cost. This
16 estimation resulted in a total capital investment for scenarios S1 and S2 of 47.71 and 53.68
17 million \$ respectively. Due to the conversion of acetic acid to methane in S2, S1 results in
18 higher amount of MP produced per unit amount of straw consumed and thus S1 is required to
19 convert a smaller amount of wheat straw(140 tonnes compared to 156 tonnes per day) in order
20 to produce 10,000 tonnes of MP per year. Consequently, the equipment size in S1 is slightly
21 smaller than in S2 and accordingly the estimated capital investment for S1 is smaller than for
22 S2. In order to test how realistic are the above estimated capital investments a comparison
23 with the results from a similar study by Humbird et al. (2011) was made. This comparison
24 revealed that for the same raw material capacity used by Humbird et al. (i.e. 2,000 tonnes of

1 raw material per day) S1 and S2 would require a total capital investment of 410,652,000 \$ and
2 426,090,000\$ respectively which is almost the same with the 422,500,000 \$ estimated by
3 Humbird et al. Operating cost was slightly higher for S2 (33.12 million \$) compared with S1
4 (27.52 million \$) scenario which (after taking into consideration that butyric acid purity for
5 S1 and S2 was 89 % and 99 % respectively) resulted in an increased (20%) unit production
6 cost for scenario S2. A small amount of credit was obtained due to electricity and steam
7 generation in the heat and power section (figure 3a) and this has resulted to a 16% reduction
8 of the unit production cost.

9 **Figure 3 here**

10 **Table 5 here**

11 **Table 6 here**

12 *Direct Fixed Capital Cost* and its breakdown to different cost categories are
13 shown in table 6. Estimated *Direct Fixed Capital Cost* for S1 and S2 is 40.32 and 45.07
14 million \$ respectively. The highest equipment purchase cost was attributed to the pretreatment
15 section (26%) followed by fermentation and extraction section (22%) and purification section
16 (21%). Detailed equipment costs and respective size or capacity of each unit are presented in
17 appendix A.

18

19 *3.2 Operating cost distribution for scenarios S1 and S2*

20 The different operating cost categories for scenarios S1 and S2 are shown in table 7. Utility
21 costs are the highest (52.7% and 55.0 % of the total operating cost for S1 and S2 respectively)
22 followed by facility dependent costs (28.4 % and 26.36%) and raw material costs (8.1% and
23 7.6%). Facility dependent costs include maintenance, depreciation and miscellaneous costs.

1 Operating costs distributed among the six sections of the process are shown in figure 3b.
2 For both S1 and S2 scenarios, purification section was the most costly one accounting for ~50
3 % of the total operating cost. Fermentation accounted for ~ 26%, pretreatment ~11 %,
4 saccharification ~5.5 % and feed stock handling ~ 4% for both S1 and S2.

5 The operating costs of the purification section was estimated at 13.62 and 17.12 million
6 \$ for S1 and S2 respectively. This means that the purification section accounted for more than
7 80% of the total utility costs followed by fermentation and separation (15%), heat and power
8 section (~ 2%) and pretreatment (~ 1%). As mentioned above, steam is relatively expensive in
9 India and thus, steam alone contributed to 34.2 % and 35.8% of the total operating cost of S1
10 and S2 respectively (table 7). A large amount of steam (154,419 tonnes for S1 and 194,274
11 tonnes for S2) and cooling water (12.83 million tonnes for S1 and 16.16 million tonnes for
12 S2) were used by the process. However, 46.7% (S1) and 44.4 % (S2) of the total steam
13 demand could in principle be covered by the CHP unit (see figure 3a).

14 The operating cost of fermentation and separation section was estimated at 7.5 and 8.5
15 million \$ (for S1 and S2 respectively), of which, utility costs were approximately 33%. A
16 significant amount of electricity was required for REED and EDBM units. Total electricity
17 purchase cost for the entire plant was estimated at 2.4 and 2.8 million \$. Almost 95% of the
18 electricity consumption of the entire plant was used in fermentation and separation section.
19 Total electricity consumption by S1 and S2 was 34.4 and 39.4 GWh/year respectively.
20 However, a very small amount of electricity (0.35 and 0.38% of the total plant consumption
21 for scenario S1 and S2) is generated by the CHP section.

22 The cost of replacement of REED and EDBM membranes corresponded to
23 approximately 20% of the operating cost of fermentation and separation section. Among the
24 different raw materials used, urea (as nitrogen source for microbes) was the most costly and

1 corresponded to almost 2.5% of the total operating costs. Costs for wheat straw, NaOH and
2 enzymes were significant but not as high. The total amount of wheat straw necessary for the
3 production of 10,000 tonnes MP from S1 and S2 was 44,060 and 49,820 tonnes respectively.

4 **Table 7 here**

5

6 *3.3 Sensitivity analysis*

7 Sensitivity analysis was performed to determine the potential effect of wheat straw prices on
8 the unit production cost for scenarios S1 and S2 and the results are shown in figure 4a. A
9 hypothetical increase of 1000% in the purchase price of feedstock may cause an 80% increase
10 in production cost for S1 and S2, indicating that in general feedstock price has a minor effect .
11 This result could be explained by the fact that, in the specific case handled in the present
12 study, wheat straw purchase cost (0.01 \$/kg) contributed with a relatively small percentage to
13 the total operating cost. Apparently, this cost increment may not be significant under the
14 assumptions of the present study but it is likely that this picture will change in the future due
15 to lower availability of wheat straw as a result of, for example, installation of a number of
16 wheat straw based production plants or low crops efficiency, due to climate change.
17 Furthermore, wheat straw prices may have had a more significant impact on the unit
18 production cost if the necessary heat and power were produced through the combustion of
19 wheat straw together with the produced biogas and solid cake. However and according to our
20 knowledge, similar phenomena have not been observed for another biomass type and, thus,
21 this alternative was not taken into consideration during the present sensitivity analysis.

22 **Figure 4 here**

23 The effect of plant size (capacity) on the unit production cost as well as revenue, net
24 profit, return of investment (ROI) and internal rate of return (IRR) for S1 and S2 may be seen

1 in figures 4b and 5. The unit production costs decrease nonlinearly with increasing plant size.
2 The unit production cost increase sharply with plant sizes less than 10,000 tonnes MP/year
3 while it is not affected significantly (the curve is almost flat) for plant sizes higher than
4 15,000 tonnes MP/year implying that a plant with a production capacity smaller than 10,000
5 tonnes MP per year would most probably be a very weak choice. This is clearly supported
6 also from the investment performance indexes (ROI and IRR) presented in figure 5 where
7 both ROI and IRR decrease sharply for plant sizes smaller than 10,000 tonnes MP /year for
8 S1 as well as for S2. While profit keeps increasing linearly with plant size, ROI and IRR
9 follow a rather different behavior where an increase of plant size above 10,000-15,000 tonnes
10 MP/year results to a disproportional smaller increase of these indexes. Given the fact that the
11 present economic evaluation has not taken into consideration the possible limitations with
12 wheat straw availability for large scale plants which could result in deterioration of these
13 indexes, one could conclude that a reasonable plant size would lie between 10,000 and 15,000
14 tonnes MP/year with an IRR (after tax) around 16%.

15 **Figure 5 here**

16 Payback time decreases and IRR increases when the selling price of the product
17 increases. The payback time for a plant with a capacity of 10,000 tonnes MP per year with
18 selling price of 3.50 and 3.95 \$/kg MP was estimated at 4.28 and 4.70 years for scenarios S1
19 and S2 respectively (see figure 6). When the selling price of MP was less than 2.8 \$/kg for S1
20 and 3.2 \$/kg for S2, IRR became zero and the investment could not be paid back. Thus one
21 can conclude that the above prices are the minimum MP selling prices for a plant with a
22 capacity of 10,000 tonnes MP per year.

23 **Figure 6 here**

24

1 *3.3 Alternative approach for heat and power production*

2 As it is evident from the figures in table 7, utility cost for both scenarios S1 and S2 became
3 quite high mainly due to the high purchase cost of steam. Therefore, instead of purchasing
4 steam, one could generate the necessary process steam in the plant's heat and power section
5 where wheat straw or rice straw or both, depending on the availability, could be combusted
6 for steam generation. As it can be seen in table 8, this would of course result in an increased
7 raw materials purchase cost (an additional 69100 tonnes/yr and 84800 tonnes /yr wheat straw
8 would be necessary for S1 and S2 respectively) and cost of heat and power section but it
9 would also considerably decrease the utility cost. Thus the total operating cost would be lower
10 and finally it would have been possible to operate the plant at the same capacity but at a lower
11 unit production cost. For example, if wheat straw alone was used for the generation of the
12 process steam required for the production of 10,000 tonnes MP per year, operating cost could
13 be reduced by 33 and 35 % and, similarly, unit production cost could be reduced to 1.84 and
14 2.16 \$/kg MP for S1 and S2 respectively (table 8). It needs to be mentioned here that, in the
15 present study, the butyric acid is meant as a commodity chemical and not as a fuel and, as
16 such, its production will always demand some external energy supplies. This production can
17 of course be pushed to a more sustainable direction if the external energy (e.g. electricity) can
18 be supplied by renewable sources such as wind or solar energy instead of fossil resources.

19

20 **Table 8 here**

21

22 **Conclusions**

23 A wheat straw based plant with a butyric acid production capacity of 10,000 tonnes per year
24 through pretreatment, enzymatic hydrolysis, fermentation and in-situ membrane extraction

1 was envisaged and economically evaluated in the present study. The plant design and
2 economic evaluation was based on processes simulation using SuperPro Designer® V9.0
3 software. The hypothetical plant was chosen to be located in India where the feedstock
4 purchase cost was found to be very low. Two different scenarios (S1 and S2) of fermentative
5 butyric acid production from wheat straw were developed and evaluated in this work.
6 Scenario S1 resulted in the production of butyric acid (89% purity) in mixture with acetic acid
7 and scenario S2 resulted in the production of butyric acid of 99% purity. The higher product
8 purity from scenario S2 was not enough for improving the economy of the process since the
9 utilities demand per unit of processed feedstock remained approximately the same and more
10 feedstock had to be handled in order to result at the same annual production capacity as S1.
11 Feedstock (wheat straw) purchase cost, which was relatively very small, was not found to
12 have any substantial impact on the economic efficiency of the plant. On the contrary, utilities
13 were the most decisive cost parameter mainly due to the consumption of relatively expensive
14 steam in the purification (distillation) section. When the selling price of butyric acid was less
15 than 2.8 \$/kg for S1 and 3.2 \$/kg for S2, IRR became zero and the investment could not be
16 paid back. Thus, one can conclude that the above prices are the minimum MP selling prices
17 for a plant with a capacity of 10,000 tonnes product per year. An alternative in-house steam
18 production through straw combustion could decrease the unit production cost down to 1.84
19 and 2.16 \$/kg of product for S1 and S2 respectively. Increasing plant size had a positive effect
20 on revenue and profit but could not significantly increase IRR. Given the fact that the present
21 study has not taken into consideration the possible limitations with wheat straw availability
22 and the resulting increase of feedstock purchase cost for large scale plants, a reasonable plant
23 size would lie between 10,000 and 15,000 tonnes of product per year.

24

1 Process flow diagrams for the two scenarios studied (S1 and S2) built on SuperPro Designer®
2 V9.0 platform are provided as supplementary material. Binary plots of 1-octanol and butyrate
3 and acetate are presented in the appendix
4

5 **Acknowledgement**

6 The authors wish to thank the Commission of the European Communities for the financial
7 support of this work under SUPRABIO project (FP7-cooperation).
8

9 **References**

- 10 Aden, A., Ruth, M., Ibsen, K., Jechura, J., Neeves, K., Sheehan, J., Wallace, B., Montague,
11 L., Slayton, A., Lukas, J., 2002. Lignocellulosic Biomass to Ethanol Process Design and
12 Economics Utilizing Co-Current Dilute Acid Prehydrolysis and Enzymatic Hydrolysis
13 for Corn Stover. Report No-NREL/TP-510-32438. 1617 Cole Boulevard Golden,
14 Colorado 80401-3393.
- 15 Antongiovanni, M., Sargentini, C., 1991. Variability in chemical composition of straws. In :
16 Tisserand J.-L. (ed.), Alibés X. (ed.). Fourrages et sous-produits méditerranéens .
17 Options Méditerranéennes Série A. Séminaires Méditerranéens 53, 49–53.
- 18 Bakker, R., Elbersen, W., Poppens, R., Lessche, J.P., 2013. Rice straw and Wheat straw.
19 Potential feedstocks for the Biobased Economy. Scientific report-. NL Agency NL
20 Energy and Climate Change, Croeslaan 15, 3521 BJ utrecht. Netherlands.
- 21 Baroi, G., Skiadas, I., Westermann, P., Gavala, H.N., 2015. Continuous fermentation of
22 wheat straw hydrolysate by *Clostridium tyrobutyricum* with in-situ acids removal. Waste
23 and Biomass Valorization. doi:10.1007/s12649-015-9348-5
- 24 Baroi, G.N., Baumann, I., Westermann, P., Gavala, H.N., 2015a. Butyric acid fermentation

1 from pretreated and hydrolysed wheat straw by an adapted *Clostridium tyrobutyricum*
2 strain. *Microb. Biotechnol.* 8, 874–882. doi:10.1111/1751-7915.12304

3 Baroi, G.N., Skiadas, I. V, Westermann, P., Gavala, H.N., 2015b. Continuous fermentation of
4 wheat straw hydrolysate by *Clostridium tyrobutyricum* with in-situ acids removal. *Waste*
5 *and Biomass Valorization*. doi:10.1007/s12649-015-9348-5

6 Batstone, D., Keller, J., Angelidaki, I., 2002. Anaerobic digestion model no. 1. Scientific and
7 technical report no. 13. IWA Task Group for Mathematical Modelling of Anaerobic
8 Digestion Process.

9 Bauer, A., Bösch, P., Friedl, A., Amon, T., 2009. Analysis of methane potentials of steam-
10 exploded wheat straw and estimation of energy yields of combined ethanol and methane
11 production. *J. Biotechnol.* 142, 50–5. doi:10.1016/j.jbiotec.2009.01.017

12 Biswas, R., Uellendahl, H., Ahring, B.K., 2013. Conversion of C6 and C5 sugars in
13 undetoxified wet exploded bagasse hydrolysates using *Scheffersomyces (Pichia) stipitis*
14 CBS6054. *AMB Express* 3, 42. doi:10.1186/2191-0855-3-42

15 Burkley, T., 2014. BRIEFING NOTE- Indian power prices. Institute for energy economics
16 and financial analysis, IEEFA, Australasia.

17 Buyukkamaci, N., Koken, E., 2010. Economic evaluation of alternative wastewater treatment
18 plant options for pulp and paper industry. *Sci. Total Environ.* 408, 6070–8.
19 doi:10.1016/j.scitotenv.2010.08.045

20 Cao, Y., Li, H., Zhang, J., 2011. Homogeneous synthesis and characterization of cellulose
21 acetate butyrate (CAB) in 1-Allyl-3-methylimidazolium chloride (AmimCl) ionic liquid.
22 *Ind. Eng. Chem. Res.* 50, 7808–7814. doi:10.1021/ie2004362

23 Dwidar, M., Park, J.-Y., Mitchell, R.J., Sang, B.-I., 2012. The future of butyric acid in
24 industry. *ScientificWorldJournal*. 2012, 471417. doi:10.1100/2012/471417

1 Galbe, M., Zacchi, G., 2002. A review of the production of ethanol from softwood. Appl.
2 Microbiol. Biotechnol. 59, 618–28. doi:10.1007/s00253-002-1058-9

3 Garde, A., 2002. Production of lactic acid from renewable resources using electro dialysis for
4 product recovery. PhD Diss. Technical University of Denmark.

5 Gavala, H.N., Angelidaki, I., Ahring, B.K., 2003. Kinetics and modeling of anaerobic
6 digestion process. Adv. Biochem. Eng. Biotechnol. 81, 57–93.

7 Georgieva, T.I., Hou, X., Hilstrøm, T., Ahring, B.K., 2008. Enzymatic hydrolysis and ethanol
8 fermentation of high dry matter wet-exploded wheat straw at low enzyme loading. Appl.
9 Biochem. Biotechnol. 148, 35–44. doi:10.1007/s12010-007-8085-z

10 Halvarsson, S., Edlund, H., Norgren, M., 2010. WHEAT STRAW AS RAW MATERIAL
11 FOR MANUFACTURE OF STRAW MDF. BioResources 5, 1215–1231.

12 Hansen, M.A., Hidayat, B.J., Mogensen, K.K., Jeppesen, M.D., Jørgensen, B., Johansen, K.S.,
13 Thygesen, L.G., 2013. Enzyme affinity to cell types in wheat straw (*Triticum aestivum*
14 L.) before and after hydrothermal pretreatment. Biotechnol. Biofuels 6, 54.
15 doi:10.1186/1754-6834-6-54

16 Harrison, R., Todd, P., Rudge, S., Petrides, D., 2013. Bioprocess Design and Economics, in:
17 Bioseparations Science and Engineering. pp. 1–83.

18 Horváth, I., Castillo, M. del P., Berglund Odhner, P., Teghammar, A., Mohseni Kabir, M.,
19 Olsson, M., Ascue, J., 2013. Biogas från lignocellulosa Tekno-ekonomisk utvärdering av
20 förbehandling med NMMO.

21 Humbird, D., Davis, R., Tao, L., Kinchin, C., Hsu, D., Anden, A., 2011. Process Design and
22 Economics for Biochemical Conversion of Lignocellulosic Biomass to Ethanol Process
23 Design and Economics for Biochemical Conversion of Lignocellulosic Biomass to
24 Ethanol.

1 Jha, A.K., Li, J., Yuan, Y., Baral, N., Ai, B., 2014. A review on bio-butyric acid production
2 and its optimization. *Int. J. Agric. Biol.* 16, 1019–1024.

3 Kazi, F.K., Fortman, J. a., Anex, R.P., Hsu, D.D., Aden, A., Dutta, A., Kothandaraman, G.,
4 2010. Techno-economic comparison of process technologies for biochemical ethanol
5 production from corn stover. *Fuel* 89, S20–S28. doi:10.1016/j.fuel.2010.01.001

6 Khanal, S.K., 2008. Methanogenic Bacteria, in: Khanal, S.K. (Ed.), *Anaerobic Biotechnology
7 for Bioenergy Production: Principles and Applications*. Wiley-Blackwell, pp. 35–37.

8 Kim, S., Dale, B.E., 2004. Global potential bioethanol production from wasted crops and crop
9 residues. *Biomass and Bioenergy* 26, 361–375. doi:10.1016/j.biombioe.2003.08.002

10 Kumar, D., Murthy, G.S., 2011. Impact of pretreatment and downstream processing
11 technologies on economics and energy in cellulosic ethanol production. *Biotechnol.
12 Biofuels* 4, 27. doi:10.1186/1754-6834-4-27

13 Kwiatkowski, J.R., McAloon, A.J., Taylor, F., Johnston, D.B., 2006. Modeling the process
14 and costs of fuel ethanol production by the corn dry-grind process. *Ind. Crops Prod.* 23,
15 288–296. doi:10.1016/j.indcrop.2005.08.004

16 Larsen, J., Haven, M.Ø., Thirup, L., 2012. Inbicon makes lignocellulosic ethanol a
17 commercial reality. *Biomass and Bioenergy* 46, 36–45.
18 doi:10.1016/j.biombioe.2012.03.033

19 Ljunggren, M., Wallberg, O., Zacchi, G., 2011. Techno-economic comparison of a biological
20 hydrogen process and a 2nd generation ethanol process using barley straw as feedstock.
21 *Bioresour. Technol.* 102, 9524–31. doi:10.1016/j.biortech.2011.06.096

22 Mangaraj, S., Kulkarni, S., 2011. Field Straw Management—A Techno Economic
23 Perspectives. *J. Inst. Eng.* 8, 153–159.

24 Marchetti, J.M., Miguel, V.U., Errazu, a. F., 2008. Techno-economic study of different

1 alternatives for biodiesel production. *Fuel Process. Technol.* 89, 740–748.
2 doi:10.1016/j.fuproc.2008.01.007

3 Molinuevo-Salces, B., Larsen, S.U., Ahring, B.K., Uellendahl, H., 2013. Biogas production
4 from catch crops: Evaluation of biomass yield and methane potential of catch crops in
5 organic crop rotations. *Biomass and Bioenergy* 59, 285–292.
6 doi:10.1016/j.biombioe.2013.10.008

7 Njoku, S.I., Ahring, B.K., Uellendahl, H., 2012. Pretreatment as the crucial step for a
8 cellulosic ethanol biorefinery: testing the efficiency of wet explosion on different types
9 of biomass. *Bioresour. Technol.* 124, 105–10. doi:10.1016/j.biortech.2012.08.030

10 Ou, L., Brown, T.R., Thilakaratne, R., Hu, G., Brown, R.C., 2014. Techno-economic analysis
11 of co-located corn grain and corn stover ethanol plants. *Biofuels, Bioprod. Biorefining* 8,
12 412–422. doi:10.1002/bbb.1475

13 OXEA, 2014. Oxea Announces Global Price Increases. News release 49, 1.

14 Peters, M.S., Timmerhaus, K.D., 1991. *Plant Design and Economics for Chemical Engineers*,
15 4th ed. ed. McGraw-Hill, Inc., New York.

16 Petersen, M.Ø., Larsen, J., Thomsen, M.H., 2009. Optimization of hydrothermal pretreatment
17 of wheat straw for production of bioethanol at low water consumption without addition
18 of chemicals. *Biomass and Bioenergy* 33, 834–840. doi:10.1016/j.biombioe.2009.01.004

19 Petrides, D., Carmichael, D., Siletti, C., Koulouris, A., 2014. Biopharmaceutical Process
20 Optimization with Simulation and Scheduling Tools. *Bioengineering* 1, 154–187.
21 doi:10.3390/bioengineering1040154

22 Purohit, P., Fischer, D.G., 2014. Second-generation biofuel potential in India: Sustainability
23 and Cost Considerations. Report from UNEP. Laxenburg, Austria.

24 Ramey, D.E., 1998. Continuous two stage, dual path anaerobic fermentation of butanol and

1 other organic solvents using two different strains of bacteria. Patent Number-5753474.

2 Rivard, C.J., Grohmann, K., 1991. DEGRADATION OF FURFURAL (2-FURALDEHYDE)

3 TO METHANE AND CARBON-DIOXIDE BY AN ANAEROBIC CONSORTIUM.

4 Appl. Biochem. Biotechnol. 28–9, 285–295. doi:10.1007/BF02922608

5 Sánchez-Segado, S., Lozano, L.J., de Los Ríos, a P., Hernández-Fernández, F.J., Godínez, C.,

6 Juan, D., 2012. Process design and economic analysis of a hypothetical bioethanol

7 production plant using carob pod as feedstock. Bioresour. Technol. 104, 324–8.

8 doi:10.1016/j.biortech.2011.10.046

9 Sauer, M., Porro, D., Mattanovich, D., Branduardi, P., 2008. Microbial production of organic

10 acids: expanding the markets. Trends Biotechnol. 26, 100–8.

11 doi:10.1016/j.tibtech.2007.11.006

12 Shafiei, M., Kabir, M.M., Zilouei, H., Sárvári Horváth, I., Karimi, K., 2013. Techno-

13 economical study of biogas production improved by steam explosion pretreatment.

14 Bioresour. Technol. 148, 53–60. doi:10.1016/j.biortech.2013.08.111

15 Shanmugam, S.R., Chaganti, S.R., Lalman, J.A., Heath, D.D., 2014. Effect of inhibitors on

16 hydrogen consumption and microbial population dynamics in mixed anaerobic cultures.

17 Int. J. Hydrogen Energy 39, 249–257. doi:10.1016/j.ijhydene.2013.10.084

18 Sikder, J., Roy, M., Dey, P., Pal, P., 2012. Techno-economic analysis of a membrane-

19 integrated bioreactor system for production of lactic acid from sugarcane juice. Biochem.

20 Eng. J. 63, 81–87. doi:10.1016/j.bej.2011.11.004

21 Stams, A.J.M., Elferink, S.J.W.H., Westermann, P., 2003. Metabolic Interactions between

22 Methanogenic Consortia and Anaerobic Respiring Bacteria, in: Ahring, B.K. (Ed.),

23 Biomethanation I. Springer-Verlag, pp. 43–45.

24 Statistik, D., 2014. Halm [WWW Document].

- 1 Taherzadeh, M.J., Karimi, K., 2008. Pretreatment of lignocellulosic wastes to improve ethanol
2 and biogas production: a review., *International journal of molecular sciences*.
3 doi:10.3390/ijms9091621
- 4 Wang, X., Wang, Y., Zhang, X., Feng, H., Xu, T., 2013. In-situ combination of fermentation
5 and electro dialysis with bipolar membranes for the production of lactic acid: continuous
6 operation. *Bioresour. Technol.* 147, 442–8. doi:10.1016/j.biortech.2013.08.045
- 7 Wooley, R., Ruth, M., Ibsen, K., Jechura, J., Neeves, K., Sheehan, J., Wallace, B., 2002.
8 Lignocellulosic biomass to ethanol process design and economics utilizing co-current
9 dilute acid prehydrolysis and enzymatic hydrolysis for Corn Stover, NREL/TP-510-
10 32438. 1617 Cole Boulevard, Golden, Colorado 80401-3393.
- 11 Zhang, C., Yang, H., Yang, F., Ma, Y., 2009. Current progress on butyric acid production by
12 fermentation. *Curr. Microbiol.* 59, 656–663. doi:10.1007/s00284-009-9491-y
- 13 Zhu, Y., Liu, X., Yang, S.-T., 2005. Construction and characterization of pta gene-deleted
14 mutant of *Clostridium tyrobutyricum* for enhanced butyric acid fermentation.
15 *Biotechnol. Bioeng.* 90, 154–66. doi:10.1002/bit.20354
- 16 Zidwick, M.J., Chen, Z.J., Rogers, P., 2013. Organic Acid and Solven Production: Propionic
17 and Butyric Acids and Ethanol, in: Rosenberg, E., DeLong, E.F., Lory, S., Stackebrandt,
18 E., Thompson, F. (Eds.), *The Prokaryotes*. Springer Berlin Heidelberg, Berlin,
19 Heidelberg, pp. 135–167. doi:10.1007/978-3-642-31331-8_385
- 20 Zigova, J., Ernest, S, Vandak D, S.S., 1999. Butyric acid production by *Clostridium*
21 *tyrobutyricum* with integrated extraction and pertraction. *Process Biochem.* 34, 835–843.
- 22 Zigova, J., Sturdik, E., 2000. Advances in biotechnological production of butyric acid. *J. Ind.*
23 *Microbiol. Biotechnol.* doi:10.1038/sj.jim.2900795
- 24 Öhrman, O.G.W., Weiland, F., Pettersson, E., Johansson, A.-C., Hedman, H., Pedersen, M.,

1 2013. Pressurized oxygen blown entrained flow gasification of a biorefinery lignin
2 residue. *Fuel Process. Technol.* 115, 130–138. doi:10.1016/j.fuproc.2013.04.009
3

1
2
3
4 Table 1. Major components of wheat straw as percentage of dry matter.

Polymers	(Petersen et al., 2009)	(Hansen et al., 2013)	(Georgieva et al., 2008)
Cellulose	35.0	42.3	41.8
Hemicellulose	22.3	24.0	25.3
Lignin	15.6	22.4	23.4
Ash	6.5	5.1	5.6
Others	20.9	Not reported	Not reported

5
6

1 Table 2: Stoichiometry of reactions and conversion efficiency assumed for the different unit
 2 processes involved in the present process model.

Reactions	Fraction (%) converted to product
<i>Pretreatment (Wet Explosion)</i>	
Cellulose + 1.11 H ₂ O → 1.11 Glucose	6.00
Cellulose → HMF + 3H ₂ O	0.09
Hemicellulose + 0.136 H ₂ O → 1.136 Xylose	61.56
Hemicellulose + 0.136 H ₂ O → 1.136 Arabinose	4.44
Hemicellulose → 0.64 Furfural + 0.36 H ₂ O	1.14
<i>Enzymatic hydrolysis</i>	
Cellulose + 1.11 H ₂ O → 1.11 Glucose	85.00
Hemicellulose + 0.136 H ₂ O → 1.136 Xylose	60.00
<i>Fermentation</i>	
Glucose + 0.63 Xylose → 0.24 Acetic acid + 1.47 Butyric acid + 2.79 CO ₂ + 2.64 H ₂ + 0.14 H ₂ O	100
<i>Methanogenesis</i>	
Acetate → Methane + CO ₂	100
Hydrogen + CO ₂ → Methane + H ₂ O	100

3

4

5

1

2 Table 3: Detailed operational parameters and technical characteristics of the unit operations and
 3 processes used in this model.

Unit Name	Type	Material of Construction	Details
WSH-101	Washer	CS	Silica removal efficiency >99%
SR-101	Shredder	CS	0.01 kW/(kg/h) Specific power
V-105	Sulfuric acid storage tank	SS316	Residence time 5 days, working to vessel volume ratio 90%
GP-101	Gear pump to transport straw into pretreatment reactor	SS316	Pressure change 5 bar, power efficiency 70%
PFR-102	Pretreatment reactor	SS316	Residence time 15 min, temperature 150 °C, total solids 15% specific power 0.1kW/m ³
V-101	Flash drum	CS	Pressure 1bar, residence time 5 min, work to vessel volume ration 60%, temperature 30°C
V-107	PH cotrol before saccharification	CS	residence time 0.5h, 0.1 kW/(kg/h) Specific power, 0.01% excess NaOH
V-106	Enzyme tank	SS316	Residence time 5 days, working to vessel volume ratio 90%
R-101	Sccharification reactor	SS316	Residence time 24h, temperature 32°C, specific power 0.1kW/m ³ , total solids 15%, working to vessel volume ratio 90%
BF-101	Belt filter for soilds seperation	CS	Solids in cake 50%, flow per unit belt width 10L/min-m, solids loading 3000 (kg/h)/m
V-104	Neutralizer	CS	residence time 0.5h, 0.1 kW/(kg/h) Specific power, 0.01% excess KOH
ST-101	Heat sterilizer	SS316	Sterilization temperature 140°C, exit temperature 41°C
R-102	Fermentation reactor	SS316	Residence time 1.28 (for S2) and 2 (for S1) days, temperature 37°C, specific power 0.1kW/m ³ , working to vessel volume ratio 90%, effluent split 0.88% of the total recirculation
V-108	Dialyzate tank	SS316	Residence time 1 day, working to vessel volume ratio 90%
G2	REED+EDBM	CS	REED (power 0.1547 kW/(kg/h), current efficiency 0.7, current density 500A/m ² , average recovery 92%); EDBM (power 0.1547 kW/(kg/h), current efficiency 0.72, current density 1000A/m ² , average recovery 100%), butyric acid final concentration 5.5%
V-103	Acid storage tank	SS316	Residence time 2h, working to vessel volume ratio 90%
MSX-101	Mixer-settler extractor	SS316	Mixer residence time 0.5h, settler residence time 1h, temperature 32 °C, specific power

0.5kW/(kg/h)

C-101	Distillation column	CS	Number of stages 25, Reboiler temperature 175 ⁰ C, condenser temperature 165 ⁰ C, column pressure 1bar, max dia 2 m, stage height 0.4m
PM-101	Boiler feed water pump	SS316	Pressure change 94 bar, power efficiency 70%
SG-101	Steam generator	CS	Excess oxygen 10%, overall heat loss 5%, flue gas exit temperature 120 ⁰ C
T-101	Steam turbine	CS	Power generator efficiency 90 % of shaft power, 3 stages (high pressure steam 180 ⁰ C, low pressure steam 150 ⁰ C and bleed)

1

2

1

2 Table 4. Raw material prices used in this model.

Item Name	Price^a	Unit	Reference
Wheat straw	0.0125	\$/kg	(Mangaraj and Kulkarni, 2011)
Enzyme	0.571	\$/kg	(Kumar and Murthy, 2011)
Sulfuric acid	0.035	\$/kg	(Kumar and Murthy, 2011)
NaOH	0.45	\$/kg	(Kumar and Murthy, 2011)
KOH	0.189	\$/kg	(Ljunggren et al., 2011)
Urea	0.649	\$/kg	(Sánchez-Segado et al., 2012)
Phosphate	0.891	\$/kg	(Sánchez-Segado et al., 2012)

^aConversion factor: 1 US\$ =0.74 EUR

3

4

1

2 Table 5: Summary of the economics and mass and energy requirements for scenarios S1 and S2

	S1	S2	Unit
Total Capital Investment	47.71	53.68	million \$
Capital Investment Charged to this project (100%)	47.71	53.68	million \$
Operating Cost	27.52	33.12	million \$/yr
Credits	4.65	5.56	million \$/yr
Net Operating Cost	22.87	27.56	million \$/yr
Revenues	35.05	39.46	million \$/yr
Unit Production Cost	2.75	3.31	\$/kg MP
Net Unit Production Cost	2.29	2.76	\$/kg MP
Unit Production Revenue	3.51	3.95	\$/kg MP
Gross Margin	34.75	30.16	%
Return On Investment	23.35	21.28	%
Payback Time	4.28	4.7	years
IRR (After Taxes)	14.92	12.42	%
NPV (at 7.0% Interest)	28.56	21.11	million \$
Cost Basis Annual Rate	10000.07	10000.04	tonnes MP/yr
Feed stock (wheat straw)	46150.21	51611.59	tonnes/yr
Efficiency (mass MP/mass wheat straw)	0.22	0.19	
Power (electricity) demand	34831.14	38960.81	MW-h/yr
Net steam demand	17553.71	19630.00	tonnes/yr
Net steam (high P) demand	162987.52	201139.12	tonnes/yr

3 MP = Total flow of acid or mixed acids as main product

4 IRR = Internal Rate of Return

5 NPV = Net Present Value

6

7

8

1

2 Table 6: Direct fixed cost summary (year 2014 prices in million \$) for scenarios S1 and S2.

	S1	S2
<i>A. Total Plant Direct Cost (TPDC) (physical cost)</i>		
1. Equipment Purchase Cost	9.42	10.53
2. Installation	3.67	4.11
3. Process Piping	2.92	3.26
4. Instrumentation	2.45	2.74
5. Insulation	0.28	0.32
6. Electrical	0.94	1.05
7. Buildings	2.73	3.05
8. Yard Improvement	1.13	1.26
9. Auxiliary Facilities	4.71	5.27
<i>B. Total Plant Indirect Cost (TPIC)</i>		
10. Engineering	3.11	3.48
11. Construction	3.40	3.80
<i>C. Total Plant Cost (TPC = TPDC+TPIC)</i>		
	34.76	38.85
<i>D. Contractor's Fee & Contingency (CFC)</i>		
12. Contractor's Fee	1.74	1.93
13. Contingency	3.82	4.27
<i>E. Direct Fixed Capital Cost (DFC = TPC+CFC)</i>		
	40.32	45.07

3

4

5

1

2 Table 7: Annual operating costs (million \$) distribution for an annual production of 10,000 tonnes

3 MP for both scenarios (S1, S2) for the year 2014.

	S1	% of Total	S2	% of Total
<i>Labor</i>				
Operator	0.73	2.65%	1.07	3.23%
<i>Raw Materials</i>				
Enzyme mix	0.40	1.45%	0.46	1.39%
Wheat straw (86%DM)	0.55	2.00%	0.62	1.87%
KOH	0.002	0.01%	0.002	0.01%
Octanol,1	0.04	0.15%	0.05	0.15%
K ₂ HPO ₄	0.14	0.51%	0.15	0.45%
NaOH	0.28	1.02%	0.32	0.97%
H ₂ SO ₄	0.03	0.11%	0.03	0.09%
Urea	0.70	2.54%	0.80	2.42%
Water	0.07	0.25%	0.08	0.24%
<i>Consumables</i>				
EDBM membrane	0.68	2.47%	0.77	2.32%
Anion exchange membrane	0.36	1.31%	0.41	1.24%
Cation exchange membrane	0.42	1.53%	0.48	1.45%
NaOH [‡]	0.003	0.01%	0.003	0.01%
<i>Waste Disposal</i>				
Ash	0.04	0.15%	0.04	0.12%
Wash waste water	0.31	1.13%	0.35	1.06%
Effluent	0.34	1.24%	0.39	1.18%
<i>Utility</i>				
Std Power	2.41	8.76%	2.76	8.33%
Steam	0.21	0.76%	0.23	0.69%
High Pressure steam	9.41	34.19%	11.84	35.75%
Cooling Water	2.61	9.48%	3.28	9.90%
<i>Facility-Dependent</i>				
Laboratory/QC/QA	0.11	0.40%	0.16	0.48%
TOTAL	27.52		33.12	

4 ‡ For the sake of calculation NaOH used in REED and EDBM system is considered as consumable

5

6

7

8

1

2 Table 8: Economic summary and operating cost distribution (year 2014) for S1 and S2 when
 3 considering in-house steam generation by CHP unit.

	S1	S2
Total Capital Investment (million\$)	49.04	54.14
Operating Cost (million\$)	19.34	22.99
Unit Production Cost (\$/kgMP)	1.84	2.16
Direct Fixed Capital (million\$)	42.53	47.24
Operating cost (2014 prices) summary (million\$)		
Cost Item		
Raw Materials	2.62	3.04
Labor-Dependent	0.73	1.07
Depreciation	4.04	4.50
Other Facility-Dependent	4.20	4.66
Laboratory/QC/QA	0.11	0.16
Consumables	1.54	2.62
Waste Treatment/Disposal	0.75	0.87
Utilities	5.26	6.36
Total	19.24	23.27

4

5

1 APPENDIX A

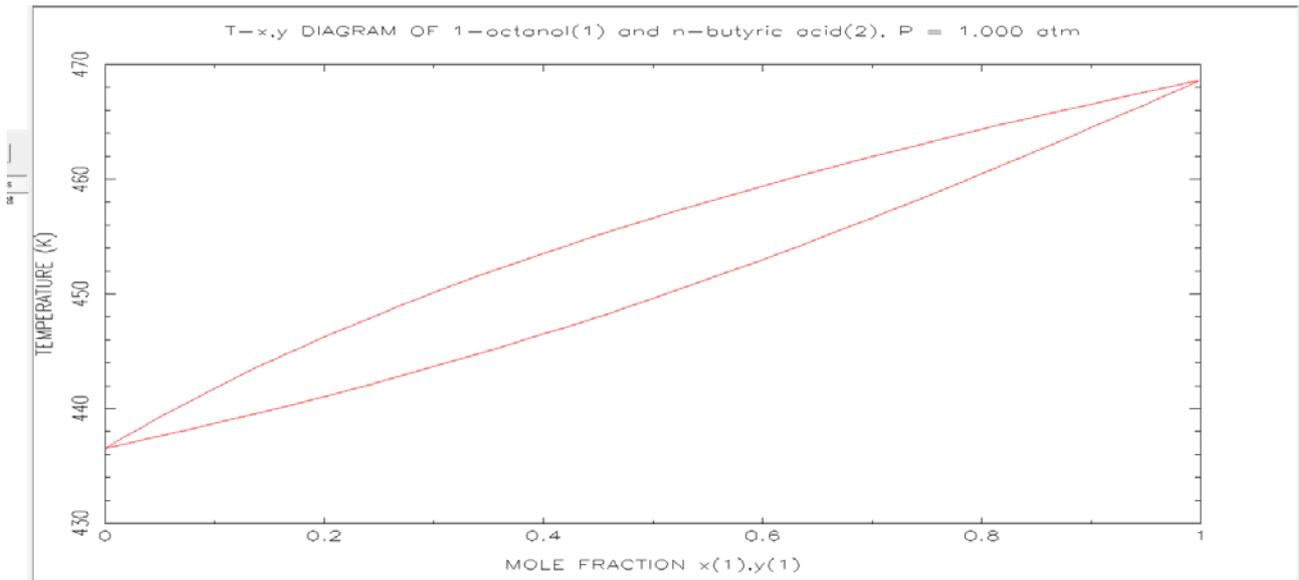
2 Table A1: Purchase cost (year 2014) and size or capacity of equipment unit used in this model for
3 10,000 tonnes MP production.

Name	Description	S1 Cost (\$)	S2 Description	S2 Cost (\$)
<i>Feed stock handling</i>				
WSH-101	Washer (Bulk Flow) Size/Capacity = 5.56 MT/h	1000	Washer (Bulk Flow) Size/Capacity = 6.29 MT/h	1000
SR-101	Shredder Size/Capacity = 5.52 MT/h	190000	Shredder Size/Capacity = 6.24 MT/h	204000
<i>Pretreatment</i>				
V-105	Vertical-On-Legs Tank Vessel Volume = 7.12 m ³	22000	Vertical-On-Legs Tank Vessel Volume = 8.05 m ³	24000
GP-101	Gear Pump Pump Power = 6.48 kW	16000	Gear Pump Pump Power = 7.33 kW	18000
PFR-102	Plug Flow Reactor Vessel Volume = 1.24 m ³	286000	Plug Flow Reactor Vessel Volume = 1.40 m ³	308000
HX-104	Heat Exchanger Heat Exchange Area = 99.60 m ²	2032000	Heat Exchanger Heat Exchange Area = 94.83 m ²	2337000
V-101	Flash Drum Vessel Volume = 4507.80 L	2000	Flash Drum Vessel Volume = 5096.95 L	2000
<i>Saccharification</i>				
V-107	Neutralizer Vessel Volume = 18.10 m ³	89000	Neutralizer Vessel Volume = 20.47 m ³	95000
V-106	Vertical-On-Legs Tank Vessel Volume = 11.96 m ³	11000	Vertical-On-Legs Tank Vessel Volume = 13.52 m ³	12000
R-101	Stirred Reactor Vessel Volume = 872.42 m ³	355000	Stirred Reactor Vessel Volume = 986.45 m ³	382000
BF-101	Belt Filter Belt Width = 0.54 m	274000	Belt Filter Belt Width = 0.61 m	276000
<i>Fermentation and seperation</i>				
V-104	Neutralizer Vessel Volume = 16.53 m ³	84000	Neutralizer Vessel Volume = 18.70 m ³	90000
ST-101	Heat Sterilizer Rated Throughput = 29.89 m ³ /h	722000	Heat Sterilizer Rated Throughput = 33.80 m ³ /h	750000
R-102	Stirred Reactor Vessel Volume = 1030.02 m ³	392000	Stirred Reactor Vessel Volume = 1746.89 m ³	539000
V-108	Vertical-On-Legs Tank Vessel Volume = 353.49 m ³	165000	Vertical-On-Legs Tank Vessel Volume = 401.63 m ³	176000
REED+EDBM	Generic Box	695000	Generic Box	767000

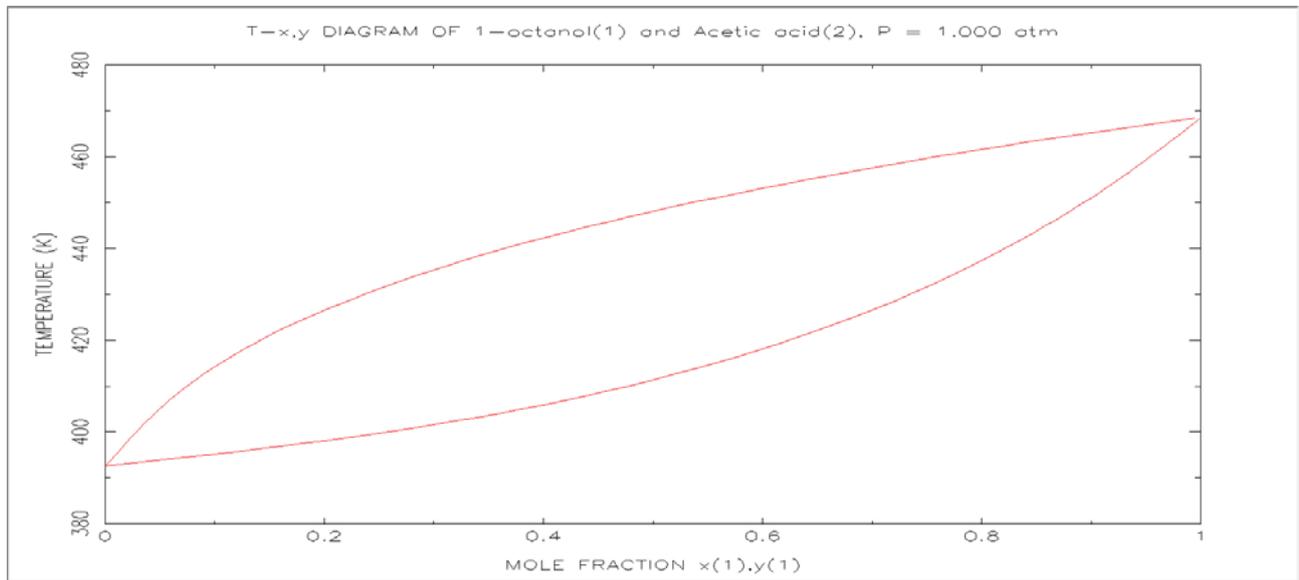
	Size/Capacity = 20638.49 kg/h		Size/Capacity = 23339.16 kg/h
<i>Purification</i>			
V-103	Flat Bottom Tank Vessel Volume = 46.46 m ³	99000	Flat Bottom Tank Vessel Volume = 52.56 m ³
MSX-101	Mixer-Settler Extractor Rated Throughput = 154333.01 L/h	325000	Mixer-Settler Extractor Rated Throughput = 174515.94 L/h
HX-102	Heat Exchanger Heat Exchange Area = 5.08 m ²	21000	Heat Exchanger Heat Exchange Area = 5.29 m ²
HX-103	Heat Exchanger Heat Exchange Area = 91.02 m ²	1200000	Heat Exchanger Heat Exchange Area = 96.02 m ²
C-101	Distillation Column Column Volume = 50.99 m ³	201000	Distillation Column Column Volume = 57.71 m ³
HX-101	Heat Exchanger Heat Exchange Area = 71.69 m ²	104000	Heat Exchanger Heat Exchange Area = 80.17 m ²
<i>Heat and power generation</i>			
PM-101	Centrifugal Pump Pump Power = 3.71 kW	34000	Centrifugal Pump Pump Power = 4.44 kW
SG-101	Steam Generator Throughput = 10116.47 kg/h	180000	Steam Generator Throughput = 12093.81 kg/h
T-101	Multi-Stage Steam Turbine Turbine Delivered Shaft Power = 16.91 kW	37000	Multi-Stage Steam Turbine Turbine Delivered Shaft Power = 21.95 kW
	Unlisted Equipment	1884000	Unlisted Equipment
	Total (\$)	9420000	10529000

1

2



1



2

3 Figure A1. Binary phase diagrams for octanol/butyrate and octanol/acetate. No azeotrope formation
 4 is predicted. Thermodynamic model used included: equation of state, Soave-Redlich-Kwong;
 5 mixing rule, Modified Huron Vidal of 1st order; excess Gibbs energy model, UNIFAC VLE1.

6

7

Figure1



Figure 1: Process flow diagram showing different process steps

Wheat Straw to Butyric acid

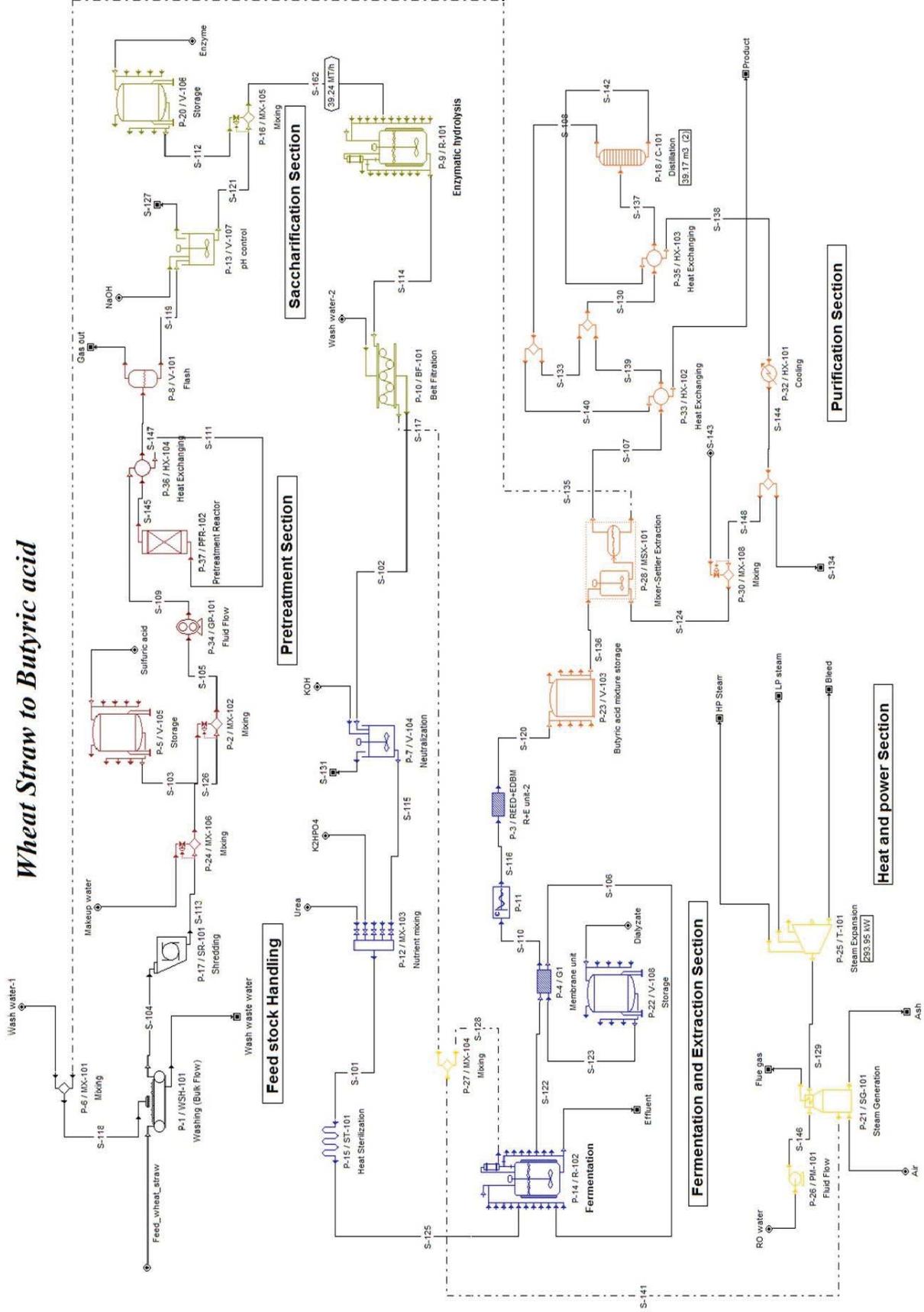


Figure 2: Process flow diagram for the production of acids from wheat straw.

Figure3

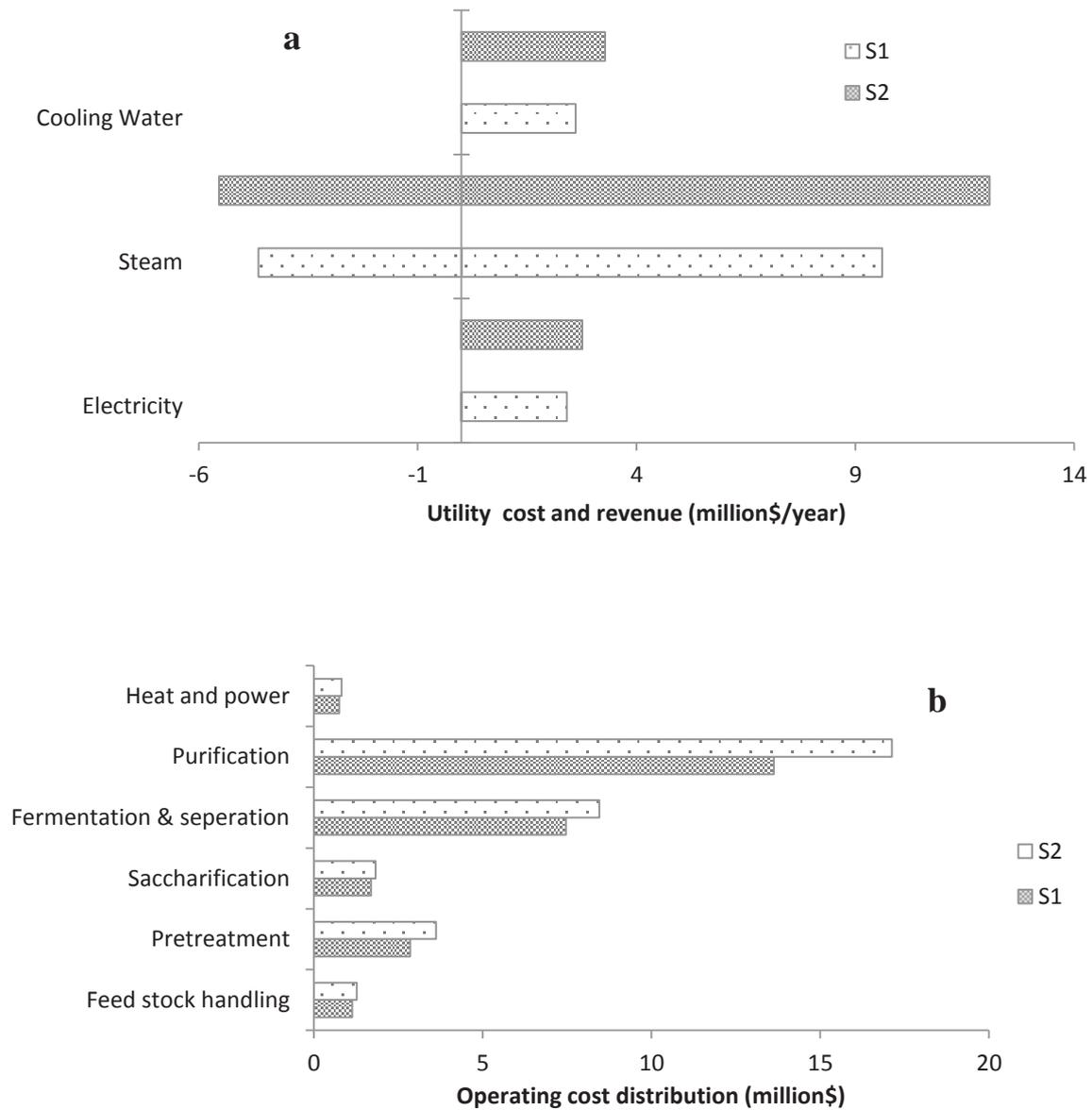


Figure 3: (a) Costs of utility and credit from heat and power section for both S1 and S2 scenarios. Credits are shown on the left side (negative) and costs are shown on the right side (positive). (b) Operating costs distributed among the six sections of the process and comparison between scenario S1 and S2.

Figure4

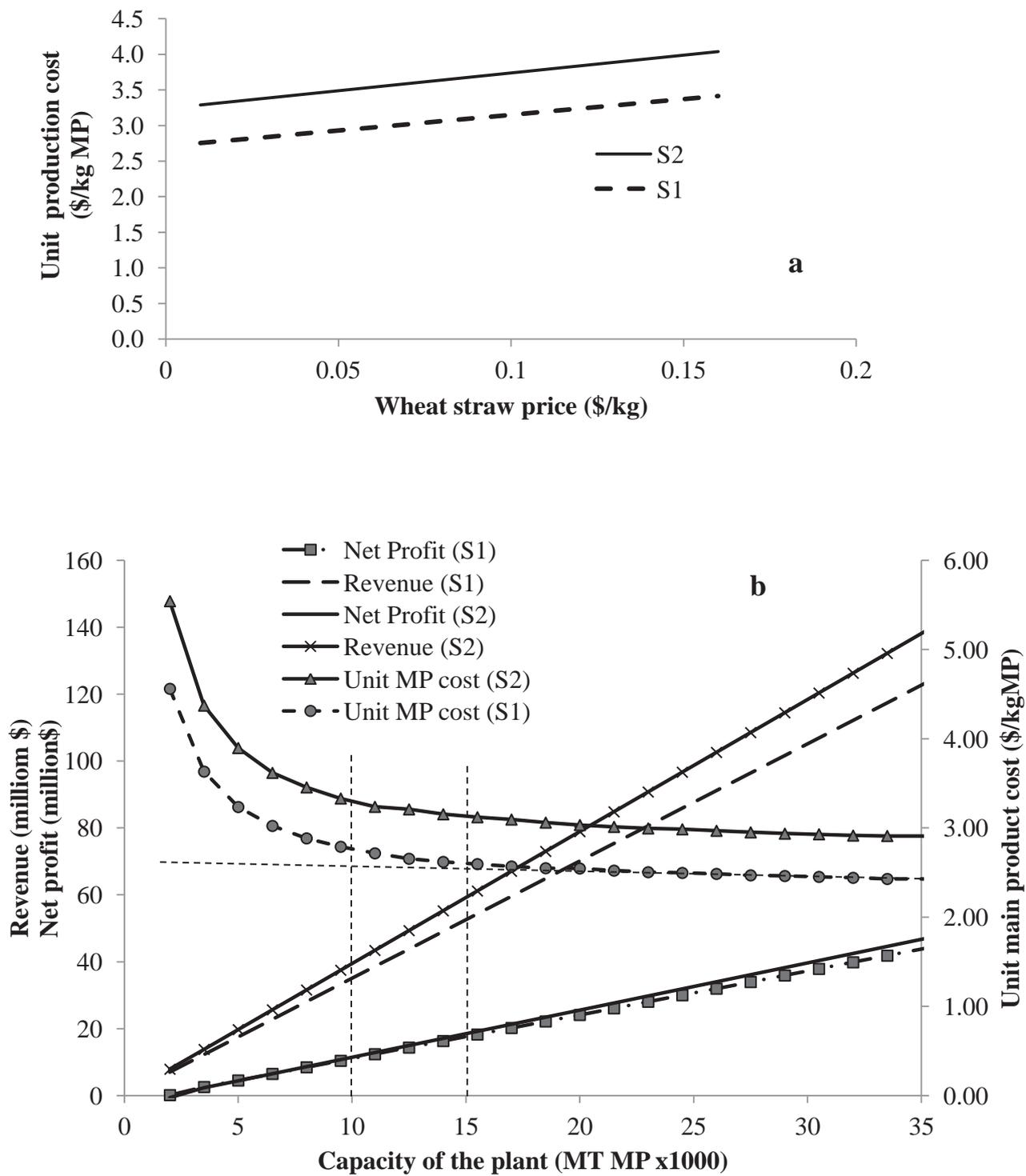


Figure 4: Effect of wheat straw price on unit production cost of MP (a) and effect of plant size on unit production cost of MP, revenue and net profit (b) for both S1 and S2 scenarios.

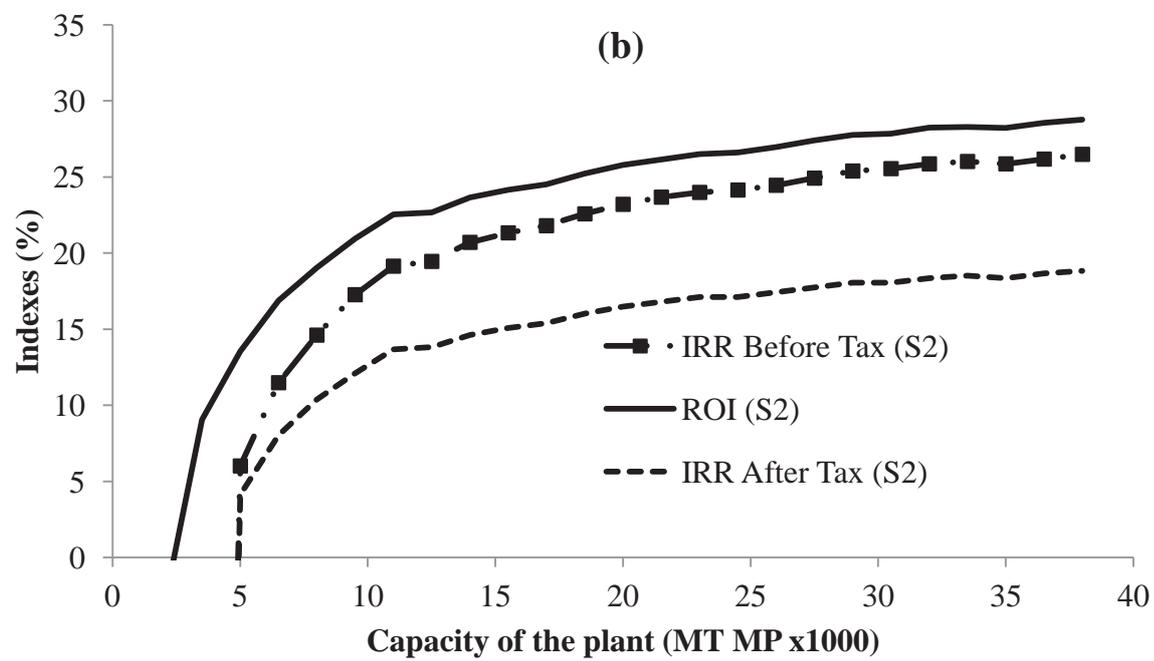
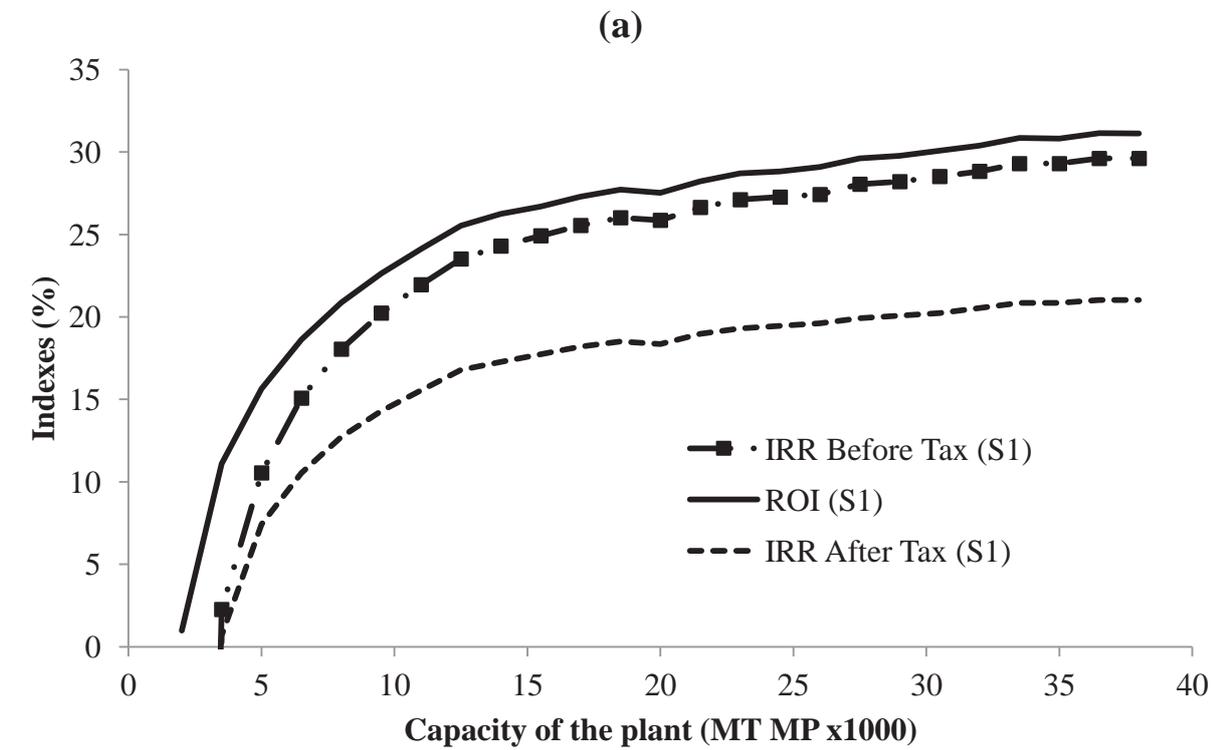


Figure 5: Effect of plant size on ROI and IRR before and after tax for scenario S1 (a) and scenario S2 (b).

Figure6

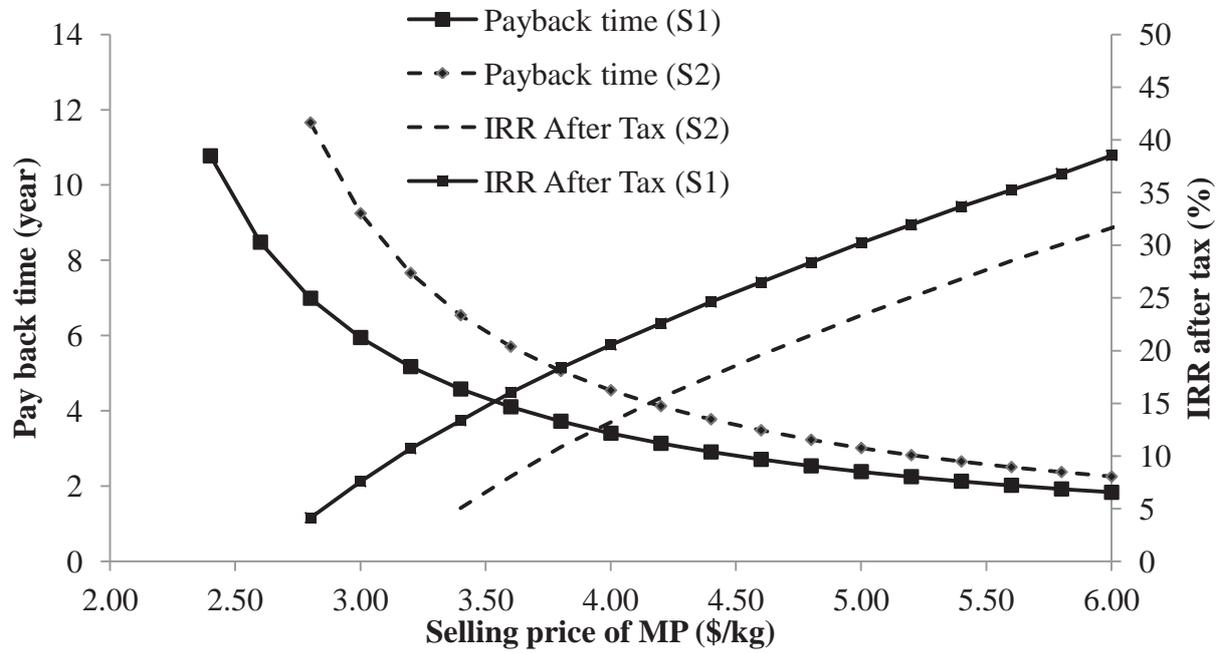


Figure 6: Effect of selling price of MP on payback time and IRR for both S1 and S2 scenarios for a plant with a capacity of 10,000 tonnes MP per year.

Figure Captions

Figure 1: Process flow diagram showing different process steps

Figure 2: Process flow diagram for the production of acids from wheat straw.

Figure 3: (a) Costs of utility and credit from heat and power section for both S1 and S2 scenarios. Credits are shown on the left side (negative) and costs are shown on the right side (positive). (b) Operating costs distributed among the six sections of the process and comparison between scenario S1 and S2.

Figure 4: Effect of wheat straw price on unit production cost of MP (a) and effect of plant size on unit production cost, revenue and net profit (b) for both S1 and S2 scenarios.

Figure 5: Effect of plant size on ROI and IRR before and after tax for scenario S1 (a) and scenario S2 (b).

Figure 6: Effect of selling price of MP on payback time and IRR for both S1 and S2 scenarios for a plant with a capacity of 10,000 tonnes MP per year.

Process flow diagram of S1 in SuperPro Designer format

[Click here to download Supplementary Interactive Plot Data \(CSV\): withoutmethane-1002-dp_octanol.spf](#)

Process flow diagram of S2 in SuperPro Designer format

[Click here to download Supplementary Interactive Plot Data \(CSV\): withmethane-1002-dp_octanol.spf](#)