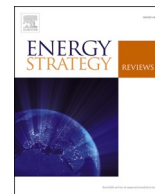


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An analysis of the risk narrative disclosed by publicly traded biofuel firms

Carlos J.O. Trejo-Pech^{*} , Bishal Bista, T. Edward Yu, James A. Larson

Department of Agricultural and Resource Economics, University of Tennessee at Knoxville, TN, USA

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ABSTRACT

Given the high level of uncertainty prevalent in the immature biofuels industry, the primary objective of this study was to identify and assess the risk factors that biofuel firms face. The study evaluated the risk factors, or specific risks, reported by biofuel firms to the U.S. Securities and Exchange Commission (SEC) over five years. The analysis was conducted for all firms in the sample, as well as for subsets of focused and diversified biofuel firms. Based on a biofuels industry risk structure derived from previous research, we coded and analyzed 4310 risk narrative disclosures, extracts from firms' annual reports filed with the SEC. The study evaluated two risk metrics—prevalence and relevance—across 25 specific risks. Risk relevance, the most comprehensive metric, was validated by comparing it with two widely used risk metrics—which measure overall firm risk rather than specific risks—the Z-score and the debt-to-equity ratio. Identification of risk metrics by quadrants, combined with quantile regression analysis, allowed us to identify the critical risks in the biofuels industry. The critical risks, particularly for focused biofuel firms, were biofuel regulation, biofuel markets, feedstock markets, conversion technologies, profitable operations, financing, and risk management. To a lesser extent, environmental and contracting risks were critical. The results of this study can guide policymakers and firm managers in developing a compelling policy mix and strategies to address the challenges faced by the biofuels industry.

1. Introduction

The trend of increasing fuel consumption globally has raised concerns about the depletion of fossil fuels. Studies examining fossil fuel consumption have predicted that mainstream crude oil, at its present consumption rate, will not fulfill the worldwide demand in the next 50 years [1]. Furthermore, fossil fuel combustion is a significant source of greenhouse gas (GHG) emissions. GHG emissions from the burning of fossil fuels are a primary source of climate change, which is widely regarded as one of the most pressing environmental concerns in recent times [2]. Provided that GHG emissions are expected to increase in the coming years due to the growing population and rising fuel consumption, biofuels—those produced from biomass—have been regarded as a replacement for fossil fuels [3–6]. Biofuels have advantages over fossil fuels because they are renewable, emit fewer GHG, have the potential to decrease diseases, particularly through the reduction of heavy metals in particulate matter, and support the rural agricultural economy [7,8].

Governments and private investors successfully promoted the development of a first generation of biofuels as an alternative to fossil fuels. For example, ethanol, produced primarily from corn and sugarcane as feedstocks, increased tenfold from 2000 to 2010 [9]. However,

the food versus fuel debate, which suggested that the expanded use of biofuels could lead to food insecurity and high food prices, prompted a shift in the biofuel industry's focus from first-generation biofuels produced from edible feedstocks to biofuels from non-edible feedstocks. The identification of sustainable lignocellulosic-based feedstocks and the development of conversion technologies have moved this industry forward. Despite this progress, it is more expensive and technically uncertain to produce biofuels than fossil fuels [6,10], and this has caused several biofuel startups to fail, while surviving firms diversify their offerings with high-value products beyond biofuels [9]. This limited growth and development could be attributed to the relatively high risks or uncertainties prevalent in this industry. High initial capital investment, rapid generation of novel technologies reducing the useful life of investment, continuous adjustments and changes in biofuel policy, feedstock and biofuel price variation, feedstock availability, and the difficulty of consistently producing high-quality biofuels due to the chemical characteristics of biomass are sources of uncertainty discouraging investments in the biofuel industry [6,10,11]. In addition, the high asset-specificity nature of investment in biofuel combined with uncertain profitability has been identified as a significant factor that makes investors hesitant to invest in biofuel ventures [12,13].

^{*} Corresponding author. Department of Agricultural and Resource Economics, University of Tennessee, 2621 Morgan Circle Drive, Knoxville, TN, 37996, USA.
E-mail address: ctrejopec@utk.edu (C.J.O. Trejo-Pech).

Given the high level of uncertainty prevalent in the immature biofuels industry, the primary objective of this study was to identify and assess the risk factors that biofuel firms list in their reports to the U.S. Securities and Exchange Commission (SEC). SEC filings constitute a unique source for the systematic identification of firm-level risk factors because firms with listed securities on a U.S. stock exchange are required to discuss and prioritize the risks they face. Furthermore, measuring the relative importance of risk factors through a risk metric, as done in this study, provides additional information not contained in available risk metrics that capture the firm's overall risk rather than the relevance of specific risk factors.¹ Since the risk factor metrics are specific rather than general for the overall firm, we refer to them as specific risks or simply risks in this paper. A secondary objective of this study was to evaluate whether focused and diversified biofuel firms ranked the risk factors differently. We expected that focused biofuel firms considered industry-specific factors in the biofuels industry as more important than biofuel diversified firms. The results of this study can guide policymakers and firm managers in developing a compelling policy mix and strategies to address the challenges faced by the biofuels industry. The study is relevant because the biofuel industry is still in development and transitioning to become an economically viable and sustainable alternative to fossil fuels. For instance, replacing conventional aviation fuel with sustainable aviation fuel (SAF) has been identified as a means to decarbonize the aviation sector if SAF production can be scaled up [14]. Several biofuel startups have failed and filed for bankruptcy because of the high risks and volatile returns associated with biofuels. While risk has been a concern in biofuel investment, limited research has identified and evaluated specific risks affecting this industry. Notably, using the political, economic, social, and technological (PEST) and value chain frameworks, Pries et al. [15] assessed the specific risks reported by a sample of U.S. and Canadian biofuel companies [16]. Our study employs Pries et al.'s methods to identify and evaluate biofuel risks, but we extend that study in several ways. First, unlike Pries et al. [15], who analyzed 2013 data, our analysis spans a five-year period—from 2017 to 2021—and focuses on firms with listed securities in U.S. stock exchanges. Given that Pries et al. [15] conducted the analysis using 2013 data, the risks faced by biofuel companies may have changed with the advent of second-generation biofuels, and updating such analysis may provide new insights. Second, by recognizing that some biofuel firms in the sample have a more diversified portfolio of products than others, our study compares focused and diversified firms. Third, our study validates the estimated risk factors' metrics against widely used—but overall firm risk metrics—proxies, such as the Z-score and the debt-to-equity ratio. This is important as one can argue that companies may falsely report their existing risks in their SEC filings to attract investment. Assessing the risk factors affecting the biofuels industry can help target actions to mitigate those risks.

2. Background on the biofuels industry

Governments worldwide have implemented policies to transition from fossil to biofuels using market-based mechanisms and command-and-control approaches [17]. More than fifty countries have developed biofuel policies and mandates to promote the transition to bioenergy consumption in sectors like transportation, heating, and power [18]. Specifically, several policies and mandates have been formulated and implemented to promote the biofuels industry in the U.S. [12]. For example, the Renewable Fuel Standard (RFS) is a federal program supervised by the U.S. Environmental Protection Agency that requires transportation fuel in the U.S. to contain a minimum volume of biofuel [19]. Although the RFS program has not had the intended impact on the

U.S. biofuels industry, it has nonetheless stimulated its growth and development [12].

The biofuels industry remains a nascent sector that prioritizes research and development activities to address the technical and economic challenges associated with biofuel production. Qiu et al. [6] and Qiu et al. [10] provide technical reviews on the research progress and challenges in improving the quality of bio-oils for biofuel production; economic challenges are discussed in the next section of the manuscript. Still, this industry has undergone some transformation. First-generation biofuels, particularly corn ethanol, were initially produced commercially to mitigate the environmental concerns associated with fossil fuels. Ethanol has been used to support the U.S. fuel industry since the beginning of this century [20]. A collaborative effort from governments and private stakeholders led to a significant upswing in the production of ethanol and other biofuels, marking a pivotal moment in the industry's trajectory. Tyner [21] argued that the ethanol boom during that period resulted from subsidies, biofuel mandates, and policies, as well as the development of efficient conversion technology. However, because regular vehicles could only use fuels with 90 % regular gasoline and 10 % ethanol, the market for ethanol was already saturated by 2012, hitting the upper limit that the U.S. fuel market could consume by producing more than 50 billion liters of corn ethanol [22].

The progress in the biofuel industry was considered a success until debates about food versus fuel started. The first-generation biofuels are extracted by fermentation or esterification of edible crops. For instance, ethanol can be obtained from the fermentation of corn or sugarcane, and the esterification of oilseed crops, such as soybeans or palm oil, generates biodiesel. Therefore, public concerns regarding food insecurity and food price inflation shifted the attention of stakeholders toward second- and third-generation biofuels [23,24]. The second-generation biofuels include bioethanol and biodiesel derived from non-edible feedstocks, specifically lignocellulosic biomass and agricultural waste [5]. Although second-generation biofuels addressed the problems generated by first-generation biofuels, the availability of feedstock and the high operating costs of producing second-generation products remain constraints in this industry. Several studies have documented that feedstock availability, conversion processes, and the financial feasibility of producing second-generation biofuels constrain the development of the biofuels industry [6,10–13,23]. Third-generation biofuels, which can utilize macroalgae and microalgae as feedstocks, are under-development technologies. Specifically, microalgae have been regarded as a promising biofuel feedstock because they can be cultivated in marine and freshwater environments—without competing with arable land—and possess desirable technical attributes, such as a rapid growth rate, high efficiency of photosynthesis, and high lipid content [5]. However, the economic viability of third-generation technology remains a significant question, underscoring the need for further exploration and development [5].

3. Literature review

As a nascent industry, biofuel enterprises are subject to a myriad of uncertainties, with sources of risk including high operating costs coupled with volatile prices, supply chain establishment, technical uncertainties, regulatory approval, political uncertainty, and inconsistent policy, among others [25]. The literature review identified research related to some of these risks, which are discussed next in no particular order.

Efficacy of biofuels policy: Kesan et al. [26] examined the impact of the RFS program on the growth and development of the U.S. ethanol industry, using data from ethanol plants that entered the market after 2000. They found that the program contributed to increasing economies of scale and promoting the competitiveness of firms. Kesan et al.'s findings emphasized the importance of biofuels policy for the viability and growth of biofuel businesses. Naylor and Higgins [27] evaluated the economic and policy factors that promote biodiesel expansion by

¹ Risk metrics measuring firm risk include debt-risk grades by rating agencies such as S&P or Moody's, and corporate risk metrics such as the Z-score. We will discuss the Z-score later in this paper.

analyzing the prospect of biodiesel growth in a scenario of low crude oil prices. They analyzed case studies in major biofuel-producing countries and documented that (1) the expansion of biodiesel in all the major producing countries was a result of explicit policy intervention, (2) vegetable oil prices have rarely been low enough for biodiesel to break even with conventional diesel in the absence of subsidies, and (3) all large biodiesel producing countries used domestic agricultural commodities as the feedstock for biodiesel development. Similarly, Ebadian et al. [28] evaluated the effectiveness of technology-push and market-pull policies in promoting biofuels across 15 major biofuel-producing countries. Technology-push policies promoted early-stage research and development, demonstration, and commercialization of biofuels technology, thereby reducing the financial burden during the initial phase of technology development. In contrast, market-pull policies were designed to support mature technology and stimulate demand for biofuels. The results revealed that biofuel policies are essential for developing and growing the biofuels market. Additionally, they found that countries with a policy mix of market-pull and technology-push instruments were more successful at increasing biofuel production. Brandt et al. [29] developed a set of techno-economic analysis tools to evaluate the impact of federal and state policies on the minimum selling price of SAF produced from various pathways. They found that government policies play a substantial role in the economic feasibility of SAF production, highlighting the importance of a consistent policy environment. In summary, results from previous research suggest that effective biofuel regulation is crucial for the development of this industry. However, Pries et al. [15] documented that U.S. and Canadian biofuel firms perceive biofuel regulation as uncertain and inconsistently implemented. Concerns have also been expressed that policy efforts are more focused on the economic aspects of the biofuel industry rather than on environmental conservation [30].

Environmental and social concerns: The growth of the biofuels industry has prompted environmental and social concerns. Martinelli and Filoso [31] discussed the environmental and social issues associated with the expansion of sugarcane cultivation for biofuel production in Brazil. Given environmental and social concerns, the authors questioned whether sugarcane ethanol could be considered a clean fuel. Environmental issues, including soil degradation, deterioration of aquatic systems, nitrogen pollution, destruction of the riparian ecosystem, and environmental consequences of sugarcane burning, were reported. Similarly, sugarcane burning, respiratory issues, and exploitation of cane cutters were reported as public health and social issues. Searchinger et al. [32] and Mariacaa and Liorb [33] documented similar findings to those of Martinelli and Filoso.

Additionally, biofuel production faces trade-offs between the food and energy markets. First-generation biofuels utilize edible crops that can be used for food products. Specifically, the U.S., a major ethanol producer that contributes 58 % of global ethanol, used nearly 40 % of corn cultivation as ethanol feedstock in 2016 [34]. The biofuels industry's consumption of such a considerable amount of food crops can potentially increase food prices. The effect of the food versus biofuels trade-off on food prices remains unclear, however, because some studies have shown that underlying fossil fuel costs appear to be the primary driver of food costs rather than competition for feedstocks [35,36]. Nevertheless, efforts have been made to encourage the production of second-generation biofuels and gradually replace those produced from food-based crops. In 2015, the European Union decided to cap conventional biofuels at 7 % of total biofuel production to minimize the use of food resources for energy conversion. These types of policies aim to mitigate the negative perception of biofuels by the public [37].

Finance, the economics of biofuels, and feedstock: The transition of biofuel firms from research and development to commercial production is highly contingent upon their ability to attract capital from investors [11]. This need is more compelling for second-generation biofuel enterprises. Investing in a biofuel enterprise poses a high risk for investors due to several factors, including substantial initial capital investment,

the ongoing development of new technologies, price uncertainty, and variations in feedstock composition and availability. Although biofuels policy attempts to incentivize investment, the risk associated with starting a second-generation biofuel production plant is still relatively high. Some existing regulatory and tax incentives for U.S. biofuel firms are Renewable Identification Number pricing, cellulosic waiver credits, state and local-level regulatory incentives, and producer tax credits [11].

McCarty and Sesmero [38] examined the importance of biofuels price risk and the high asset-specificity nature of investment in a cellulosic biofuel plant. Their analysis revealed uncertainty as a significant barrier to investors' entry into the cellulosic biofuels industry. Petter and Tyner [39] examined the impact of biofuel selling price and technical uncertainty on investment risk in a catalytic fast pyrolysis-derived biofuel production facility. They analyzed the effect of uncertainty associated with capital costs, hydrogen prices, biofuel yields, feedstock costs, and biofuel selling prices on the appeal of project investment to a private investor. Similarly, Miller et al. [40] studied the investment risk in the second-generation biofuels industry. The research identified economic, rather than technical, barriers as the significant challenge for the commercial development of cellulosic biofuels. The authors concluded that current policies and market conditions were not sufficiently promising to generate attractive returns, thereby discouraging private investment in the biofuels industry. The research suggested that (1) efficient policy can reduce the risk associated with the second-generation biofuel industry, and (2) revising the existing incentives to reduce risks for private investors could encourage investment and speed up investment decisions.

Extensive research based on techno-economic studies has been conducted to assess the feasibility of various conversion technologies and feedstocks for second-generation biofuel production. A study using three feedstock alternatives—brown grease, yellow grease, and carinata oil—analyzed the feasibility of catalytic hydrothermolysis aviation biofuel technology [41]. The analysis concluded that the venture was not financially viable without Renewable Identification Numbers (RINs) and Low Carbon Fuel Standard credits. Similarly, Mungodla et al. [42] reviewed techno-economic analyses of second-generation biofuels by evaluating the studies based on technology selection, feedstock availability and suitability, process simulation, and economic considerations. The results confirmed that relatively high capital investment, plant operation costs, and feedstock costs increase the likelihood of biofuel operations being unprofitable. Notably, feedstock cost was the most sensitive parameter affecting firm income. Other studies have confirmed that feedstock price constitutes a significant cost to biofuel production. The price uncertainties associated with biofuels are closely related to the price level and price volatility of the feedstocks. These uncertainties are a serious concern to countries like the U.S. and Brazil, which have large shares of biofuels in the energy market [34]. Aui et al. [43] reported similar results to Mungodla et al. [42] from a meta-analysis of several techno-economic analyses for cellulosic ethanol production. The authors concluded that government policies, including financial incentives, biofuel mandates, and assistance programs, are essential for the industry to thrive in the long run. Overall, prior research indicates that the risk of operating an unprofitable biofuel operation is relatively high, with feedstock being a significant source of risk.

Infrastructure: Logistical and socio-economic challenges tend to become significant as the industry matures. A study to address the supply chain challenges in the biofuels industry was conducted by exploring the conceptualization of Regional Biomass Processing Depots (depots) [44]. The authors suggested depots are a means of addressing rural concerns, including rural economics, food security, and social and environmental issues. Establishing depot infrastructure could also address concerns about biorefinery supply, such as the need for homogenous feedstock, stable feedstock prices, low transportation costs, and, in general, economies of scale.

Risk categorization research: A few studies have addressed biofuel

risks across categories. For instance, Uddin et al. [45] distinguished economic policy uncertainty, geopolitical risk, financial distress, and biofuel market volatility when analyzing the ethanol industry in the U.S. and Brazil. In addition, Hargadon [46] evaluated risks by categories, finding that surveyed firms considered, in order of importance, policy uncertainty, market uncertainty, business feasibility, and technical uncertainty as critical to their businesses. Pries et al. [15] studied risks using a more comprehensive categorization based on the PEST and value chain frameworks [16] to separate external and internal risks and, most importantly, identify specific risks within each category. Our study closely follows the methods by Pries et al. [15], which will be discussed in more detail in the next section.

4. Data and methods

4.1. Sample selection

A systematic search was conducted to identify biofuel companies with listed securities on a U.S. exchange market. We utilized the North American Industry Classification System (NAICS), Google Scholar-indexed journal articles, and Standard and Poor's (S&P) as sources to identify biofuel firms. We initially identified 106 firms available under four NAICS codes in S&P COMPUSTAT [47], a financial database of publicly traded firms. This initial list included *potential* biofuel-related firms from various industries.² To identify which companies out of these 106 firms were biofuel firms, we reviewed the business descriptions of these firms (i.e., the variable 'busdesc' in S&P COMPUSTAT) and removed non-biofuel companies. To ensure redundancy and to refine the search, we examined the most recent annual reports filed by these firms with the U.S. SEC. This examination confirmed (e.g., further reduced the preliminary list) which companies were biofuel firms. In most cases, the "Item 1- Business" section of the annual reports disclosed the firm's involvement in biofuel-related activities. A total of 19 companies were identified as biofuel firms after screening their most recent annual reports. Biofuel firms were defined as companies supplying feedstocks for biofuels or involved in the production, logistics, storage, and distribution of biofuels.

In addition, we systematically searched journal articles related to biofuel firms in Google Scholar to identify more biofuel firms besides the 19 already identified. The search used the keywords "biofuel companies," "biofuel firms," and "biofuel industry." To confirm whether the identified companies were involved in the biofuel business, we repeated the screening process by reviewing their business descriptions, as discussed. We identified seven additional biofuel firms. Furthermore, using "quick comparables," a module of S&P NetAdvantage [48], we identified peers of biofuel firms. We repeated the screening process discussed to ensure that a 'peer' was indeed a biofuel firm. Nine additional biofuel firms were identified, bringing the total to 35 after these searches. Our final filter ensured the following requirements for firms included in the sample: (1) firms listed their securities on a U.S. stock exchange and therefore filed a 10K or 20F annual report with the SEC, (2) the firms' annual reports were available in S&P NetAdvantage for five consecutive fiscal years, from 2017 through 2021, and (3) the firms' financial statements were available in S&P COMPUSTAT for the same period. Annual reports served as the source for the identification and coding of risk factors into specific risk metrics (i.e., prevalence and relevance, discussed below). Financial statements were used to calculate firms' overall risk metrics (i.e., the Z-score and debt-to-equity ratio) to validate the specific risk metric relevance. Our final sample consisted of 22

² Due to the lack of NAICS codes for the biofuels industry, we used the following NAICS codes to identify potential biofuel-related companies: 324110 (petroleum refineries), 324199 (all other petroleum and coal products manufacturing), 325193 (ethyl alcohol manufacturing), and 325199 (all other basic organic chemical manufacturing).

biofuel firms with the necessary data for the analysis.³

The sample selection was conducted in late 2022, when it was presumed that all firms had filed their 2021 fiscal year reports [49]. Thus, the sample is likely to contain all biofuel firms with listed securities on a U.S. exchange and the necessary data for the analysis. However, it is possible that we missed some biofuel firms with newly listed securities starting in 2022, and this is one limitation of our study. We do not consider this a severe limitation, as an active flow of firms entering and exiting an immature industry is expected at any point in time. For instance, in 2025, we revised the status of the 22 firms in our sample, finding that three firms had exited the industry or had been acquired. In terms of sample size, previous studies analyzing U.S. publicly traded biofuel firms have included about ten biofuel firms in their samples [11, 50, 51]. Although our sample comprises a larger number of firms, we acknowledge that it remains a relatively small sample, which limits its ability to accurately represent the overall U.S. biofuel industry. Given the high risk associated with biofuel startups, most biofuel enterprises likely operate as private firms, funded by venture capital firms and private equity funds [11]; however, these firms do not disclose their financial information or risk data. We are less concerned with the accuracy of the risk metrics because we coded and analyzed more than 4 thousand risk narratives or observations.

4.2. Data and coding

Data for the analysis were obtained from S&P NetAdvantage [48] and S&P COMPUSTAT [47], accessed through institutional subscriptions. The data for the risk analysis consisted of "risk narrative disclosures," which are management's discussions of risks listed in the "Risk Factors" section of firms' annual reports filed with the SEC and retrieved from S&P NetAdvantage. Firms may discuss their risks in other parts of their annual reports, such as the Management's Discussion & Analysis of Financial Condition and Results of Operations (MD&A) section.⁴ Firms may also discuss their risks during earnings calls, particularly during "investor Q&A sessions," and make the transcripts publicly available. However, firms *systematically* identify and discuss material risks in the "Risk Factors" section of their annual reports, and unlike earnings calls, annual reports are mandatory for publicly traded companies.

We retrieved risk narrative disclosures from the annual reports and coded them using a two-step hierarchical approach, employing a concept-driven methodology. First, broad risk categories were identified using the PEST and value chain framework. PEST categorizes external sources of risk, whereas the value chain categorizes internal sources of risk. Specific risks within risk categories were also coded following Pries et al.'s [15] biofuels risk structure. We used Pries et al.'s 22 risks when coding and added three risks (stock price risk, public perception, and cybersecurity) that biofuel firms in our sample commonly reported. The first column in Appendix A lists the 25 specific risks, and the second column provides an example of risk narrative disclosures or extracts from the "Risk Factors" section of annual reports. We will further

³ List of firms in the sample, with their trading tickers in parenthesis: Adecoagro S.A. (AGRO), Aemetis Inc. (AMTX), Alto Ingredients Inc. (ALTO), Archer-Daniels-Midland Company (ADM), Bunge Limited (BG), Cardinal Ethanol LLC (CRDE), Clean Energy Fuels Corp. (CLNE), Darling Ingredients Inc. (DAR), Delek US Holdings Inc. (DK), Ecopetrol S.A. (EC), FutureFuel Corp. (FF), Gevo Inc. (GEVO), Granite Falls Energy LLC (GFGY), Green Plains Inc. (GPPE), Green Plains Partners LP (GPP), Petróleo Brasileiro S.A. (PBR), Red Trail Energy LLC (REGX), Renewable Energy Group Inc. (REGI), REX American Resources Corporation (REX), Royal Dutch Shell plc (SHEL), The Andersons Inc. (ANDE), Valero Energy Corporation (VLO).

⁴ While firms may discuss risks in the MD&A section of annual reports, this section mainly provides an overall business assessment with emphasis on key performance indicators, results of operations, critical accounting estimates, and, in general, an assessment of the firm's financial statements.

describe the specific risks in the discussion section. We considered the frequency and ranking of these specific risks to calculate risk metrics prevalence and relevance. Additionally, using firm-level financial statement data from S&P COMPUSTAT, we calculated risk metrics, such as the Z-score, which we used to validate the objectivity of firms' risk disclosures.

4.3. Risk metrics

The study employed mainly two risk metrics—prevalence and relevance—to assess the seriousness of risks reported by biofuel firms. These risk metrics were proposed by the Committee of Sponsoring Organizations of the Treadway Commission [52] and employed by Pries et al. [15] to analyze risk in biofuels. (We use the term relevance instead of significance, which is used in the previous references. We preferred 'relevance' to avoid confusion when statistical significance is mentioned in this study.) Prevalence measures the extent to which a risk affects the biofuel industry. It represents the number of firms in the sample that report a particular risk each year, or equivalently, the proportion of firms that report a risk. Prevalence was calculated every year by counting the number of companies reporting a distinct risk. For example, a prevalence score of 20 for "biofuel regulation" risk indicates that, on average, 20 out of the 22 biofuel firms in the sample, or 91 %, reported biofuel regulation as a prevalent risk that year.

Relevance is a more elaborate metric that measures the severity of a risk by considering the frequency with which a risk is reported/discussed by firms in their annual reports, as well as the importance or priority assigned by firms to that particular risk. We calculated the risk metric relevance for a specific risk each year by summing the normalized risk score ranks for that risk and dividing by the risk prevalence (the number of companies in the sample that reported that particular risk). Normalized risk score ranks were calculated following this algorithm.

- (a) We assigned a rank value from 1 to n to the n coded risk narrative disclosures reported by firm i ($i = 1$ to 22) per year t ($t = 1$ to 5), according to the *order* in which each risk was reported/discussed in the company's annual reports. The number of risk disclosures by firm per year (n) varied and was generally different from 25 (the number of specific risks defined in this study, Appendix A, discussed), as some firms may report/discuss a particular risk more than once or not report it at all. For example, in 2021, Aemetis Inc. reported six risk narrative disclosures that were coded as "financing" risk, and the firm reported a total of $n = 57$ risk disclosures.
- (b) We reversed the rankings of risk disclosures (i.e., n re-ranked as 1, $n-1$ as 2, ..., 1 as n) to assign higher values—or more relevance—to the risks firms prioritized. This is because the securities regulator requires companies to report the risk factors in order of priority or seriousness in their annual reports [15,53].
- (c) The reverse rankings were normalized by calculating "normalized risk score ranks" per firm every year. This was done by dividing each reverse rank value by the total sum of reverse ranks. This normalization generated values between 0 and 1 by firm i in year t , preserved the ordering of the risks as assessed and reported by firms, and ensured that each firm contributed with equal weight to the industry-wide measure of risk relevance because the sum of all normalized ranks per company/year is equal to 1.0. These normalized risk score ranks were the primary raw data for the risk metric calculations and analysis.⁵

We employed the median values of prevalence and relevance to discuss risks, risk categories, and overall risk in the biofuels industry. To illustrate the discussion, we plotted these values to construct a matrix

with the industry's overall median of prevalence on the horizontal axis and relevance on the vertical axis. Industry prevalence and relevance medians are the quadrants' borders that help locate where a particular risk stands in the matrix and assess its severity. The risks that are more important to biofuel firms are located in the top-right quadrant, while less critical risks are positioned in the lower-left quadrant. The risks in the lower right quadrant are prevalent but not relevant, and those in the top left quadrant are relevant but not prevalent. We use the term 'critical' to refer to prevalent and relevant risks in the top-right quadrant of the figures to be discussed. Similarly, we refer to the top-right quadrant as the critical quadrant.

Additionally, we conducted equality of medians tests to identify the most critical risks statistically. For each of the 25 risks, we created a binary variable coded with 1 for all observations associated with that particular risk and 0 for the remaining observations. Thus, two groups were created per risk. For instance, for biofuel regulation risk, we had one group with only narrative disclosures coded as 'biofuel regulation' and another group with the remaining observations. Then we tested the null hypothesis of median equality between the two groups for a given risk using quantile regression [54,55]. Specifically, the dependent variable was the risk metric relevance,⁶ and the explanatory variable was the binary variable created for each risk. A positive and statistically significant quantile regression coefficient indicates that the median relevance of that risk is statistically higher than that of all other risks and, therefore, is a critical risk in the biofuels industry. We employed the STATA procedure *qreg* with the option *vce(robust)* for robust standard errors.

4.4. Focused and diversified firms

The biofuel firms were further classified into two categories: focused and diversified. Firms were classified as focused firms if their revenue from biofuels or closely related products exceeded 50 % of their total revenue. Otherwise, they were considered diversified firms. In some cases where firms did not disclose data from biofuel sales, we classified the firm after reviewing its annual reports. We employed a conservative approach during this qualitative classification, classifying firms as diversified if the yearly report lacked sufficient evidence to justify the company as a focused firm. Eleven biofuel companies were focused, and the same number were diversified firms. The prevalence and relevance risk metrics for these groups of firms were calculated following the procedures discussed in the previous section. However, these metrics were calculated separately for each group. Therefore, the scale of these metrics changes, particularly for prevalence, because the sample size changes. The maximum prevalence values are 11 for these groups of firms instead of 22 for the whole biofuels sample.

The diversified firms were also involved in food and agribusiness (Adecoagro SA, Archer-Daniels-Midland Company, Bunge Limited, Darling Ingredients Inc., The Andersons), crude oil business (Royal Dutch Shell plc, Petróleo Brasileiro S.A., Valero Energy Corporation, Delek US holdings, Ecopetrol SA), and biofuel logistics (Green Plains Partners LP). Diversified biofuel firms associated with food and agribusiness were probably looking to integrate agricultural feedstock with biofuels to secure feedstock supply. Similarly, the crude oil-dominant companies may have been involved in the biofuel business to reduce their dependency on other biofuel companies and become self-sufficient in meeting the biofuel blending obligation as required by regulatory agencies.

⁶ Risk prevalence was also examined using quantile regressions, but for the sake of brevity, we only present and discuss relevance.

⁵ These data are available upon request to the authors.

5. Results

5.1. Descriptive statistics

Table 1 presents descriptive statistics on the prevalence and relevance of identified risks for all biofuel firms in the sample from 2017 to 2021. These statistics summarize the 4310 risk narrative disclosures coded and scored. The overall mean and median of prevalence were 13.6 and 14.0, respectively, whereas the mean and median of relevance were 0.58 and 0.50. Our prevalence and relevance estimations in this study were lower than the averages reported by Pries et al. [15] at 14.9 and 0.08, suggesting that the overall risk in the biofuels industry has decreased relative to 2013. This result was expected because risk tends to decline as industries mature. The top five most prevalent risks, those that firms most reported, were risk management, profitable operations, financing, general regulation, and cybersecurity. In terms of relevance, risk management, biofuel markets, profitable operations, financing, and biofuel regulation were the risk factors with the highest relevance medians.

To illustrate how firms ranked risks across categories, Fig. 1 plots the medians of prevalence and relevance by risk category. Primary activities, support activities, economic, and political sources of risk were ranked above or around the median values of the biofuel industry. In contrast, the social and technological risk categories were below the overall medians. Overall, Fig. 1 suggests that firms considered internal factors, classified into primary and support activities, as more relevant than external, macroeconomic PEST factors. This can be explained by the fact that managers are more exposed to day-to-day internal activities than to external factors, which are considered in less frequently conducted strategic management assessments [16]. We also examined descriptive statistics for focused and diversified firms, but for the sake of brevity, we do not tabulate them here. As expected, focused biofuel firms reported biofuel-related risks as more prevalent than diversified biofuel firms. For instance, biofuel regulation was reported by all 11 focused firms, whereas seven out of the 11 diversified firms reported this risk. Furthermore, focused firms considered biofuel regulation more relevant than diversified firms.

5.2. Prevalence and relevance of risks by category

This section primarily discusses the seriousness of risks within each of the six PEST plus value chain categories. In the analysis that follows, we use the median as the main unit for the graphical analysis. Specifically, industry prevalence and relevance medians are the quadrants' borders that help locate where a particular risk stands in the matrix and assess its severity. We also conducted the analysis using mean values instead of medians, obtaining similar conclusions. Additionally, this section discusses the quantile regressions that tested whether the median value of a risk was statistically higher than that of the remaining risks. The regression analysis results complemented our assessment of risks.

5.2.1. Political risks

Fig. 2 plots the political risks for all biofuel firms in the sample, while Appendix B disaggregates those risks for focused and diversified firms. General regulation and biofuel-specific regulation were the risks reported as critical (prevalent and relevant) by all biofuel firms in the sample, with biofuel regulation being the most relevant risk. Biofuel regulation relates to risks such as biofuel blend requirements, tax benefits, subsidies, and incentives for biofuel production. General regulation encompasses risks like laws, regulations, and mandates in general, which could adversely affect the company's operation [15]. Fig. 2 also shows that environmental policy was a critical risk. Environmental risks encompass policies related to greenhouse gas emissions, global warming, and laws and regulations governing worker safety in this industry.

The quantile regression results, presented in Table 2, helped us

identify critical risks. The positive and statistically significant coefficient of biofuel regulation and general regulation indicated that their relevance (median) values were statistically higher when compared with all other risks. Table 2 also shows that environmental risk, located close to the border of the critical quadrant (Fig. 2), was indeed statistically on the border of the critical quadrant. To visualize the critical risks, these are circled in Fig. 2 (and the other Figures in this section). To summarize, a risk was assessed as critical if the risk (1) was located in the critical quadrant based on the overall industry medians, and (2) if its relevance median was statistically equal to or higher than the median of all other risks according to quantile regression. Finally, to a lesser extent, biofuel firms reported international risk (encompassing laws associated with global markets relevant to those firms) as close to being relevant and prevalent, implying that this could be an important risk for firms operating globally.

Panel A of Appendix B, which plots the results for *focused* firms only, highlights that biofuel regulation was even more prevalent and relevant (e.g., the biofuel regulation plot shifted to a right-higher position in the upper right quadrant relative to Fig. 2) for biofuel-focused firms. Furthermore, unlike Fig. 2, Panel A of Appendix B shows that biofuel regulation is the only critical risk reported by focused firms. General regulation was still prevalent, but it was no longer relevant. In contrast, Panel B of Appendix B shows that *diversified* firms reported international, environmental, and general regulation as critical risks, with biofuel regulation being not prevalent. This disaggregation confirmed that focused firms were more concerned about biofuel-specific rather than general risk sources.

5.2.2. Economic risks

Fig. 3 displays the economic risks reported by the biofuel companies over the five years. General economic conditions, biofuel markets, feedstock markets, and competition (to a lesser extent) were considered critical economic risks. As before, the quadrant plots and quantile regression results (Table 2) helped us to assess these risks. General economic conditions include risks such as economic downturns, regional economic volatility, and seasonal fluctuations. The feedstock market risk is related to the production, availability, and pricing of feedstocks. The biofuel market risk, which encompasses uncertainties about demand, supply, and pricing of biofuels, was highly relevant, indicating that this type of risk is particularly important for focused firms, as shown in Panel A of Appendix C. In contrast, Panel B of Appendix C shows that diversified firms reported general economic conditions, rather than biofuel-specific risks, as the most critical risk. Overall, feedstock inputs for producing biofuels and the biofuels themselves were critical biofuel-specific risk factors in the biofuels industry. Finally, risk related to firm competition was consistently reported as prevalent by most firms, but was considered critical only for diversified firms.

5.2.3. Social risks

Fig. 4 provides social risks reported by all biofuel firms. Public perception and opposition were reported as not critical for biofuel firms. Public perception encompasses risks such as consumer perception of biofuels and reluctance to use them. Public opposition is related to risks such as social movements against biofuel firms or biofuel policies, as well as debates about the trade-off between food and biofuels. Disaggregated results from focused and diversified firms are presented in Appendix D. While social risks were more prevalent among focused firms than among diversified ones, they are not ranked as critical by these biofuel firms.

5.2.4. Technological risk

Fig. 5 displays the technological risks. Cybersecurity was the only prevalent risk in this category. However, cybersecurity risk was not relevant for this sample of firms (i.e., its relevance was statistically lower than that of the industry, as indicated by the quantile regression results in Table 2). Cybersecurity includes risks such as security breaches,

Table 1
Prevalence and relevance scores of risks reported by biofuel firms from 2017 to 2021.

Risks by categories	N	Prevalence				Relevance			
		Mean	Median	Min	Max	Mean	Median	Min	Max
Political:									
Biofuel regulation	251	16.0	17.0	15.0	19.0	0.077	0.078	0.075	0.079
Environmental	150	16.0	16.0	15.0	17.0	0.048	0.047	0.044	0.052
Infrastructure	70	10.4	10.0	8.0	12.0	0.039	0.038	0.036	0.044
International	189	12.9	13.0	11.0	14.0	0.054	0.052	0.044	0.063
General regulations	399	18.9	19.0	17.0	20.0	0.063	0.067	0.050	0.071
Economic:									
Feedstock markets	104	14.4	14.0	13.0	16.0	0.070	0.069	0.064	0.078
Biofuel markets	158	12.4	12.0	11.0	14.0	0.110	0.112	0.080	0.140
Competing fuel markets	81	12.7	12.0	11.0	14.0	0.050	0.051	0.038	0.059
Energy markets	33	6.3	6.0	6.0	7.0	0.051	0.050	0.035	0.063
Competition	133	17.4	17.0	16.0	19.0	0.050	0.047	0.046	0.056
Gral. econ. conditions	182	17.5	17.0	16.0	20.0	0.075	0.075	0.073	0.077
Stock price risk	317	13.8	14.0	13.0	14.0	0.028	0.029	0.020	0.036
Social:									
Public opposition	39	6.1	6.0	5.0	7.0	0.025	0.025	0.023	0.028
Public perception	73	10.4	10.0	9.0	12.0	0.038	0.038	0.035	0.041
Technological:									
Conversion technology	94	11.4	11.0	11.0	12.0	0.043	0.044	0.040	0.045
Fuel compatibility	6	1.7	2.0	1.0	2.0	0.027	0.032	0.015	0.033
Intellectual property	73	6.4	6.0	6.0	7.0	0.026	0.025	0.022	0.031
Cybersecurity	134	19.0	19.0	14.0	21.0	0.036	0.037	0.030	0.039
Primary Activities:									
Facilities development	83	10.1	10.0	9.0	11.0	0.053	0.052	0.040	0.065
Profitable operations	300	19.8	20.0	18.0	22.0	0.099	0.101	0.087	0.112
Support Activities:									
General management	178	16.6	17.0	16.0	17.0	0.042	0.042	0.041	0.044
Risk management	578	20.9	21.0	20.0	22.0	0.145	0.144	0.136	0.154
Financing	297	20.3	20.0	19.0	21.0	0.088	0.096	0.068	0.099
Contracting	288	18.6	18.0	17.0	20.0	0.079	0.076	0.068	0.091
M&A	100	12.8	13.0	12.0	13.0	0.034	0.035	0.030	0.038
Totals	4310	13.6	14.0	1.0	22.0	0.058	0.050	0.015	0.154

Note: N refers to the number of coded risk narrative disclosures.

interruption of information systems, loss of company information, and data theft. Conversion technology was interesting because it fell statistically on the border of the industry median average (Table 2). Additionally, conversion technology posed, by far, a greater risk for focused biofuel firms, as illustrated in Appendix E. For this reason, we ranked conversion technology as a critical risk for biofuels in Fig. 5. Conversion technologies relate to uncertainties associated with rapid changes in conversion technology (i.e., feedstock-to-fuel conversion).⁷

Overall, the PEST-related results in the biofuel industry revealed critical risks across the political, economic, and technological categories. Specifically, biofuel regulation, biofuel markets, feedstock markets, and conversion technologies were identified as critical sources of risk, particularly for focused biofuel firms. To a lesser extent, environmental risk was also a concern for biofuel firms. As expected, focused companies were more susceptible to risks directly related to biofuels. In contrast, diversified companies are more vulnerable to general risks. The PEST risks are external to firms. Internal risks are discussed next.

5.2.5. Primary activity risks

Fig. 6 shows the primary activity risks reported by all biofuel firms. Risk related to having a profitable operation was reported as critical. As discussed in the descriptive statistics section, profitable operation risk was ranked as highly relevant and reported by 20 out of the 22 biofuel firms. Facilities development, related to uncertainties arising from biofuel firms' facilities construction and setup, was reported as being close

⁷ Fuel compatibility and intellectual property risks were in the lower left quadrant, indicating they were irrelevant. Fuel compatibility has risks related to blending and the feasibility of using biofuels as drop-in fuels. Intellectual property includes risks like the inability to protect intellectual property rights or patents.

to relevant. Results disaggregated for focused and diversified firms were similar to those for all firms, as shown in Appendix F.

5.2.6. Support activity risks

Finally, Fig. 7 illustrates the risk factors associated with firms' support activities. Biofuel companies identified risk management, financing, and contracting as critical sources of risk. Notably, risk management was reported as highly relevant and prevalent. This risk is associated with uncertainties, including foreign currency exchange fluctuations, natural disasters, and pandemics. Financing risk involves challenges in obtaining funds to operate the facilities and uncertainties related to financial arrangements. Contracting risk includes uncertainties associated with long-term contracts or agreements with partners and subsidiaries. General management risk, related to key employees and general managerial issues, was prevalent but not relevant. Similar to primary activities, the risks associated with support activities, disaggregated for focused and diversified firms, were comparable to those for all firms, as shown in Appendix G.

5.3. Validating risk relevance

One can argue that companies may falsely report their existing risks to attract investment. Therefore, to validate the objectivity of the firms' risk disclosures analyzed in the previous section, and as a robustness procedure, we incorporated additional external risk data in the analysis. Specifically, using firm-level financial statement data available in S&P COMPUSTAT, we calculated the Z-score, a risk-related index widely used to predict the likelihood of a firm's bankruptcy [56]. The Z-score combines financial ratios measuring a firm's working capital efficiency,

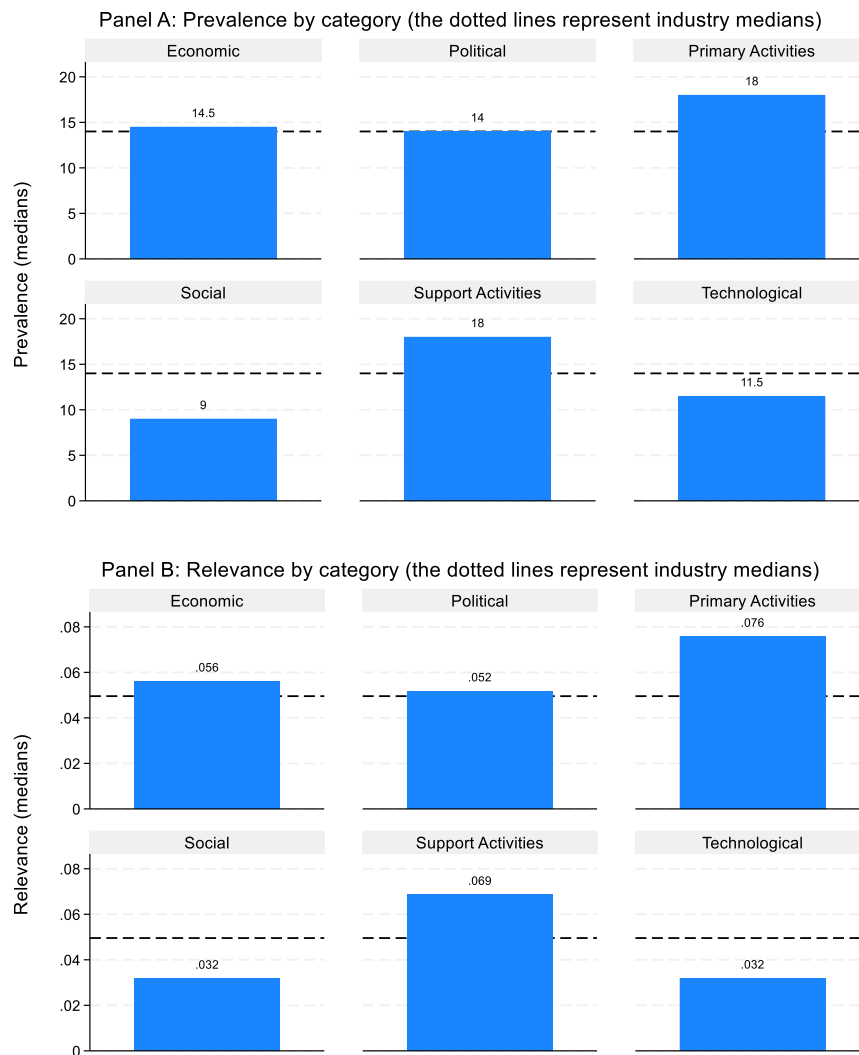


Fig. 1. Prevalence and relevance by risk category for biofuel firms over 2017–2021. Note: The medians of prevalence and relevance are the values provided in Table 1.

capitalization, earnings power, leverage, and margin.⁸ The calculated firm-year Z-scores were categorized into three risk levels: Z-scores higher than 2.99 were recoded as 1, indicating low risk; Z-scores between 1.81 and 2.99 were coded as 2, suggesting medium risk; and Z-scores lower than 1.81 were coded as 3, indicating high risk. These are the cut-offs reported by Altman [56] to indicate the ‘safe zone,’ ‘grey zone,’ and ‘financial distress zone’ leading to bankruptcy. In addition, we calculated the debt-to-equity ratio, which measures financial risk [57,58]. A positive correlation between the Z-score categories and/or debt-to-equity with our risk prevalence metric would validate that risk prevalence indeed captures a firm’s risk, with one caveat: the Z-score and debt-to-equity values proxy overall firm risk, whereas risk prevalence measures *specific* risks (25 risks identified in this study). Therefore, we did not expect strong correlations between the prevalence and these overall risk measures, nor did we expect all specific risks to correlate with the overall risk measures, given that the analysis in the previous

section showed that only a few risks reported by firms were ranked as critical.

Table 3 presents the pairwise Pearson correlation coefficients between the Z-score categories and risk prevalence, as well as between debt-to-equity and risk prevalence. The results confirmed that biofuel regulation, general regulation, biofuel markets, profitable operations, and financing risks are positively correlated at the 5 % level of significance with Z-score categories and/or debt-to-equity ratios. These results are encouraging, given that these risks were assessed as critical according to the analysis in the previous section. Table 3 also shows that some risks are negatively correlated with Z-score categories and debt-to-equity ratios. Negative correlations are counterintuitive, but they may occur, for instance, if highly risky firms rank or report some risk factors as low-relevant. Notably, this is the case of the negative correlation of ‘facilities development’ in Table 3. Generally, as a firm’s overall risk increases in a particular year, it may identify a specific risk (e.g., biofuel regulation) as more relevant and consequently reduce the relevance of other risks (e.g., contracting) because risk relevance is a measure relative to other risk factors. Therefore, identifying and valuing specific risks, as done in this study, provides additional insight into risk analysis beyond focusing solely on overall firm risk measures.

⁸ Specifically, the Z-score is calculated by: $Z = 1.2 \times X_1 + 1.4 \times X_2 + 3.3 \times X_3 + 0.6 \times X_4 + 0.999 \times X_5$, where $X_1 = (\text{current assets} - \text{current liabilities})/\text{assets}$, $X_2 = \text{retained earnings}/\text{assets}$, $X_3 = \text{operating income}/\text{assets}$, $X_4 = \text{the market value of equity}/\text{debt}$, and $X_5 = \text{revenue}/\text{assets}$.

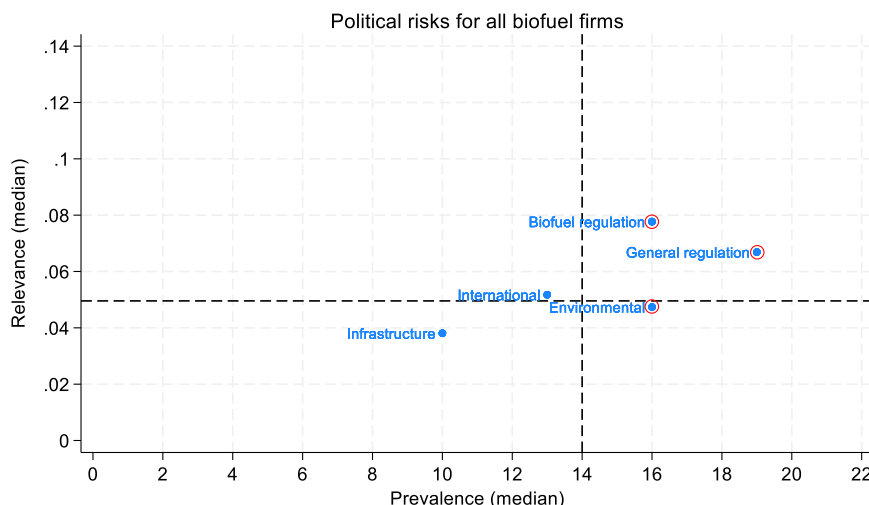


Fig. 2. Political risks for biofuel firms over 2017–2021.

Note: A circled risk, if any, was considered a critical risk. A risk was assessed as critical if the risk (1) was located in the critical quadrant based on the overall industry medians, and (2) if its relevance median was statistically equal to or higher than the median of all other risks according to quantile regression (results in Table 2).

Table 2

Equality in median tests through quantile regressions for risk relevance of biofuel firms from 2017 to 2021.

	Risk relevance (medians)		Q reg coeff.
	In the group	Not in the group	
Political:			
Biofuel regulation	0.0777	0.0474	0.0303***
Environmental	0.0474	0.0493	-0.002
Infrastructure	0.0381	0.0503	-0.0122***
International	0.0517	0.0490	0.003
General regulations	0.0669	0.0474	0.0195**
Economic:			
Feedstock markets	0.0694	0.0474	0.022***
Biofuel markets	0.1117	0.0474	0.0644***
Competing fuel markets	0.0514	0.0490	0.002
Energy markets	0.0496	0.0475	0.002
Competition	0.0475	0.0493	-0.002
Gral. econ. conditions	0.0753	0.0474	0.028***
Stock price	0.0291	0.0503	-0.0212***
Social:			
Public opposition	0.0250	0.0503	-0.0253***
Public perception	0.0375	0.0503	-0.0128***
Technological:			
Conversion technology	0.0442	0.0503	-0.006
Fuel compatibility	0.0315	0.0503	-0.0188*
Intellectual property	0.0246	0.0503	-0.0257***
Cybersecurity	0.0369	0.0503	-0.0134***
Primary Activities:			
Facilities development	0.0519	0.0475	0.004
Profitable operations	0.1010	0.0474	0.0536***
Support Activities:			
General management	0.0421	0.0503	-0.0082**
Risk management	0.1438	0.0474	0.0964***
Financing	0.0957	0.0474	0.0483***
Contracting	0.0759	0.0474	0.0286**
M&A	0.0345	0.0503	-0.0158***

Note: Quantile regressions were used to test the null hypothesis of median equality between two groups for a given risk. We created a binary variable with 1s for observations associated with that particular risk (column ‘in the group’) and 0s for the remaining observations. The dependent variable for the regression was the risk metric relevance, and the explanatory variable was the binary variable created for each risk.

6. Discussion and conclusion

6.1. Political risks

This study found that general and biofuel-specific regulations were critical risk factors. As expected, biofuel regulation was more critical for focused biofuel firms with listed securities in U.S. exchange markets. This result is consistent with Pries et al. [15], who found that biofuel regulation was the only prevalent and relevant political risk reported by a sample of 26 U.S. and Canadian biofuel companies (Pries et al. did not disaggregate their results by firm type, however). Živković et al. [59] also addressed the governments’ inconsistent biofuel policies as a relevant problem in both the short and long term for the growth of the global biofuel industry. Similarly, White et al. [60] reported policy inconsistency as a challenge for the renewable energy sector. They noted that large, unexpected policy changes hurt investment in biofuel firms in Canada and Norway. Therefore, our findings regarding the importance of biofuel regulation align with prior research and underscore the need for consistently implemented policies to attract investment in this sector. Well-designed and consistent policies can make high-cost biofuels competitive in the fuel market through economic incentives, including subsidies, tariffs, and tax incentives. Additionally, we found that, to a lesser extent, environmental risk is a critical risk factor for biofuel firms. Van der Horst and Vermeylen [61] argue that biofuel policies are narrowly defined to address energy security and the economics of biofuels rather than environmental and social concerns. Our results suggest that policymakers should also prioritize environmental, health, and safety issues, as they are potential concerns for biofuel firms.

6.2. Economic risks

Investors prefer to operate in economically favorable and stable industries [62]. Thus, identifying economic risks is the first step in mitigating those risks and making sectors attractive for investment. This study found that the biofuel market, the feedstocks market, and, to a lesser extent, market competition, are critical risk factors, particularly for focused biofuel firms. Our results differ from Pries et al. [15], who identified the feedstocks market as the only critical risk. Our findings are consistent with the fact that, despite several policies, mandates, tax exemptions, and tax credits favoring investors in the biofuel industry, market price risk for feedstocks and biofuel products remains a problem

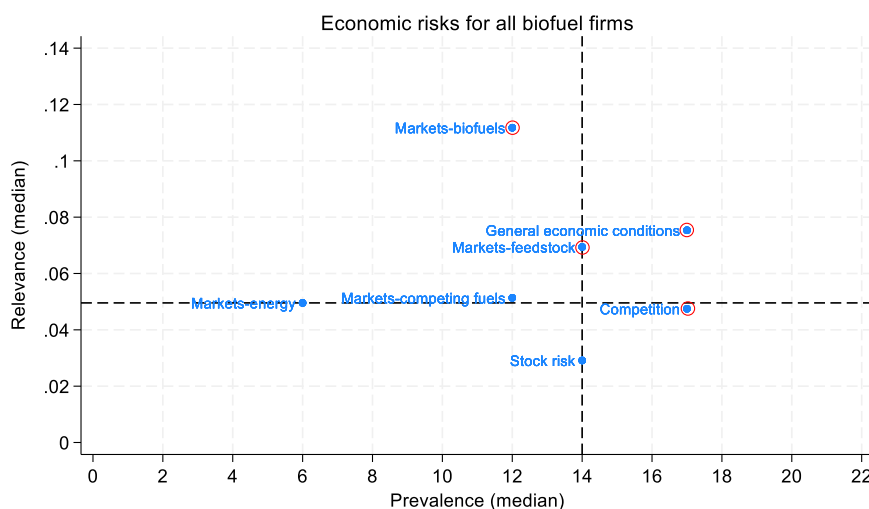


Fig. 3. Economic risks for biofuel firms over 2017-2021

Note: A circled risk, if any, was considered a critical risk. A risk was assessed as critical if the risk (1) was located in the critical quadrant based on the overall industry medians, and (2) if its relevance median was statistically equal to or higher than the median of all other risks according to quantile regression (results in Table 2).

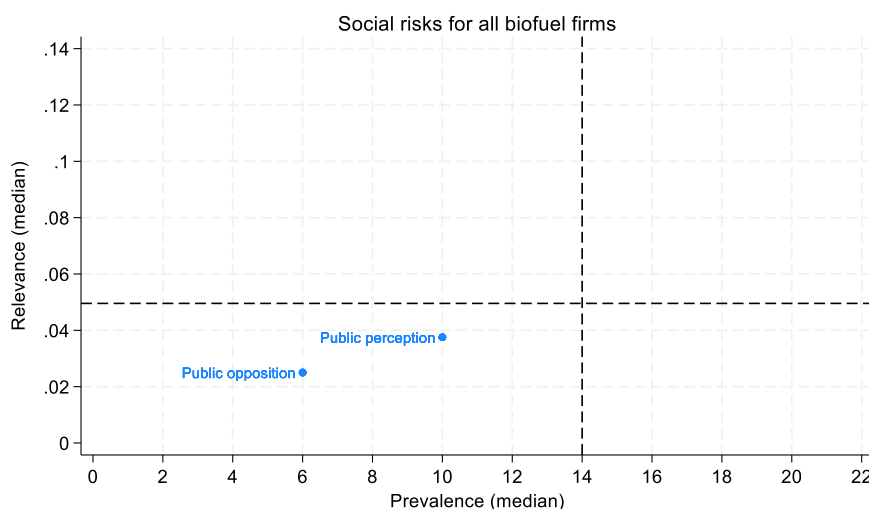


Fig. 4. Social risks for biofuel firms over 2017-2021

Note: A circled risk, if any, was considered a critical risk. A risk was assessed as critical if the risk (1) was located in the critical quadrant based on the overall industry medians, and (2) if its relevance median was statistically equal to or higher than the median of all other risks according to quantile regression (results in Table 2).

in this sector [63]. Price risk is particularly important, but not exclusive, for second and third-generation biofuels, for which the high cost of production and uncertain feedstock supply are often cited as risks affecting firm profitability [5,59].

6.3. Technological risks

Our study found that conversion technology represented the only critical risk factor, particularly for focused biofuel firms. Pries et al. [15] reported that technological risks were of minor importance, as no risk factor was ranked as critical in their study. Based on the analysis of a survey of 35 U.S. low-carbon innovative firms, Hargadon [46] also reported technological risks to be of minor importance where risk categories, ranked in order of importance, were policy uncertainty, market uncertainty, business feasibility, and technical uncertainty. Our findings confirm that, relative to political and economic risks, technological risk

is less critical; however, conversion technology is a concern for focused biofuel firms. This result is significant because conversion technology risk may become even more crucial as the industry transitions to second and third-generation biofuels.

6.4. Social risks

This study found that social risks, such as public perception and opposition towards biofuel, were not critical risk factors, consistent with Pries et al. [15]. This finding is also consistent with research on the food versus fuel debate, which affects social perception and opposition. Specifically, based on a survey of U.S. experts on the U.S. biorefinery supply chain, Chen and Smith [64] analyzed the drivers and constraints to scaling up the U.S. cellulosic biofuel industry. They concluded that the food vs. fuel debate ranked as the least important driver, after government policies, added value from non-fuel co-products, carbon

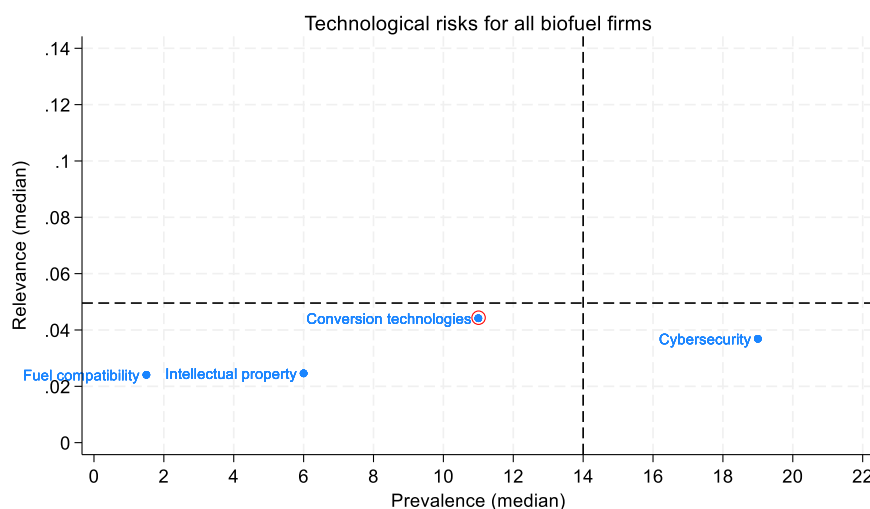


Fig. 5. Technological risks for biofuel firms over 2017-2021

Note: A circled risk, if any, was considered a critical risk. A risk was assessed as critical if the risk (1) was located in the critical quadrant based on the overall industry medians, and (2) if its relevance median was statistically equal to or higher than the median of all other risks according to quantile regression (results in Table 2).

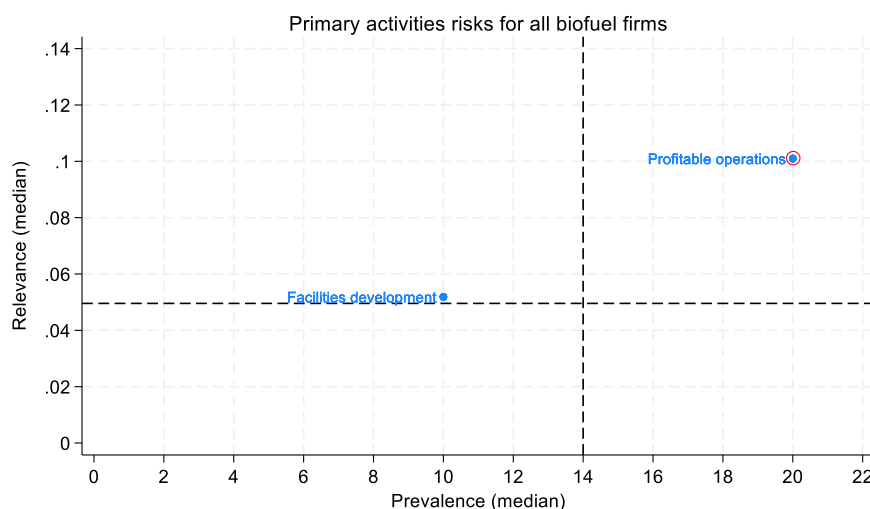


Fig. 6. Primary activity risks for biofuel firms over 2017-2021

Note: A circled risk, if any, was considered a critical risk. A risk was assessed as critical if the risk (1) was located in the critical quadrant based on the overall industry medians, and (2) if its relevance median was statistically equal to or higher than the median of all other risks according to quantile regression (results in Table 2).

emission reduction, volatile oil prices, dependence on fossil fuels, and rural economic development. While some studies suggest that biofuels pose a major threat to farmers due to the change in land-use patterns for biofuel production [3], firms and industry experts appear not to perceive public perception and opposition to biofuels as a critical risk. Furthermore, the social impact of biofuel products and consumption in developed countries is relatively low compared to that in developing countries, which have established large-scale, export-oriented production systems that are more likely to impact communities [65]. While the previous study supports our findings because most companies in this study operate mainly in the U.S., the study is outdated. Recently, most countries in the world (either developing or developed countries) focusing on biofuels industry development have discouraged using food crops as the primary feedstock. Thus, public awareness of feedstock usage for biofuel has become more widespread, rather than being limited to the developed countries alone.

6.5. Primary and support activity risks

Regarding primary activities risk, almost all biofuel firms in this study reported the risk of having an unprofitable operation as critical, as in Pries et al. [15]. This suggests that despite several subsidy programs, tax credits, and economic incentives, biofuel enterprises, on average, have not been profitable enough for investors. The relatively high costs of current technology for feedstock cultivation and conversion to biofuel hinder profitability, making biofuels noncompetitive compared to fossil fuels, as has been widely documented. To address the low profitability of biofuels, previous studies have suggested focusing research efforts on developing alternative non-food second-generation feedstocks (less costly), efficient conversion technologies, and furthering the exploration of third-generation biofuels [5,6,10,59].

This study found that support activities related to risk management, financing, and contracting were critical risks. Unlike Pries et al. [15],

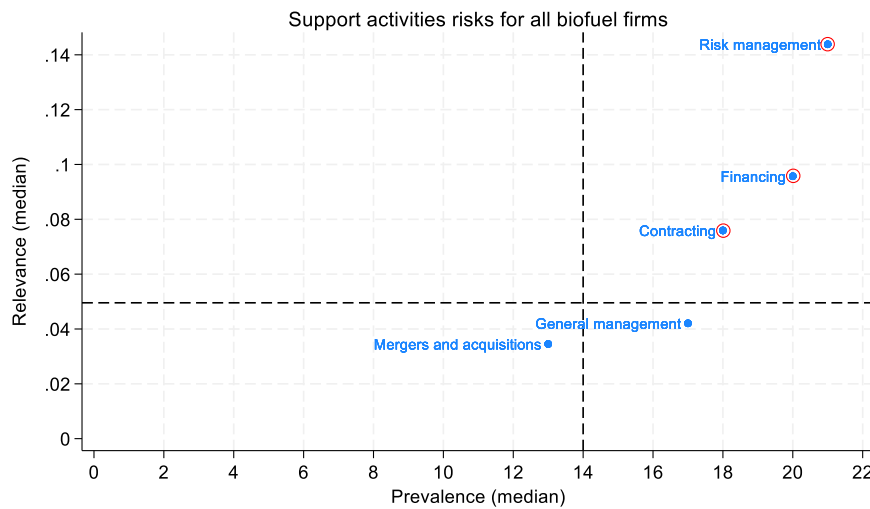


Fig. 7. Support activity risks for biofuel firms over 2017-2021

Note: A circled risk, if any, was considered a critical risk. A risk was assessed as critical if the risk (1) was located in the critical quadrant based on the overall industry medians, and (2) if its relevance median was statistically equal to or higher than the median of all other risks according to quantile regression (results in Table 2).

Table 3
Correlations of selected risk and profit metrics and risk prevalence.

	Z-scores	Leverage
Biofuel regulation	0.1495*	0.0552
Environmental	-0.127	-0.0398
Infrastructure	-0.047	-0.0913
International	-0.2170*	-0.0569
General regulations	0.0349	0.0832*
Feedstock markets	-0.0097	0.0768
Biofuel markets	0.1657*	0.0858
Competing fuel markets	0.0735	0.091
Energy markets	-0.0959	0.0167
Competition	0.0301	0.0588
Gral. econ. conditions	-0.0489	-0.0902
Stock price	-0.1957*	-0.1514*
Public opposition	-0.0844	0.1362
Public perception	0.0062	0.0452
Conversion technology	-0.0214	-0.0137
Fuel compatibility	NA	NA
Intellectual property	0.1249	-0.0067
Cybersecurity	0.0031	-0.0653
Facilities development	-0.2324*	-0.2255*
Profitable operations	0.1887*	0.1712*
General management	0.0873	0.0652
Risk management	-0.1067*	-0.0659
Financing	0.1702*	0.1491*
Contracting	-0.1478*	-0.1291*
M&A	-0.0735	-0.0088

Pairwise Pearson correlation coefficients, with an asterisk indicating statistical significance at 5 %. NA indicates that, because of the small number of observations for that particular risk, the correlations could not be calculated. Z-scores refer to three Z-score categories, as defined in the “validating risk relevance” section. Leverage is the debt-to-equity ratio.

our study found that general management is not a critical risk factor for biofuel firms, implying that management expertise has improved over the last decade. This is plausible, as specific industry knowledge tends to accumulate over time in the nascent biofuels industry. Regarding financing, Miller et al. [40] argue that the success of second-generation biofuel firms in the U.S. depends significantly on external and high-risk funding, as these firms are relatively new to the market. In contrast, highly profitable firms in mature industries, with internally accumulated funds, do not rely much on external financing [66].

One challenge to a profitable biofuel business is the inability of

biofuel firms to obtain cost-effective feedstocks in the proper quantity and quality. Bijman et al. [67] identified contract farming as an option for reducing transaction costs and transaction risks for the supply chain of jatropha, an emerging biofuel crop in Mozambique’s biofuel industry. A similar assertion by Yang et al. [68] is that long-term contracts with farmers are essential to establishing perennial energy crops as feedstocks for the cellulosic biofuel industry. Vertical integration and contracts with independent farmers are risk mitigation mechanisms resulting from risk-sharing in production and marketing, technological progress and innovation dissemination, consumer demand for a quality product, and access to capital [69]. Such marketing schemes may become more prevalent in this industry as firms work to mitigate contract risk. Finally, risk management, the most significant and prevalent risk within this category, appears to be a broad category encompassing firms’ efforts to address the relatively high risks associated with biofuels.

6.6. Final remarks

This study analyzed the risks disclosed by a sample of biofuel firms that listed their securities on U.S. exchange markets. The study primarily evaluated two risk metrics—prevalence and relevance—across 25 specific risks (or risk factors) over a five-year period. Risk relevance, the most comprehensive metric, was validated by comparing it with other widely used—but measuring overall firm risk rather than specific risks—risk metrics. The analysis was conducted for all firms in the sample, as well as for subsets of focused and diversified biofuel firms. Identification of risk metrics by quadrants, combined with quantile regression analysis, allowed us to identify the critical risks. The critical risks, particularly for focused biofuel firms, were biofuel regulation, biofuel markets, feedstock markets, conversion technologies, profitable operations, financing, and risk management. To a lesser extent, environmental and contracting risks were critical.

To address critical risk factors, collaborative efforts could be made among government stakeholders, industry stakeholders, and researchers to establish stable and long-term policies that mitigate the identified critical risks. Successful enterprise cooperation requires a coordinated effort. Policymakers may propose programs that require stakeholders to collaborate to receive subsidies. One example of such programs is the Biomass Crop Assistance Program (BCAP) issued by the US Department of Agriculture (USDA). The USDA requires feedstock producers and biorefineries to reach an agreement on the production and purchase of

feedstock for biofuel production to receive BCAP payments. Such a mechanism can mitigate the potential challenges of cooperation, reduce the risk, and foster industry development. Research institutions may increase their efforts on biofuels conversion technologies and feedstocks, as the outcomes are likely to be well-received by the industry. Moreover, financing institutions should find creative schemes to fund and share risks with biofuel enterprises. Overall, findings in this study can provide a basis for developing policies to mitigate risks and expedite the scaling of the biofuel industry.

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Appendix

Appendix A. Risks by categories disclosed by selected biofuel firms

Risk factors	Examples of risk narrative disclosures from annual reports
<i>Political</i>	
Biofuel regulation	"A change in government policies may cause a decline in the demand for our products."
Environmental, health, and safety	"Concerns regarding the environmental impact of biofuel production could affect public policy which could impair our ability to operate at a profit and substantially harm our revenues and operating margins."
International	"A substantial portion of our assets and operations are located in India, and we are subject to regulatory, economic, and political uncertainties in India."
Infrastructure	"Our success depends on our ability to manage the growth of our operations."
General regulations	"We could be adversely affected by violations of the U.S. Foreign Corrupt Practices Act."
<i>Economic</i>	
Markets-feedstock	"Fluctuations in the price of corn and other feedstocks may affect our cost structure."
Markets-biofuels	"Increased alcohol or essential ingredient production or higher inventory levels may cause a decline in prices for those products, and may have other negative effects, adversely impacting our results of operations, cash flows and financial condition."
Markets-competing fuels	"Fluctuations in petroleum prices and customer demand patterns may reduce demand for renewable fuels and bio-based chemicals."
Markets-energy	"Fluctuations in the price and availability of energy to power our production facilities may harm our performance."
Competition	"The industries in which we operate are extremely competitive. Many of our significant competitors have greater production and financial resources and could use their greater resources to gain market share at our expense."
General economic conditions	"There is no public market for our units and no public market is expected to develop."
Stock price	"Our quarterly operating results may fluctuate in the future. As a result, we may fail to meet or exceed the expectations of investment research analysts or investors, which could cause our stock price to decline."
<i>Social</i>	
Public opposition	"Consumer resistance to the use of ethanol-based on the belief that ethanol is expensive, adds to air pollution, harms engines and/or takes more energy to produce than it contributes may affect the demand for ethanol."
Public perception	"Public perception, consumer acceptance and overall consumer demand for transportation fuel, any of which could negatively affect demand for fuel-grade ethanol and our results of operations."
<i>Technological</i>	
Conversion technology	"We may not be able to successfully develop and commercialize our technologies, which may require us to curtail or cease our research and development activities."
Fuel compatibility	"Demand for ethanol may not grow unless ethanol can be blended into gasoline in higher percentage blends for conventional automobiles."
Intellectual property	"We may be unable to protect our intellectual property."
Cybersecurity	"Our information technology systems, processes, and sites may suffer interruptions, security breaches or failures that may adversely affect our ability to conduct our business."
<i>Primary Activities</i>	
Facilities development	"We may not be able to recover the costs of our substantial investments in capital improvements and additions, and the actual cost of such improvements and additions may be significantly higher than we anticipate."
Profitable operations	"We are currently not profitable and historically, we have incurred significant losses. If we incur continued losses, we may have to curtail our operations, which may prevent us from successfully operating and expanding our business."
<i>Support Activities</i>	
General management	"Our Chief Executive Officer has outside business interests that could require time and attention."
Risk management	"We may be subject to liabilities and losses that may not be covered by insurance."
Financing	"Our business is dependent on external financing and cash from operations to service debt and provide future growth."
Contracting	"We have entered into agriculture partnership agreements in respect of a significant portion of our sugarcane plantations."
Mergers and acquisitions	"Our mergers, acquisitions, partnerships, and joint ventures may not be as beneficial as we anticipate."

Fund.

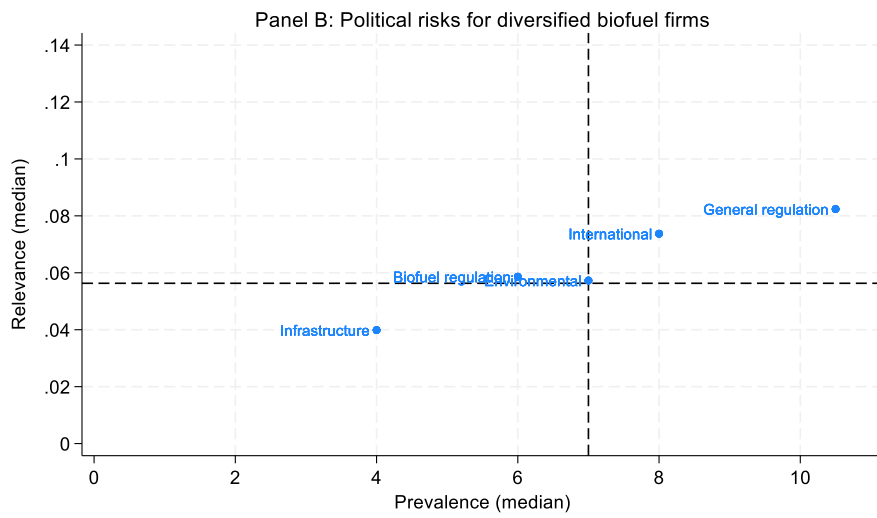
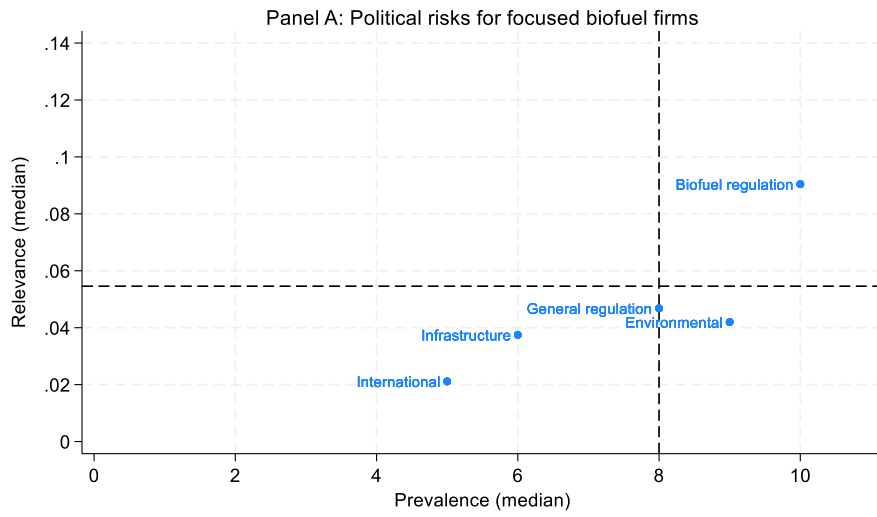
Credit author statement

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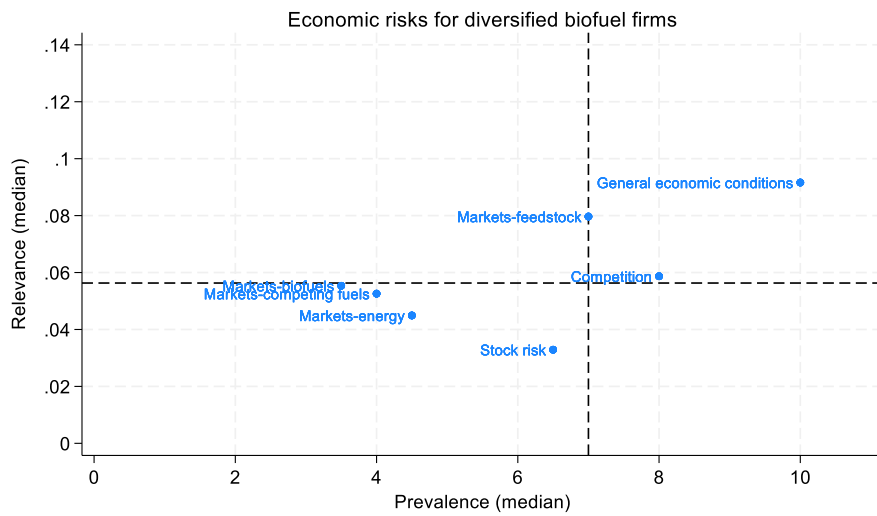
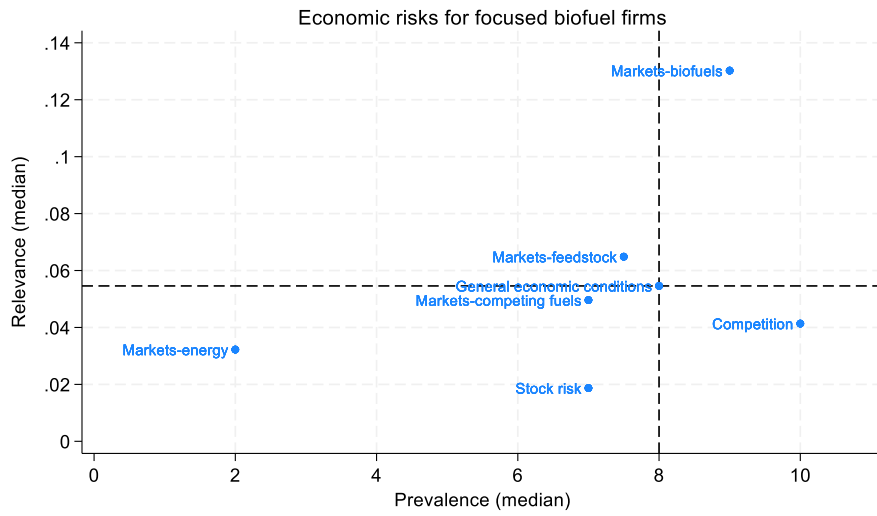
Declaration of competing interest

The authors declare that the research was conducted without any commercial or financial relationships that could potentially create a conflict of interest.

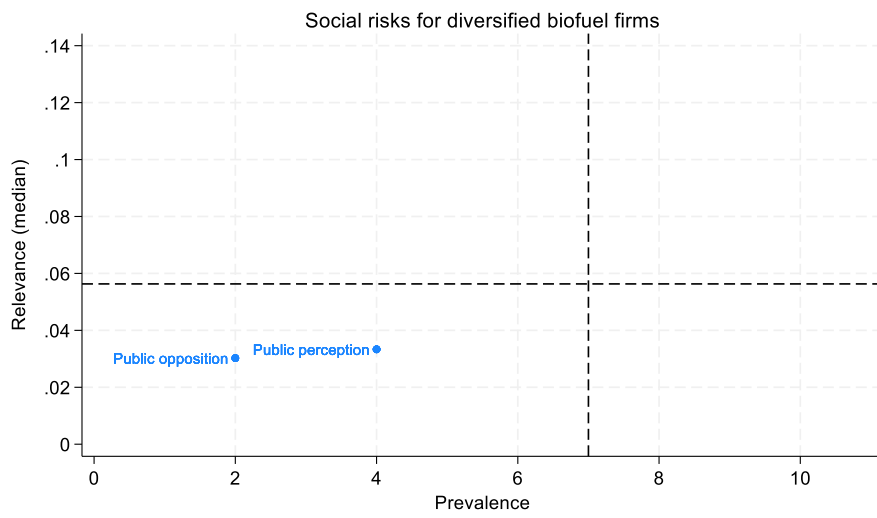
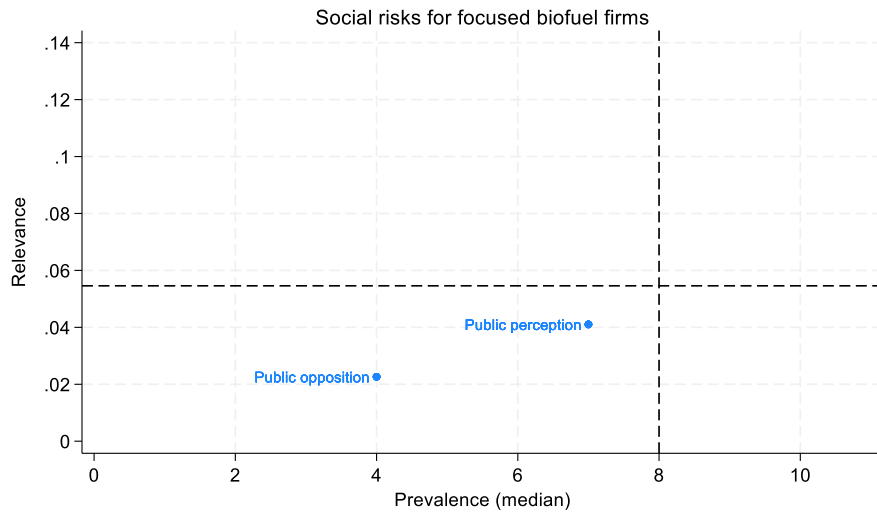
Appendix B: Political risks for focused and diversified biofuel firms over 2017–2021



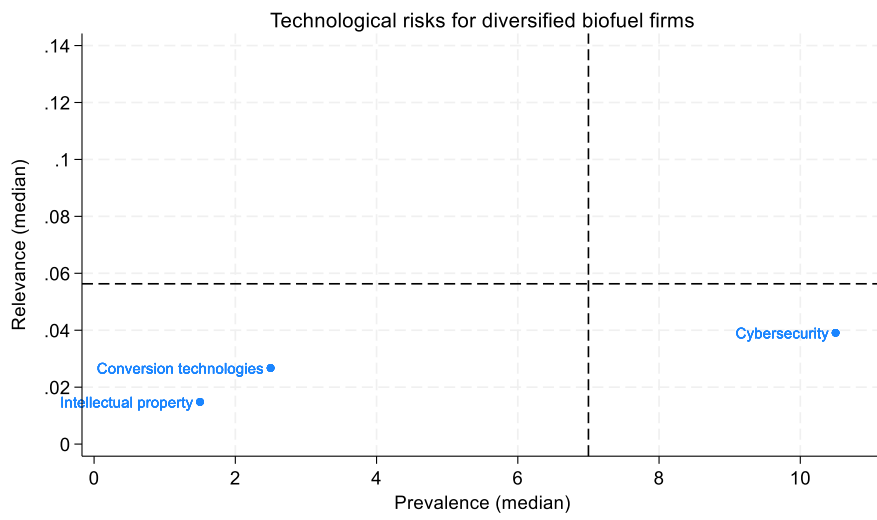
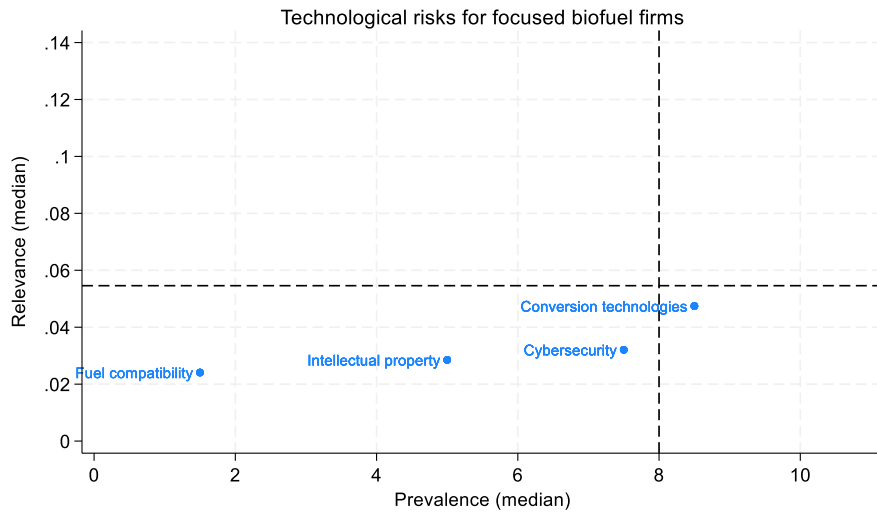
Appendix C: Economic risks for focused and diversified biofuel firms over 2017–2021



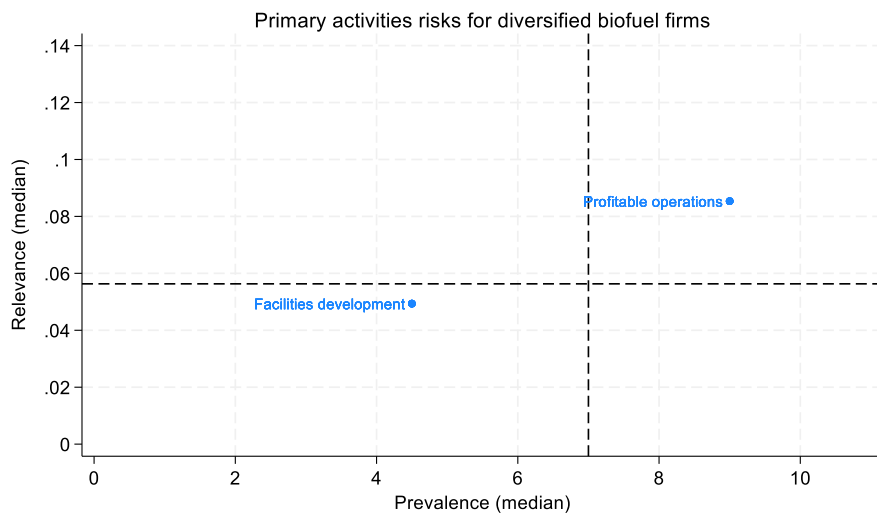
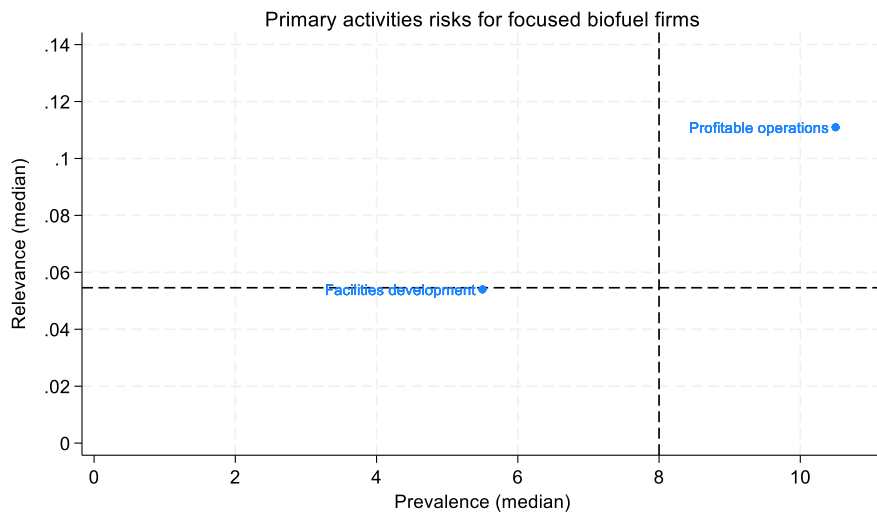
Appendix D: Social risks for focused and diversified biofuel firms over 2017–2021



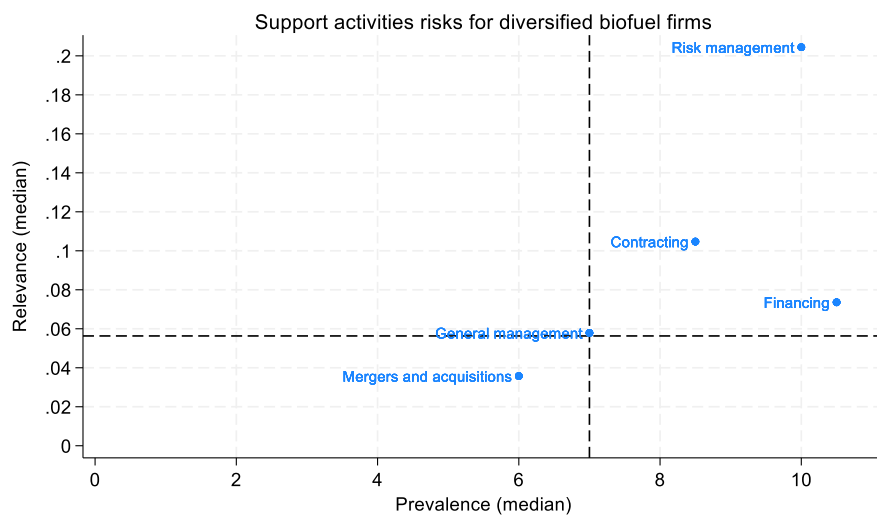
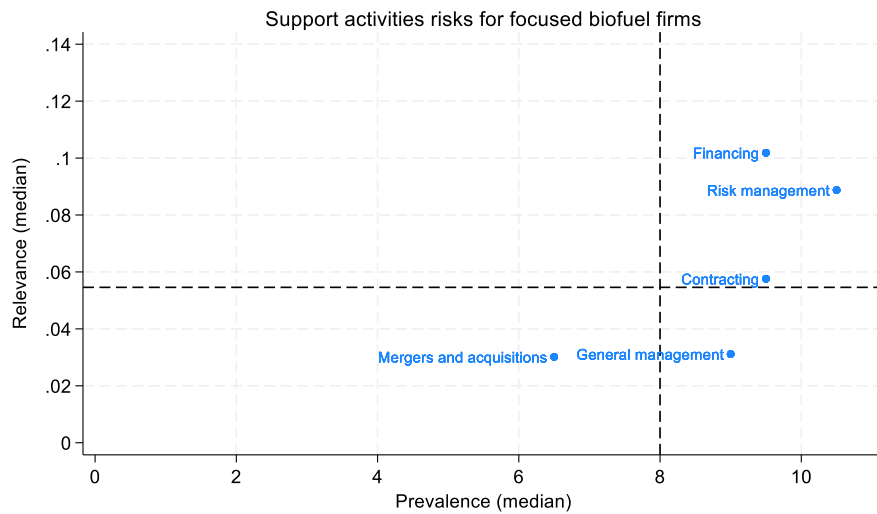
Appendix E: Technological risks for focused and diversified biofuel firms over 2017–2021



Appendix F: Primary activities risks for focused and diversified biofuel firms over 2017–2021



Appendix G: Support activities risks for focused and diversified biofuel firms over 2017–2021



Data availability

Only part of the data can be shared due to database restrictions. We have specified in the manuscript data that can be shared upon request.

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