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“A future beyond sugar”: Examining second-generation biofuel pathways in Alagoas, northeast Brazil

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ABSTRACT

In this article, we examine an early example of lignocellulosic, or second-generation (2G), ethanol production amid wider efforts to address concerns over harmful socio-environmental effects of the bioethanol sector. Focusing on a bioethanol-from-cellulose refinery in Alagoas, northeast Brazil, and recent efforts in the region to enroll alternative sources such as eucalyptus as feedstock, our findings underscore the continued importance of primary crops as inputs for new enzyme development for 2G production, with potential to intensify monoculture agriculture pathways in Alagoas and other sites of expansion. Accordingly, we highlight the value of transdisciplinary approaches to shape the early stages of scientific research into novel enzyme applications, including the selection of potential new crops for feedstocks, their local socio-environmental consequences, and their wider linkages in a global agrarian economy. We argue that determining which, if any, varieties of biomass are best suited for enzyme development entails seeking the input of multiple stakeholders and sources of knowledge to avoid reproducing socioeconomic inequalities and injustices or endangering local environments.

1. Introduction

Sugarcane bioethanol has been widely regarded as an important energy carrier and a clean and sustainable alternative to fossil fuels. Proponents of bioethanol from sugarcane have promoted it as a vital component of the transition to a carbon-neutral future, reducing emissions while enhancing energy security and strengthening rural economies (Raman and Mohr, 2014; Moreira et al., 2014; Mol, 2007). In the past 15 years, however, biofuels have come under heightened scrutiny, particularly for their potential effects on land dedicated to food production, and consequently on food supplies, prices, and scarcity (see Tomei and Helliwell, 2016; Mohr and

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Raman, 2013; Benites-Lazaro et al., 2020). In response to these critiques, biofuels champions have refocused attention on the potential for lignocellulosic, or second-generation (2G), innovations in biofuels. This technology promises to convert efficiently potentially any type of biomass into liquid fuel, particularly the non-edible parts of plants (Graham-Rowe, 2011; Moreira et al., 2014). 2G ethanol production involves the use of sugars released by enzymes from the cellulose content found in various crop residues, including sugarcane. Yet, the implementation of these production processes in a handful of sites—set to increase in other biomass-rich regions—raises concerns over how and whether they can adhere to social and environmental justice goals as articulated in the UN Sustainable Development Goals (SDGs) (cf. Newell, 2021). These include questions around reconfiguring land with monocultures, water depletion, loss of soil fertility, labor conditions, new forms of social inequality and exclusion, and the extent to which reparative alternatives are possible.

The extent to which 2G ethanol can contribute to these goals is debatable, as the adoption of this technology and establishing a cross-border market requires large investments and takes time. Ongoing challenges include securing production sites, transport routes and the regulation of an international market (Mol, 2007; Raele et al., 2014). Here, the question arises of how and whether 2G bioethanol contributes to a just energy transition for all.

In this article, we suggest that the material forms and practices surrounding energy systems and technologies have continued importance. In particular, the lower power densities of renewable systems including biofuels, as compared with fossil fuels, imply a range of tradeoffs, particularly because larger areas of land must be incorporated into energy production (Huber and McCarthy, 2017). In this sense, renewable energy production "once again becomes a significant driver of land use" amid the global transition to net-zero energy (Bridge, 2018: 15).

Within this larger, global socioeconomic context, we examine 2G bioethanol development in Alagoas state, northeast Brazil, as a case through which to explore wider pathways and prospects for this technology. The analysis we present stems from a one-year transdisciplinary research project spanning the social and natural sciences (title removed for peer-review) in collaboration between UK and Brazil-based researchers. We focus in this paper on the socio-environmental and distributional implications of production using this technology. To do this we examine the links between the continued importance of primary crops as starting materials, or feedstock, in the 2G production process and the ways this creates the potential to change or reinforce preexisting monocultural agrarian pathways. Accordingly, we highlight the value of collaborative partnerships, spanning disciplines, stakeholder perspectives and local knowledge, to inform research on innovations for 2G biofuels to avoid the top-down imposition of technologies on communities and other adverse impacts. As 2G applications are expanding to other global regions, these debates resonate beyond Brazil. We further examine the possibilities for integrating broader perspectives in environmental research, and within studies of biofuels development specifically, given the complex interplay of social, economic, political, and physical environments that are affected. What are the possibilities and constraints for moving beyond a scenario in which the social sciences play a subordinate role in shaping scientific discourse to one in which the social sciences *inform* how problems are defined, how future research trajectories are set out, and resources allocated (cf. Szerszynski and Galarraga, 2013)?

Our argument is structured in six sections, including this introduction. Section 2 presents the theoretical framework. In the third section, we provide an updated review of recent food-versus-fuel controversies and efforts to position 2G technologies to resolve these concerns. Section 4 is the methods section and discusses stakeholder interviews and data analysis. We then present findings on 2G biofuel production in Alagoas, Brazil in section 5. In section 6, implications of the findings on alternative feedstocks for 2G biofuels development in Alagoas, including eucalyptus and cassava, are discussed. The article concludes with reflections on 2G biofuels, the benefits and challenges of pursuing a "future beyond sugar" in Alagoas, and the implications for research on sustainability transitions.

2. Changing global geographies of energy

Our starting point is the wider political economy in which energy resources gain value and developments take place. The emergence of new forms of energy supply and demand is shaped by multiple interactions between social and technological innovations, along with existing structures and relations of power (Calvert, 2016; Meadowcroft, 2011). Through these interactions, some physical entities with certain energetic qualities can become energy resources, and the material features of those resources play an active—if unintentional—role in shaping human-environment relations, production networks, development pathways and social encounters (Bakker and Bridge, 2006). Geographers have contributed to exploring the drivers and dynamics of energy transitions, broadly defined as a radical, systemic, and purposive change towards more sustainable and effective patterns of energy provision and use (Bridge et al., 2013). Researchers have conceived of energy transitions as all-encompassing changes in the ways societies produce, use and value energy (Verbong and Geels, 2007; Araújo, 2014).

Geographical thinking enables us to understand how energy transitions vary across space and territory, and how they shape our social, economic, and political relations and interactions with our nonhuman surroundings (Bridge et al., 2013; Calvert, 2016). Geographers and environmental studies scholars have emphasized that pursuing just and sustainable systems of energy provision is a challenge with underlying spatial features. Defining what constitutes 'just' energy systems is itself highly contested and permeated with relations of power that vary across space (Jenkins et al., 2021; Healy and Barry, 2017). Opening dialogue, decision-making and accounting for social change are thus crucial aspects of low-carbon energy transitions.

Studies of energy transitions often neglect the importance of spatial contexts and geographical difference (Cowell, 2020; Axon and Morrissey, 2020). In a widely-read article exploring the spaces of low-carbon transition, Bridge et al. (2013) called for research that mobilizes geographical concepts to investigate policy proposals for the low-carbon economy, and their influence on—and intersection with—contemporary patterns of uneven development. Building on this work, Hansen and Coenen (2015) emphasized that sustainability transitions emerge in situated places while conversely, space underpins and shapes local innovation pathways. Besides this conceptual commitment to the ways that space and place give shape and form to energy systems, understanding the drivers and outcomes of transition also encompasses discursive elements, such as debate, exchange of ideas, ethical questions, value positioning, and political framing (Hajer and Versteeg, 2005). Studies of energy system coordination and decision-making—primarily the domain of public officials and incumbents already established in energy systems—have given less attention to these features.

While deliberative policy design can address a range of political, economic and social impacts, as in the case of biodiesel production from "social soybeans" in Brazil,[1] the pace and directionality of change, and whether and to what extent local communities have a contributing voice, matters deeply. A narrow focus on policy management characterizes much of the literature, reflecting an effort for explicitly guiding and managing sustainable development, yet this often entails a "tendency towards techno-economic determinism" rather than systemic or structural transformations (Lawhon and Murphy, 2012: 359). In response, multidisciplinary scholars have called for more holistic approaches towards fair and equitable energy systems and to this end have developed the concept of energy justice, which underscores the need to consider social questions, referring for instance to questions of distribution or people's needs (McCauley et al., 2019; Healy and Barry, 2017). Energy justice also includes fundamental questions of who gains, who loses and who extracts value within changing energy systems (Newell, 2021). This more holistic approach highlights the largely hidden social, economic, health and environmental externalities across the lifecycle from production or extraction to final disposal of energy-related commodities (Jenkins et al., 2021).

There is scope for climate scientists, ecologists, geographers, and environmental social scientists to engage with efforts in green chemistry to facilitate inclusive, low-carbon development more widely. Iles and Mulvihill (2012): 5647, for example, called for an interdisciplinary approach to green chemistry [that] "uses collaboration and integration between various experts and actors to increase information flows along the product life cycle and feed data into repeating cycles of design based on learning about how the product performs and affects the environment." Geographers and environmental scholars can contribute to such efforts through place-based studies of socioecological relations across multiple sites and product life cycles (Romero et al., 2017). Such engagement could include green chemistry innovations, such as the example investigated here of enzymes that can act on non-edible feedstock and waste. At present, these innovations are largely managed by large corporations, including Denmark's Novozymes (Lane, 2012), which are often spatially distant from the energy carrier's production and use, raising questions of uneven exposure to social and environmental impacts. This reflects a larger tendency for capital-rich but resource-poor countries to invest in land to secure food and energy supplies, a pattern that has been observed in Africa, Asia and Central Europe (Huber and McCarthy, 2017; Wilkinson and Herrera, 2010).

The overarching objective of the present study was to enhance future biofuels research and policy understanding of the challenges involved in meeting the competing targets of the SDGs. We aimed to understand how previous scientific interventions in bioenergy development prioritized criteria of assessment and framed desirable development outcomes, and to open and facilitate interdisciplinary dialogue that explores social and ecological complexity from different theoretical perspectives.

3. Reframing biofuels: fuel-from-food to the second-generation

3.1. The emergence of ethanol in Brazil and the rise of global ethanol markets

Brazil has assumed a leading role in the promotion and production of biofuels. Its plans and programs occupy a central place in global debates and the emergence of global biofuels markets (Wilkinson and Herrera, 2010). Sugarcane has been cultivated in Brazil since its introduction in the 16th Century, becoming an important commodity and "economic vector" in the colonial period, particularly in the northeast (Cortez and Baldassin, 2016: 142). Given weaknesses in the country's energy security, state planners introduced ethanol fuel in the 1930s. Subsequently, its use expanded during the oil shocks of the 1970s, when the state created PROALCOOL (Cortez and Baldassin, 2016; Hira and de Oliveira, 2009).

Brazil's military government launched the large-scale, state-led program Pro-Alcohol Program (PROALCOOL) in 1975, aiming to substitute 20–25 percent of gasoline (petrol) with anhydrous ethanol. The state then promoted the production of hydrous ethanol for use in light vehicles especially adapted for alcohol. A highly regulated market was created to guarantee the adoption of ethanol, involving price controls, compulsory supply at gas stations, and a range of subsidies (Eaglin, 2019; Wilkinson and Herrera, 2010). Increased demand for ethanol prompted the incorporation of new lands for sugarcane production, and this period also saw important advances in research and engineering capacity involving seeds, agricultural practices, fermentation technology, equipment, and machinery (ibid).

Brazil is widely considered the most successful biofuels producer due to low production costs, advanced technology and management systems, hybrid sugar/ethanol complexes and favorable CO_2 reduction rate (Mol, 2007; Hira and de Oliveira, 2009). Given fuel blending mandates, cars and other vehicles in Brazil are designed to flexibly run on an ethanol and petrol 'flex-fuel' mix, introduced in 2003 (ibid). Successive federal governments have viewed the sugarcane sector as strategic national importance and integral to Brazil's wider industrialization (Eaglin, 2019; dos Santos e Silva et al., 2019).

Globally, biofuels can easily adapt to the existing infrastructure of conventional petroleum fuels (e.g., distribution and retailing, cars, and combustion systems), making it a more cost competitive fuel source than other alternatives, such as hydrogen. A key challenge with first-generation biofuels, however, is that production either competes for land dedicated to alternative food crops (e.g., sugarcane) or directly utilizes staple food resources (e.g., corn, soybeans). Critics responding to expanding biofuels production across

[1] See César et al. (2019) on Brazil's *National Program for Production and Use of Biodiesel*, launched in 2004, which promotes diversification of feedstock sources, social inclusion and regional development through generating employment for small farmers.

multiple global South regions in the 2000s raised concerns over contention with food production and resulting effects on food prices and security, along with deforestation, mono-cropping, and long-term biodiversity loss (Clancy, 2008; Mol, 2007; Franco et al., 2010).

3.2. Second generation biofuels

Recent initiatives have sought to address the 'food versus fuel' controversy through using non-food crops (grasses, waste products, woods) along with municipal solid waste, for conversion into a new, second-generation (2G) form of bioethanol (Clancy, 2008; Tomei and Helliwell, 2016). Initiatives in Brazil have led research on uses of the whole sugarcane plant, spurring further expansion of investments in the country's sugarcane complex centered in São Paulo state, along with new expansion zones (Wilkinson and Herrera, 2010; Machado et al., 2015; Raele et al., 2014).

Before 2G bioethanol can be produced, the sugars must be released, a technically demanding process, as they are encased in cellulose fibers in plant cell walls (dos Santos e Silva et al., 2019). Initially, 2G biofuels require a chemical pretreatment of the plant biomass, which increases its porosity. This allows plant-specific enzymes to act on the cell walls of the non-edible lignocellulosic biomass ("depolymerizion"), releasing sugars, followed by fermentation via genetically manipulated yeasts. This means that waste products from 1G bioethanol sugarcane processing ('bagasse,' or the ground-up remains of pressed canes, and straw) may become feedstocks for 2G bioethanol. Proponents have posited such technology as the future of biofuels (Raman and Mohr, 2014; Clancy, 2008).

Producers can potentially use any cellulose-rich organic material to make 2G biofuels, subject to the identification and development of appropriate enzymes. This includes leaves and waste from sugarcane, grasses, trees, and other plants that can grow on so-called 'marginal' land, regarded as unsuitable for intensive agriculture. This offers benefits for a range of stakeholders while interfering less with food production. Yet, often overlooked is the fact that 2G cellulosic technologies non-food raw materials still require land on which the biomass will be produced (Raman and Mohr, 2014), along with biodiversity issues and other negative environmental consequences, including loss of crop residues and associated nutrients (Gasparatos et al., 2017; Graham-Rowe, 2011). Furthermore, the capital requirements and large processing facilities needed for 2G production to date pose challenges for poorer countries and regions. While it may be possible to develop small-scale facilities, such research would require investment and may face opposition from corporations currently controlling this market (Wilkinson and Herrera, 2010).[2]

Globally, analysts expect that biofuels will account for as much as 30% of energy generation by 2040, requiring extensive transformation of available land for this purpose (IEA, 2019). Since the enzymes required are specific for different feedstocks, there is a potential for further demand for monoculture for 2G biofuels. Large monoculture production often requires substantial inputs of fertilizer and pesticides spurring loss of biodiversity, nutrient run-off and associated downstream shifts in vegetation (Gunkel et al., 2007; Bunzel et al., 2015). Even where 2G biofuels use bagasse from sugarcane already under cultivation for other uses, there are potential long-term consequences of removal of biomass residues, which may cause soil displacement and erosion, potentially require even more intensive fertilization regimes, and exacerbate pollution downstream (Blanco-Canqui and Lal, 2009.) Multiple studies suggest that human demand for biofuels sufficient to replace energy generated from fossil fuels may lead to changes in land use, property relations, and wider landscape transformations (Franco et al., 2010; Tomei and Helliwell, 2016; Calvert et al., 2017).

An alternative to using sugarcane bagasse is using grasses grown on less nutrient-rich soil, thus not requiring agricultural land. However, land considered 'marginal' by one set of social, economic, or ecological criteria might be conceived as useful and productive by another, while land considered 'abandoned' for commercial or industrial purposes might support a thriving subsistence economy, as geographers and environmental researchers have demonstrated through ethnographic studies (Calvert et al., 2017; Baka, 2014). Multinational corporations and agri-food producers, with frequent support from state governments, impose categories such as 'marginal' or 'idle' on certain landscapes to create legal and institutional contexts in which large plantations are considered acceptable land uses (Baka, 2014; Neimark, 2016). Such a process can reproduce the social and environmental injustices and destructive effects found in conventional fossil fuel-based regimes. Some observers have analyzed how growing competition over land relates to deeper contradictions within capitalism, spurring a continuous search for land and the creation of new commodity frontiers through relations of control and power (Rasmussen and Lund, 2018; Queiroz, 2021). Increasingly 'green' technologies are intertwined in this effort (Yenneti et al., 2016; Dunlap, 2020). Resulting spatial transformation processes can illuminate latent conflicts over land ownership, externalities, and priorities, among others. The effect is often an increasing socioecological regimentation and ordering of space, such as through plantation-style extraction (Kröger, 2022; Scott, 1998).

These three related points, avoiding the food-versus-fuel conflict, environmental ramifications, and identification of 'marginal' lands, are each controversial. In contrast to relatively scarce arable land available for food production, so-called marginal lands have been described as environmentally unimportant ("wastelands") and "abundant in the global south" (Kang et al., 2013; Raman and Mohr, 2014: 231). Accordingly, while opposition to first-generation biofuels is "assumed to be about conflict with food security," 2G from bio-waste is framed as an alternative that avoids such conflict (Mohr and Raman, 2013: 114–115). However, this line of reasoning arose during a period when key actors envisioned biofuel production primarily in national territorial terms, with such tradeoffs potentially managed through domestic policymaking. Given the relationship of these debates to efforts to reduce carbon emissions associated with energy use and sustainable energy access in the global South, and the emergence of global commodity ethanol markets

[2] The share of E2G in Brazil's ethanol production remains small. The production of E1G in Brazil in 2021 was 32 billion litres (sugarcane and corn) while E2G was much less than the 60 million installed capacity. The production was around 20 million litres. https://www.bnb.gov.br/s482-dspace/bitstream/123456789/914/1/2021_CDS_184.pdf.

in the 2000s (Mol, 2007), this has become a transnational issue. As such, it intersects with uneven global power relations (Calvert, 2016; Newell, 2021).

Still, the specific nature of feedstock for 2G biofuels and associated demands on land create highly localized social and environmental impacts. As one study found, the problems of biofuels are more complicated than implied by a generic conflict with food. Rather, "they arise from a globalized system with a spatially uneven distribution of sustainability risks and benefits" (Raman and Mohr, 2014: 231). In this case, frequent reference to the 'food-versus-fuel' conflict is inadequate to address the challenges posed by first generation biofuels, nor does it provide the basis from which to consider the range of issues that 2G biofuels might raise (Mohr and Raman, 2013; Franco et al., 2010). In relation to these questions, we must consider the ways that biofuels, through the socio-political systems in which they are embedded, become drivers of land use changes (Strapasson et al., 2017; Huber and McCarthy, 2017).

The challenge of accessing suitable land for production is further complicated by the need for specific enzymes to break down the cellulose in different types of biomass—the enzyme used for sugarcane has distinct chemical properties from the one suitable for jatropha, for example (Farinas et al., 2018). Developing these enzymes is time consuming and expensive. Such conditions may increase the demand for large-scale mono-cultivated crops, with the accompanying risk of long-term degradation of land and soil fertility (Blanco-Canqui and Lal, 2009). Greater scrutiny is therefore needed concerning the regulation of 2G biofuels to foster a socially inclusive, transparent, and just transition. Moreover, such decisions require consideration on a local basis if they are to meet the aims of just energy transitions at multiple scales (Healy and Barry, 2017; Wang and Lo, 2021).

More broadly, some scholars have critiqued dominant policy visions as overly focused on the techno-scientific solutions to social challenges, rather than on rethinking the socio-political and geographical contexts in which agriculture and forestry for fuel production and commercialization is pursued (Ponte and Birch, 2014; Raman and Mohr, 2014). Such concerns have persisted, as biofuels are reconfigured using new techniques, chemical processes, and new locations, along with new markets and forms of capital accumulation, as suggested by recent developments in Alagoas, northeast Brazil.

4. Research process, methodology and location of study

This study uses a methodology of interdisciplinary co-production, combining qualitative methods with processes that integrate the knowledge of biological and chemical scientists, energy and development specialists, education and facilitation experts, infrastructure managers and communities through participatory workshops. Rather than adopting a single analytical framework for the empirical data, natural and social scientists met for interdisciplinary workshops where meanings of key terms were shared, and contributions of different theoretical perspectives identified. Through these discussions, themes, questions and hypotheses were developed for empirical exploration in the field. The research question we explore is 'what are stakeholders' perspectives on the present and future of 2G bioethanol production?'

4.1. Methodology

The data informing this study were gathered during two field visits to Maceió, the state capital, and São Miguel dos Campos, the site of Granbio, a 2G-ethanol project, in Alagoas, Brazil in July and September 2019. We aimed to gather perspectives across five main areas: 1) local community or civil society actors in São Miguel, 2) local academics working on biofuels, sugarcane or energy production, 3) local and regional government officials or planners, 4) practitioners, farmers and landowners working in biofuels, sugarcane, or energy production, 5) staff at Granbio. We identified these as key to gaining a balanced view of the various perspectives on the issue of 2G biofuels in the area.

The first field visit included eight semi-structured interviews. We interviewed officials in local and state government with responsibility for regional development policy and planning. We visited a civil society organization and the local vocational training institute (IFAL) in São Miguel, where we interviewed personnel involved in training for local sugarcane/biofuel industry. We interviewed academics and practitioners in economic development and agronomy at the Federal University of Alagoas in Maceió (UFAL) and conducted an external site visit to Granbio and surrounding communities.

In the second visit, we conducted six follow-up interviews with further stakeholders at UFAL, IFAL and regional government advisors from SEDETUR.[3] We held a one-day workshop at UFAL with 19 academics (from agronomy, engineering, business, economics, and geography from two institutions – UFAL and IFAL), landowners, policymakers and practitioners involved in bioethanol research, notably plant breeders from the national research network RIDESA[4] working on new high fiber cane varieties. We visited two farmer cooperatives pursuing alternative feedstock for bioethanol and interviewed two of their founding members. Taken together, these interviews and group discussions gave us an overview of the perspectives of 1–4, although we were unable to access sugarcane producers in the vicinity of GranBio. In terms of 5, we held a series of communications with GranBio officials, but the site tour was postponed due to renovation works in the biorefinery (and later cancelled during the pandemic). We analyzed this perspective through drawing on company press releases, annual reports, and websites. We supplemented the data collection with analysis of policy documents from local and regional government.

This approach enabled us to gain insights into all five of the perspectives we mapped at the outset, although with a relatively small sample of each we recognize the need for caution when drawing conclusions from this data. A subset of the author team conducted an

[3] The Alagoas Department for Economic Development and Tourism (*Secretaria do Desenvolvimento Econômico e Turismo*, SEDETUR).
[4] The Inter-University Network for the Development of the Sugar-Alcohol Sector (RIDESA).

analysis using an iterative, grounded approach, based on principles of constant comparison and theoretical sampling. The qualitative data were analyzed through open coding. In this article, they are presented in narrative synthesized form. Key themes were discussed further in team meetings and collaborative writing exercises. This process ensured that perspectives across the disciplines represented in the project were present and avoided dominance of single discipline or stakeholder perspective. Interviews and workshops were held in Portuguese and later translated into English; there was at least one Portuguese speaking researcher on every workshop facilitation/ interview team.

4.2. Location of study

The regional market center of São Miguel dos Campos, Alagoas (pop. 62,000) hosts GranBio's biorefinery (see Fig. 1). São Miguel has longstanding ties to sugarcane production, with the local economy further reliant on natural gas, cement, and livestock. Regarding GDP per capita, São Miguel occupies the 19th place in Alagoas (with 102 municipalities) (IBGE, 2020). In comparison with other traditional sugarcane producing states (São Paulo and Goiás) and sugarcane expansion zones (Mato Grosso and Mato Grosso do Sul, in Brazil's Center-West region), Alagoas's socioeconomic indicators are low, with over 40% of residents living under half of Brazil's minimum wage, and life expectancy five years below the national average (Machado et al., 2015).

Source: OpenStreetMap.

Amid recent efforts towards bioethanol innovations, the Brazilian biotech firm GranBio has opened the "Southern hemisphere's first commercial-scale 2G ethanol plant," in Alagoas (GranBio, 2014). With investors confirming substantial commercial potential for the technology, the stage was set for a "green" success story to unfold (cf. Banerjee, 2021). In the next two sections, we draw on primary data and analysis of site-specific documents relating to GranBio's biorefinery, a previously unstudied case of 2G biofuels. We present findings in two key thematic areas: experiences of 2G biofuel production and futures beyond sugar.

Historically, Alagoas was one of Brazil's largest producers of sugarcane (Lehtonen, 2011; Queiroz, 2021). Under Portuguese colonial rule, northeast Brazil provided up to 80% of Europe's sugar by the late 16th century (Lehtonen, 2011). Alagoas's eastern flank (known as the *Zona da Mata*) previously formed part of the Atlantic Forest, which was subsequently cleared for large-scale agriculture, predominantly sugarcane, except for a few remnants. Little available land remains in the state to expand sugarcane fields in its productive areas (see Manzatto et al., 2009).

5. Experiences of 2G biofuel production: between environmental sustainability and vulnerability

Alagoas has become an important research site for developing new, higher-yielding cane varieties and a potential hub for regional innovation, with investors regarding it as a prime location to install a 2G bioethanol plant. In contrast, the western half of Alagoas, which forms part of the semi-arid *Sertão* region of the northeast Brazilian interior, is largely reliant on livestock and subsistence and cash crops such as cassava and cotton (interviews, SEDETUR, Sept 2019).

The sugarcane industry stagnated in Alagoas during the 2010s amid the financial crisis and falling global prices, with a 30% reduction in land use cover for sugarcane plantations statewide in the early 2000s (Rosário et al., 2016; interviews, UFAL, July 2019). Investors in the 2G biorefinery raised expectations that technological innovation would propel regional economic revitalization while replacing income lost from the traditional sugarcane sector through socially inclusive innovation (Rosário et al., 2016). Local figures regarding employment opportunities suggest otherwise, even pre-pandemic. In 2018, the rate of working people amongst the total local population was 18.1% in São Miguel (IBGE, 2020), suggesting high levels of unemployment.

A first-generation biorefinery plant run by the private company Caeté is one of São Miguel's largest employers. Granbio, founded in 2011, has begun producing 2G cellulosic ethanol at its Bioflex 1 unit on the town's outskirts (see Fig. 2). It utilizes waste from the Caeté facility for processing, leveraging economies of scale and decreasing operational costs. In 2013, GranBio received a US$150 million low-interest loan from *Banco Nacional de Desenvolvimento Econômico e Social* (BNDES, Brazil's Development Bank) to finance the plant's construction, with a total of US$220 million invested in the project (Nielsen, 2013; Rosário et al., 2016). BNDES later became a 15% shareholder in the company (ibid).

Source: Wikipedia creative commons.

GranBio claims its 2G cellulosic ethanol enables it to increase Brazilian production capacity per acre by up to 50% using sugarcane straw and bagasse, without the need to expand cane fields (GranBio, 2014). It has developed a system to harvest, store and process 400, 000 metric tons of straw annually for Bioflex 1, using pretreatment technology from the Italian firm Beta Renewables and enzymes from Novozymes in Denmark. It has also begun genetically engineering cane varieties, aiming to increase fiber content for future 2G production (ibid). These activities would enable GranBio to operate in all phases of the value chain – from advanced research to raw materials to distribution to end users.

Since starting production in 2014, however, GranBio has encountered a series of setbacks, raising questions about whether its operation may be at risk socially and financially. These have included successive fire outbreaks in its bagasse storage facilities (two in late 2015, one in early 2016), raising concerns over exposure to toxins and pollutants for communities living near the biorefinery (workshop, UFAL, Sept 2019). There was a resulting increase in reported respiratory problems and search for emergency medical services for children and the elderly (interviews, IFAL, Sept 2019). The *Instituto do Meio Ambiente* (National Environment Institute) fined GranBio US$45,300 for damages (Globo.com, 2016). The company also faced technical complications in the pretreatment stage (interviews, IFAL, July 2019).

By 2019, GranBio began to continuously produce cellulosic ethanol, with daily production reaching 99,000 L, or 40% of its licensed capacity. The operation could produce up to 30 million gallons per year, but according to a press release, it does not yet "yield the

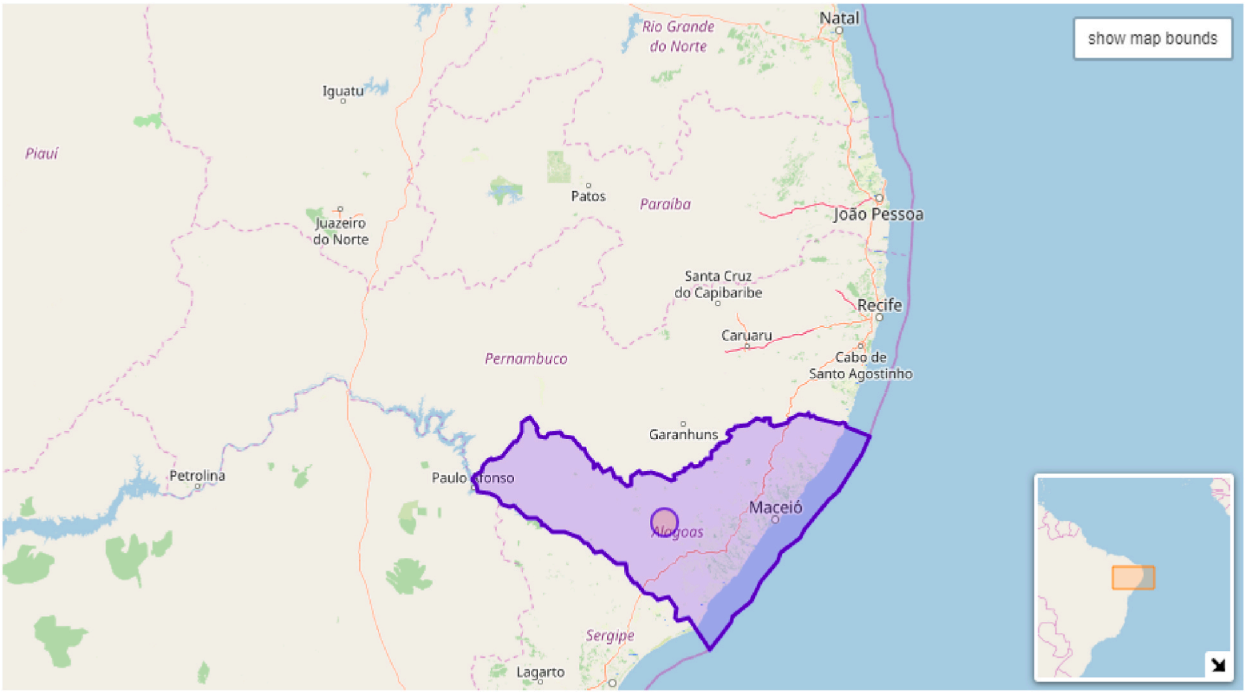

Fig. 1. Map of the state of Alagoas, northeast Brazil.

Fig. 2. GranBio's Bioflex 1 plant, São Miguel dos Campos, Alagoas.

required return."[5] The remaining bagasse is incinerated to generate electricity for use in the biorefinery (Granbio, 2020). Granbio does not intend to open additional biorefineries and plans to focus on developing and marketing new biomass technologies.

The burning of bagasse and other crop residues for power generation has gained importance in Brazil in the past decade (Salomon et al., 2015; Moraes, 2011).[6] In parallel, falling global crude oil prices, price shocks for certain agricultural commodities, offshore oil discoveries in Brazil, and insufficient access to finance have combined to slow the national ethanol sector (Fraundorfer and Rabitz, 2020). As a result, some bioethanol producers have invested in sugar mills and started producing and exporting sugar and sugarcane-derived food and industrial products (Tomei and Helliwell, 2016). According to one participant, diversification was "essential in surviving this period." He added that power generation was "pivotal" to balance their finances (workshop, UFAL, Sept 2019).

[5] Translation by the authors.

[6] Electricity production derived from biomass in Brazil during 2021 was around 4%, of which 79% of that was derived from sugarcane bagasse. It generated a total of 20,200 Gwh. https://summitagro.estadao.com.br/noticias-do-campo/cana-de-acucar-gera-energia-eletrica-no-brasil/.

Many producers expressed interest in "value webs" rather than value chains, meaning they seek to grow or add value to crops that can be sold flexibly in different markets (workshop, UFAL, Sept 2019). 2G bioethanol producers must compete with these alternative markets for the bagasse. For example, livestock farmers in the Sertão use bagasse as input for cattle feed (interviews, SEDETUR, Sept 2019). Suggesting the dilemmas at stake in policy debates, one participant explained, "Alagoas cannot let go of … the old economy, the economy of the oligarchy, the old industry, and monoculture. [This] was one the last few states to start this diversification process. We will either diversify to achieve balance, or we are destined for oblivion" (workshop, UFAL, Sept 2019).

At the national scale, the right-wing Bolsonaro administration, elected in late 2018, has compounded political challenges, as the national policy framework shifted towards supporting market-based, deregulatory approaches to the detriment of environmental, social, labor and climate policy (Fraundorfer and Rabitz, 2020; Queiroz, 2021). In 2009, the Brazilian federal government, led by former President Lula da Silva, proposed a zoning law prohibiting new sugarcane investments in the Amazon and Pantanal biomes (Manzatto et al., 2009). Bolsonaro eliminated these protections in 2020, facilitating sugarcane expansion in these regions (Lima et al., 2020). Amid these policy shifts, GranBio announced its intention to open an IPO on the Brazilian stock market in 2020, aimed at accelerating technological investment. In parallel, it has diversified its operations into adjacent technologies, including nanocellulose for tire manufacturing (GranBio, 2020).

6. Towards a future beyond sugar?

By most accounts, sugar as a commodity—and a way of life—remains deeply embedded in the political economy and social lifeworld of Alagoas. Local artwork depicting the sugarcane harvest, shown prominently alongside similar artifacts in a permanent exhibition in the Théo Brandão Museum of Anthropology and Folklore, housed in a renovated 19th Century mansion in Maceió, suggests the integral position of sugarcane within society (see Fig. 3). In its latest iteration, GranBio has begun to focus on patenting new varieties of sugarcane genetically engineered to yield more bagasse, and thus better suited to 2G biofuel production rather than agriculture (workshop, UFAL, Sept 2019). This approach, which would focus on a limited number of genetically modified bagasse varieties, competes with calls for diversification of feedstock and the growing demand of alternate agricultural residue uses (ibid). Such developments further cloud the fuel-versus-food debate and evidence the competing impacts on vulnerable groups, with the role of farmers, cutters and producers of other crops all impacted by such decisions (workshop, UFAL, Sept 2019).

Land ownership remains highly concentrated in coastal Alagoas and other sugarcane regions of Brazil (Franco et al., 2010; Lehtonen, 2011; interview, Rosário, July 2019). As workshop participants in our study explained, small farmers, who do not own land or whose land tenure is insecure, are unlikely to benefit from 2G innovations, as the start-up costs and enabling environment remains complex and costly. The sole commercial scale 2G bioethanol plant currently in operation in Brazil is owned by Raizen, a subsidiary of British multinational Shell, in São Paulo state. Raizen currently exports "almost all its production of 2G ethanol" to California (Raizen, 2020: 17).

Several regional civil society actors in Alagoas, including small farmer cooperatives, agricultural advisers, and smallholders, are currently pursuing crop diversification to confront these challenges. One policy analyst told us, "A new format will take place based on a new organizational structure, cooperativism" (workshop, UFAL, Sept 2019). Cooperatives and small farmer associations may allow greater access to resources and technical assistance, along with potentially adding value through developing processing capabilities (cf. Wilkinson and Herrera, 2010).

One possible alternative feedstock for 2G bioethanol under development in Alagoas is cassava husks. Most of the cassava grown in Alagoas is on small family farms, defined as smaller than 50 ha (Salomon et al., 2015). A project led by a graduate student at UFAL converted cassava residue into bioethanol and biohydrogen using anaerobic fermentation (interview, Almeida, July 2019; Ivon, 2019). Some 20–30 percent of a cassava tuber's mass is its husk or skin, and these are normally discarded in flourmills. This waste can leach cyanide if not handled properly but converting to fuel would prevent this, and generate electricity in the mills, which often use firewood for power generation, producing high levels of carbon dioxide (ibid).

Eucalyptus cultivation as feedstock is also under consideration in São Miguel (workshop, UFAL, Sept 2019). Eucalyptus in Brazil,

Fig. 3. Artwork depicting local sugarcane harvest (woodcutting by Enéias Tavares dos Santos), Théo Brandão Museum, Maceió, Alagoas.

however, has been controversial since its introduction in the early 1900s (Navarro de Andrade, 1941). It offers high energy density and short rotation, and can be grown on shallow, structurally poor, low-nutrient soils less suited to cultivation of food crops. Yet concerns remain over the extent to which eucalyptus cultivation alters water tables and creates water stress (de Barros Ferraz et al., 2019). There are also concerns about the ecological costs associated with introducing another large-scale non-native crop that may accelerate biodiversity loss and water depletion, along with potentially displacing small farmers pressured to sell their lands to large agribusinesses (interview, Almeida, July 2019; Beringer et al., 2011). Other researchers have argued that eucalyptus production would reduce pressure on timber extraction from indigenous forests and help to preserve fragments of the Atlantic Forest (Salomon et al., 2015).

Apart from concerns over eucalyptus cultivation at scale, any use of eucalyptus (and other trees or perennial grasses such as *Miscanthus*) in 2G bioethanol production would require further research to identify and isolate novel enzymes for use in cellulosic conversion and to study adaptations to pretreatment technology (workshop, University of York, January 2019). Given challenges associated with lifecycle assessments due to lack of available data on environmental impacts, and specifically greenhouse gas emissions associated with the production and use of enzymes for the hydrolysis stage (Nogueira et al., 2021), it is difficult to determine the environmental desirability of 2G biofuels from eucalyptus. This is notwithstanding the fact that making such data available would support suppliers' claims of enzymes as a 'clean and green' product (Nogueira et al., 2021: 10). Further, this development raises distributional and procedural questions of who gets to decide these important, and often contentious issues, such as selection of species for further development (via available research funding), who benefits from the process and who is harmed, as foregrounded by critical energy justice scholars (interviews, IFAL, Sept 2019; Jenkins et al., 2021). Despite these challenges, over five centuries of sugarcane production in coastal Alagoas may yet give way to imagining a "future beyond sugar" (interview, IFAL, Sept 2019).

A future beyond sugar, however, would alter biophysical landscapes, land prices, economic relations, socio-ecological processes, and ways of life in Alagoas. Any move towards integrating alternative biomass for feedstock production would need careful consideration, given its multifaceted and multi-scalar impacts—including unintended ones. To what extent will the uneven exposure to effects of new rounds of commodity production spurred by innovations in agrochemicals research impact different social groups? In what ways will expanded production affect smallholders and other vulnerable groups? We argue that determining which, if any, varieties of biomass are best suited for enzyme development in specific contexts is essential. This must include the recognition of multiple stakeholders' input and sources of knowledge, to avoid reproducing (or worsening) socioeconomic inequalities and injustices or endangering local environments (Jenkins et al., 2021; Newell, 2021).

At the subnational scale, a transparent, accountable, and integrative governance structure is needed to address these concerns and coordinate stakeholders' input (Benites-Lazaro et al., 2020). Globally, there is still uncertainty regarding collaboration on standards and harmonization within trade networks, market regulation and potential areas of application for 2G, as biofuels join what Mol (2007: 303) termed "a global integrated biofuel network." Such applications may include long-distance air and sea transport where battery-based use of electricity is not yet feasible (dos Santos et al.,2019).

Assessing whether and how broader environmental and social justice goals are met, or neglected, is crucial. Despite 2G ethanol's purported advantages, questions of environmental sustainability and protection of biodiversity, and social vulnerabilities, such as uneven exposure to costs and benefits, economic fairness, and working conditions of canecutters in Brazil require careful examination. Such discussion must occur within scientific, policy and civic communities before it can be considered a clean and sustainable fuel source (Machado et al., 2015; Martinelli and Filoso, 2008). This research speaks to a deeper question in energy transitions research: to what extent do shifts in technology towards low emissions lead to corresponding changes in energy governance or to addressing social and environmental vulnerabilities? (Newell, 2021; Banerjee, 2021). Yet, with all these questions and uncertainties, there is little to suggest that the current mode of local and global interactions in the Alagoas biofuels sector will change regarding 2G bioethanol production and export.

Accordingly, the specific context, particularly around land-use change, agrarian structure, and spatial scales of production, needs careful consideration to inform the decisions within the chemistry research on how to proceed with enzyme development for 2G biofuels as part of a just energy transition. Indeed, greater 'epistemological responsibility' (Szerszynski and Galarraga, 2013: 2818) is called for in energy and environmental research, and in the context of biofuels specifically, using transdisciplinary approaches to engage societal actors in the early phases of research, enabling collaborative partnerships and new scientific inquiry into the issues that the stakeholders value most (cf. Hajer and Versteeg, 2005).

This study underscores the need for transdisciplinary research that can work towards addressing land-use controversies from different perspectives and determining desirable (and less desirable) pathways that account for social needs, before investing in costly and time-consuming research where technology is, potentially, imposed on communities. Yet the current orientation of scholarship, in part motivated by the funding mechanisms for research, tends to be technology-led, with social and environmental impacts considered as an afterthought.

7. Conclusions

In this article, we have situated an early example of 2G cellulosic ethanol production amid wider efforts to remedy the controversies over harmful socio-environmental effects of first-generation bioethanol. Examining the mixed experience of GranBio in Alagoas, along with recent efforts in the region to enroll alternative sources such as eucalyptus as feedstock, our findings underscore the continued importance of primary crops as sources for new enzymes in 2G production, with potential to intensify preexisting monocultural agrarian pathways. Rather than resolving the food-versus-fuel controversy, 2G ethanol producers such as GranBio have largely sidestepped it.

Given these unresolved questions, we argued for the importance of transdisciplinary and multi-stakeholder approaches to shape the early stages of scientific research into novel enzyme applications, with a view to supporting actionable science for just and equitable futures for 2G biofuels in Alagoas, and in other emerging production sites. This includes the selection of new crops for feedstocks, and their local socio-environmental impacts and linkages within a global agrarian economy. Such efforts may enable alternatives to sugar but also may reproduce, and even reinforce, inequalities in access to land, capital, and other resources.

We also note that uncertainties remain in data on climate impacts, via greenhouse gas emissions associated with enzymes used in hydrolysis in 2G processes along with ongoing operational, institutional, social, and political challenges faced in 2G cellulosic ethanol production in Alagoas. It is unclear how and whether these innovations at the nexus of chemistry and next-generation fuels will contribute to a wider sustainable energy transition. Greater transparency is needed in the information used to justify environmental and social claims about 2G innovations, such as the potential to resolve competition with food production. Additional cases warrant further study, such as in India and Madagascar, where there has been international investor interest in developing 2G bioethanol facilities amid expansion of commodity frontiers (see, e.g., Neimark, 2016). Although Raizen is currently the only operation in Brazil producing 2G ethanol at commercial scale, with GranBio's project stalled, new actors are expected to invest in 2G biofuels in coming years, amid rising global demand for sustainable fuels (dos Santos e Silva et al., 2019; César et al., 2019). Demand is expected to intensify, as ethanol-derived aviation fuel becomes feasible (McMahon, 2019).

Wider social, political, and geographical questions remain. These include the extent to which shifts in the ways that energy is generated, circulated, and consumed can create corresponding shifts in governance, including inclusive and democratic systems that recognize disadvantaged actors—ranging from smallholder farmers, cane cutters and unemployed workers—in potential benefits (cf. Calvert, 2016). Further research is needed to examine the ways that expectations and visions being mobilized to support 2G biofuels compare with outcomes on the ground, and to identify key actors linking dominant and local bodies of knowledge. We must also consider the ways that land use practices, land tenure relations and livelihoods are enmeshed in the bioeconomy as it continues its inexorable expansion. So, while we do not claim to have the answers, this research has enabled us to identify the questions and the perspectives that cast light on this issue, in the hope that this can lead to future research, led by principles of social and environmental justice, in the inevitable development of 2G biofuels.

Author statement

JK: Conceptualization, Methodology, Writing – original draft preparation, conceptual framing and investigation. EB: Writing – original draft preparation, Investigation, Funding acquisition. LB: Writing- Reviewing and editing. JPFC: Investigation, Writing-Reviewing and Editing. KR: Writing- Reviewing and Editing. FV: Investigation, Writing- Reviewing and Editing. SB: Investigation, Reviewing and Editing. SK: Writing- Reviewing and Editing. PWW: Investigation, Conceptualization.

Declaration of competing interest

The authors declare that they have no competing interests.

Data availability

Data will be made available on request.

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