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In Situ Two-Stage Gas Stripping for the Recovery of Butanol from Acetone-Butanol-Ethanol (ABE) Fermentation Broths

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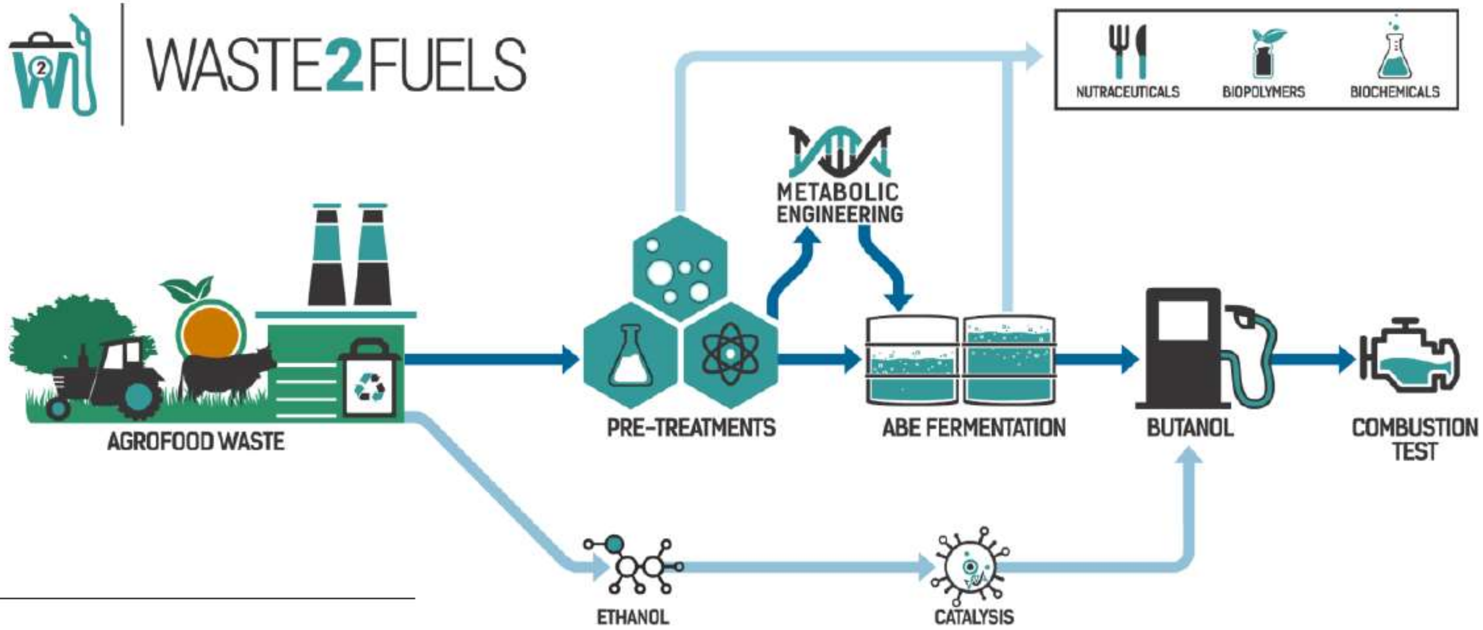
INTRODUCTION

Waste2Fuels project

Sustainable production of next generation biofuels from waste streams

- Twenty participants from Spain, Italy, Austria, Ireland, United Kingdom, Greece, Germany, France and Israel.
- From 1 January 2016 to 31 December 2018.



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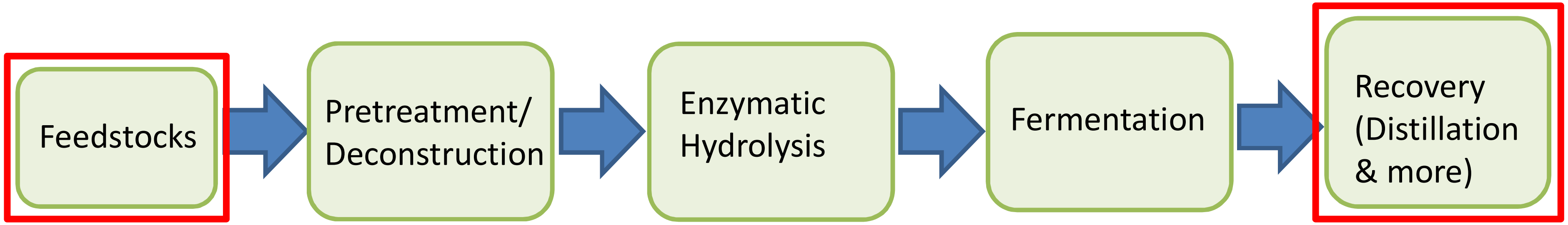
www.waste2fuels.eu

Overview of ABE fermentation process



Pros of Butanol as Biofuel	Challenges of ABE fermentation
High energy content	High cost of traditional feedstock
Low water absorption	Clostridia strains don't ferment naturally cellulosic substrates
Low vapour pressure	High cost of pretreatment/deconstruction processes
Less corrosive	Substrate and product inhibition processes
Low volatility	Low productivity
Good blending ability	High cost of solvent recovery processes

Alternative Feedstock: AgroFood Wastes (AFWs)

Solvent Recovery step

Typical distillation ABE recovery unit in batch processes

Alternative In situ Product Recovery (ISPR) techniques in research
Gas Stripping
Vacuum Fermentation
Pervaporation
Liquid-Liquid Extraction
Perstraction (Membrane Extraction)
Adsorption

Ni, Y. & Sun, Z. Appl Microbiol Biotechnol (2009) 83: 415. https://doi.org/10.1007/s00253-009-2003-y

OBJECTIVES

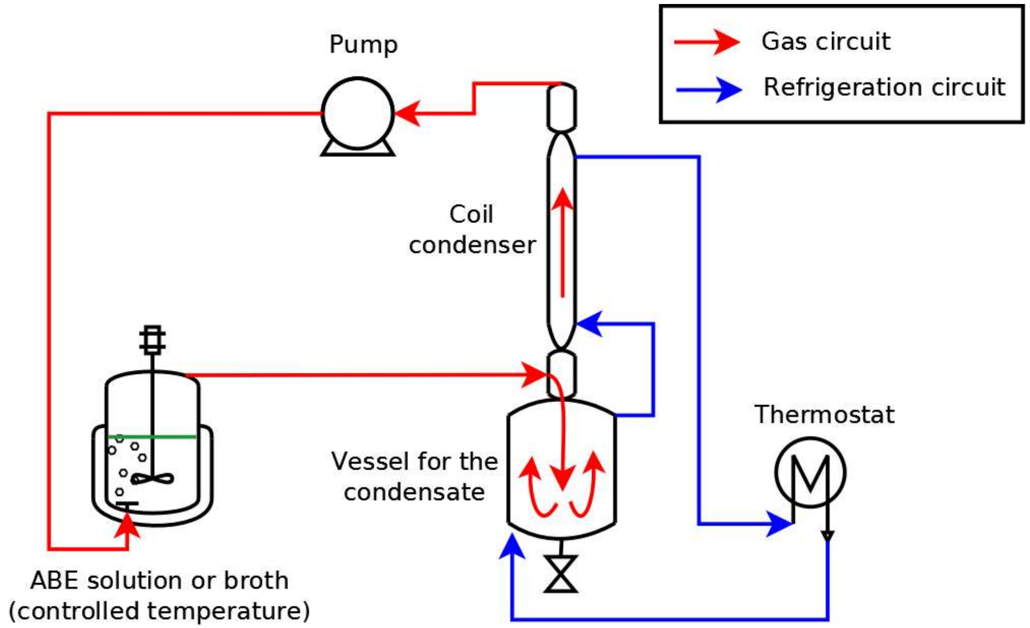
Objectives:

- To improve the ecoefficience of butanol recovery using two-stage gas stripping.
- To optimise one-step stripping working conditions (feed temperature, gas flow and refrigeration temperature) for a maximal simultaneous butanol selectivity (α_B) and butanol recovery efficiency (η_B).
- To assess the effect of in-situ gas stripping in ABE fermentation bacteria (*Clostridium beijerinckii* CECT 508).

EXPERIMENTAL SECTION

Gas stripping optimization

- Feed solution: a synthetic aqueous solution A:B:E (3:6:1) (5 g/L acetone, 10 g/L butanol and 1.67 g/L ethanol).
- Gas stripping setup scheme:



- Response Surface Methodology (RSM) experimental design.
- Experimental validation of RSM equations at various operation times (4-18h).

Gas stripping optimization

- **Response Surface Methodology (RSM) experimental design**
  - 20 experiments and included 8 cube points, 6 central points and 6 axial points (α = 1.68179).
  - 3 working conditions: feed temperature (T_{feed}), gas flow (G) and refrigeration temperature ($T_{ref.}$).
  - Optimum combination to maximize the response values (butanol selectivity (α_B) and butanol recovery efficiency (η_B)):

$$\propto_i = \frac{y_i / (1 - y_i)}{x_i / (1 - x_i)}$$

$$\eta_i = \frac{m_i C}{m_i F} \times 100$$

- **Two-stage gas stripping**
  - The aqueous phase (8 % (w/w) butanol) subjected to a 2nd gas stripping.

Fed-batch fermentation system coupled with gas stripping

Fermentation broth:

Substrate: Cheese whey (L_0= 40 g/L) with nutrient supplementation.

Volume: 500 mL.

Microorganism: *Clostridium beijerinckii* CECT 508T.

Bacterial density: $7 \cdot 10^8$ cell/mL.

Stripping conditions:

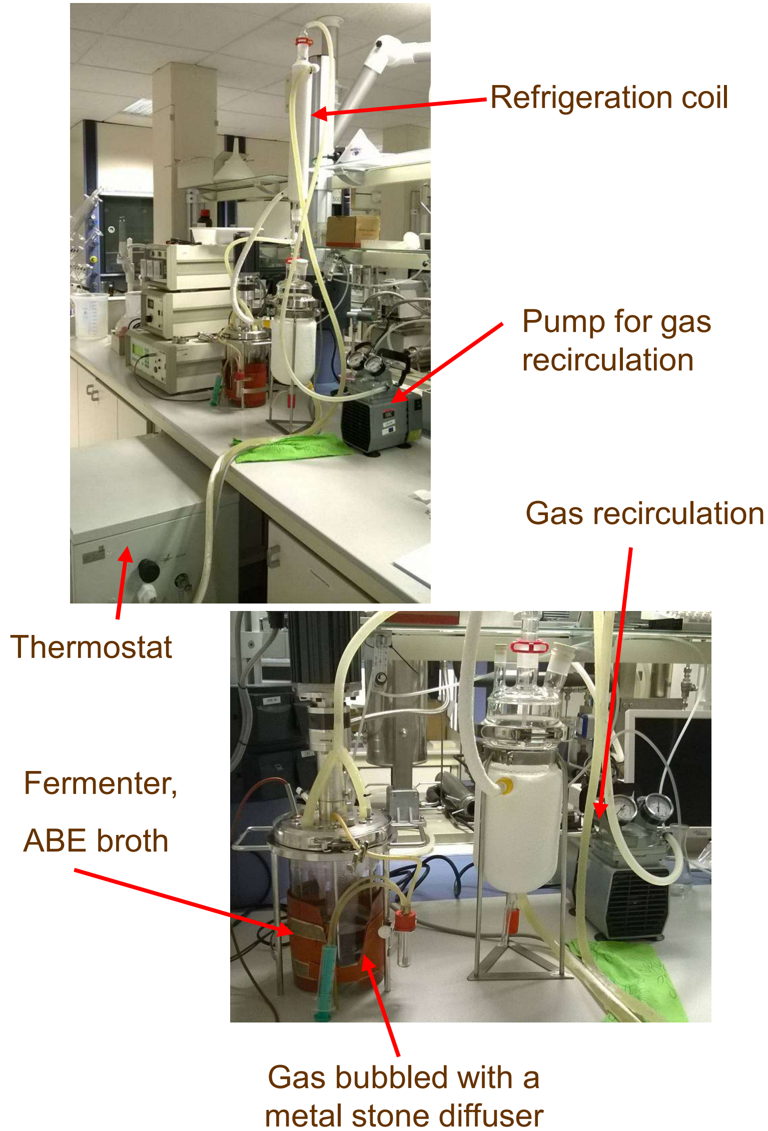
Initial ABE composition: 3.02 g/L acetone; 12.04 g/L butanol; 0.23 g/L ethanol; 0.99 g/L acetate; 1.15 g/L butyrate.

Working conditions:

- Time: 4h.
- T_{feed}, G, T_{ref} : optimum RSM results.

Antifoaming was added.

Experimental gas stripping setup



RESULTS

Gas stripping optimisation

- Estimated RSM optimal working conditions were experimentally validated at various gas stripping operation times (4-18 h) with an synthetic aqueous medium and a fermentation broth to improve global energy efficiency.
- Alternative feed temperatures (T_{feed}= 35°C) more suitable for bacteria were tested.
- A two-stage gas stripping was proposed to highly concentrate the condensate in butanol.
- The effect of gas stripping conditions on bacterial development was assessed.

Gas stripping optimisation

Response Surface Methodology (RSM) experimental design

The number of variables to be optimised was reduced to three in order to simplify the process.

RSM variables to be optimized	
T feed (°C)	25 to 50
Gas flow rate (L/min)	2.6 to 10
T refrigeration (°C)	-20 to -5

Fixed parameters	
Time (hours)	18
ABE composition (g/L)	5:10:1.67
Volume (mL)	500

According to the RSM mathematical estimations:

Optimal working conditions:

T_{Feed}: 60 °C

Gas Flow rate: 1.34 L/min

$T_{ref:}$ 5 °C

Simultaneous response:

Separation factor, α_B= 6.9

Efficiency, η_B=82.9 %

Gas Stripping optimisation

Response Surface Methodology (RSM) experimental design

Validation of the RSM model

The optimal estimated values for T_{feed} (60 °C), G (1.34 L/min) and T_{refr} (5 °C) were experimentally validated at different stripping times.

	Selectivity, α			Recovery efficiency, η (%)			Concentration in the distillate (g/L)		
Stripping time (h)	A	B	E	A	B	E	A	B	E
18	1.74	3.61	3.64	41.67	84.57	86.95	9.41	34.71	6.34
10	3.66	5.52	5.32	59.16	86.76	86.65	19.23	51.32	9.46
4	6.28	10.36	7.74	51.30	79.79	64.24	32.55	92.14	13.69

Concentrations above water solubility value. Two phases appear.

Shorter stripping times increase selectivity (α) without drastically reducing recovery efficiency (η).

Modification of RSM gas stripping optimum conditions

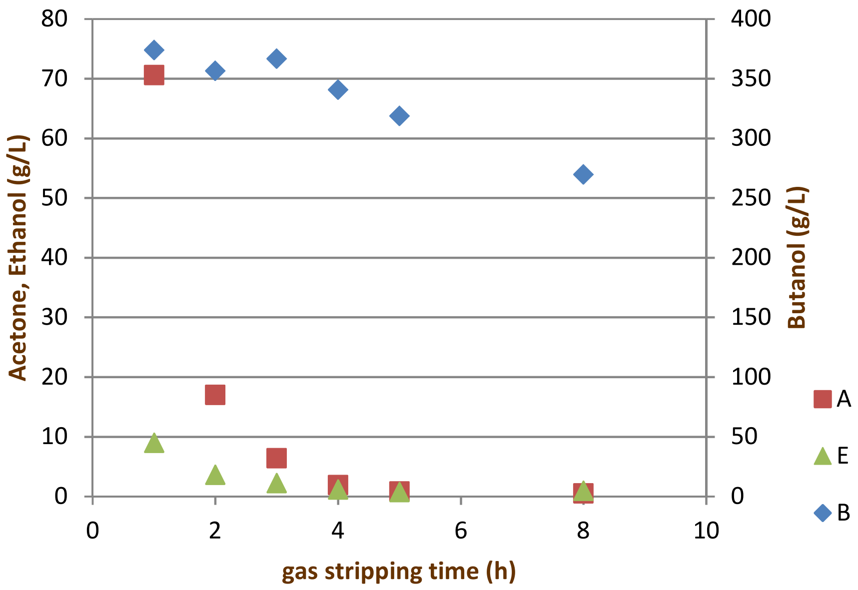
Optimal working conditions:
T_{Feed}: **35 °C**
Gas Flow rate: 1.34 L/min
$T_{ref.}$: 5 °C

Simultaneous response:
Separation factor, α_B= 4,2-5,7
Efficiency, $\boldsymbol{\eta_B}$**=15,3-35,9 %**

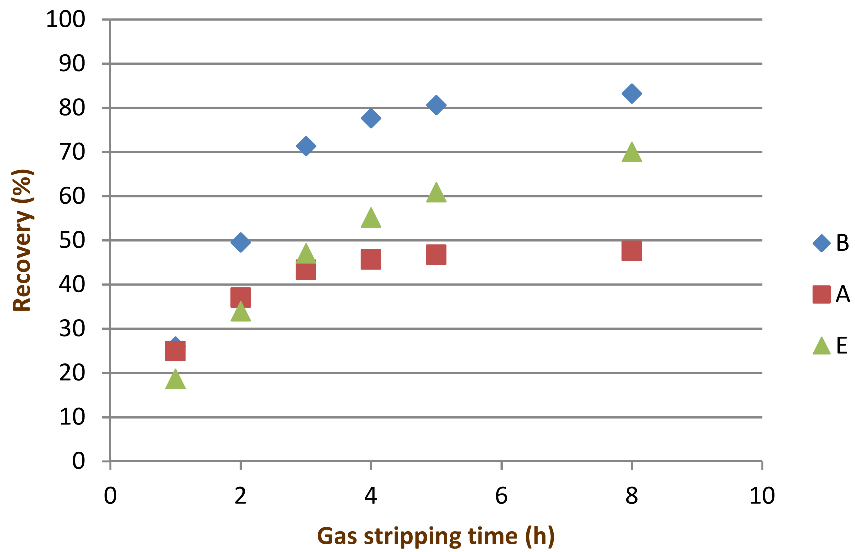
Two-stage gas stripping

The condensate collected from the 1st gas stripping was subjected to a 2nd gas stripping.

Dynamic evolution of parameters during 2nd gas stripping:



a) Dynamic evolution of ABE solvent concentration in the condensate during second-stage gas stripping



b) Dynamic evolution of ABE solvents recovery during second-stage gas stripping.

Fed-batch fermentation system coupled with gas stripping

Fermentation broth

- Gas stripping conditions (T_{feed} = 60 °C, Gas flow = 1.34 L/min, T_{refr} = 5 °C) were tested to check butanol recovery and cell viability.
- Stripping time: 4 h.

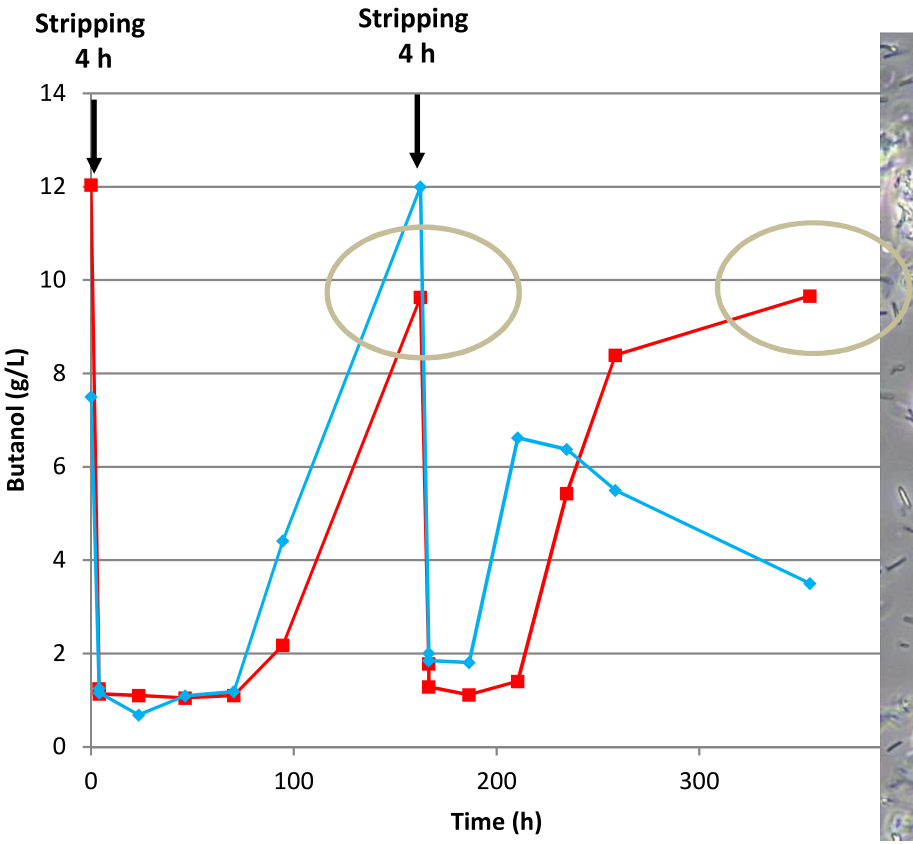
		1st Cycle	2nd Cycle
Selectivity, α	A	4.65	4.79
	B	11.08	13.95
	E	9.32	17.11
Recovery efficiency, η (%)	A	27.60	25.41
	B	59.29	66.97
	E	55.83	91.99
Concentration in condensate (g/L)	A	13.89	22.16
	B	118.97	119.43
	E	2.14	4.94

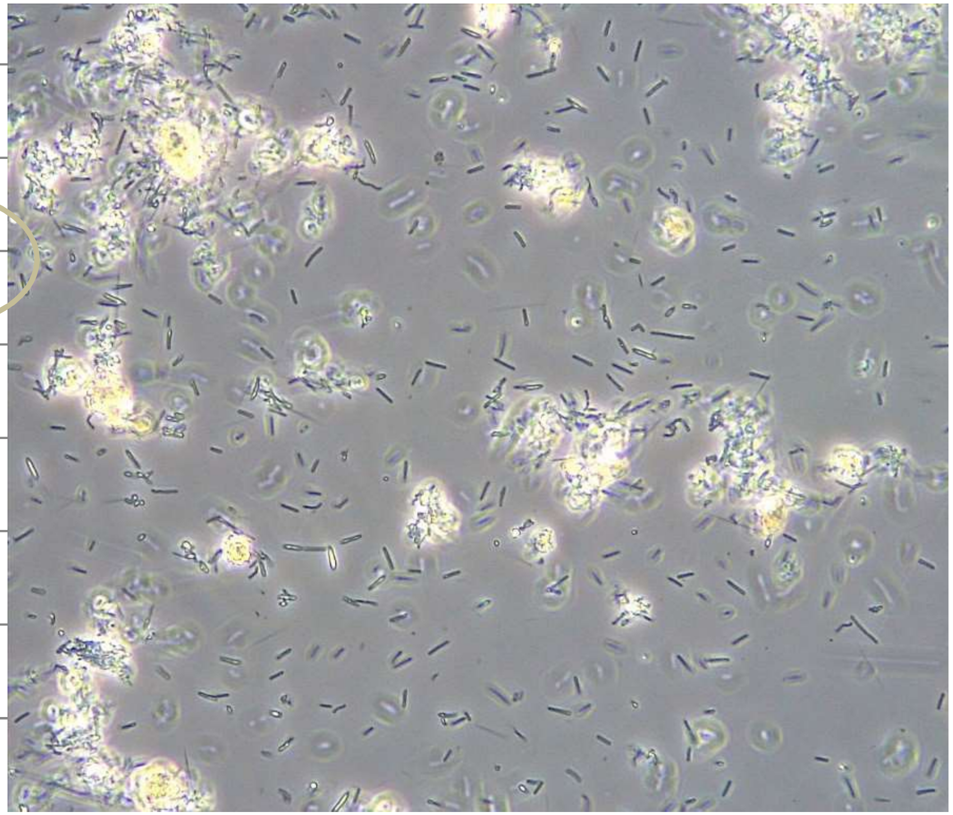
Concentrations above water solubility value. Two phases appear.

Butylic phase (7% volume):
661.50 g/L B
Aqueous phase (93% volume):
77.08 g/L B

Fed-batch fermentation system coupled with gas stripping

Effect of gas stripping conditions on bacterial development





CONCLUSIONS

Conclusions

- **Optimization of gas stripping parameters, including feed temperature, gas flow rate and refrigeration temperature are crucial for in situ butanol recovery.**
- **A two-stage gas stripping allows recovering highly concentrated butanol condensates, reducing energy consumption during the dewatering process.**
- ***Clostridium beijerinckii* CECT 508 strain resisted *in situ* gas stripping in fed-bad fermentation process but was negatively affected (too high feed temperature).**

Acknowledgements

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MH-V is supported by a postdoctoral contract (DOC-INIA, grant number DOC 2013-010) funded by the Spanish Agricultural and Agrifood Research Institute (INIA) and the European Social Fund.

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