**Producción por LGAC – Artículos**

I&EC research
Industrial & Engineering Chemistry Research
Article
pubs.acs.org/IECR

# Optimization of the Supply Chain Associated to the Production of Bioethanol from Residues of Agave from the Tequila Process in Mexico

Pascual Eduardo Murillo-Alvarado,[†] José Ezequiel Santibañez-Aguilar,[†] José María Ponce-Ortega,[*,†] Agustín Jaime Castro-Montoya,[†] Medardo Serna-González,[†] and Mahmoud M. El-Halwagi[‡,§]

[†]Chemical Engineering Department, Universidad Michoacana de San Nicolás de Hidalgo, Morelia, Michoacán, México 58060

[‡]Chemical Engineering Department, Texas A&M University, College Station, Texas, United States 77843-3122

[§]Adjunct Faculty at the Chemical and Materials Engineering Department, King Abdulaziz University, Jeddah, Saudi Arabia

Supporting Information

ABSTRACT: The Mexican economy is highly dependent on the tequila industry, where there are associated several residues of agave (i.e., the plant used to make tequila), which is lignocellulosic matter that can be used as feedstock for bioethanol production. The residues of agave are obtained in the harvesting sites located in several states of Mexico and from the tequila factories that are mainly located in two places in Mexico. This paper presents an optimization framework for designing a supply chain for the bioethanol production from residues of agave bagasse obtained in the tequila processing in Mexico, where central and distributed bioethanol processing plants are considered. The bioethanol production process in the central and distributed plants is modeled according to conversion factors for the different processing steps obtained from experimental data. The proposed optimization formulation also considers the total available agave and the bioethanol demand in Mexico. Several scenarios are analyzed for the bioethanol production from agave bagasse in Mexico, where positive results are obtained from the reuse of residues of agave bagasse for bioethanol production, obtaining considerable profits and satisfying a significant demand of the gasoline required in the area.

## 1. INTRODUCTION

The agave is a perennial arid plant that consists of thin sheets around a pineapple (or plant head), whose main elements are fibers, sugars, minerals, and water. Juice with high concentration of fructose and other vitamin properties is naturally produced in the center of the pineapple; also, agave has some fat particles that yield its distinctive taste and smell. This way, a large number of products can be obtained from agave as honey water, paper, textiles, *mezcal* (i.e., a fermented beverage similar to tequila), and tequila. Mexico is one of the areas with the greatest diversity of species of agave in the world. For this reason, agave is one of the most important industries associated to tequila and *mezcal* production, where the agave plant is used as source of fermentable sugars. The agave is mainly cultivated in the central-western part of Mexico (in the states of Jalisco, Guanajuato, and Michoacán), and most of the factories associated to the tequila industry are located in this region. During the processing of agave to yield tequila, several lignocellulosic residues from the agave are produced. These residues correspond to the stalks that are obtained in the cultivation areas because these are not used for the tequila process, and also, there are other lignocellulosic residues obtained in the factories associated to the tequila processing from the plant heads after the fermentation process. Nowadays, the residues from the agave generated in this region represent a considerable pollution problem because these residues are not used at all. However, these lignocellulosic residues can be used as raw material to produce several value-added products, including bioethanol and solid fuel. Furthermore, satisfying the fuel requirements is a serious problem due to the reduction of oil reserves around the world and the associated greenhouse gas emissions. In this regard, biofuels are expected to decrease the negative environmental impact for energy use. These biofuels are produced from biomass and organic wastes with high carbon content; for example, bioethanol is one of the most accepted biofuels that can be used as substitution of gasoline. Furthermore, there are several routes to produce bioethanol, most of them through fermentation. Huang et al.[1] studied the effect of biomass species and plant size on cellulosic ethanol. Dutta et al.[2] presented an economic comparison of different fermentation configurations to obtain ethanol using various microorganisms to observe the advantages with respect to the configuration of the production process. Also, a techno-economic analysis comparing several routes for bioethanol production from corn stover and lignocellulosic materials was reported by Kazi et al.[3] In addition, several chemical and biochemical routes have been proposed for the bioethanol production from lignocellulosic materials such as wheat straw, wood chips, different bagasse, and others. Kaparaju et al.[4] proposed the utilization of wheat straw to obtain different biofuels as ethanol, hydrogen, and biogas via hydrothermal pretreatment. Cardona et al.[5] discussed the profitability of bioethanol production from lignocellulosic materials consider-

Received: September 24, 2013
Revised: February 17, 2014
Accepted: March 5, 2014
Published: March 5, 2014

Resources, Conservation and Recycling 84 (2014) 44–56

Contents lists available at ScienceDirect

Resources, Conservation and Recycling

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

# Optimal design of rainwater collecting systems for domestic use into a residential development

Andrea Bocanegra-Martínez [a], José María Ponce-Ortega [a,*], Fabricio Nápoles-Rivera [a], Medardo Serna-González [a], Agustín Jaime Castro-Montoya [a], Mahmoud M. El-Halwagi [b,c]

[a] Chemical Engineering Department, Universidad Michoacana de San Nicolás de Hidalgo, Morelia, Michoacán 58060, Mexico
[b] Chemical Engineering Department, Texas A&M University, College Station, TX 77843, USA
[c] Chemical and Materials Engineering Department, King Abdulaziz University, Jeddah, Saudi Arabia

ARTICLE INFO

*Article history:*
Received 18 September 2013
Received in revised form 5 January 2014
Accepted 6 January 2014

*Keywords:*
Rainwater collecting systems
Domestic water
Optimal planning and design
Rainwater reuse
Recycling

ABSTRACT

This paper proposes an optimization-based approach for designing rainwater harvesting systems for domestic use in a residential development. The optimization model accounts for the implementation of rainwater harvesting devices, pipes and reservoirs for the optimal sitting, collecting, storing and distribution of harvested rainwater. The optimization model consists in satisfying the water domestic demands and considers as objective function the minimization of the total annual cost associated to the fresh water, the capital costs for the catchment areas, storages and pumps, and the cost associated to the pumping, maintenance and treatment. A case study for a residential development in Morelia, Mexico is presented. The city of Morelia is characterized for having complications to satisfy the water demands, especially during dry seasons. The application of the proposed optimization approach shows that it is possible to satisfy a significant percentage of the domestic water demands using a harvesting rainwater system decreasing the associated cost in the time horizon. Several scenarios have been presented to show the potential solutions identified in the case study.



## 1. Introduction

Water is one of the most valuable resources in the world; due to its vital role in life, recently the water demands have dramatically increased due to the population growth and also to the change in the precipitation patterns because of the climate change. This way, there are several highly populated regions of the world where there is water scarcity. This has motivated the development of harvesting water strategies to satisfy the water demands (Abdulla and Al-Shareef, 2009; Appan, 2000; Chilton et al., 2000). In the industry, several strategies for water reuse, recycling and regeneration have been proposed in order to satisfy specific demands and this way to reduce the consumption of freshwater (see for examples Deng and Feng, 2011; Fu et al., 2012; Ng et al., 2010; Yu et al., 2013). Particularly, mathematical programming-based techniques have represented powerful tools for the optimal design of industrial water networks reducing the fresh water consumption and the wastewater discharge to the environment (see Burgara-Montero et al., 2012; Deng et al., 2013; Khor et al., 2012; Nápoles-Rivera et al., 2010, 2012; Ponce-Ortega et al., 2011, 2012; Rojas-Torres et al., 2012; Rubio-Castro et al., 2010, 2011, 2012, 2013; Sotelo-Pichardo et al., 2011; Vázquez-Castillo et al., 2013). On the other hand, the water consumption for domestic use represents around 10% of the total fresh water demand in the world, and satisfying these domestic demands represents a major problem in places with water scarcity. In this context, several strategies have been implemented to satisfy the domestic water demands involving rainwater harvesting as shown in Fig. 1 (see Domènech and Saurí, 2011; Domènech et al., 2012; Gikas and Angelakis, 2009; Hadadin et al., 2010; Li et al., 2010; Morales-Pinzón et al., 2012); however, these strategies have been based on heuristic approaches that frequently do not produce an optimal solution for the addressed problem. Recently, several systematic techniques to satisfy the domestic water demands based on the optimal storing and distribution for the available water have been proposed. Khastagir and Jayasuriya (2010) presented a model for the optimal sizing of tanks for rainwater with domestic purposes. Imteaz et al. (2011) presented a decision support tool for sizing rainwater tanks associated to large roofs. Liu et al. (2011) presented a mixed integer linear programming model for using desalinated water to satisfy domestic demands. Atilhan et al. (2012) presented a system-integration

* Corresponding author. Tel.: +52 443 3223500x1277; fax: +52 443 3273584.
*E-mail addresses:* jmponce@umich.mx, jose_maria_ponce@yahoo.com (J.M. Ponce-Ortega).

0921-3449/$ – see front matter © 2014 Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.resconrec.2014.01.001

# Optimization of Particle Size for Hydrolysis of Pine Wood Polysaccharides and its Impact on Milling Energy

Miguel Angel Zamudio-Jaramillo*, Agustín Jaime Castro-Montoya*‡ Rafael Maya Yescas*, María del Carmen Chávez Parga* Juan Carlos González Hernández** and Jaime Saucedo Luna*

*Facultad de Ingeniería Química, Universidad Michoacana de San Nicolás de Hidalgo, Morelia, Michoacán, México

**Depto. Ingeniería Química e Ingeniería Bioquímica, Instituto Tecnológico de Morelia, Morelia, Michoacán, México

(mikezamjara@hotmail.com, ajcastrofiq@gmail.com, rafaelmayayescas@yahoo.com.mx, carmen_pchavez@yahoo.com, jcgh1974@hotmail.com, saucedol@hotmail.com)

‡ Corresponding Author; Agustín Jaime Castro-Montoya, Francisco J. Múgica s/n Col. Félix Ireta, 58030, Morelia, Michoacán, México, Tel: 01(443) 3223500 ext. 1207, ajcastrofiq@gmail.com

*Received: 03.03.2014 Accepted: 22.05.2014*

**Abstract-** Wood milling is an intensively energy consuming operation that has a significant effect on energy yield of ethanol production processes as particle size is an important factor in productivity of saccharification methods. Fiber particle size was optimized for a very wide range of treatment conditions (temperature, agitation, and solid loads) for acid hydrolysis in a batch reactor. Also, heat and mass transfer effects were analysed by calculating the Thiele and Prater modulus at experimental conditions. Multivariate optimization results show that using a length-weighted fiber mean diameter ($D_{1,21}$) of 1.21-2.68 mm, a better sugar yield, concentration and lower furan production can be achieved. Agitation allowed a simultaneous particle size reduction and hydrolysis of polysaccharides. Heat and mass transfer studies suggest that acid diffusion is only important for hemicellulose hydrolysis at very high temperature and that particles are nearly isothermal. These results show that about 30% of the required energy for milling can be saved by using optimal particle size.

**Keywords-** Wood, ethanol, acid hydrolysis, saccharification.

## 1. Introduction

Bioethanol from lignocellulosic biomass is one of the most promising technologies for fuel production because of the abundance of lignocellulosic biomass [1, 2], its very low net greenhouse gases emissions and its renewability [1, 3, 4]. To produce ethanol from lignocellulose biomass it is necessary to hydrolize its structural polysaccharides (cellulose and hemicellulose) to monomer sugars (mainly glucose and xylose) so they can be fermented by microorganisms. Although there are several methods of hydrolysis including acid, enzymatic, steam explosion and microwave treatments, acid hydrolysis is one of the most frequently used method due to its technological readiness [2,5]. In this process lignocellulosic biomass is treated with an acid solution to break the glycosidic bond in the cellulose and hemicellulose chemical structure by the addition of a water molecule. In this reaction a proton from the acid solution catalyses the hydrolysis of the glycosidic bonds. As hydrolysis takes place, monomeric sugars also are converted to degradation products like furans, i.e. furfural and hydroxymethylfurfural (HMF), which are inhibitors for the subsequent fermentation process [6, 7]. Hydrolysis of cellulose and hemicellulose from biomass is a heterogeneous, solid-liquid reaction. Some studies in continuous reactors report a flow rate-dependent reaction rate [8,9], negative effects over sugar yield at high solid loads [10]; deviations from Arrhenius model predictions on temperature changes [11] and effects of cellulose crystalline index in hydrolysis reaction rate [12,13]. However studies in this area are limited. Particle size in wood hydrolysis is important for both, reaction rate and yield to monomeric sugar, and also for

I&EC research
Industrial & Engineering Chemistry Research
Article
pubs.acs.org/IECR

# Optimization of the Supply Chain Associated to the Production of Bioethanol from Residues of Agave from the Tequila Process in Mexico

Pascual Eduardo Murillo-Alvarado,[†] José Ezequiel Santibañez-Aguilar,[†] José María Ponce-Ortega,*[,†] Agustín Jaime Castro-Montoya,[†] Medardo Serna-González,[†] and Mahmoud M. El-Halwagi[‡,§]

[†]Chemical Engineering Department, Universidad Michoacana de San Nicolás de Hidalgo, Morelia, Michoacán, México 58060

[‡]Chemical Engineering Department, Texas A&M University, College Station, Texas, United States 77843-3122

[§]Adjunct Faculty at the Chemical and Materials Engineering Department, King Abdulaziz University, Jeddah, Saudi Arabia

*S* *Supporting Information*

ABSTRACT: The Mexican economy is highly dependent on the tequila industry, where there are associated several residues of agave (i.e., the plant used to make tequila), which is lignocellulosic matter that can be used as feedstock for bioethanol production. The residues of agave are obtained in the harvesting sites located in several states of Mexico and from the tequila factories that are mainly located in two places in Mexico. This paper presents an optimization framework for designing a supply chain for the bioethanol production from residues of agave bagasse obtained in the tequila processing in Mexico, where central and distributed bioethanol processing plants are considered. The bioethanol production process in the central and distributed plants is modeled according to conversion factors for the different processing steps obtained from experimental data. The proposed optimization formulation also considers the total available agave and the bioethanol demand in Mexico. Several scenarios are analyzed for the bioethanol production from agave bagasse in Mexico, where positive results are obtained from the reuse of residues of agave bagasse for bioethanol production, obtaining considerable profits and satisfying a significant demand of the gasoline required in the area.

## 1. INTRODUCTION

The agave is a perennial arid plant that consists of thin sheets around a pineapple (or plant head), whose main elements are fibers, sugars, minerals, and water. Juice with high concentration of fructose and other vitamin properties is naturally produced in the center of the pineapple; also, agave has some fat particles that yield its distinctive taste and smell. This way, a large number of products can be obtained from agave as honey water, paper, textiles, *mezcal* (i.e., a fermented beverage similar to tequila), and tequila. Mexico is one of the areas with the greatest diversity of species of agave in the world. For this reason, agave is one of the most important industries associated to tequila and *mezcal* production, where the agave plant is used as source of fermentable sugars. The agave is mainly cultivated in the central-western part of Mexico (in the states of Jalisco, Guanajuato, and Michoacán), and most of the factories associated to the tequila industry are located in this region. During the processing of agave to yield tequila, several lignocellulosic residues from the agave are produced. These residues correspond to the stalks that are obtained in the cultivation areas because these are not used for the tequila process, and also, there are other lignocellulosic residues obtained in the factories associated to the tequila processing from the plant heads after the fermentation process. Nowadays, the residues from the agave generated in this region represent a considerable pollution problem because these residues are not used at all. However, these lignocellulosic residues can be used as raw material to produce several value-added products, including bioethanol and solid fuel. Furthermore, satisfying the fuel requirements is a serious problem due to the reduction of oil reserves around the world and the associated greenhouse gas emissions. In this regard, biofuels are expected to decrease the negative environmental impact for energy use. These biofuels are produced from biomass and organic wastes with high carbon content; for example, bioethanol is one of the most accepted biofuels that can be used as substitution of gasoline. Furthermore, there are several routes to produce bioethanol, most of them through fermentation. Huang et al.[1] studied the effect of biomass species and plant size on cellulosic ethanol. Dutta et al.[2] presented an economic comparison of different fermentation configurations to obtain ethanol using various microorganisms to observe the advantages with respect to the configuration of the production process. Also, a techno-economic analysis comparing several routes for bioethanol production from corn stover and lignocellulosic materials was reported by Kazi et al.[3] In addition, several chemical and biochemical routes have been proposed for the bioethanol production from lignocellulosic materials such as wheat straw, wood chips, different bagasse, and others. Kaparaju et al.[4] proposed the utilization of wheat straw to obtain different biofuels as ethanol, hydrogen, and biogas via hydrothermal pretreatment. Cardona et al.[5] discussed the profitability of bioethanol production from lignocellulosic materials consider-

Received: September 24, 2013
Revised: February 17, 2014
Accepted: March 5, 2014
Published: March 5, 2014



dx.doi.org/10.1021/ie403171s | Ind. Eng. Chem. Res. 2014, 53, 5524−5538

Computers and Chemical Engineering 63 (2014) 140–151

Contents lists available at ScienceDirect

Computers and Chemical Engineering

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

# An MFA optimization approach for pollution trading considering the sustainability of the surrounded watersheds

Francisco López-Villarreal[a,b,*], Luis Fernando Lira-Barragán[c], Vicente Rico-Ramirez[a], José María Ponce-Ortega[c], Mahmoud M. El-Halwagi[d]

[a] Instituto Tecnológico de Celaya, Departamento de Ingeniería Química, Avenida Tecnológico y García Cubas S/N, Celaya, Guanajuato 38010, Mexico
[b] Instituto Tecnológico de Pachuca, Departamento de Ingeniería Química y Bioquímica, Carretera México-Pachuca Km. 87.5, Pachuca de Soto, Hidalgo 42080, Mexico
[c] Chemical Engineering Department, Universidad Michoacana de San Nicolás de Hidalgo, Edificio V1, Ciudad Universitaria, Morelia, Michoacán 58060, Mexico
[d] Chemical Engineering Department, Texas A&M University, College Station, TX 77843, USA

ARTICLE INFO

*Article history:*
Received 27 May 2013
Received in revised form 3 January 2014
Accepted 8 January 2014
Available online 20 January 2014

*Keywords:*
Pollution trading
Material flow analysis
Optimization
Watershed
Sustainable design

ABSTRACT

This paper proposes a mathematical programming model for the pollution trading among different pollution sources which considers the sustainability of the surrounding watershed. The formulation involves the minimization of the costs associated to the implementation of the required technology to satisfy the environmental constraints in order to achieve optimal water quality conditions. The model uses a material flow analysis technique to represent changes on the behavior of the watershed due to the polluted discharges. The material flow analysis considers all discharges and extractions (i.e., industrial and residential discharges, pluvial precipitation, evaporation, etc.) as well as the chemical and biochemical reactions taking place in the watershed. In the context of pollution trading, the implementation of the proposed formulation determines if an industrial source must buy credits to compensate the violation of environmental constraints, or if it requires the installation of treatment technologies to sell credits to another source. The formulation was applied to a case study involving the drainage system of the Bahr El-Baqar region in Egypt; the results show the advantages of the proposed approach in terms of cost and sustainability.



## 1. Introduction

Current economic development policies must consider the sustainability of the systems under analysis. Sustainability includes environmental issues and social welfare. Important efforts have been made recently to improve the environmental quality and various environmental management policies have been implemented. The command and control policies and those programs that use economic incentives for environmental compliance, such as pollution trading, are among these strategies. The pollution trading concept is attributed to Crocker (1966), Dales (1968) and Montgomery (1972). Former applications of this market strategy have been the trading of $SO_X$ and $NO_X$ emissions for acid rain control (Ferral, 1991) with positive effects (Burtraw, 1996; Burtraw, Evans, Krupnick, Palmer, & Toth, 2005; Burtraw, Krupnick, Mansur, Austin, & Farrel, 1998; Burtraw & Mansur, 1999). The benefits obtained from the implementation of this strategy are: (i) significant cost reductions related to pollutant treatment, (ii) flexibility to dischargers in meeting pollutant load reductions, (iii) creation of incentives for control beyond current limits, (iv) promotion of technological innovation and (v) investment to obtain credits and extra profits. Additional environmental benefits (such as improved wildlife and co-control of other pollutants) have also been reported (Rousseau, 2001; USEPA, 2004). This strategy has also been used in water quality control with successful results (Lal et al., 2009; Rousseau, 2001; Selman et al., 2009; Smajgl, Heckbert, Ward, & Stratton, 2009; USEPA, 2008; Woodward, 2002).

Literature reports several models to describe the trading mechanisms between pollution sources. Some of the models consider pollutant nonpoint sources (Ghosh, Ribaudo, & Shortle, 2011; Luo, Maqsood, Huang, Yin, & Han, 2005; Wang, Zhang, Huang, & Li, 2004; Zhang & Wang, 2002), market equilibrium and permits (Bosetti, Carraro, & Massetti, 2009; Hung & Shaw, 2005; Innes, 2002). Also, recent works analyze the effect of more complex issues in the trading policies, such as pollutant dynamics and pollutant interactions

* Corresponding author at: Instituto Tecnológico de Celaya, Departamento de Ingeniería Química, Avenida Tecnológico y García Cubas S/N, Celaya, Guanajuato 38010, México. Tel.: +52 771 71 1 30 73; fax: +52 771 71 1 33 99.
*E-mail addresses:* iq.pacolopez@gmail.com, iq.pacolopez@hotmail.com (F. López-Villarreal).

0098-1354/$ – see front matter 
http://dx.doi.org/10.1016/j.compchemeng.2014.01.005

Computers and Chemical Engineering 69 (2014) 1–15

Contents lists available at ScienceDirect

Computers and Chemical Engineering

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

# Optimal design of sustainable water systems for cities involving future projections

Ma. Guadalupe Rojas-Torres [a], Fabricio Nápoles-Rivera [a,*], José María Ponce-Ortega [a], Medardo Serna-González [a], Mahmoud M. El-Halwagi [b,c]

[a] Chemical Engineering Department, Universidad Michoacana de San Nicolás de Hidalgo, Morelia Michoacán 58060, Mexico
[b] Chemical Engineering Department, Texas A&M University, College Station, TX 77843, USA
[c] Adjunct Faculty at the Chemical and Materials Engineering Department, Faculty of Engineering, King Abdulaziz University, Jeddah 21589, P.O. Box 80204, Saudi Arabia

ARTICLE INFO

*Article history:*
Received 3 August 2013
Received in revised form 1 May 2014
Accepted 29 May 2014
Available online 6 June 2014

*Keywords:*
Water management
Water harvesting and reclamation
Optimal water use
Sustainable water use
Optimal water storage and distribution in cities

ABSTRACT

Water scarcity is one of the main concerns of several countries around the world. In this context, several approaches have been proposed for resource conservation and available water augmentation through specific actions such as process intensification and the use, reclamation, reuse, and recycle of alternative water sources. Nonetheless, there are no reported methodologies optimizing the multiannual planning of water usage, discharge, reclamation, storage and distribution in a macroscopic system considering natural and alternative water sources. In this paper, a multi-period mathematical programming model for the optimal planning of water storage and distribution in a macroscopic system is presented. The model addresses important factors such as population growth, change in the time value of money and change in the precipitation patterns. The proposed model is applied to the case of a Mexican city. The results show important advantages from the economic and sustainability points of view.


## 1. Introduction

In the recent years the concern for the overexploitation of water bodies has stimulated research in the field of water conservation and resource augmentation. This phenomenon has been driven by human factors such as population growth, industrial development, life standard enhancement, irrational use of the resources and climate change. But also due to natural causes like uneven distribution of the water in the world and geographical limitations (for example in the case of islands and arid regions). The main focus of recent research efforts is the resource conservation and water augmentation through specific actions such as regeneration, reuse and recycle of water. These strategies have been successfully implemented in the industrial context by several authors. In this context, Foo (2009) presented an extensive review of pinch-based techniques for water network synthesis in continuous processes. Although pinch-based techniques have shown being useful, they have at least one of the following limitations: they are suited only for small or medium size problems, they are generally limited to the single contaminant case, they do not consider stream regeneration and/or cannot include multiple fresh utilities; thus several authors have proposed mathematical programming approaches to overcome these limitations. This way, Gouws et al. (2010) presented a review for water minimization techniques involving batch processes. Furthermore, Jezowski (2010) presented another review rewarding water networks using graphical and mathematical programming techniques. More recently, the synthesis of water networks has been extended for the case of industrial complexes (i.e. eco-industrial parks). This way, Chen et al. (2010) considered the problem of interplant water optimization with central and decentralized water mains; they considered two separate objective functions: reducing the water consumption and reducing the total annual cost of the network. Then, Rubio-Castro et al. (2011) also considered the synthesis of multi contaminant water networks in an eco-industrial park. Tudor and Lavric (2011) proposed an approach to minimize simultaneously the water consumption and the operating cost. These works have been successfully extended by several authors (see for example Burgara-Montero et al., 2013; Lira-Barragán et al., 2010, 2011, 2012; Martinez-Gomez et al., 2013) through mathematical programming approaches to consider the problem of water networks and its impact in the surrounding watersheds; these models are also multi-objective optimization problems and have taken into account different optimization criteria such as economic,

* Corresponding author. Tel.: +52 443 3273584; fax: +52 443 3273584.
*E-mail addresses:* fnapoles@umich.mx, fabricio_napoles@yahoo.com.mx (F. Nápoles-Rivera).

http://dx.doi.org/10.1016/j.compchemeng.2014.05.026
0098-1354/

CHEMICAL ENGINEERING TRANSACTIONS
VOL. 42, 2014
A publication of AIDIC
The Italian Association of Chemical Engineering
www.aidic.it/cet
Guest Editors: Petar Sabev Varbanov, Neven Duić

ISBN 978-88-95608-33-4; ISSN 2283-9216
DOI:10.3303/CET1442010

# Optimal Planning of Supply Chains for Multi-Product Generation from Municipal Solid Waste

José Ezequiel Santibañez-Aguilar[a], José María Ponce-Ortega*[a], Janett Betzabe González-Campos[b], Medardo Serna-Gonzaléz[a], Mahmoud M. El-Halwagi[c]

[a]Chemical Engineering Department, Universidad Michoacana de San Nicolás de Hidalgo, Morelia, Michoacán, México
[b]Chemical-Biological Research Institute, Universidad Michoacana de San Nicolás de Hidalgo, Morelia, Michoacán, México
[c]Chemical Engineering Department, Texas A&M University, College Station, Texas, USA
jmponce@umich.mx

In recent years there has been increased the amount of generated municipal solid waste in most of the developing countries, where the waste management systems are not adequate because of lack of organization and infrastructure. A special case is Mexico, where the municipal solid waste management is responsibility for the government; however, the waste management in Mexico is not adequate due to the lack of landfills and culture about of waste separation.
In this regard, this work proposes a mathematical model for the optimal planning of supply chains based on municipal solid waste, where several processing technologies for different waste as well as the total costs for the entire waste management network are considered. This planning problem is mathematically formulated as a multi-objective optimization problem that seeks to maximize the net annual profit (economic objective) and minimize the environmental impact, which is measured through the percentage of the total utilized waste respect to the waste that can be used as raw material.
The proposed optimization approach was applied to a case study in Mexico. The results show that it is possible to implement a supply chain for using municipal solid waste that maximizes the net profit of the network reducing significantly the impact to the environment. Furthermore, the results are shown through a Pareto curve that can be used by decision makers to implement a network for waste processing to obtain multiple products in places where there is not any waste management system at all.

## 1. Introduction

Municipal solid waste management is a challenge for authorities of cities in developing countries, mainly due to the increasing of waste generation (Abarca-Guerrero et al., 2013). This is a serious problem in countries like Mexico because the size of landfills is not sufficient, the waste disposition is not adequate, and the garbage is mixed with several recyclable and non-recyclable materials, which increases the separation costs and makes the waste recycling process more difficult. In this way, several alternatives have been proposed to solve the waste management problem from different points of view. For example, Antonioni et al. (2012) simulated a two-stage dry flue gas cleaning process for a municipal solid waste incinerator and Kropáč et al. (2013) developed a simulation model for waste-to-energy production. Furthermore, a waste management system can be addressed as a supply chain design problem; in this context, Young et al. (2013) presented an approach for evaluating and designing sustainable supply chains based on waste. Furthermore, Čuček et al. (2012a) presented an approach to reduce the number of objectives in multi-objective optimization, and then Čuček et al. (2012b) applied this approach for biomass-to-energy supply chains. Varbanov et al. (2012) analyzed the energy generation from waste. Šomplák et al. (2013) introduced an interesting approach for facility planning in the field of waste management, where the goal was to obtain the minimum cost for the municipal solid waste treatment in municipalities. In this way, the supply chains focused on the waste management should consider the waste generation, collection, separation, transportation, conversion, distribution, and waste disposal for the

Please cite this article as: Santibañez-Aguilar J.E., Ponce-Ortega J.M., González-Campos J.B., Serna-Gonzaléz M., El-Halwagi M.M., 2014, Optimal planning of supply chains for multi-product generation from municipal solid waste, Chemical Engineering Transactions, 42, 55-60 DOI:10.3303/CET1442010

Journal of Cleaner Production 65 (2014) 270–294

Contents lists available at ScienceDirect

Journal of Cleaner Production

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

# Optimal planning and site selection for distributed multiproduct biorefineries involving economic, environmental and social objectives

José Ezequiel Santibañez-Aguilar [a], J. Betzabe González-Campos [b], José María Ponce-Ortega [a,*], Medardo Serna-González [a], Mahmoud M. El-Halwagi [c,d]

[a] Chemical Engineering Department, Universidad Michoacana de San Nicolás de Hidalgo, Morelia, Michoacán 58060, Mexico
[b] Institute for Chemical and Biological Research, Universidad Michoacana de San Nicolás de Hidalgo, Morelia, Michoacán 58060, Mexico
[c] Chemical Engineering Department, Texas A&M University, College Station, TX 77843, USA
[d] Adjunct Faculty at the Chemical and Materials Engineering Department, King Abdulaziz University, Jeddah, Saudi Arabia

ARTICLE INFO

*Article history:*
Received 27 June 2012
Received in revised form
19 June 2013
Accepted 1 August 2013
Available online 14 August 2013

*Keywords:*
Biorefinery supply chain
Multiple processing and harvesting sites
Multi-objective optimization
Planning
Sustainability
Environmental and social assessment

ABSTRACT

Biorefineries appear to be a viable solution to replace traditional fossil fuel refineries, but their implementation requires the exploration of several aspects, including feedstock selection, processing routes, products, harvesting sites, processing and markets, as well as numerous other sustainability criteria. The optimal solution to these problems is not immediately obvious. Therefore, this study presents an optimization model to design and plan sustainable biorefinery supply chains that considers numerous relevant issues. These issues include the multiple available biomass feedstocks at various harvesting sites, the availability and seasonality of biomass resources, different potential geographical locations for processing plants that produce multiple products using diverse production technologies, economies of scale for the production technologies, demands and prices of multiple products in each market, locations of storage facilities and a number of transportation modes between the supply chain components. Sustainability considerations are incorporated into the proposed model by including simultaneous economic, environmental and social performance data in the evaluation of the supply chain designs. The problem was formulated as a multi-objective, multi-period, mixed-integer linear program that seeks to maximize the profit of the supply chain, minimize its environmental impact and maximize the number of jobs generated by its implementation. The environmental impact was measured by the Eco-indicator99 according to the life-cycle assessment technique, and the social objective was quantified by the number of jobs generated. The Pareto-optimal solutions were obtained using the $\varepsilon$-constraint method. To illustrate the capabilities of the proposed multi-site system model, a case study was presented that addresses the optimal design and planning of a biorefinery supply chain to fulfill the expected ethanol and biodiesel demands in Mexico. The results indicate that cost-effective and sustainable solutions can be obtained that satisfy Mexican demand by choosing feedstocks that are available year-round and do not significantly adversely impact the environment. Furthermore, the number of jobs generated by implementing the biorefinery supply chain would have a significant social impact.


## 1. Introduction

During the last three decades, several authors have developed diverse assessment frameworks that integrate a number of dimensions required for sustainable development, which is defined as "*development that meets the needs of the present without compromising the ability of future generations to meet their own needs*" (WCED, 1987). In this context, Jansen (2003) identified three relevant dimensions for sustainable development: the interactions between culture, structure and technology, the optimization/improvement/renewal approaches and the parts involved. Vachon and Mao (2008) assessed the linkage between supply chain characteristics and three suggested dimensions of sustainability, namely, environmental performance, corporate environmental practices and social sustainability. An overview of environmental, social, and economic footprints indicators that can be used to measure sustainability was presented by Cucek et al. (2012). Recently, Lozano (2008) proposed the concept of two-tiered sustainability equilibria for depicting sustainability. This concept centers on the interaction between economic, environmental and

* Corresponding author. Tel./fax: +52 443 3273584.
*E-mail addresses:* jmponce@umich.mx, jose_maria_ponce@yahoo.com (J.M. Ponce-Ortega).

0959-6526/$ – see front matter 
http://dx.doi.org/10.1016/j.jclepro.2013.08.004

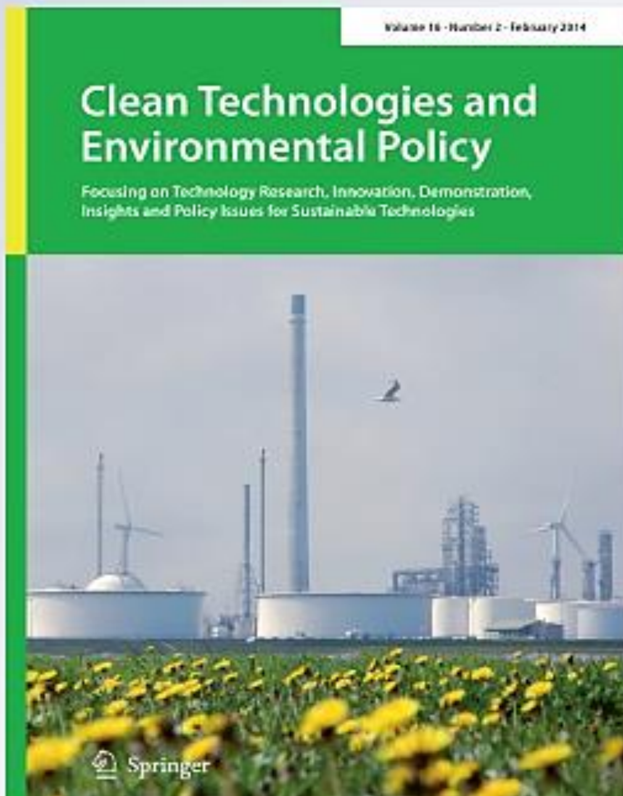
# Optimal reconfiguration of water networks based on properties

César Sotelo-Pichardo, José María Ponce-Ortega, Fabricio Nápoles-Rivera, Medardo Serna-González, Mahmoud M. El-Halwagi, et al.

**Clean Technologies and Environmental Policy**
Focusing on Technology Research, Innovation, Demonstration, Insights and Policy Issues for Sustainable Technologies

ISSN 1618-954X
Volume 16
Number 2

Clean Techn Environ Policy (2014) 16:303-328
DOI 10.1007/s10098-013-0631-5




Springer

I&EC research
Industrial & Engineering Chemistry Research

Article

pubs.acs.org/IECR

# Optimal Synthesis of Property-Based Water Networks Considering Growing Demand Projections

César Sotelo-Pichardo,[†] Hisham S. Bamufleh,[‡] José M. Ponce-Ortega,*[,†] and Mahmoud M. El-Halwagi[‡,§]

[†]Chemical Engineering Department, Universidad Michoacana de San Nicolás de Hidalgo, Morelia, Michoacán 58060, México

[‡]Department of Chemical & Materials Engineering, Faculty of Engineering, King Abdulaziz University, P.O. Box 80204, Jeddah 21589, Saudi Arabia

[§]Chemical Engineering Department, Texas A&M University, College Station, Texas 77843, United States

*Supporting Information*

ABSTRACT: This paper presents a mathematical programming model for the optimal synthesis and retrofitting of water networks based on the properties of the streams that impact the processing in the plant and the environment. One important feature of the proposed approach is that it accounts for changes in the operation through a time horizon with growing demands. The optimization formulation considers changes in the demands and accounts for time-based variations in the flow rates required for the process sinks and constraints for properties in the process sinks and in the environment. Furthermore, the proposed model allows the installation of different units and the retrofitting of the water network over the considered time horizon. The objective function minimizes the total cost associated with the entire life of the project while accounting for the time value of money and the specific demands for the process and the environment that change through the life of the project. Two case studies are solved to show the applicability of the proposed approach.

## INTRODUCTION

The refining and process industries are characterized by the enormous usage of fresh water and discharge of wastewater. Because of the continued retrofitting projects to increase the capacities of refineries and process industries, usage and discharge of water are growing. With the scarcity of fresh water resources, there is a critical need for effective water conservation strategies. Water recycle approaches are among the most effective water conservation strategies. The substitution of fresh water with recycled process- and wastewater streams may be carried out through direct recycle or following treatment of the recycled streams to meet the requirements of process units (sinks) that use fresh water. These process sinks require that the recycled water streams meet specific constraints on flow rate, concentration of impurities, and properties. Various tools have been proposed for the synthesis of water-recycle networks. Foo[1] has reviewed many of these tools. An interesting problem associated with water networks is the retrofitting of existing networks that were not properly designed or when the process and/or environmental constraints have changed. In this context, Fraser and Hallale[2] presented a retrofitting approach based on the pinch point technology. Alfadala et al.[3] presented a methodology based on a set of heuristic rules with the goal of minimizing the total annual cost. Cheng and Hung[4] developed an mixed-integer nonlinear programming (MINLP) formulation for retrofitting single units of mass exchange considering the use of external agents to facilitate the separation. Tan and Cruz[5] developed a linear programming model to retrofit a water network with one component. Tan and Manan[6] presented a systematic methodology to retrofit water networks and introduced regeneration units using a sequential approximation, and Sotelo-Pichardo et al.[7] proposed a mathematical programming model for the retrofitting of water networks based on the constraints given in terms of limits for the composition of the manipulated streams. This approach was later improved to incorporate property constraints by Sotelo-Pichardo et al.[8] Bishnu et al.[9] developed a multiperiod synthesis approach for water networks involving multiple industrial processes with seasonal variations. Faria and Bagajewicz[10] presented a mathematical programming approach for retrofitting water networks to maximize net present value. A common limitation in these foregoing research efforts is that retrofitting was carried out for a specific current requirement. In many cases, retrofitting is needed over a time horizon to meet future demand increases that are associated with capacity-increase projects. A simplistic approach to satisfy the future requirements and increasing demands for water is to overdesign the water network to meet the maximum future demand through a single retrofit. A better approach is to develop a time-based strategy for retrofitting that considers the future projections for increase in water demand over multiple periods and the possibility of stage-wise retrofitting over multiple periods while accounting for the existing infrastructure. This is the focus of this paper which is aimed at developing a systematic method for synthesizing and simultaneously retrofitting a multiyear water network that accounts for future projections. The proposed optimization formulation takes into account from the design stage future projections and expansions and the possibility of multiannual retrofitting that avoids an overdesigned network. The objective function is the minimization of the total cost in the entire horizon time

Received: August 5, 2014
Revised: October 24, 2014
Accepted: November 4, 2014
Published: November 4, 2014

   dx.doi.org/10.1021/ie503127p | Ind. Eng. Chem. Res. 2014, 53, 18260−18272

Chemical Engineering and Processing 77 (2014) 38–41

Contents lists available at ScienceDirect

Chemical Engineering and Processing: Process Intensification

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

Short communication

# Use of glycerol as entrainer in the dehydration of bioethanol using extractive batch distillation: Simulation and experimental studies

Salomón Navarrete-Contreras[a], Mauricio Sánchez-Ibarra[a], Fabricio Omar Barroso-Muñoz[a], Salvador Hernández[a,*], Agustín Jaime Castro-Montoya[b]

[a] Universidad de Guanajuato, Campus Guanajuato, DCNyE, Departamento de Ingeniería Química, Noria Alta s/n, 36050 Guanajuato, Guanajuato, Mexico
[b] Universidad Michoacana de San Nicolás de Hidalgo, Facultad de Ingeniería Química, Ciudad Universitaria, Col. Felicitas del Río, 58060 Morelia, Michoacán, Mexico

ARTICLE INFO

*Article history:*
Received 9 November 2013
Received in revised form 2 January 2014
Accepted 13 January 2014
Available online 23 January 2014

*Keywords:*
Glycerol as entrainer
Bioethanol dehydration
Extractive batch distillation
Ethanol–water azeotrope

ABSTRACT

In this paper the dehydration of bioethanol via extractive batch distillation using glycerol as entrainer is studied. Simulation and experimental tests were carried out in order to use glycerol to produce bioethanol with a composition higher than that of the azeotropic point. The results are compared to those reported using ethylene glycol and ionic liquids as entrainers for the same separation. The simulation and experimental results indicate that it is possible to produce high purity bioethanol that can be used as a fuel oxygenate. Among the entrainers used in the experimental tests, the glycerol presented the best performance in terms of the purity in the distillate. Also, it is important to highlight that glycerol has a lower cost in comparison to ethylene glycol and ionic liquids and that is considered a by-product in the biodiesel production.



## 1. Introduction

Nowadays biofuels are a possible source to satisfy the increasing energy requirements. Among them are the bioethanol and the biodiesel. According to Szulczyk et al. [1], worldwide bioethanol demand has grown rapidly due to government mandates such as the Energy Independence Security Act of 2007 and environmental regulations forbidding the use of methyl terbutyl ether (MTBE) as a fuel oxygenate. In addition, Balat and Balat [2], mentioned that bioethanol production represented 4% of total gasoline consumed around the world in 2007, and worldwide production may exceed 125 billion liters by 2020, thereby enhancing renewable energy production – expected to supply 60% of the global energy demand in 2070 according to the World Committee of Energy Council [3].

In this context, and concerning the production of bioethanol via a fermentative process, a diluted mixture of bioethanol and water (less than 10% in volume) is produced, from which the bioethanol can be recovered to the desired purity [4,5]. In order to use bioethanol mixed with gasoline, high purity bioethanol (with a content of water less than 0.5% in weight) is required involving a concentration step and a subsequent dehydration operation to avoid having two liquid phases that may cause damage to the combustion engine. The purification process involves two stages (Fig. 1), in the first stage (column C1) most of the water is removed and a distillate with a composition close to the azeotropic point is obtained (around 96% in weight), during the second stage (column C2) the breaking of the azeotrope is achieved by using an extractive distillation column where the final ethanol purity is achieved (around 99.5% in weight). The first distillation column (C1) requires energy in the reboiler to accomplish the separation and the second distillation column (C2) requires both energy and a mass separation agent (entrainer). Several entrainers have been used in simulation studies of the reported distillation sequence of Fig. 1.

Regarding the use of entrainers, Ravagnani et al. [6] have studied the breaking of the ethanol–water azeotrope using ethylene glycol and tetraethylene glycol, reporting that the ethylene glycol gives better results than the tetraethylene glycol, but the ethylene glycol can be forbidden in the future due to its toxicity. Zhao et al. [7] reported the use of several ionic liquids, including 1-butyl-3-methylimidazolium bromide and 1-butyl-3-methylimidazolium chloride for the separation of the mixture of ethanol–water. Also, Chávez-Islas et al. [8] reported a mixed-integer nonlinear programming formulation in order to obtain the molecular design of several ionic liquids to recuperate ethanol with a purity of 99 mol% or higher suitable for mixing with gasoline.

Gil et al. [9] and García-Herreros et al. [10] studied the design and control of an extractive distillation process to produce anhydrous ethanol using glycerol as entrainer, concluding that the glycerol can be used in the production of high purity ethanol taking advantage of its low cost and high availability; no control problems were

* Corresponding author. Tel.: +52 473 7320006x8142; fax: +52 4737320006x8139.
E-mail addresses: hernasa@ugto.mx, hernasa@me.com (S. Hernández).

0255-2701/$ – see front matter © 2014 Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.cep.2014.01.003

International Review of Chemical Engineering (I.RE.CH.E.), Vol. 6, N. 1
ISSN 2035-1755 January 2014

# Vegetable Oils for Biodiesel Production as Friendly Energetic Alternative: the Case of Mexico

D. Alvarez-Barrera[1], G. Segovia-Hernández[2], A. J. Castro-Montoya[1], R. Maya-Yescas[1], M. C. Chávez-Parga[1]

**Abstract** – *Among the current cited biofuels, biodiesel production using vegetable oils as raw materials exhibits technical, social and economic advantages. Some crops exhibit untapped potential as source-alternatives for satisfying the increasing energy demand; therefore, it is important to study the feasible reaction routes to transform triglycerides, mainly, into biodiesel. Mexico has been taken into account as case of study, in order to estimate the potential utility and economic impact of vegetable oils in its development. It is noticed that about 90% of the Mexican territory exhibits favorable climatic characteristics to crops able to produce vegetable oils useful in biodiesel production.* 

***Keywords:*** *Biodiesel, Energy Alternative, Mexico, Vegetable Oils*

## I. Introduction

### *I.1. Energy Use and Demand in Mexico*

Since the man appeared on the planet, energy consumption was imminent to realize all kind of works that would allow surviving and, eventually, comforts for a more pleasant life.

Therefore, over time energy needs have increased and, in Mexico, this demand has reached higher levels each year and is being covered by the use of petroleum based fuels, mainly.

Unfortunately, the use of oil as energy source in the case of Mexico will become very expensive in the future. According to the data presented by the Mexico's Ministery of Energy (SENER) (Fig. 1), the proved inland oil reserves in January of 2010 amount to a total of 14,000 million barrels of oil and the current daily demand is 3 million barrels. It means that proved oil's lifetime of 12.8 years. Hence, it is necessary to replace petroleum fuels by those obtained from renewable sources.

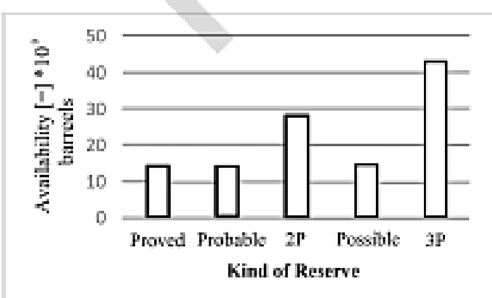



Fig. 1. Mexican reserves of oil (SENER, 2010)

### *I.2. Biodiesel*

Biodiesel is now one of the proposed transition energies of greater global importance. Biodiesel is a synthetic liquid biofuel derived from natural fats such as vegetable oils, new or used, by the industrial processes of esterification and transesterification.

Its main contribution is partial or total substitution of gasoil (obtained from oil) in heating processes and engines.

In particular, it is very easy to replace diesel by biodiesel in internal combustion engines because:

- No modifications are required by an old diesel engine to switch to biodiesel.
- Biodiesel exhibits higher cetane number than diesel (51 *versus* 42, respectively). Since this is an indicator of the engine knock at start-up, an engine that switches to biodiesel will start-up softer than previously using diesel [1].
- Biodiesel exhibit better solvent properties with respect to diesel, such as cleaning effect on the engine parts.
- Biodiesel provides better lubricant properties with respect to diesel; therefore engine parts will last longer.
- A liter of biodiesel might replace between 0.90 and 0.95 liters of diesel, in relation to calorific values; therefore there is no need to replace the fuel reservoir.

The first technical tests with biodiesel were held in Austria and Germany in1982, but only until 1985 the first pilot plant producer of rapeseed methyl-esters was built in Silberberg, Austria.

Some years later, biodiesel production becomes more important and larger quantities of raw materials were processed. Table I shows the main European biodiesel producer countries.

*Manuscript received and revised December 2013, accepted January 2014*