Process design and economic analysis of a hypothetical bioethanol production plant using carob pod as feedstock

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Abstract

A process for the production of ethanol from carob (Ceratonia siliqua) pods was designed and an economic analysis was carried out for a hypothetical plant. The plant was assumed to perform an aqueous extraction of sugars from the pods followed by fermentation and distillation to produce ethanol. The total fixed capital investment for a base case process with a capacity to transform 68,000t/year carob pod was calculated as 39.61millon euros (€) with a minimum bioethanol production cost of 0.51€/L and an internal rate of return of 7%. The plant was found to be profitable at carob pod prices lower than 0.188€/kg. An increase in the transformation capacity of the plant from 33,880 to 135,450 t/year was calculated to result in an increase in the internal rate of return from 5.50-13.61%. The obtained results in this study show that carob pod is a promising alternative source for bioethanol production.

Keywords: bioethanol, carob pod, economic analysis, process design

1. Introduction

The EU target for 2020 is for biofuels to contribute 10% of the energy used by the transport sector. In the EU, bioethanol is mainly produced from wheat, corn, rye and sugar beet, crops which are also used for human consumption. Ethanol production from non-food crops or waste biomass would be preferable, and carob (*Ceratonia siliqua*) has been studied as a crop from the Mediterranean region for ethanol production (Sánchez *et al*., 2010). The carob tree is an evergreen shrub or tree native to the Mediterranean region and is being evaluated as a crop for dryland areas for diversification and revitalization of coastal agriculture (Tous, 1996). Carob is drought-resistant, requires little attention and produces seeds from which locust bean gum (LBG) is obtained. The pods are currently used for animal feed or ground into carob powder (Avallone et al., 1997; Roukas, 1994; Tous, 1984). The pods have a sugar content of around 50% and the sugars can be extracted with water in less than 30 min (Sánchez *et al*., 2010). Fermentation of the aqueous extracts provided ethanol yields of 47.5%. Studies concerned with the production of ethanol from carob pod have focused mainly on technical aspects. Fermentation carried out with *Zymomonas mobilis* yielded a maximum ethanol production of 0.34 g g^{-1} initial sugars (Vaheed et al., 2011), and utilizing *Saccharomyces cerevisiae*, maximum ethanol yields of 0.37 (Turhan *et al*., 2010), 0.47 (Sánchez *et al*, 2010),and 0.21 g g^{-1} initial sugars (Roukas, 1994) were obtained. Since no economic studies on carob-based ethanol production have been carried out, the economic feasibility of a proposed industrial process was examined in the present study. The effect of variations in the cost of the feedstock and plant capacity was analyzed.

2. Material and Methods

2.1. Process description

Figure 1 shows a schematic diagram for the overall carob to ethanol process proposed and assessed in this study, and Table S.1 (see Supplementary data) shows the equipment list and its specifications. The base case process was assumed to be 68,000 tons carob pod per year as the annual carob pod production in Spain ranges from 60,000 to 65,000 tons/year (Mondial Carob Group, personal communication) but capacities from 33,880 to 135,450 tons per year were also considered. Since the pods contain 13.6% of moisture and 45.0% of total sugars, (4.1% glucose, 8.4% fructose and 32.4% of sucrose) (Sánchez *et al.* 2010), the global carob to ethanol process yield (extraction, fermentation, distillation and dehydration stages) ranges between 19,200 and 20,800 m^3 of fuel ethanol (>99.95%) per year (Sergio *et al.*,2010). The proposed process was assumed to operate 330 days/year and is composed of the following sections: (i) storage, (ii) sugar extraction, (iii) fermentation, (iv)ethanol recovery and (v) drying sections and (vi) co-generation plant..

[Insert Figure 1 about here]

2.1.1. Storage section

The total stored capacity was assumed to be 6000 tons. Storage of weighed pods is envisioned in three storage piles (one is working, one is in stock and the last one is in charge), each with a capacity of 2,000 tons and are covered by a sunshade for a maximum period of a month. Then, the pods are stored in five hoppers (F 101 to F-105) to ensure a continuous feeding to the plant. And finally its transported to sugar extraction facility by means of a bucket conveyor (J-101).

2.1.2. Sugar extraction section

In this section, the size of the pod is decreased to an average of 0.57 mm by wet milling (C-201), which is the first stage of a system withfour counter-current extraction stages at room temperature. The others three stages are composed of three stirred tank reactors (R-201 to R-203) with a solid/liquid (S/L) separation among stages (H-201 to H-203). These solid/liquid separations are carried out using a vibrating screen with a 0.5 mm mesh size. With the aim of reducing the solid waste moisture content to 30-40%, the resulting slurry is introduced in two parallel filter presses (H-204 to H-205). The yield of the process is aproximately 97% sugar recovery from the pod (Sergio *et al.*, 2011).

2.1.3. Fermentation section

A batch fermentation process with *Saccharomyces cerevisiae* is envisioned. The sugar solution is sterilized in two stages using heat exchangers. In the first stage (H-301) the solution is heated by using the recirculated sterilized solution from the second heat exchanger as heating fluid, and in the second stage (H-302) its temperature is increased to 95 ºC with steam. The working temperature for the fermentation process is 35 ºC, which is reached in two stages, by using the fresh solution as cooling fluid (H-301) and cooling water in the second stage (H-303). The initial pH value of 4.0 is kept constant automatically (F-301). Phosphate and urea solutions are added to the fermentation broth using storage tank F-302.

The fermentation process is carried in a set of jacketed, stirred bioreactors in three progressive scales: (i) three inoculated bioreactors (10 m^3 capacity) (R-301 to R-303), (ii) four medium bioreactors (75 m^3 capacity) (R-304 to R-307) and (iii) five large bioreactors (600 m^3 capacity) (R-308 to R-312). In the last set of bioreactors 95.5 g/L of ethanol can be obtained for every 200 g/L of total sugars (Sergio *et al.*, 2010).

2.1.4. Ethanol recovery section

Ethanol recovery was simulated using the process simulator CHEMCAD 6.0 (ChemCad, 2011). The UNIFAC (**Poling *et al.*, 2004)** method was used to estimate equilibrium conditions. The bioreactor outlet is envisioned to be connected to the distillation columns. In the first column (T-401), the minimum number of ideal stages was 20 and the energy consumption of the reboiler was 1165.8 kcal/kg of ethanol. In this column a head product with 82.3% weight of ethanol is obtained. This stream goes to the second distillation column (T-402) where the minimum number of ideal stages was found to be 10 with an energy consumption of 285 kcal/kg of ethanol in the reboiler. A head stream with 87% weight of ethanol was obtained. This is then concentrated in two parallel molecular sieves (D-401 to D-402) until fuel grade ethanol (> 99.5%) is obtained (Simo *et al*., 2008).

2.1.5. Drying section

The solid wastes produced in the sugars extraction section are envisioned to be dried in a rotary oven (Q-501) to 10% moisture and used for livestock consumption (dried distillers grains, DDG´s). The oven is heated by the hot gases coming from the co-generation plant (section 2.1.6). The dry solids are stored in piles of 1,500 tons.

2.1.6. Co-generation plant.

In this section, 3.15 Nm^3 natural gas,/kg ethanol are burnt in a gas turbine (N-A01) to produce electricity. The hot gases are the inlet of a steam generator (H-A01), which supplies steam for the distillation and fermentation sections, and feed a steam turbine (N-A02) with the aim of producing more electricity.

The outlet gases from the steam generator are hot enough to be used for solid waste drying. The overall yield of this process was estimated at 60%, while the electricity produced was 18.24 KWh/kg ethanol, which is enough to cover the whole electricity demand with an extra of 16.46 KWh/kg ethanol.

Table 1 summarizes the technical data for inputs and outputs in the hypothetical ethanol refinery considered for the base case.

[Insert Table 1 about here]

2.2. Economics

For economic evaluation, yields and process parameters were extracted from Sánchez *et al.* (2010). Equipment, chemicals and labor costs were indexed to 2009 using Marshall and Swift cost index (Chemical Engineering, 2010). Working capital was taken to be 40% of fixed capital investment, grants from Spanish Council (Ministry of Industry, 2009), represent 30% of fixed capital investment, and loans are 30% of fixed capital investment with an amortization rate of 10% for five years starting one year before implementation. The project life was fixed in 10 years, and annual inflation was fixed at 4%, following the modified accelerated cost recovery system method (Brown, 2007). The residual value of the investment is taken as 50%.

The equipment was sized using material balances given by Sánchez *et al.* (2010) and the recommendations of Branan (2002) and Brown (2007). The fixed capital investment (FIC) of the plant is the total cost of major equipment, auxiliary equipment, cost of buildings and other costs, such as contract fees, freight, engineering, contingencies, research and development. **The capital cost investment for the base case was evaluated using the Chilton method (Peters *et al.*, 2003).** Table 2 summarizes the operating cost used in the economic evaluation.

[Insert Table 2 about here]

Following Lohrasbi *et al.* (2010), ethanol production costs were calculated as the selling price of ethanol at the plant gate that makes the net present value (NPV) of the process (Eq.1) equal to zero.

$$NPV = \sum_{t=0}^{t=n+1} \frac{CF_t}{(1+r)^t (1+p)^t} \qquad [1]$$

where CF_t is the cash flow at time t, r is the discount rate, p is the inflation rate and n is the number of years.

2.3. Sensitivity analysis

In order to choose a suitable discounted cash flow rate of return, the following interval [5:1:12] was tested to solve the base case and analyze the ethanol production cost.

Variations in the cost of the feedstock and its influence in the internal rate of return (IRR) were studied for the base case (Fig.4.).

The plant capacity was also investigated. For this purpose, plant sizes of 33.88, 50.85, 68.00, 101.61 and 135.45 thousand tons of carob pod per year were **evaluated**. The cost of utilities, as well as the number of employees, were assumed to be unaffected. **The price of feedstock, DDG´s and bioethanol credits were fixed at 0.17 €/kg, 0.17 €/kg and 0.55 €/L, respectively.**

The equipment cost for other capacities and the new invesment cost for **the** different capacities **were calculated using Williams (Eq.2)** and Chilton method (Peters *et al.*, 2003), with the base case as reference, respectively. The Williams exponent selected was 0.6.

$$New\ Cost = Original\ Cost \left(\frac{New\ Capacity}{Original\ Capacity} \right)^{0.6} \qquad [2]$$

3. Results and Discussion

3.1. Capital cost investment

Table 3 shows a summary of the process evaluation and the factors used for calculating the fixed capital investment.

[Insert Table 3 about here]

The capital investment of a bioethanol plant depends on the type of feedstock and the location and scale of the plant. Deurwaarder and Reith (2006) estimated the capital cost of bioethanol plants in Europe in 2003. By updating these results for the year 2009 using Marshall and Swift's annual index (Chemical engineering, 2010), for small installations (15,800 ton/year bioethanol), the capital investment is 26.2 millon € for sugar plants and 39.3 millon € for potato and grain plants. The FIC for a bioethanol production plant utilizing carob pod with a production 15,053 ton/year bioethanol (base case) is 39.6 million euros, which is similar to that reported by these authors for potato and grain plants.

3.2. Discounted cash flow rate of return

With the aim of choosing a suitable discounted cash flow of return, the base case was evaluated for values of this parameter of between 5 and 12%. Fig. 2 shows the results obtained for bioethanol production costs.

[Insert Figure 2 about here]

Ethanol production costs increase with an increase in the discounted cash flow of return. A minimum bioethanol production cost of 0.51 €/L gives a discounted cash flow rate of return of 7%, which is a suitable value, and allows fixing the price of bioethanol at 0.55 €/L. Bearing in mind the bioethanol production costs from different feedstocks depicted in Table 4 (Balat and Balat, 2009), the fixed price of bioethanol obtained from carob pod (0.55 €/L) is competitive with that obtained from other feedstocks, such as wheat, corn, sugar beet and lignocellulosic materials.

In Spain bioethanol is mainly produced by corn and barley, the production capacity of these crops are 0.30 Kg bioethanol/kg corn and 0.26 Kg bioethanol/kg barley respectively (Lechón et al., 2005), for carob pod this value is 0.22 Kg bioethanol/kg pod. As can be seen from the above data, carob pod yield is slightly lower. The prices of these feedstocks are 0.17 €/kg for barley and carob pod and 0.21 €/kg for corn (Consejería Agricultura y Agua (2010). The main reason why carob pod is not a major source for bioethanol production is the time needed to obtain sufficient biomass from each tree. Tous (1984) reported an average of 15 years for a production capacity of 60-120 Kg pods/tree year; however, advances in genetic engineering might overcome this disadvantage.

[Insert Table 4 about here]

3.3. Effect of the feedstock price in base case process economics

For this evaluation we considered the operating costs summarized in Table 2. As can been observed in Table 2, the DDG´s credits are considered to be the same as the feedstock acquisition price for economic evaluation in all cases. The bioethanol price was fixed at 0.55 €/L. Fig. 3 shows the variation of the internal rate of return with the feedstock price.

[Insert Figure 3 about here]

IRR values higher than 7% can be reached if the price of the feedstock falls below 0.188 €/kg, which makes the process profitable (Fig.3).

3.4. Effect of the plant capacity

In Fig. 4.,the variation of the IRR with the plant capacity is shown.

[Insert Figure 4 about here]

The results show that the production of bioethanol from carob pod is suitable for plant treatment capacities higher than 45.87 thousand tons of carob pod, since such a treatment capacity allows an IRR value higher than 7%.

Bearing in mind that the total carob pod production in the Mediterranean region is about 211.455 thousand tons per year, the amount of ethanol that could be produced is 59,481 m^3 per year, which allows an IRR value of 16.62%.

4. Conclusions

The total fixed capital investment estimated for a proposed industrial process and the ethanol production cost (0.55€/L) are similar than those reported for other traditional feedstocks with a discounted cash flow rate of return of 7%. Assuming 0.55€/L as the ethanol production cost, the initial price considered for feedstock of 0.17€/kg could be increased until 0.188€/kg and the minimal plant treatment capacity could be 45.87 thousand tons of carob pod, providing an internal rate of return higher than 7%. The designed process and its economic assessment suggest that carob pod could be considered a profitable feedstock for bioethanol production.

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Table 1. Equipment list and specifications.

EQUIPMENT ID	DESCRIPTION	SPECIFICATIONS
F-101 to F-105	Hoppers	Material: Steel, Size 3x 4x 5 m
J-101	Bucket conveyor	Material: Steel, Capacity: 20 t/h, Power 20 KW
C-201	Ball mill	Material: Steel, Capacity: 14.58 t/h, Power 80 KW
R-201	Stirred Reactor	Material: Steel, Volume: 50 m^3, Power: 20 KW
R-202 to R-203	Stirred Reactors	Material: Steel, Volume: 50 m^3, Power: 12 KW
H-201 to H-203	Vibrating screen	Material: Stainless Steel, Mesh size: 0,5 mm, Area: 2 m^2
F-201, F-202 and F-204	Stirred Process vessel	Material: Steel, Volume: 50 m^3, Power: 12 KW
F-203 A/B	Stirred Process vessels	Material: Steel, Volume: 50 m^3, Power: 12 KW
P-201 A/B, P-202 A/B and P-204 A/B	Centrifugal pumps	Material: Steel, Capacity: 80 m^3/h, Power: 35 KW
P-203 A/B	Diaphragm pumps	Material: Steel, Capacity: 45m^3/h, Pressure: 1.38 – 6.91 atm
H-204 and H-205	Filter press	
H-301	Shell and tube heat exchanger	Material: Stainless Steel, Heat exchange capacity: 16,5 10^5 Kcal/h, Area: 95 m^2
H-302	Shell and tube heat exchanger	Material: Stainless Steel, Heat exchange capacity: 16,5 10^5 Kcal/h, Area: 116 m^2
H-303	Shell and tube heat exchanger	Material: Stainless Steel, Heat exchange capacity: 16,5 10^5 Kcal/h, Area: 120.8 m^2
F-301 and F-302	Stirred Process vessel	Material: Stainless steel, Volume: 10 m^3, Power: 5 KW
F-303 and F-304	Stirred Process vessel	Material: Stainless steel, Volume: 50 m^3, Power: 20 KW
F-305	Process vessel	Material: Stainless steel, Volume: 50 m^3
R-301 to R-303	Bioreactor	Material: Stainless steel, Volume: 10 m^3, Power: 4 KW
R-304 to R-307	Bioreactor	Material: Stainless steel, Volume: 75 m^3, Power: 30 KW
R-308 to R-312	Bioreactor	Material: Stainless steel, Volume: 600 m^3, Power: 60 KW
P-301 and P-302	Centrifugal pumps	Material: Stainless steel , Capacity: 10 m^3/h, Power: 5 KW
P-303 A/B and P-304 A/B	Centrifugal pumps	Material: Stainless steel , Capacity: 75 m^3/h, Power: 17.5 KW
P-305 A/B	Centrifugal pump	Material: Stainless steel , Capacity: 40m^3/h, Power: 8 KW
P-306 A/B	Centrifugal pump	Material: Stainless steel , Capacity: 70m^3/h, Power: 15 KW
P-307 A/B	Centrifugal pump	Material: Stainless steel , Capacity: 50m^3/h, Power: 8 KW
H-401	Shell and tube heat exchanger	Material: Stainless Steel, Heat exchange capacity: 11,7 10^5 Kcal/h, Area: 70 m^2
T-401	Distillation column	Material: Stainless Steel, Reboiler duty: 2.45 10^6 Kcal/h, Condenser duty: 1.83 10^6 Kcal/h
T-402	Distillation column	Material: Stainless Steel, Reboiler duty: 5.92 10^5 Kcal/h, , Condenser duty: 1.18 10^5 Kcal/h,
D-401 and D-402	Molecular sieve	Total Volume: 0.8 m^3 Packed Volume: 0.6 m^3, Pressure: 4 bar
F-401	Process vessel	Material: Stainless steel, Volume: 5 m^3
F-402 to F-405	Process vessel	Material: Stainless steel, Volume: 150 m^3
P-401 A/B	Centrifugal pump	Material: Stainless steel , Capacity: 30m^3/h, Power: 8 KW
J-501	Bucket conveyor	Material: Steel, Capacity: 10 t/h, Power 10 KW
Q-501	Rotary oven	Material:Stainless steel, Capacity: 10 T/h, Power 15 KW
H-501	Tubular rotary cooler	Material: Steel, Capacity: 8500 Nm^3/h, Power 15 KW
G-502 and G-501	Centrifugal fan	Material: Steel, Capacity: 8500 Nm^3/h, Power 5 KW
P-501 A/B	Centrifugal pump	Material: Steel , Capacity: 200m^3/h, Power: 50 KW
T-501	Cooling tower	Material: Stainless steel Diameter: 5m, Height: 10 m
G-A01	Centrifugal fan	Material: Steel, Capacity: 35000 Nm^3/h, Power 5 KW
N-A01	Gas turbine	Material: Stainless steel, Capacity: 2500 Nm^3/h, Electricity generation: 24300 KWh
N-A02	Steam turbine	Material: Stainless steel, Electricity generation: 7500KWh
H-A01	Boiler	Material: Steel, Steam generation: 22 t/h, Output pressure: 2.5 atm
H-A02	Cooler	Material:Stainless steel, Capacity: 22 t/h, Heat exchange: 5.92 10^6 Kcal/h,
P-A01	Centrifugal pump	Material: Stainless steel , Capacity: 25m^3/h, Power: 5 KW

X-100: Storage Section
X-200: Sugars Extraction Section
X-300: Fermentation Section
X-400: Ethanol Recovery Section
X-500: Drying Section
X-A10: Co-generation Plant
A/B: means two equal equipment in parallel

Table 2. Inputs – Outputs in ethanol refinery for the base case.

	Quantity	Unit
Carob pod treatment capacity	68000	t/year
Electricity	28.15	GWh/ year
Chemicals		
Sulphuric acid	150.53	t/year
Urea	150.53	t/year
Yeast	225.80	t/year
Phosphate	150.53	t/year
Products		
Ethanol	15053	t/year
DDGs (10% wet)	30106	t/year
Electricity	246.42	GWh/ year
Carbon dioxide	14398	t/year
Utilities		
Process water	301.060	m^3/year
Natural Gas	47.41	$x10^6$ Nm^3/year
Labour	110220	Hours/year

Table 3. Operating Costs used in evaluation (base case).

	Price	Reference
Feedstock		
Carob Pod	0.17	Consejería Agricultura y Agua (2010)
Chemicals		
Sulphuric acid (€/ kg)	0.12	Chemical Market Report
Urea (€/ kg)	0.48	Chemical Market Report
Yeast (€/ kg)	0.36	Chemical Market Report
Phosphate (€/ kg)	0.66	Kabir *et al.* (2010); Lohrasbi *et al.* (2010)
By- products credits		
DDGs (10% wet) (€/ kg)	0.17	
Electricity (€/ KWh)	0.04	Boletín Oficial del Estado (2010)
Utilities		
Process water (€/ ton)	0.23	
Natural Gas (€/ KWh)	0.018	Boletín Oficial del Estado (2007)
Other costs		
Labour (€/employee year)	34000	Own authors
Maintenance (%FIC)	2	Lohrasbi *et al.* 2010
Insurance (%FIC)	1	Lohrasbi *et al.* 2010

Table 4. Process evaluation summary for the base case capacity of 68,000 tons carob pod per year.

Item	Description	Amount	Unit
Equipment cost		16.38	millon €
Equipment installation cost	35% of equipment cost	5.73	millon €
Pipeline installation cost	60% of equipment cost	9.82	millon €
Instrumentation	10% of equipment cost	1.64	millon €
Isolation	10% of equipment cost	1.64	millon €
Electrical engines		0.22	millon €
Electrical installation	100% of electrical engines cost	0.22	millon €
Land cost	90.36 €/m^2	1.26	millon €
Buildings	15% of equipment cost	2.46	millon €
Auxiliary services	25% of equipment cost	4.10	millon €
Total installed cost		**27.11**	**millon €**
Project and site management	25% of total installed cost	6.81	millon €
Other costs	6% of total installed cost	1.63	millon €
Project contingency	15% of total installed cost	4.06	millon €
Fixed capital investment		**39.61**	**millon €**

Table 5. Bioethanol production costs from several feedstocks

Feedstocks	Price (€/l)	Average price (€/l)
Sugar Cane	0.20 – 0.40	0.30
Wheat	0.47 – 0.63	0.55
Corn	0.55 - 0.75	0.65
Sugar beets	0.47 – 0.63	0.55
Lignocellulosic materials	0.63 – 0.87	0.75

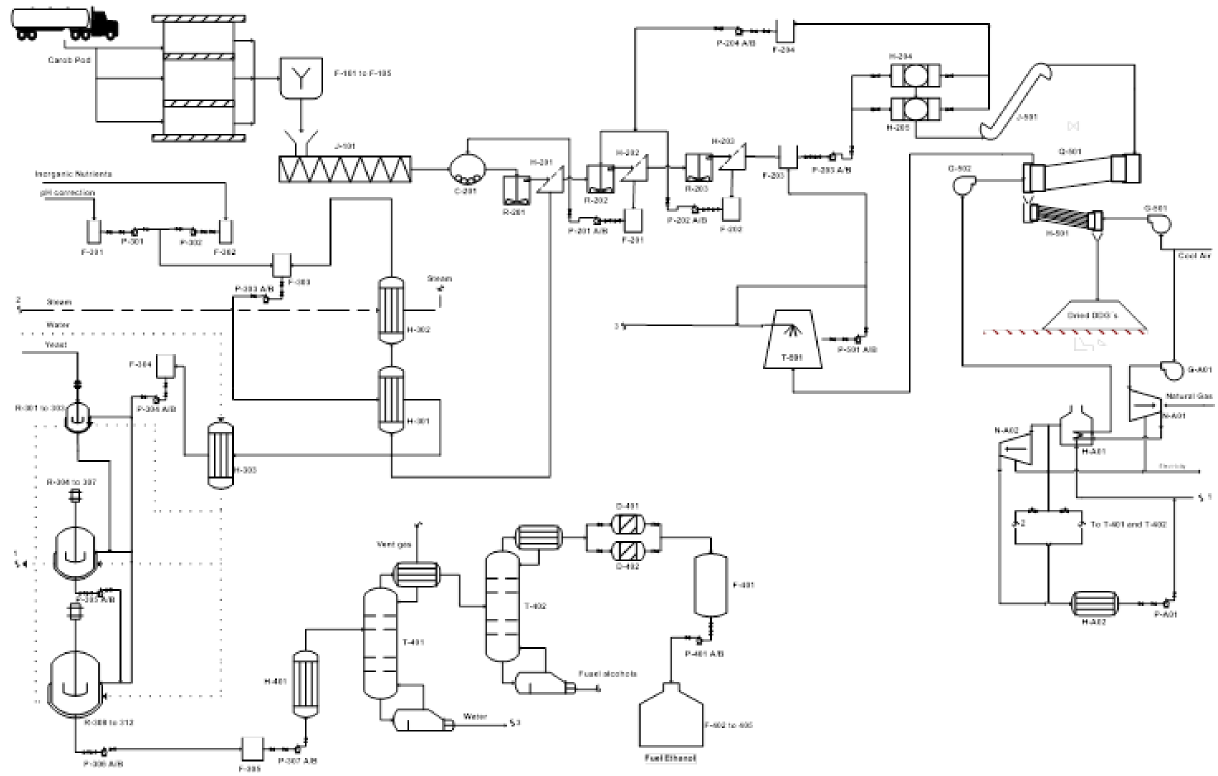

Figure 1. Process flow diagram.

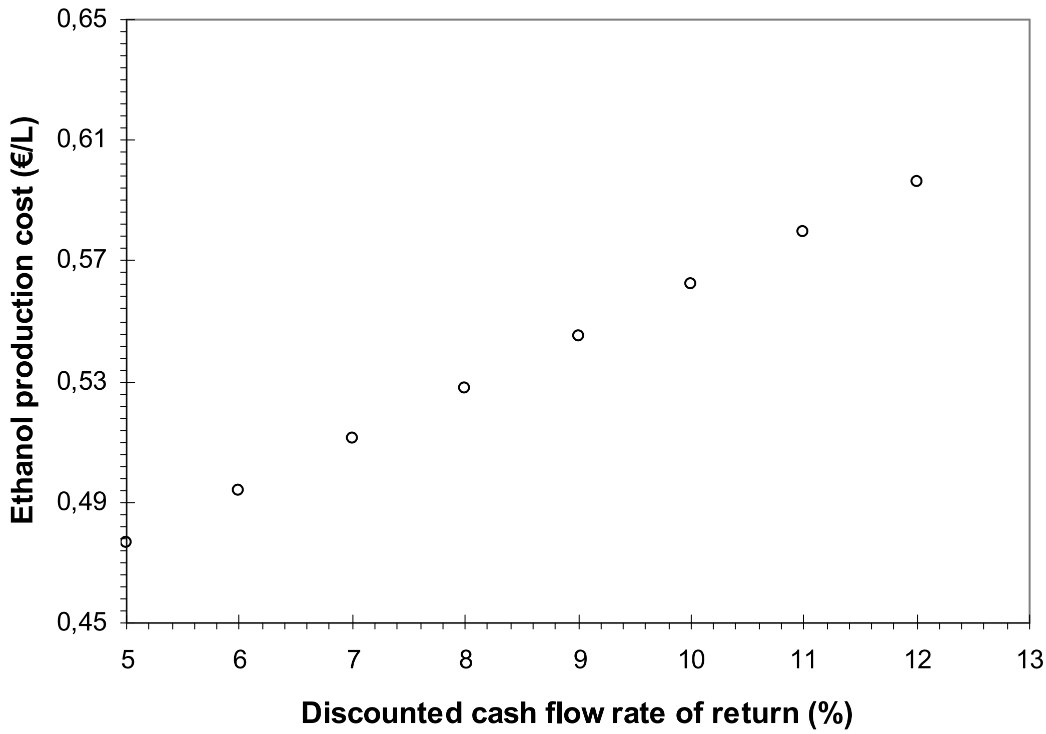

Figure 2. Variation of ethanol production cost with the discounted cash flow rate of return.

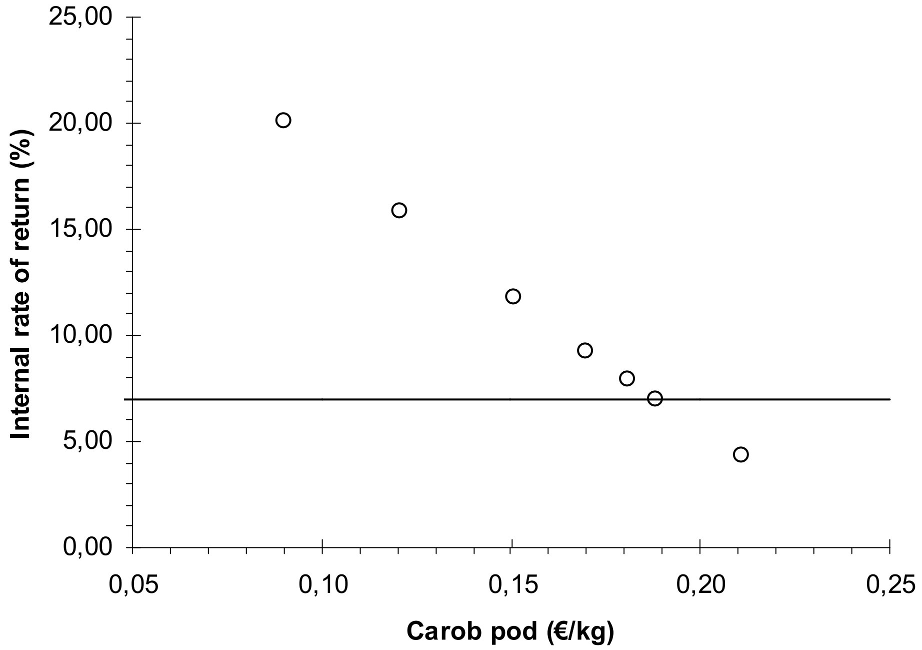

Figure 3. Variation of the internal rate of return with the feedstock price.

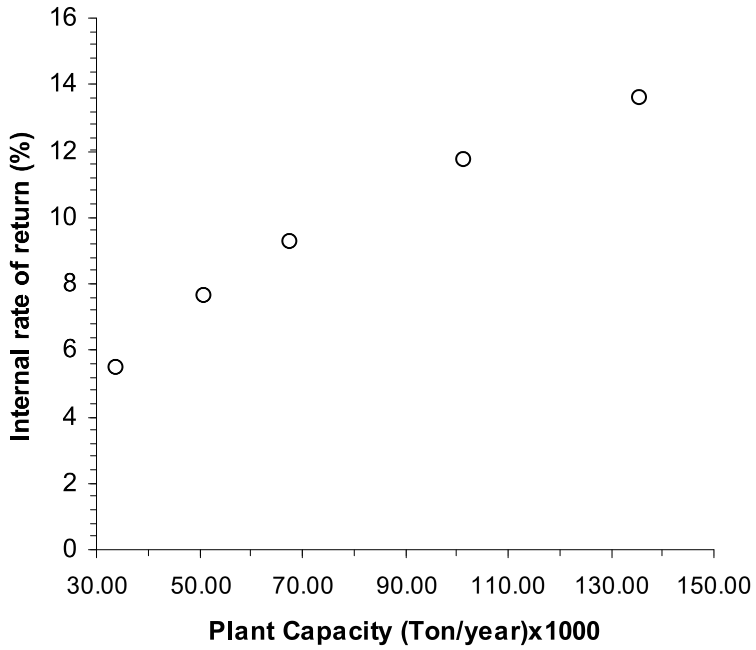

Fig. 4. Variation of the internal rate of return with the plant capacity.