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The synergy between stakeholders for cellulosic biofuel development: Perspectives, opportunities, and barriers

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ABSTRACT

While understanding individual stakeholders' perspectives on the adoption and conversion to a biofuel-based landscape has been a subject of many previous studies on biofuels, there has been relatively little attention given to understanding how the interaction between multiple stakeholders involved in biofuel development could influence the widespread adoption of biofuel production. This paper analyzes the key stakeholder interactions utilizing various data sources including survey results, social media posts, and empirical and theoretical analyses. An intensive review is conducted for a number of surveys and research papers on different aspects of biofuel development such as land use choices, biorefinery and transportation, infrastructure development, consumer priorities, environmental impacts, etc. Following that, a stakeholder synergy approach is applied to synthesizing typical responses of stakeholders, such as producers, consumers, biorefineries, rural communities, and the government, and discussing how their responses influence each other's decisions and the overall system performance. Based on the findings of inadequate stakeholder synergy, it is recommended that new surveys and further research should be conducted to understand why synergy between stakeholders in biofuel development is absent. Additionally, this paper provides research perspectives, including (1) applying cutting-edge text-mining techniques to conduct sentiment analysis, and research and public attention analysis; (2) using an agent-based model to simulate stakeholder interactions and understand the factors that influence stakeholder synergy and the emergence of a bioeconomy.

1. Introduction

Throughout the Midwestern United States (U.S.), agricultural production, particularly of corn and soybeans, provides immense economic value to the region. However, heightened attention to climate, energy, and environmental concerns has shifted ideas about the role of agriculture in response to climate change and dependence on foreign countries for fossil fuels. A new bioeconomy is emerging based on the use of farming landscapes to produce renewable energy in the form of biofuels. In particular, advanced biofuels have been studied for over a decade in the U.S. As opposed to conventional biofuels produced from corn, advanced biofuels produce low greenhouse gas (GHG) emissions directly, as well as any additional GHG emissions as a result of indirect land use change (ILUC). Advanced biofuels include non-food crops such as grasses (Miscanthus and switchgrass) and algae [1]. This classification of advanced biofuels is used by the U.S. government for planning biofuel development in the country as detailed below.

The Renewable Fuel Standard (RFS) program, mandated by the U.S. government, began in 2006 and has continually expanded to increase biofuel production requirements in alignment with the goals of the Clean Air Act (1990), the Energy Independence and Security Act (EISA, 2007), and the Biomass Crop Assistance Program (BCAP, 2008). Enforced by the U.S. Environmental Protection Agency (EPA), RFS mandates 4.92 billion gallons of advanced biofuels and 19.92 billion gallons of total renewable fuel in 2019 [2]. The goal is to produce 36 billion gallons by 2022, of which about 58% consists of advanced biofuels [3]. However, in recent years, the EPA had to decrease expectations for advanced biofuel production volumes (e.g., the 2019 cellulosic biofuels target has been downward adjusted by 95%, reaching to 418 million gallons) given the large gap between the advanced biofuel production and the RFS targets since 2015. Understanding the variety of factors (e.g., a lack of private investment, lack of supporting

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infrastructure, technology setbacks, and limited federal assistance) that have led to challenges in meeting the government production requirement and how these challenges affect stakeholders in the bioenergy industry is crucial.

Despite the growing literature on second-generation biofuels, there is currently little broader social research to analyze the network of stakeholders involved. In this perspective study, it is hypothesized that untangling the complex web of interactions between these stakeholders will help us design a set of policies to bolster the emergence of a market. Through surveys, previous studies have successfully identified stakeholders' perspectives and responses to the bioeconomy in isolation, but they fall short to address issues beyond this limited outlook [4–7]. As a response, a framework is developed under the overarching concept of 'stakeholder synergy' to evaluate the complex nonlinear interactions among stakeholders and their spill-over effects, and the potential barriers for the onset of positive feedbacks among stakeholders. By definition, synergy is "*the interaction or cooperation of two or more organizations, substances, or other agents to produce a combined effect greater than the sum of their separate effects*" [8]. Stakeholder synergy is necessary because trade-offs are intrinsic to the biofuel supply chain given a multitude of sources of value creation for different stakeholders [9–12].

It is anticipated that the expansion of biofuel production will follow a similar synergistic feedback loop as that of soybean expansion in the U.S.—the emergence of initial demand followed by technology development to meet the demand, and then a continued rise in demand triggered by the increased diversity of products from technology improvements. Partially due to these stakeholder synergies, soybean production quickly became a multi-billion-dollar enterprise. The explosivity of soybean production in the twentieth century, particularly in the U.S., can be attributed to a variety of factors [13]. First, political unrest and trade disruptions during World War II created the need for domestic sources of fats and oils. Second, technology advancements created immense diversity of soybeans products, including livestock feed, fats and oils in food, biofuel and biodiesel, etc. More diverse products drove consumer demand higher, which encouraged producers to increase supply and created a competitive market for soybeans. Therefore, synergies between all components of the soybean supply chain put pressure on the soybean economy to evolve. Over the past 100 years, soybeans have scaled from a minor forage crop to the second largest row crop in the U.S. [13]. Researchers and policymakers can learn lessons from this shift in soybean agriculture that can inform the biofuel industry as a whole. This anecdote could be telling for the future of biofuel feedstocks as product diversification continues, the need for domestic and sustainable sources of energy rises, and consumer demand increases. However, several parts are still missing in the expansion pathway of biofuels. This study addresses this gap by analyzing barriers along the biofuel supply chain; and, in particular, by analyzing stakeholder interactions and identifying areas of weaknesses.

In order to understand and predict the expansion of the bioeconomy in the U.S., particularly of the second-generation biofuel feedstocks from perennial crops such as Miscanthus and switchgrass, this study reviews recent papers and surveys to synthesize knowledge regarding the stakeholders of the biofuel industry on a finer scale, their values and beliefs, as well as their interactions with each other. In this manner, this paper addresses a crucial gap in the literature with respect to stakeholder synergy and its role for U.S. to achieve a bioeconomy. Among the myriad of literature reviews, 22 published surveys, many of which include additional interviews and focus group studies, provide valuable information about how different stakeholders view biofuel and their own rules in biofuel development.

In the rest of this paper, by evaluating previous literature and survey studies, and by applying cutting-edge text mining techniques to conduct sentiment analysis using the data from both public media and the research community, the following issues will be addressed: (1) the current preferences, attitudes, and viewpoints of the biofuel industry's key stakeholders, (2) the synergy between stakeholders in the biofuel industry, (3) the barriers that prevent the widespread adoption of the second-generation bioenergy feedstocks, and (4) necessary actions that can promote sustainable growth of the second-generation biofuels. Section 2 will give a brief overview of the five relevant stakeholders involved in the production and consumption of second-generation biofuels. Section 2 will further address individual stakeholder preferences, barriers, and opportunities in biofuel development. Section 3 will analyze the interaction among multiple stakeholders. Section 4 will provide research suggestions including the use of advanced text-mining and agent-based modeling (ABM) to extract, simulate, and understand stakeholder views and interaction among them. Section 5 will summarize the major findings of this perspective paper and future research directions.

2. Multiple stakeholder communities involved in biofuel development

Members of the biofuel supply chain include bioenergy crop producers, biorefineries, rural communities, biofuel consumers, and the government. Additional intermediary stakeholders include storage facilities and blending stations. Awudu & Zhang [14] provide a more detailed description of the biofuel supply chain (BSC), as well as decision making and uncertainties in BSC management. All of these groups of stakeholders have an ongoing and elemental relationship with the decision of producing biofuels, while different stakeholder communities deal with specific but interconnected decision-making issues. Bioenergy crop producers grow feedstocks to sell to biorefineries. Biorefineries convert biomass into bio-based products including fuels, pellets, and other forms of energy. Biofuel consumers, the end-users involved in the biofuel value chain, tend to make decisions on biofuel use based on efficiency, availability, costs, environmental impacts (e.g., emissions), and other performance standards [15], and their preferences on energy use greatly affect their demand for bio-energy and the acceptance of the biofuel industry more generally. The government develops policies (both command-and-control and market-based) to ensure and incentivize feedstock and biofuel production by farmers and biorefineries, and to protect the environment (e.g., Renewable Fuel Standard, RFS [16]; Energy Independence and Security Act, EISA [17]; and Biomass Crop Assistance Program, BCAP [18]).

Meanwhile, each key stakeholder group is impacted by the decision to implement biofuel production in a multitude of ways. As shown in Fig. 1, there are five areas of consideration for stakeholder decision-making: environmental, economic, technical, social, and legal [19]. By recognizing that each decision has tradeoffs in these primary categories, stakeholder decisions can be optimized to mitigate these tradeoffs and increase utility for multiple stakeholders simultaneously. According to Youngs [20], stakeholders consider two wide-ranging core axis points – perceived economic effects, which includes the price of energy and food, as well as rural economies; and anticipated environmental effects, which includes GHG mitigation, soil and water quality, and ecosystem impacts.

Stakeholders can be grouped into three levels based on their spheres of influence: macro, intercommunity, and intracommunity [21], with fluid boundaries between the levels of interaction, as shown in Fig. 2. Macro stakeholders include the government, energy suppliers, biorefineries, and commercial developers. Intercommunity stakeholders include nearby communities and intermediary organizations, such as farm cooperatives. Intracommunity stakeholders include bioenergy crop producers, local communities, local businesses, people living near biorefineries, and local champions. Each group of stakeholders has unique values in terms of the costs and benefits associated with the implementation of biofuel development. In the following sections, at least one type of stakeholder from these three main categories will be introduced, with an emphasis on the interactions among the multiple stakeholder groups involved in the biofuel development.

Fig. 1. A schematic diagram showing the five aspects (elements in the outer circle) affecting decisions of biofuel stakeholders (elements in the inner circle); stakeholder tradeoffs between the five aspects could potentially make their interactions synergistic (After Fawzy [19]).

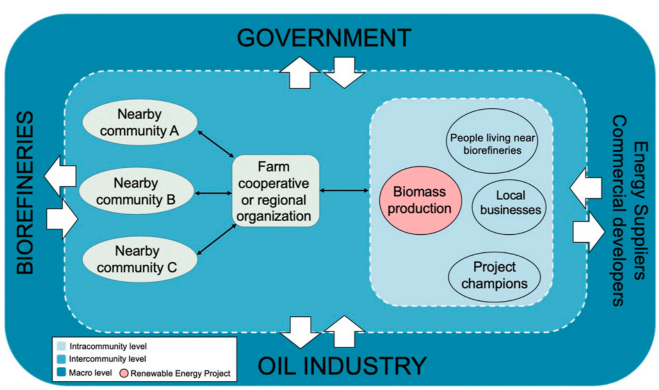

Fig. 2. Biofuel stakeholders at the macro, intercommunity, and intra-community levels. Dotted lines represent fluid boundaries between the level of influence (After from Ruggiero et al. [21]).

2.1. Producers

Numerous surveys have provided insights into the driving and resisting forces of biofuel crop adoption by farmers. Currently, farmers have varied opinions on the success of biofuel development in their area. Heterogeneity among farmers' biofuel crop choices, risk and time preferences, contract preferences, local biorefineries, and environmental priorities will largely affect their acceptance of new biofuel crops and the effectiveness of policies to achieve the desired outcomes.

2.1.1. Perceptions on economic, environmental, and social aspects of biomass production

Recent literature on farmer behavior reveals that farmers value environmental conservation as it directly correlates to agricultural production, but they prioritize economic factors above environmental conservation and community concerns in their land management decisions [22]. For example, through a survey, Smith & Sullivan [23] find farmers in Australia place a high value on ecosystem services, but they also recognize the tradeoff between the economic cost of maintaining the ecosystem services of the landscape as a threat. Farmers' above preferences, particularly in regard to adapting land management practices with changing climatic conditions, are verified by an additional study [24]. However, heterogeneity in farmer preferences towards environmental schemes varies between farmers with different land use practices and among farmers with the same practice [25]. Therefore, market-based schemes and policies that subsidize sustainable agricultural practices should take into account the heterogeneity among producers, in order to enhance the cohesion between farmers, industry, and policymakers to align sustainability with economic profit [26].

2.1.2. Emerging cellulosic biomass production

Small-scale farmers are already adapting their practices to grow perennial grasses given their perceived benefits. For example, a farmer in Pesotum, Illinois, sells Miscanthus (encompassing 4% of his 672 acres of land) both as an energy crop and as animal bedding used by local livestock farmers. Moreover, Miscanthus is planted near a drainage ditch where it also serves to mitigate runoff and add significant profits to his land operation [27]. The Green Lands Blue Waters (GLBW) perennial biomass initiative, founded in 2018, encourages these types of practices [28]. It helps farmers establish perennial grasses on plots of land, including STRIPS (Science-based Trials of Row-crops Integrated with Prairies) to demonstrate the positive environmental and economic impacts of such crops. By integrating a continuous living cover framework [28], where soils with marginal productive capacity are planted with perennial bioenergy crops, farmers can attain a multitude of benefits, including relatively high returns and low input costs on marginal land, as well as the reduction of farm risk through crop diversification [5,29]. By proving the benefits of perennial grasses, even on a small scale, other farmers in the surrounding area could be convinced to adopt similar practices.

Farmers' willingness to adopt perennial grasses varies by region, farm size, education level, whether they are full-time farmers, etc. [30]. Smith et al. [5] find that respondents to a survey of Minnesota agricultural landowners who describe themselves as part-time farmers have a greater willingness to supply perennials. Jensen et al. [31] find farmers in Tennessee are more willing to grow switchgrass if they have higher educational attainment and off-farm incomes, and when their farm size is smaller. The diverse responses of farmers to the idea of growing these grasses might be caused by the various advantages and disadvantages of each feedstock option. For example, perennial grasses such as switchgrass and Miscanthus may be supplemental crops grown on marginal lands with low workloads, while corn stover is a value-added enterprise, and sorghum can be grown in rotation with traditional cash crops.

2.1.3. Barriers to cellulosic biofuel adoption

Previous research studying the willingness of farmers to adopt perennial grasses identifies several important barriers such as long term contracts with biorefineries, the existence of local markets, willingness to take risks, and knowledge of bioenergy crops [4,5,32,33]. It has been found that farmers will only supply cellulosic feedstocks if a contract is offered by processors (biorefineries) [30,34]. However, the success of these contracts is based on many factors, such as the relative profitability over other alternative land uses, length of the contract, cost share with a biorefinery, additional financial incentives, and insurance [30]. More farmers may be willing to grow biofuel crops if they can receive a contract with attributes that favor both producers and processors.

One of the key concerns for farmers is to recover high initial investment for growing bioenergy crops. This could be fulfilled by the provision of an initial cost share program [35] or long-term contracts that ensure adequate profit margins [22]. For example, Khanna et al. [35] find the share of establishment cost borne on the refinery and net gain in income, out of many other contract attributes, serve as the main factors for explaining farmers' willingness to adopt a bioenergy crop contract. Alexander et al. [36] highlight the importance of balancing the optimality and the complexity of farmer-refinery contracts. Overall, the authors find that four important principles must be considered to create successful contracts, which are: (1) balanced risk and incentives, (2) balanced incentives with fewer conflicts, (3) effective matching of growers' characteristics and contract type using screening, and (4) increased contract credibility through a renegotiation-proof mechanism [36].

Another prominent economic factor that influences farmers' decisions to grow biofuel crops is the lack of local markets for farmers to sell bioenergy crops [33,37]. Local markets are important for bioenergy crops because the biomass transportation cost is so high that the geographical distance between the raw material sources and biorefineries must be minimized [14]. As a result, there is usually a strong spatial dependence between the locations where bioenergy crops are grown and the refineries (e.g., in the Northeastern U.S.) [38]. Similarly, Villamil et al. [4] find in their study of Miscanthus adoption in Illinois that 30% of the surveyed farmers may agree to adopt, with the assumption that local markets and supplemental infrastructure for Miscanthus production exist. In another study, Cope et al. [37] apply survey methods and a geographic-targeted focus group to obtain farmers' attitudes towards growing perennial energy grasses such as switchgrass in Central Illinois. At the time of the study, almost all respondents were unwilling to convert cropland to perennial grasses unless a local market existed. Overall, this survey highlights the same economic barriers discussed above – profitability, lack of local markets, and upfront cost, including the time and money invested in changing crops.

In some circumstances, the farmer may need landowner approval to convert land to biofuel crops, which is considered controversial (see more discussion in Ref. [39]). Local opportunities for the use of biomass include co-firing biomass with coal in industrial cogeneration boilers to produce both electricity and steam; or pelletize biomass, which can be used as a fuel for heating homes or commercial buildings [40]. There is a well-established market for wood pellets for heating fuel in parts of the U.S.; however, capital investments in processing facilities and market development will be needed to establish a grass fuel-pellet enterprise [41]. A successful example of implementing a local market for biomass is the University of Illinois' installation of a 198 kW Heizomat biomass boiler, which serves as the primary energy source for heating at the University's Energy Farm research complex (with total energy equivalent to the demand of 16 average homes) and an educational tool for improving students' environmental awareness [42]. Currently, Europe is the leading producer and consumer of wood pellets for biomass heating systems, but European countries are still looking to expand to the use of perennial grasses [40]. Local bioenergy markets have broader implications on the economic feasibility and environmental sustainability of growing biofuel crops and can enhance the synergy between grass farmers and the biofuel industry.

Farmers' risk tolerances play a key role in their decision-making, especially the decision on planting biofuel crops. Inherently, farming is a risky enterprise because of the uncertainties surrounding growing conditions, prices, yields, and costs in any given year. Bioenergy crops can be even more uncertain than traditional crops due to the complexity of the biomass market. In a study of perennial crop adoption in rainfed areas of the U.S., Miao & Khanna [43] investigate the impact of uncertainty, including farmers' risk and time preferences, as well as liquidity constraints on thir willingness to produce energy crops. They find that high risk aversion, large discount rate, credit constraints, and availability of crop insurance for conventional crops together can lead to 43% higher cost and 15% higher land requirements to provide enough biomass to meet the EPA's one-billion-gallon cellulosic biofuel mandate. Among all the policy options, Miao & Khanna [43] find that establishing a cost subsidy is the most cost-effective way to improve perennial grass adoption, even under a spectrum of assumptions about farmers' time and risk preferences. The authors further demonstrate that even if expected returns are high, risks such as biomass price variability and required establishment costs can dissuade farmers from producing bioenergy crops. A survey of farmers by Fewell et al. [44] suggests that risk reduction through bioenergy crop insurance programs will be a primary factor in incentivizing producers to grow bioenergy crops. Risk reduction strategies implemented by the government that take into account these findings can help reduce uncertainty as a deterrent to bioenergy crop adoption.

Another major barrier affecting farmers is a lack of knowledge and understanding about bioenergy crops and how to grow them [4,33,37,38]. As a result, they may be willing to grow bioenergy crops after learning technical information from neighboring early adopters [38]. However, Jiang et al. [38] find that risk-averse farmers may still be hesitant to grow bioenergy crops even after watching early adopters. A survey of Minnesota farmers [5] hypothesizes that those farmers who are land stewards are more influenced by their peers. Additionally, farmers who are already concerned about soil quality and land stewardship may not have the need to grow perennials because they already use some approaches for land conservation.

Farmer characteristics and demographics are regularly analyzed in surveys surrounding bioenergy crop adoption due to their high level of influence on land management decisions. Studies have shown that farmers with more knowledge about bioenergy crops, higher education level, and less experience (younger) have higher probabilities of adopting an innovation [4,33]. Farmers with these characteristics highly value farm plant diversity and soil and water ecosystem services. Given that producers' views about on-farm issues might have more significant effects than broader national policy issues on their willingness to grow perennial energy grasses [31], tailoring strategies to specific farmer socio-demographic groups, such as landowner category clusters identified by Mattia et al. [33], may improve adoption success for each of these farmer groups. As suggested by Atwell et al. [7], initiatives for future landscape development should couple social and biophysical analyses in order to identify the discrepancies between individual and community values, social norms and networks, institutions, and ecosystem dimensions. Stakeholder synergy is one way to aggravate those connections, and research is needed to identify ways to remove the barriers that prevent farmers from adopting bioenergy crop production.

In summary, farmers are already growing perennial grasses on a small scale. Studies find that producers consider on-farm issues, especially economic factors, more than national policies in their land use decisions. Economic feasibility must be coupled with risk reduction strategies that guarantee an established market and an attractive price to bolster perennial grass production. The adoption decision will be highly dependent on the level of risk. Long-term contracts with biorefineries will help ensure profitability despite uncertainties in production outcomes and the market. Well-established, local markets will be needed to incentivize farmers and reduce farmers' risk to adopt perennial grasses. Continuing to provide information and technical expertise to farming operations will also give farmers confidence in perennial grass adoption.

2.2. Rural communities

Currently, rural communities, including farmers, families, project managers, and community leaders, have varied opinions on the possibility of biofuel development in their area. Both hope and skepticism have been recorded in terms of the economic, environmental, and societal benefits and risks associated with biofuel development. Although biofuel production has the potential to produce large returns for local farmers, as well as providing new jobs for community members, this is not always the case due to outside influence in the local community from industry players. Attitudes toward cultural norms, including farm stewardship, neatness, scenic beauty, and progressiveness, influence farmers' land use decisions [7]. One issue is that often when practices are motivated by cultural norms, they may not align with conservation goals [7]. In order to create a community welcoming of biofuel development, overall attitudes and mindsets must change in regard to a social perspective.

2.2.1. Rural revitalization

Rural revitalization focuses on local or regional economic development beyond national growth. Overall, U.S. governmental strategies for a bioeconomy employ a large-scale focus [32]. This does not align with the perspectives of local farmers and communities centered around rural prosperity and opportunities. The rural revitalization framework would be lost if the bioeconomy is dominated by large corporations [32].

Studies have found that participants voice a positive outlook surrounding the opportunity created for individual purposes and regional relevance in advancing national goals of energy independence from the emerging bioeconomy [32]. Yet, communities are still concerned that economic benefits may only be temporary, as biorefineries might be closed and relocated after substantial profits are achieved. Farmers also favor long-term economic benefits that detract from large-scale plantation companies [45].

2.2.2. Barriers to acceptance of biofuel development by local communities

Previous interviews and focus groups on the acceptance of rural communities to biofuel development identify several important barriers in terms of growing domination by agribusiness, uncertain economic opportunity, resource constraints on infrastructure expansion, and impact of biorefineries on quality of life and community values. Generally, local influence on biofuel development is perceived as passive consent by larger stakeholders including policy makers and industry players. However, enhancing public involvement by measures that can directly address relevant concerns can lead to greater community acceptance [45]. Efforts are needed to give rural communities a sense of empowerment and to increase their likelihood of acceptance include but not limited to allowing community members to be actively involved in decision making in biofuel development; keeping community members informed about the technological progress, environmental value, as well as risk; and consulting community members and gathering feedback from them.

Rossi & Hindrichs [32] find that skepticism in community members surrounding biofuel development stems from the role of large agribusiness. Many believe the growing domination by agribusinesses in the food system will transfer to the bioeconomy. Farming is shifting from small, local businesses to large corporations, which unravels farmers and their family's strong ties to the countryside, causing people to move elsewhere [7]. Additionally, outside control on biofuel production would limit economic benefits seen by the local community [46]. Recent studies have shown that locally owned biorefineries reap much greater economic benefits such as local income and employment than absentee-owned biorefineries [46,47]. Kleinschmidt finds a 50 Million Gallon/year dry mill ethanol plant can provide an initial surge of $142 million to the local economy, over 40 full-time jobs, and a long-term annual consumer economic activity enhancement in the community by $56 million [46]. The size and scale of the biorefineries largely depend on their ownerships. Smaller decentralized biorefineries may offer more diverse economic opportunities to rural communities than large centralized plants, because of the relatively lower investment requirement for smaller plants [46].

In addition to biorefineries, the emerging bioeconomy will create inevitable infrastructure demands including agricultural, transportation, and water infrastructures, which will influence the environment at local rural communities. Infrastructure expansion decisions will have to be made with considerations of environmental and social constraints, including land, water, social welfare, and acceptance of local communities. For example, the water requirement of ethanol production is a serious concern for communities and caused a lot of local opposition [3]. In Champaign, Illinois, the proposal for a $140 million ethanol refinery was rejected over concerns surrounding its planned water withdrawal of 2 million gallons/day from the Mahomet aquifer, which serves as the primary water source for the local area. Another proposed ethanol plant in Illinois was also blocked for similar reasons [3]. In regard to transportation infrastructure, road and rail traffic will require significant expansion at the local, regional, and national level due to biofuel development. The necessary investments in physical and human capital are starting to be constructed to accommodate these changes in transportation; however, further efforts will be needed as the bioeconomy emerges [3].

A study by Selfa et al. [47] demonstrates how the expected reduced quality of life affects local community's support of grain-based ethanol plants. Using a case study of three local communities in Kansas and Iowa, this paper examines what community members perceive to be the promises and the pitfalls of the materializing of the biofuel industry. Overall, these findings have produced great opposition to the growth in constructing ethanol plants due to the negative impacts on the local quality of life. Increased heavy truck travel and roadway congestion is a byproduct of infrastructure expansion for biofuel development. Biorefineries also can have negative effects on air and water quality. They create potential odors and air pollution directly and indirectly. Biorefineries create water pollution and competition, as well as increased water rates. This is particularly relevant in areas facing water stress, such as Kansas [47].

Community values and culture might be compromised when implementing biofuel production in rural areas. Atwell et al. [7] examine the most important factors relevant to rural stakeholders about their countryside in regard to biofuel development based on in-depth interviews. The authors find that there was widespread acceptance of perennial cover crops on marginal agricultural land; however, the implementation of these practices was neither a priority nor strongly aligned with rural ethics. Traditional cultivation practices are often preferred, especially by farmers who are unfamiliar with bioenergy crops [45]. Additionally, Atwell et al. [7] find that community-level values such as the desire for connectedness and ethics of care have the ability to create collaboration between independent rural households together to achieve landscape change. A follow-up paper by Atwell et al. [48] highlights the importance of coupling financial incentives for conservation approaches such as bioenergy with community development and local-level conservation support networks in achieving landscape-scale goals. Removing these barriers will enhance rural revitalization and thus the positive synergy between rural communities and other stakeholders (e.g., government and biorefineries).

In summary, support of perennial grass adoption by rural communities is based on many perceived effects of the emergence of the biofuel industry. Community's support of biorefineries depends on the creation of new job opportunities and fulfillment of rural revitalization, and the economic benefits of biorefineries will play an important role. Additionally, minimizing adverse effects such as outside control from large agribusiness, maintaining the quality of life as biorefineries become established, and prioritizing community values and culture will help rural communities support biofuel development in their area. In addition, public awareness and community involvement will provide a mentality of independence and contribution to societal advancements.

2.3. Biorefineries

According to the Renewable Fuels Association (RFA), as of January 2019, 199 out of 210 biorefineries serve as operating ethanol production facilities, largely based in the Midwestern U.S [49]. Of these facilities, less than 6% are capable of using cellulosic biomass (Fig. 3). Together, the refineries produced approximately 16.5 billion gallons of ethanol in 2018, an increase from 13 billion gallons in 2010. However, the RFS mandates that efforts take place to improve technology for producing cellulosic ethanol from lignocellulose feedstocks. This priority will likely lead to the construction of cellulosic ethanol refineries where feedstocks for advanced biofuels are readily available. Current barriers preventing the rise of cellulosic biorefineries include technology limitations, lack of

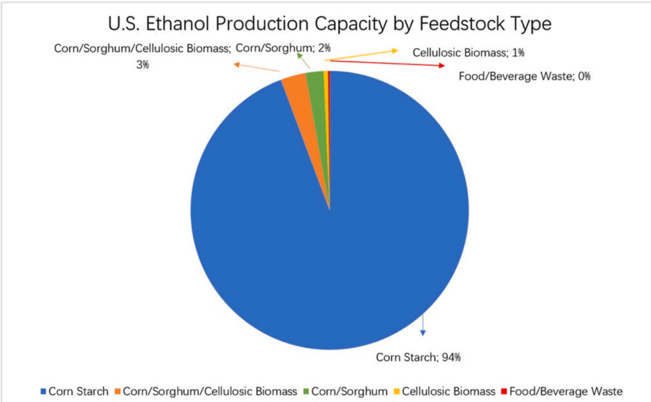

Fig. 3. U.S. Ethanol production capacity by feedstock type (after Wilson and Cooper [49]).

private investment for biorefinery establishment, resource and infrastructure limitations, as well as the lack of cellulosic biomass at the economies-of-scale.

Technical challenges are prevalent in the economic and environmental aspects of biofuel conversion. The major steps in the biomass conversion process include (1) suitable biomass feedstock selection, (2) effective pretreatment, (3) hydrolysis to produce saccharolytic enzymes-cellulases and hemicellulases, (4) fermentation of hexoses and pentoses, and (5) downstream processing such as distillation and separation [50]. Extracting or converting reactive intermediates for biofuel from cellulosic biomasses is challenging at present because of the biomass recalcitrance imposed by the complex and difficult-to-penetrate structure formed by cellulose, hemicellulose, and lignin [51]. Processes such as hydrolysis, pyrolysis, and gasification could overcome the above recalcitrance issue at various costs. Hydrolysis uses special enzymes to degrade lignocellulosic biomass into easily convertible glucose and xylene. However, enzymes could account for more than 50% of the total cost in cellulosic biofuel production [52]; further, the enzyme activities are inhibited by the end-products of hydrolysis, hence reducing the biofuel yields [52]. Pyrolysis uses heat to decompose biomass into char, condensable, and non-condensable gaseous products, which could be further used to produce biofuels. Pyrolysis usually associates with high energy consumption, and the produced biofuels require further upgrading before they are used by vehicles [53,54]. Gasification generates gaseous intermediate products through pressurized steam or air at high temperature, and the required pressurized equipment imposes high capital costs for implementing this technology [53,54]. A more practical technology challenge is the rocks and dirt in cellulosic feedstocks that harm the preprocessing facilities. It is estimated that cellulosic biorefineries might need to take up to five years to adjust their facility to feedstock pretreatment needs and operate at the nameplate capacities [55].

Meanwhile, cellulosic feedstocks (agricultural residues and energy crops) are harvested for a relatively short period of time, while biorefineries require a steady supply year-round. This inconsistency between the supply and demand of feedstock introduces high demand in the cellulosic biofuel industry for feedstock storage at refinery plants [56]. Extraordinary new storage facilities are needed given the current technologies and practices in refinery plants using cellulosic feedstock. It is estimated that feedstock production and logistics could account for over 35% of the total cost of cellulosic biofuel production in the U.S [57]. The refinery technologies also face the problems of ethanol-producing bacteria inhibition during fermentation, concerns of gene-modified enzymes and feedstocks, energy-use during distilling, and solid residues treatments [52,54]. The issues above significantly increase the costs of cellulosic biofuels, inhibit industry investments, which in turn, disincentivize farmers' energy crop adoption and consumers' willingness to use such fuels. The solutions, therefore, require efforts from the key stakeholders synergistically, e.g., production of diverse energy crops for a more steady supply of feedstocks, provision of public funding and subsidies, and, very importantly, development of more advanced conversion technologies.

One example would be the "plants as factories" approach adopted by the Center for Advanced Bioenergy and Bioproducts Innovation (CABBI) funded by the U.S. Department of Energy and located at the University of Illinois at Urbana-Champaign [58], which focuses on research where biofuels, bioproducts, and foundation molecules for conversion are synthesized directly in plant stems. High-value chemical compounds can be directly extracted from feedstock material, while avoiding biomass recalcitrance. Remaining plant materials can be easily broken down by enzymes. This "plants as factories" approach eliminates many obstacles previously identified while providing a cost-effective refining technology. Additionally, high-value chemical compounds are attained, creating greater market flexibility for both biomass producers and bioenergy consumers. In particular, this approach could reduce transportation and storage infrastructure needs and costs significantly due to the smaller volume of solid material transported after pretreatment (V. Singh, personal communication, 2019).

The commercialization of lignocellulosic ethanol will need continued investment in research and pilot project demonstration with both the private and public sectors, in conjunction with suitable policy backing, as discussed in the following section. Through a text mining program applied to 57,849 research publication abstracts related to "biofuel" [59], it is found that cost is the most common concern among finance related keywords (Table 1). Cost issues are mostly mentioned not only in a technology context but also have quite frequently appeared in topics on policies and general energy issues (Table 1). It is estimated that the cost of cellulosic biofuel production is around 0.7–1.1 $/L (2015 dollar), compared to that for corn ethanol 0.4–0.7 $/L, and gasoline 0.3 $/L [60]. The extra cost between cellulosic biofuels and their competitors presents a serious barrier to the market expansion of cellulosic biofuels. Possible solutions include investments in technology to reduce the costs and providing subsidies for feedstock production, cellulosic biofuel production, and infrastructure development.

The investments to the next-generation biofuels and biochemicals have, however, declined globally in recent years, from the peak value of ~$3 billion in 2011 to nearly a quarter of it in 2016 [61], mostly caused by the frustration of the failure of some early attempts (e.g., the shut-down of cellulosic biorefineries invested by DuPont, Abengoa, and INEOS Bio). The uncertainty in cellulosic biofuel supporting policies is cited as another major reason for the lack of investment [56] (the RFS cellulosic biofuel mandates are only set through 2022, while a cellulosic biorefinery might need up to five years before stable production [55]). Such a drastic reduction of funding leads to a decline of cellulosic biofuel related patent files since 2015 [62]. The set-back of private sectors leaves this industry to rely more on public investments and subsidies.

Table 1
Frequencies of finance related keywords in biofuel research publication abstracts.

Topic	Incentive	Cost	Benefit	Profit	Financial
Technology in General	151	1671	519	370	167
Low-emission Diesel	16	386	240	14	14
Biodiesel	23	687	169	48	18
Energy in General	272	1300	830	214	276
Gasoline Blending	18	253	66	20	7
Fuel Cell	3	341	77	7	2
Feedstocks	51	505	418	151	34
Pyrolysis	17	590	176	67	16
Policy	61	661	110	31	19
Algae	6	952	189	55	20
Genetic Engineering	3	546	147	19	9
Biogas	17	516	194	59	35
Total	638	8408	3135	1055	617

While subsidy is necessary at the early stage of cellulosic biofuel development to cover at least part of the price gap between cellulosic biofuel and gasoline estimated above (~0.4$/L), the subsidy is expected to be reduced in the future given the experiences of learning-by-doing and the economy-of-scale [61]. The government should design policies and subsidies carefully to enable fast learning and reduce risks. For example, the U.S. Department of Energy funds diverse biorefinery projects, known as integrated biorefineries, in order to reduce marketplace risk for new technologies. Projects are diversified across conversion processes (biochemical or thermochemical conversion), biorefinery scales (pilot, demonstration, commercial), feedstock inputs (conventional biomass, perennial grasses, algae), and final outputs (corn or cellulosic ethanol, renewable hydrocarbon, other high-value chemicals) to reduce risks [63].

Biorefineries are both water and energy intensive in nature. This creates infrastructure demands including water supply and transportation infrastructure, which will put stress on local natural resources and communities. Currently, most biorefineries are located in close proximity to the feedstock source, commonly in the Midwestern U.S., while water availability for biorefinery has probably not given sufficient consideration [3,64]. The spatial mismatch of water availability and feedstock availability can exacerbate in the future. Based on previous studies [65,66], cellulosic-based biorefineries can be more water intensive than corn ethanol. Being driven by the RFS cellulosic biofuel mandate, biorefinery capacities for cellulosic feedstocks are expected to grow in some regions which are already threatened by water stress. Following the spatial distribution of cellulosic biomass availability [67], those additional cellulosic biorefineries will mostly appear in the Great Plains and the southwest U.S., where future water availability for additional demands limited [68,69]. Additionally, the wastewater generated puts stress on local wastewater treatment facilities that cannot accommodate. Therefore, the optimal location of biorefineries in terms of minimizing the transport distance of feedstock material often conflicts with areas faced with water stress [70], as well as other constraints such as the lack of experienced labor [3].

In summary, due to technology limitations, lack of economic viability, local resource constraints, and infrastructure requirements, cellulosic ethanol biorefineries are far from widespread commercialization. Though there have been minor improvements in the production capacity of biorefineries, many biorefinery projects have not come to fruition in terms of meeting production and economic goals set forth by the government mandate. Building on existing infrastructure and streamlining new technologies could create a smoother transition to integrated biorefineries [71]. Cooperation with rural communities on biomass production, land and water use for biorefineries, job opportunities, etc., is needed for the development of cellulosic ethanol biorefineries.

2.4. Government

Policymakers, governing bodies, and non-governmental organizations (NGOs) are the most complex stakeholders and assume multiple roles acting as an intermediary stakeholder and overseeing body. The government is considered a direct investor in biofuel development and a guarantor to provide subsidies in feedstock development for various biofuel projects [20]. Policy makers harmonize the goals of NGOs and environmentalists with pertinent industry and public stakeholders to encourage environmental protection in addition to economic growth and social welfare [20]. Additionally, government support schemes with climate change focus to promote land management decisions with long-term GHG emission reduction potentials [22]. Successful policy incentives must provide farmers and other stakeholders a continued sense of independence and societal contributions [6]. In particular, policies are needed to reduce the risk of involvement in the emerging bioeconomy. Such policies could have an impact on every step of the biofuel supply chain (e.g., inducing demand among consumers, investment among processors, or production of crops by farmers). The optimal degree of policy intervention along each step of the supply chain to ignite further expansion of biofuels should be explored [34].

For instance, one policy to promote biofuel production is the Biomass Crop Assistance Program (BCAP). This program requires the government to allocate $25 million of subsidies from 2014 to 2018 to individual farmers or companies for the production, harvest, collection, and transportation of feedstocks that can be used in biorefinery facilities. However, the actual biomass production improvement induced by BCAP is small (2.7 million metric ton/year), especially for perennial crops such as Miscanthus and switchgrass, due to budget limitations and restrictions on establishment payments [72]. The potential benefits of BCAP are expected to be even smaller because of its reduced funding from $25 million to $3 million via the 2018 Farm Bill [73]. This provides a clear example of the disparities between the government and biomass and biofuel producers. Instead, it is estimated that the BCAP funding should have had increased funding, a higher subsidy rate for establishment costs, and an efficient selection mechanism for enrolling land in the program. In addition, in the case of more effective government incentives for producers such as BCAP, policies must be geared toward the two-part decision process where farmers first decide whether or not to adopt perennial bioenergy crops and then determine the amount of acreage they are willing to convert. Policy creators must have a clearly defined goal on whether they would like to stimulate more agricultural landowners to enter the market, stimulate increased acreage grown by current farmers in the market, or both. Additionally, they must understand the fundamental factors that affect each of these separate decision processes in order to implement effective policy measures [5].

Other governmental measures include research and development programs, tax cuts and exemptions, investment subsidies, feed-in tariffs for renewable electricity, and mandatory blending for biofuels quotas [14]. All stakeholders have been found to identify government support as a top preference for the promotion of the bioenergy industry [74]. However, government measures must target specific barriers to the market and the key stakeholders involved. Policies must be analyzed and reviewed, along with proper communication with multiple stakeholders to create effective outcomes, reduce policy uncertainty, stimulate the biofuel market, and avoid shortcomings as seen in BCAP.

In summary, the role of the government is to remove barriers identified by other stakeholders either directly or indirectly. This includes generating institutional capacity, establishing research practices and bolster development institutions, fostering an environment for investment, and distributing information to promote biofuel development [75]. Policies and funding to support stakeholders in the biofuel supply chain must be optimized to avoid policy failures such as the BCAP example. Biofuel sustainability standards and other energy and agricultural policy goals can be assessed using cost-benefit analysis, a framework widely applied in the global climate change economics community [76]. Clear and realistic goals by the government will seed the market for future biofuel development. Conversely, setting unrealistic mandates strains relationships between stakeholders. Mandates must be flexible, while taking into consideration the global energy market. The government, as an overarching body, may be the most important player to create synergy between stakeholders; thus far, they have fallen short in this regard.

2.5. Consumers

Understanding consumer priorities is critical for biofuels to become more accepted by the public. Almost all individuals can be considered as consumers of heat, electricity, or mobility. Biofuels have strong ties to the general liquid fuel markets, which may affect the public directly through transportation costs and indirectly through the prices of consumer goods and services [20]. Consumer perspectives on biofuel development can be split into community acceptance and market acceptance [45]. This section focuses on market acceptance, which indicates consumers' willingness to choose bioenergy for vehicles, heating, and electricity.

Largely, consumer preferences on biofuels are based on their attitudes towards green pricing schemes, which can be described as the consumers' willingness to voluntarily accept the increased price of energy due to personal sustainability goals and moral considerations [75]. Safety and quality assurance are also important factors in the acceptance of biofuels. In a study of consumer beliefs about biofuels in vehicles in Belgium, Van de Velde et al. [15] conduct a questionnaire on key fuel characteristics in order to understand consumer rankings. The authors find that younger respondents are more performance- and convenience-oriented, while older respondents are more society- and environment-oriented. Based on the priorities of certain demographic groups, different communication strategies could be used to influence the acceptance of biofuel adoption.

Market failures can occur due to a lack of awareness and information on the product, technology, costs, and benefits of biofuel [75]. A survey in Finland studying public acceptance of biofuels in the transport sector finds that all respondents are environmentally conscious and most of them are concerned about global warming and overpopulation [77]. However, because of the lack of information, awareness, and experience with biofuels, and the limited availability of biofuel at petrol stations [77], consumption of biofuels is low [77,78]. Consumer trust in key stakeholders and technologies plays an important role in biofuel adoption [79]. Consumers with higher confidence levels and greater trust in regulatory institutions tend to have higher risk acceptances and perceive greater benefits of new technologies, including biofuels [79]. For example, many people still engage in the "food vs. fuel" debate, despite the evidence that advanced biofuel production will not detract from food crop production or agricultural lands that produce food crops [49]. Furthermore, people are concerned that using and purchasing biofuels might increase food prices due to the competition between food and fuel production [80]. Therefore, by educating and empowering consumers about the role of advanced biofuel production, greater synergy can be established between the demand and the supply side of cellulosic biofuels.

Consumer perception of the benefits and risks related to biofuels plays an important role in the biofuel market. Delshad et al. [80] conduct a survey to investigate the public's stance toward political and technological biofuel pathways, and they conclude that consumers are more concerned about the economic and environmental impacts of biofuels than national energy independence. This correlates strongly to our previous discussion of farmers' self-interest over larger national goals. In addition, consumers are often more concerned with immediate consequences or impacts over future consequences. Therefore, consumers are more likely to base their evaluation of fuel alternatives on immediate concerns, such as price, as opposed to trying to maximize the planet's long-term well-being [78].

Additionally, the skepticism that bioenergy is not economically or environmentally efficient and cannot reduce pollution deters some consumers from accepting biofuels as a source of renewable energy. This partially explains why participants favor other renewable fuel sources as opposed to biofuels in a survey conducted by Delshad et al. [80]. Particularly, considering the fact that most biofuels are made from genetically modified organisms (GMOs), people are concerned about the corresponding environmental risk for natural ecosystems [80]. Thus, there is greater support for biofuels derived from non-edible crop sources, such as perennial grasses, than edible sources [80].

In summary, consumer support for biofuel development is based on the demand for green energy systems. Many consumers support green pricing schemes, and therefore are willing to pay a premium for sustainable products and services. However, higher fuel prices can be a disincentive for some consumers. Information and awareness from other key stakeholders on biofuel technologies and benefits, potentially through social media platforms, can create stakeholder synergy through trust and transparency, which will formulate positive responses to biofuel development from consumers. Attention should also be given to the inconsistencies between government biofuel development mandates and consumers' priorities; education and scientific support can help mitigate consumer concerns on the risks of biofuels.

3. Stakeholder interactions

The reviews of individual stakeholders above already highlight the interactions among them. Producers, as the initial stakeholders in the biofuel supply chain, prefer economic and environmental incentives to join a new, unestablished market. However, other factors, including information and knowledge surrounding feedstocks, technical and financial support with biorefineries and government organizations, and a sense of certainty of success could reassure farmers to invest in the bioeconomy. Consumer preferences on fuel type, environmental concerns, and knowledge, information, and trust with other key stakeholders affect the demand for biofuels as an alternative energy source. The government plays a key role to enforce the desired level of advanced biofuel production through the Renewable Fuel Act; however, the shortcomings of governmental policies could be attributed to the insufficient synergy with other important groups in the biofuel supply chain. Technology advancements to use the second-generation bioenergy crops as high value chemical compounds in new products can stimulate investments in biorefineries. However, the collapse of recent biorefineries has led to hesitation in this sector given that the growth of the bioeconomy through feedstock production and biorefineries may lead to adverse effects on local rural communities. Therefore, the expansion of this industry and these complex interactions must be monitored carefully, while stronger stakeholder synergy should be encouraged to prevent resistance from society.

3.1. Visions for the bioenergy economy

In the future, widespread production of novel energy crops such as perennial grasses will shift agricultural landscapes and diversify the sources, levels, and variability of farm income. Coordinated efforts by policy makers, biorefineries, farmers, and consumers can be seen in a projected vision of a bioenergy economy: A processor will invest in a biofuel conversion facility (biorefinery) provided that the processor has a confirmed contract from the oil industry to produce biofuel. This requires demand for biofuel from the end users or consumers, where a consumer's decision to invest in compatible bioenergy technologies will depend on the evolving bioenergy market, diversification of bioenergy products, and the net benefits of corresponding investments. Therefore, the adoption of bioenergy must be coordinated between the connected players—the biomass producers (farmer), processors, oil industry, and consumers. The stakeholder synergy underlying this framework is similar to the "two-step dance" in the process of farmer adoption of perennial grasses, described by Rajagopal et al. [34]. Industry takes the first step by investing in processing capacity; farmers follow by establishing contracts for bioenergy crop production. However, such investments in processing capacity at biorefineries require long-term commitments to biofuels which warrants government incentives to reduce foreseen risks in the market and initiate the supply chain. Classical oil-based refineries have had more than 100 years to reach the scale and economies of today [63]. The biorefinery sector, where stakeholders are faced with decisions to enter a new, unestablished market, will also take time to build up over the coming decades, which requires significant effort and investment from the industry as well as the right regulatory environment [34]. Analysis of key stakeholders in biofuel development and existing barriers to widespread adoption of biofuel as a source of renewable energy sheds light on how stakeholder synergy can be achieved. In particular, hypotheses for understanding what catalyst or "pushing hands" could drive stakeholder synergy and then the appearance of the expected bioeconomy should be addressed in terms of the role of policies and scientific information and education, as further discussed below.

3.2. The role of policy

In the U.S., the government is responsible for developing policies (both command-and-control as well as market-based) to incentivize biofuel feedstock production by farmers and consumption of biofuel by consumers. For example, biofuel production tax credits stimulate processors to invest in biorefineries. Additionally, consumers are offered incentives to adopt vehicle technologies, such as hybrid, electric, or flex-fuel vehicles, compatible with reduced car emissions to align with personal environmental goals. Therefore, the government has previously intervened at nearly every step in the supply chain to encourage the adoption of biofuel production, biofuel technology, and biofuel end use. Further research is needed to determine the optimal stage(s) of government intervention in the supply chain in order to minimize intervention while maximizing the desired outcomes.

In addition, although some of the current government mandates, such as RFS, have not to be realized, de Gorter & Just [76] find that quantity-based biofuel mandates have greater efficacies than price-based consumption subsidies. Using quantity-based mandates could increase social welfare through a lower level of total fuel consumption, reduced carbon dioxide emissions, and reduced miles traveled [76].

3.3. The role of scientific information and education

Even with policy incentives, consumer and farmer adoption of biofuels depends on their individual knowledge of biofuel and technology development, and their expected benefits of joining the bioeconomy. Other intermediary stakeholders, including research scientists and investors, play an important role in biofuel technology development by providing trustworthy technological and economic assessments to build overall trust between the key stakeholders discussed in this paper [79]. Moreover, scientists play an additional role to educate farmers and the public on biofuels, and to inform government and NGOs on the risks and benefits of new technologies [20]. Research institutions, governments, and NGOs help bring awareness to biofuel technology, economy and health, and safety issues [20]. According to a study by Van de Velde [15], research scientists and NGOs are the most trustworthy and reliable source of biofuel information for consumers. However, currently, there is a large gap in public knowledge about bioenergy from fuel producers or media, and the views and attention on biofuels from the research community and the public are considerably different in many aspects. Especially research has not provided sufficient scientific support for policy development; nor has research meet the needs of the public on the industrialization of some advanced technologies, such as fuel cells, pyrolysis, and algae-based biofuel production [59]. It is recommended that research scientists should communicate with other stakeholders directly to avoid confounding information by industrial and political interests [81]. For example, in Tennessee, there are many education programs to encourage local landowners to diversify crops and inform farmers on the benefits and risks of switchgrass cultivation. Additionally, public adoption of energy crops is not only dependent on science literacy or knowledge, but also on worldviews, ethics, and trust [79]. Therefore, a change in mindset by many stakeholders is needed through knowledge and information sharing.

4. Future research suggestions

Following the highlights of the key stakeholders involved in the biofuel supply chain and their interactions with each other, future research as follows are suggested for more understanding of current perspectives and barriers and to explore decisions that achieve synergy among stakeholders.

4.1. Further data and surveys

There is still a limited understanding of the interactions between farmers and other key stakeholders, and their attitudes toward the interactions discussed above. In order to fill this critical gap, additional surveys of biofuel producers should be conducted in the future with “new” questions, as well as new outlooks on questions from previous surveys, to see how farmers view the possible interactions with local rural communities, biorefineries, and the government. This could give insights into the main factors farmers consider when choosing whether or not to grow bioenergy crops, concerns of the local rural community, effective policy changes that would influence their decisions, land management preferences that align with national environmental goals, and their preferences for contracts with biorefineries. New questions could also highlight farmer-farmer interactions, which could improve our understanding of how farmers respond to neighboring farmers and peers, and how knowledge transfers to land management decisions, and the sharing of information and technology, as well as nearby infrastructure. Additionally, questions are needed to understand why farmers are currently growing bioenergy crops, whether on a small scale or large commercial scale. Through analyzing the incentives and advantages of small-scale operations, the possible transition to a larger bioeconomy can be better understood. Questions regarding farmers’ overall economic, environmental, social, and cultural preferences are needed in future surveys to help establish suggestions that will create a synergistic environment with other key stakeholders individually, regionally, and nationally. Particular sets of questions can be designed to obtain information about farmers’ land use choices for advanced biofuel feedstock production such as the use of marginal lands [3], and for the existing planting of perennial grasses for bioenergy generation. Besides the stakeholder survey described above, a focus group study with representatives from multiple stakeholder communities can be conducted as a “living lab” for analyzing stakeholder synergy. Key questions about and barriers to stakeholder synergy can be explored through choice experiments and discussions; survey responses can also be validated and clarified via the focus group study.

4.2. Modeling the emergence of the cellulosic biofuel market

The synergistic interactions of stakeholders in the advanced biofuel supply chain can be simulated by an agent-based model (ABM). ABM derives system-level outcomes through simulation of heterogeneous individual agents and their interactions. In ABM, the agents are simulated to follow certain ‘behavior rules’ where stakeholders’ financial and behavioral perspectives and attributes are incorporated, and they are interconnected to represent the between-group (e.g., farmer-refinery interaction) and within-group (farmer-farmer interaction) feedbacks and interactions. The heterogeneities among agents and the feedbacks between agents make ABM highly suitable for modeling complex systems that the outcome of individuals’ interactions differs from the simple aggregation of them (i.e., synergy and/or antagonism between agents) [82]. For example, in their ABM for simulating plug-in hybrid vehicle (PHEV) market penetration, Eppstein et al. [83] identify an effective policy that, by imposing a gasoline tax to fund long-range PHEV battery research, positive feedback from both customers and developers can be formed. It is shown that the stakeholder synergy in the PHEV market significantly reduces gasoline usage in the transportation sector. Similarly, in supply chain analysis, ABM is used to simulate the synergy between companies that benefit each other through the exchange of by-products [84].

In particular, ABM has been applied to understanding farmers’ adoption of perennial bioenergy crops [85], the interaction between farmers and refineries [86], interactions along the biofuel supply chain including multiple stakeholders, i.e., farmer, biorefinery, and biofuel distributor [87], biofuel market penetration [88], etc. Though synergy is not specifically discussed in the aforementioned ABM studies, it could potentially be identified in those studies that investigate farmers' interactions, i.e., an ABM allowing farmers' interactions would result in positive feedback between farmers, whose land use decisions are highly influenced by peer pressure and exchange of information [85,86,89], and between farmers and refinery plants. Farmers with low productivity land can grow and sell energy crops to local refineries to improve profit, and refineries with reliable feedstocks would expand their capacity and be more profitable because of the economy of scale [86,87]. However, one major drawback in existing ABM studies in the biofuel system is the overemphasis of suppliers (farmers) and the lack of consideration of other stakeholders that are difficult to fit into the dominating optimization-based ABM (e.g., rural community). An ABM that incorporates all major stakeholders and their interactions in the advanced biofuel system (see Fig. 4), as discussed in this paper, is critical for identifying the barriers for stakeholder synergy and designing effective policies to foster such synergy and eventually the market of advanced biofuels. In addition, more data regarding agent behaviors and interactions are needed for modelers to simulate realistic agent interactions that could potentially result in synergistic effects (e.g., peer pressure, dependence structures in the supply chain, and the institutional structure related to biofuel), which could be collected through focus groups and surveys [87,90].

4.3. Text mining applications

Text mining techniques allow analyzing large amount of research publications and social media to discover new perspectives on biofuel development. As a preliminary analysis, the comparative text mining technique [91] is applied to two text data collections on biofuel development, one from research paper abstracts [92] and the other from public news sources [93]. Fig. 5 (adapted from Zhao et al. [59]) shows 12 major topics identified from the two data sources and the distributions of the topics in the collected abstracts. Specifically, among the 12 identified topics, two general topics, including technology and energy in general receive the highest attention followed by pyrolysis and genetic engineering; feedstocks, algae-based biofuel, biodiesel (primarily related to production techniques), and low-emission diesel (primarily related to environmental impacts and utilization issues) receive moderate attention; fuel cell techniques, biogas and policy issues receive relatively low attention, with gasoline blending receiving the lowest attention from the research community.

Furthermore, social media plays an important role in connecting different stakeholders, and it does so instantaneously and without supervision. Problems may arise from amplified emotional responses of some stakeholders and from defending against untrue claims on the Internet [20]. A sentiment analysis is conducted with the collected news data, which identifies the words related to positive or negative attitudes of some stakeholders. The analysis result shows that, in general, there are significantly more sentences classified as positive than those

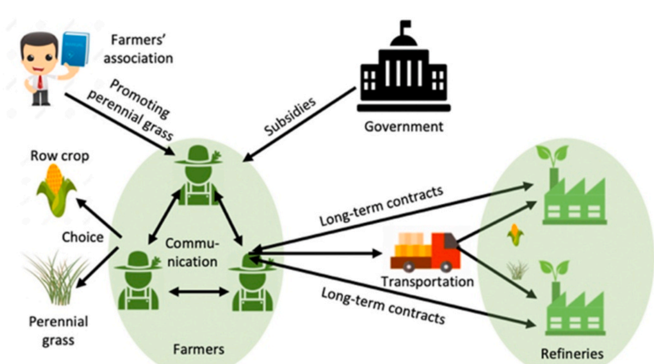

Fig. 4. An example of ABM for identifying synergy in stakeholder interactions.

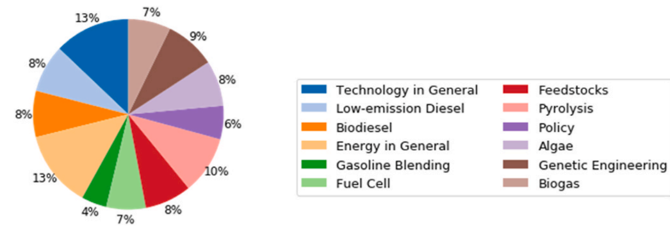

Fig. 5. Major research abstracts (After Zhao et al. [59]).

classified as negative. Fig. 6 (adapted from Zhao et al. [59]) shows the words that are most relevant to positive sentiments and negative sentiments, respectively. As can be seen, in the context of biofuel development, people are in general positive when talking about the positive impacts of biofuel production (such as job creation, environmental impacts, and energy security), continuous achievements (including project milestones and technology breakthroughs), and optimistic expectations on the market and technology development; while negative attitudes are mostly related to the abuse of biofuel program benefits (relevant words include "scheme", "fraud", "claim", "statement", and "lawsuit"), with minor concerns on the unintended negative consequences caused by biofuel development and policy controversies, such as the complaints on policies of CARB (California Air Resources Board), and unreasonable high RIN (renewable identification number) price.

5. Conclusions

This perspective paper provides a vision of cellulosic biofuel and emphasizes the role of stakeholder synergy that enhances mutual benefits for all stakeholders. Stakeholder synergy is currently missing in the U.S. for the emergence of the bioeconomy. The future of the U.S. bioenergy vision, particularly in the Midwest, largely depends not only on farmers' land management and bioenergy crop adoption, but also on the connected players they interact with—local rural communities, biorefineries, the government, and bioenergy end users. Understanding the connection between community conditions, social networks and societal views, farmer decisions, and government priorities can provide the basis for effective action for the bioenergy industry and the biofuel supply chain. It is proposed that the realization of a synergistic approach to biofuel development may provide effective mechanisms for removing identified barriers. The realization of the synergy will provide solutions that maximize the benefits of bioenergy products for the economy and environment, mitigate the tradeoffs among multiple stakeholder groups, and minimize harmful, unintended outcomes on any one. The potential for increasing shared benefits among stakeholders is strong, but realizing these benefits will require further research and continued cooperation, especially implementaing appropriate policies. In particular, research is needed to model (e.g., the agent-based model) and analyze (e.g., based on a text mining technique) how stakeholder synergy can be achieved most effectively in the bioeconomy. Promoting discussions between key stakeholders is probably the first step. By highlighting

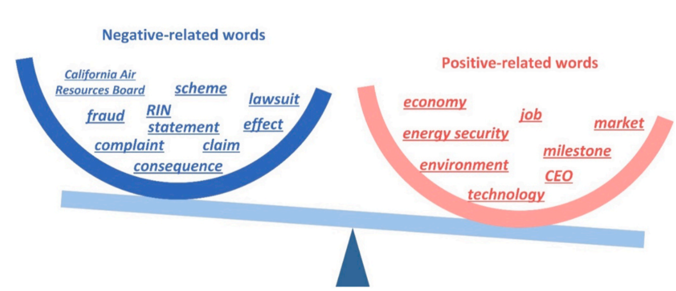

Fig. 6. Words most relevant to positive and negative sentiments (After Zhao et al. [59]).

positive opportunities and eliminating recognized barriers, steps can be made to initiate changes in this industry. How regional and national planning transpires, in a coordinated synergistic framework or not, will surely set a precedent for future biofuel development.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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