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Biorefining and industrial symbiosis: A proposal for regional development in Brazil

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ABSTRACT

The consolidation of the biorefinery concept has the potential to contribute to the sustainable development of agro-industrial regions, particularly in developing countries. The industrial symbiosis (IS) approach can leverage this potential through industrial cooperation, fostering new businesses, innovation and job creation coupled with reduced environmental impacts. We argue that coupling the biorefinery concept and the IS approach would invigorate traditionally agricultural regions, relying on endogenous vocation to promote sustainability. The purpose of this study is to examine the potential for development of an agro-industrial symbiosis network (ISN) from the construction of a biorefinery in the Norte Fluminense region (Brazil) – a region that has become highly dependent on oil & gas revenues but still has a tradition in agriculture and agro-industry. In this paper, we present the scenario analysis performed to design the agro ISN and an initial quantification of potential benefits. Four scenarios were developed (reference, short, mid and long terms) with the support of a synergy matrix and material flow analysis. Eighteen waste streams were identified and sixteen were addressed through the scenarios. In the long-term scenario, 14 productive activities could compose the agro-industrial symbiosis network, 8 of them as newcomers. "Quick-wins" were identified as residues in the reference scenario (CO_2, fusel oil and used yeast) that could be absorbed by industries currently operating in the region. The emission of respectively 350 thousand and 55 thousand tonnes per year of solid waste and CO_2 would be avoided in the long term. Also, the production of succinic acid would provide additional revenue of at least US$19 per tonne of bagasse, adding higher value to the feedstock in comparison to electricity production. This study can prompt current recycling regulation towards multi-sectorial arrangements, which can better contribute to regional resilience than the single-sector reverse logistics' arrangements that became recently mandatory with the National Policy on Solid Waste.

1. Introduction

The deployment of the modern bioeconomy – the part of the economy based on renewable biomass, biosciences and biotechnology – is fundamentally tied to the consolidation of biorefineries as basic input suppliers (European Commission, 2011; Kircher, 2014). Biorefineries are facilities capable of converting biomass into products ranging from electricity and biofuels to polymers and fine chemicals (Cherubini, 2010). They promise to drastically change the world's still fossil-based production system (Bennett and Pearson, 2009; Werpy and Petersen, 2004), and also hasten sustainable development in emerging economies (Blanco-Rosete and Webb, 2008; Doelle and DaSilva, 2004; Jong and Jungmeier, 2015).

In Brazil, biorefining has been essentially tied to biofuel production (Bohlmann and Cesar, 2006; da Costa et al., 2010). The country's relevance in this industry lies mostly in its great feedstock availability (e.g., 634 million tonnes of sugarcane were harvested in the 2014-15 season (CONAB, 2015a)). Studies of sugarcane bagasse biorefineries in Brazil often emphasize technical and economic feasibility analyses (Dantas et al., 2013; Pacca and Moreira, 2011; Seabra and Macedo, 2011) and environmental performance evaluation (Agostinho and Ortega, 2013; Renó et al., 2014; Souza et al., 2012). While most of them focus on energy carriers' production, bio-based chemicals need to be further explored. Also, despite

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Abbreviations

IS	Industrial symbiosis
ISN	Industrial symbiosis network
Bio-SA	Bio-succinic acid
CHP	Combined heat and power generation
FIRJAN	Federation of Industries of the State Rio de Janeiro
INEA	Rio de Janeiro State Institute for the Environment
PM	Particulate matter
PNRS	Brazilian National Policy on Solid Waste
RRM	Renewable raw material
SM	Synergy matrix

some comprises business model analysis (Dias et al., 2013, 2012; Palacios-Bereche et al., 2013), none of them consider either innovative sustainable business models, such as the industrial symbiosis (IS) approach (Short et al., 2014), nor the investigation of implications for regional or local sustainable development.

Besides the use of renewable raw materials (RRM), the biorefining concept also addresses waste management issues (Fahd et al., 2012; Pervaiz and Sain, 2015; Poggi-Varaldo et al., 2014), since it envisions the integral use of biomass (Bragatto et al., 2013; Mooibroek et al., 2007; Rodrigues, 2011). The intensification of agricultural and agro-industrial production that followed the Second World War caused waste management to gain increasing attention in the sector (Loehr, 1974; Spadotto and Ribeiro, 2006).

Among the waste management approaches, IS involves the exchange of residues and byproducts among distinct productive activities. One firm's waste becomes another's feedstock (Chertow, 2000; Yu et al., 2013) and it can also drive local and regional sustainable development, going beyond the environmental dimension (Deutz and Gibbs, 2008; Deutz and Lyons, 2008). For instance, the British National Industrial Symbiosis Programme helped create or preserve 100 job positions in one year (Bryan, 2004). In China, the IS network (ISN) of Guangxi province improved the local labor market and reduced brain drain, since better educational background was needed by the research institutes created, assuring competitiveness through innovation and added value. In Australia, the ISN of Kwinana Industrial Area proved to be a key strategy to achieve regional economic development and sustainability (MacLachlan, 2013).

In Brazil, IS practices are mainly concentrated in projects aimed at improving sustainability practices in industrial clusters. From the eleven cases known, three were greenfield (Camparotti, 2015; Elabras Veiga and Magrini, 2009; Natura, 2014). Among the brownfield cases, two applied IS principles spontaneously while six were partially implemented projects (Cavalcante, 2015; Fragomeni, 2005; Tanimoto, 2004) and (Branco and Mañas, 2009; Rocha et al., 2015). In the agricultural and agro-industrial sectors, some projects of integrated biosystems for hog breeding (Bezerra, 2002; Casagrande, 2003; Medeiros et al., 2003), fish farming (Hermes et al., 2009; Junior et al., 2009) and sugarcane farming (Ometto et al., 2007) were conducted in early 2000s. Hence, the exploration of IS uses in such strategic sectors of the Brazilian economy demands further investigation.

The agro-industry is responsible for 20% of the Brazilian GDP (CEPEA, 2016) and the sugarcane sector play a major role in it. The sugarcane industry is active in 24 of Brazil's 27 states (UNICA, 2015a). Five of them concentrate 88% of the national sugar and ethanol production (CONAB, 2015b). However, the other 19 still process 82 million tonnes of sugarcane per season in 97 mills/distilleries (NovaCana, 2016; UNICA, 2015a). The case of Rio de Janeiro state is emblematic. Its northern region, referred here as Norte Fluminense, was once the major sugar producer in the country but lost this position to become Brazil's main oil & gas (O&G) producer (offshore fields).

Hence, given the alignment of the biorefinery concept and IS approach for competitiveness and sustainable regional development, our aim is to verify the potential of developing an agro industrial symbiosis network (ISN) through the construction of a biorefinery adjacent to a sugarcane mill in the Norte Fluminense region. This paper presents the design such agro ISN with a hypothetical biorefinery as the central tenant and an initial quantitative assessment of its potential benefits. The biorefinery would convert sugarcane bagasse into bio-based succinic acid (bio-SA). The methodological approach for the design is built upon Magrini and Masson (2005) and Tanimoto (2004). It applies scenario analysis and a synergy matrix (SM), relying on literature data, institutional reports and interviews with stakeholders. The estimation of potential benefits should be regarded as a first-proxy quantification of the outcomes expected from the agro-ISN proposed (van Berkel et al., 2009) since the pre-assessment of synergies provides an incentive for the materialization of ISNs (Trokanas et al., 2014).

This study is part of a broader academic study aimed at proposing innovative sustainable perspectives for smaller scale sugarcane facilities in Brazil using the biorefining concept. It was recommended as a strategic project by the Brazilian Ministry for National Integration. The paper is organized into six sections besides this introduction. In the second section, we present the theoretical foundations of this study, encompassing the biorefinery concept and the application of the IS approach to biorefineries. In section 3, we provide contextual information about the region. The materials and methods used are described in the fourth section while in sections 5 and 6 we present and discuss the main findings of the study, before presenting some conclusions and final remarks in section 7.

2. Literature review

The background presented is mainly based on material compiled from literature platforms such as Scopus, Web of Science and Google Scholar. The keywords used were “industrial symbiosis”, “waste exchange”, “biorefinery”, “biorefining”, “bioindustry” and “agro-industry”. Institutional reports, news stories and corporate websites were also consulted.

2.1. The biorefining concept: feedstocks, processes and products

According to the International Energy Agency (IEA), biorefining is the sustainable processing of biomass for the production of a range of marketable bio-products and bioenergy (IEA, 2011). Cherubini (2010) and Horta Nogueira et al. (2008) define a biorefinery as an integrated complex of processes and equipment capable of producing different products based on different biomasses, and hence involving a broad range of possibilities in terms of feedstocks, technological routes and products.

In terms of sources, the RRM can be either from farming (dedicated crops and waste), aquaculture (algae), planted forests; industry (leftovers and process waste) and urban areas (sewage and municipal solid waste) (Assunção et al., 2010; Cherubini, 2010). In terms of composition and structure the inputs are mainly oleaginous, starchy or lignocellulosic materials (Cherubini, 2010). Studies of the use of residual RRM have gained relevance in comparison to other feedstocks, since it is likely: (1) not to compete with food