Applied Energy 104 (2013) 517–526

Contents lists available at SciVerse ScienceDirect

Applied Energy

journal homepage: www.elsevier.com/locate/apenergy

# Integration of bioethanol as an in-process material in biorefineries using mass pinch analysis

Elias Martinez-Hernandez [a], Jhuma Sadhukhan [b,*], Grant M. Campbell [c]

[a] Centre for Process Integration, School of Chemical Engineering and Analytical Science, University of Manchester, Manchester M13 9PL, UK
[b] Centre for Environmental Strategy, University of Surrey, Guildford GU2 7XH, UK
[c] Satake Centre for Grain Process Engineering, School of Chemical Engineering and Analytical Science, University of Manchester, Manchester M13 9PL, UK

## HIGHLIGHTS

- ▶ Bioethanol integration approach based on mass pinch analysis.
- ▶ Bioethanol exchange network design to maximise recovery between sources and demands.
- ▶ Graphical targeting approach allows minimum fresh bioethanol consumption.
- ▶ Biorefinery debottlenecking by bioethanol integration and added value co-production.
- ▶ Graphical targeting and cost-benefit analyses for synthesis and retrofit design.

## ARTICLE INFO

*Article history:*
Received 21 September 2012
Received in revised form 20 November 2012
Accepted 22 November 2012

*Keywords:*
Biorefinery
Bioethanol
Pinch analysis
Arabinoxylan

## ABSTRACT

A biorefinery involving internal stream reuse and recycling (including products and co-products) should result in better biomass resource utilisation, leading to a system with increased efficiency, flexibility, profitability and sustainability. To benefit from those advantages, process integration methodologies need to be applied to understand, analyse and design highly integrated biorefineries. A bioethanol integration approach based on mass pinch analysis is presented in this work for the analysis and design of product exchange networks formed in biorefinery pathways featuring a set of processing units (sources and demands) producing or utilising bioethanol. The method is useful to identify system debottleneck opportunities and alternatives for bioethanol network integration that improve utilisation efficiency in biorefineries with added value co-products. This is demonstrated by a case study using a biorefinery producing bioethanol from wheat with arabinoxylan (AX) co-production using bioethanol for AX precipitation. The final integrated bioethanol network design allowed the reduction of bioethanol product utilisation by 94%, avoiding significant revenue losses.



## 1. Introduction

Starch crops (e.g. corn, wheat), sugar crops (sugar cane and sugar beet) and lignocellulosic material (agricultural residues, wood, grass, etc.) are the main biomass feedstocks employed for bioethanol production [1–4]. Even in the case of processes using biomass feedstocks, such as algae [5,6] and black liquor [7] to produce other biofuels such as biodiesel or methanol, some valuable components in these feedstocks represent a significant fraction that ends up in low value by-products. In the case of starch crops, the by-product is the Distillers Dried Grains with Solubles (DDGS). As supply of bioethanol increases, more DDGS is produced resulting in a lower market value. Extraction of valuable biomass feedstock fractions in added value products along with process integration is then necessary to enhance the economics of biorefinery systems producing bioethanol [8–10]. In addition to its intended application as a product to be used as transportation fuel, ethanol could also become an important intermediate feedstock or utility that could be used within a biorefinery. For example, ethanol can be used as a solvent for fractionation or extraction of added value products from biomass [8]. This offers potential for effective integration of various processing pathways to achieve efficient use of bioethanol within a biorefinery, especially where there are various source streams containing bioethanol at different concentrations and various demands requiring bioethanol.

Methodologies for biorefinery process design have emerged to address the particular nature of biomass processing and the complexity of the task of biorefinery integration at different levels. Feedstocks, processing technologies and products are the three

* Corresponding author. Tel.: +44 1483 68 6642; fax: +44 1483 68 6671.
*E-mail address:* jhumasadhukhan@gmail.com (J. Sadhukhan).

0306-2619/$ - see front matter © 2012 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.apenergy.2012.11.054

levels of complexity concerning the integration of biorefineries [11]. There are methodologies based on process integration and assessment tools to improve internal material and energy recovery within a site and reduce external resource requirements. In the case of bioethanol production, heat pinch analysis, water pinch analysis and life cycle assessment have been applied to several configurations including value added production pathways and combined heat and power generation [11–23]. In addition, there are methodologies that combine process synthesis and optimisation through mathematical programming allowing screening of alternatives and creation of innovative biorefinery configurations [24–27]. Pham and El-Halwagi have proposed a "forward–backward" approach for biorefinery process synthesis and optimisation when a feedstock and a target product are specified using matching and interception procedures [25]. The method was applied for bio-alcohols production from lignocellulosic feedstocks and provided a configuration with optimised pathways between feedstock and end products along with possible open pathways for by-product production. However, the pre-treatment of biomass is not included as a conversion step and the biorefinery integration at the product level (i.e. potential utilisation of the various products within the biorefinery processes) is not considered. The interactions resulting from product integration could potentially reduce import of raw materials.

Whilst optimisation frameworks are worthwhile when well established technologies and real plant data are available, their solutions can be computationally demanding as more advanced and complex process technologies will emerge. Methods giving knowledge about the behaviour of integrated biorefinery processing networks, by intervention of the process engineers throughout the design task, can be of great value at the current stage of the learning curve of the field of biorefineries. The knowledge acquired then can be introduced within the mathematical formulations for better representation of a process and improved optimisation results. Furthermore, the potential for mass integration of biorefinery products within the processes has not been explored in the mentioned methodologies. In this sense, conceptual developments using the pinch analysis approach based on source–demand models of process integration can prove to be valuable as in the case of energy sector planning [28,29].

As discussed above, although the traditional process integration tools have been successfully applied for reduction of energy and environmental impact and to maximise profits, new tools are required to enable integrated processing of starch and lignocellulosic feedstocks for bioethanol production, in which ethanol can be used as utility for biomass fractionation or pretreatment as well as chemical reactant. A systematic "bioethanol pinch" methodology for the design and analysis of bioethanol exchange networks is proposed in this paper, adapted from hydrogen pinch analysis [30]. The methodology is a particular case of mass pinch analysis for synthesis of mass exchange networks [31]. According to the extended definition recently introduced by Ponce-Ortega et al. [32], it is an example of process intensification which includes any activity that reduces the use of material utilities and/or feedstock. The case study elaborated in the current paper is arabinoxylan (AX) extraction integrated with bioethanol production, in which ethanol streams of different purities are required for arabinoxylan precipitation and for feedstock washing [8,33,34]. The proposed methodology has been used to minimise the bioethanol requirement within the biorefinery.

In Fig. 1, opportunities for bioethanol integration between sources and demands (streams numbered 1–12) within a biorefinery producing bioethanol and arabinoxlylans from wheat have been identified. The route to extract arabinoxylans (AX) using bioethanol to precipitate the extracted AX presented in this figure has recently been explored [8,33,34]. In this process ethanol is used for bran purification (at 70% purity) and for AX precipitation and washing (at 96% purity). In a more complex design, the Organosolv process could be used to fractionate lignocellulosic materials for the production of bioethanol and other added value products. The Organosolv process similarly uses ethanol within the process at 50–60% purity to separate lignocellulosic feedstock into cellulose, hemicellulose and lignin [35]. The cellulose and hemicellulose fractions are sent to hydrolysis to produce more bioethanol whilst the lignin fraction is refined for further valorisation (in composites, wood-adhesives, fuel additives, etc.) or as fuel. Some furfural is also produced which can be sold as a solvent. A third common process

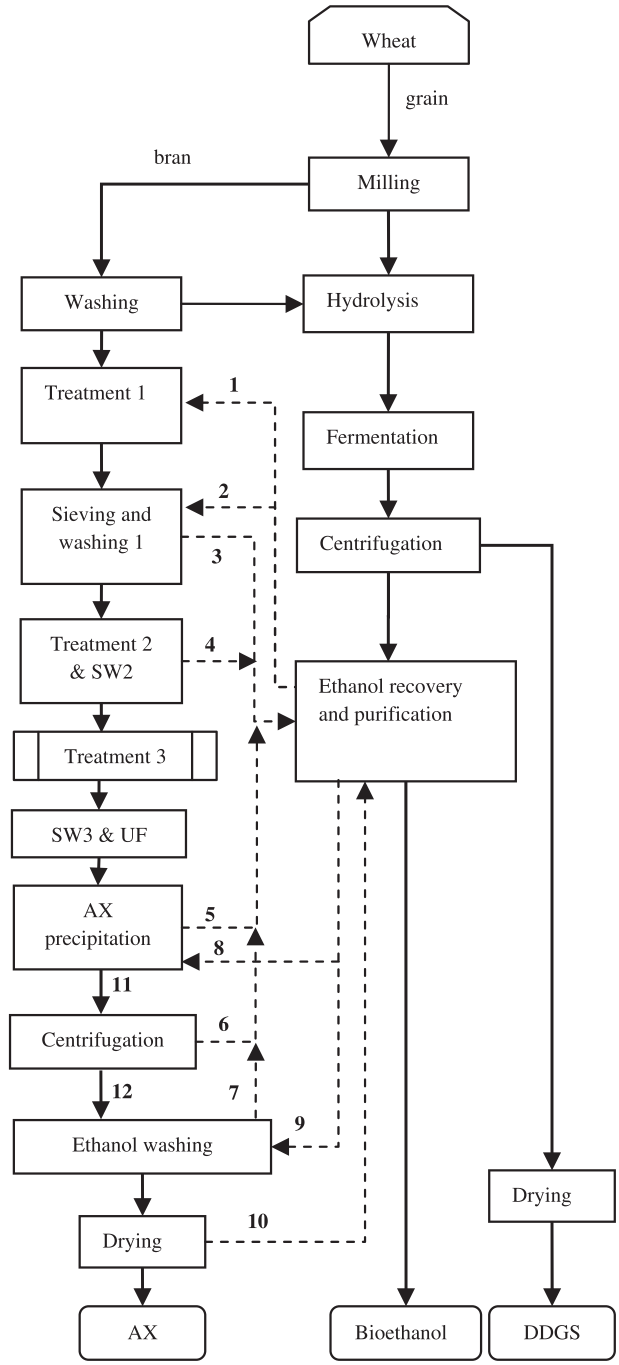


**Fig. 1.** Bioethanol pathways in a biorefinery using starch and lignocellulosic feedstock. The various bioethanol rich streams are indicated by the dashed lines. SW: Sieving and washing, UF: ultrafiltration, AX: arabinoxylan, DDGS: distillers dried grains with solubles.