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Associations Between Biofuel Production and Sustainable Development Goals 2, 6, 7, 13, and 15

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ABSTRACT

Total biofuel demand in areas like transport and energy is set to grow by almost 30% annually to reach 50 billion gallons by 2026. Biofuels' association with sustainable development has been a subject of discussion among researchers and policymakers. Even the most robust studies on this topic examine only a small number of sustainable development indicators across a limited number of countries. This study analyzes whether biofuel production could advance, impede, or have no association with targets of Sustainable Development Goals (SDG) 2, 6, 7, 13, and 15, which relate to biofuel production on a global scale. Correlations between ethanol, biodiesel, and total biofuel production datasets and 23 indicators of the selected targets in 34 of the world's largest biofuel-producing countries for 2009–2019 were compiled and analyzed in the context of the existing literature. Findings suggest that biofuel production has varying associations with SDG targets.

Introduction

Background on Biofuels

Biofuels are fuels derived from biomass; the specific type of biomass used for production determines the "generation" of biofuel; currently, there are four generations of biofuels either in use or under development. Most biofuels are used as transportation fuels but may also be used for heating and electricity generation. First-generation biofuels make up the majority of the biofuels used today and are the only generation that is viable on a commercial scale. The feedstocks used in their production are starch crops (sugarcane, sugarbeet, corn, sorghum) and oilseed crops (soybean, canola, rapeseed), grown on arable agricultural land, many of which could otherwise be consumed by people. Starch crops are converted through fermentation to form bio alcohols, including ethanol, butanol, and propanol. Oil-based crops are processed into biodiesel. Ethanol is the most widely used bio alcohol fuel. Most vehicles can use gasoline-ethanol blends. Second-generation biofuels are obtained from nonfood yields, for example, wood, forest waste, food crop waste, waste vegetable oil, industrial waste, and ecological biomass crops. The emerging third-generation biofuels utilize algae-derived biomass, and fourth-generation biofuels utilize specially genetically modified algae biomass. The second generation, and to a greater extent, third and fourth generations, are still produced at an experimental level. Most biofuels are consumed as a blend with refined petroleum products such as gasoline, diesel fuel, heating oil, and kerosene-type jet fuel.

The primary economic motivation for biofuel expansion has been that they can be produced domestically using the existing agricultural infrastructure, making them a competitive substitute for oil and other fossil fuels, which are becoming more expensive due to recent supply disruptions. There is a strong belief that replacing fossil fuels with biofuels, which use renewable organic biomass, can help address the negative impacts of fossil fuel production and use on the planet and the climate, including greenhouse gas emissions (GHG) and other pollutants. Demand for biofuels is also likely to lead to increased farm income, which is critical for developing countries. On the other hand, the most widely used biofuel feedstocks require land, water, and other resources, which, according to research, suggests that biofuel production may also have negative impacts. These may include changes to land use patterns that may lead to additional GHG emissions, additional pressure on already scarce freshwater resources, increased air and water pollution, and increased food production costs. According to data from the US EIA, biofuel production has increased since 2009.

Sustainable Development Goals

The Sustainable Development Goals (SDGs) are the most recent comprehensive attempt to advance sustainable development worldwide. Conceptualized by the United Nations, they are a set of 17 interlinked global goals focused, among other issues, on ending poverty and hunger, ensuring good health and quality education, providing clean water and sanitation along with affordable clean energy, guaranteeing the availability of decent work and economic growth, tackling climate change, and are complemented by 169 specific targets. The SDGs were developed with the ambition of being achieved by the global community by 2030. They have been adopted by and implemented by UN member countries as the world's shared plan to end extreme poverty, reduce inequality, and protect the planet from the impacts of the changing climate. As an energy source, biofuels' contribution or impediment to attaining the SDGs has been a subject of discussion in academia and among policymakers. In particular, the impact biofuel production can have on meeting the energy targets of SDG 7, climate change mitigation efforts for SDG 13, and (more indirectly) the expansion of economic opportunity of SDG 8 are the topics of numerous recent works. Researchers also address the potential negative impacts of biofuels on land use and food production (SDG 2), water (SDG 6), and biodiversity (SDG 15). A few studies explore the realized contribution of biofuel production more comprehensively through a large set of related SDG indicators across a group of countries engaged in the biofuels market. Most papers hone in on biofuels' impact on specific goals and indicators. A few researchers examine more holistically the relationship between biofuels and the SDGs over a more extended period. Santika et al. (2019) identified 25 significant links to many SDGs, noting that these linkages depend on a country's priorities, resources, and capabilities. Many of the linkages identified in that study will be examined in this paper as well.

The rest of the paper is organized as follows: section two will provide a review of the existing literature on the associations between biofuels and SDGs 2, 6, 7, 13, and 15; section three will show and name the sources for the statistical summary data of ethanol, biodiesel, and total biofuel production and all of the sustainable development indicators in the selected countries and period, and give an overview of the methods of this study; section four will show the findings of the correlation analyses between biofuel production and sustainable development indicators, and provide an analysis of this data; finally, section 5 will discuss the conclusions of this study.

Literature Review

Only some studies have used statistical modeling to examine the relationship between biofuel production and sustainable development indicators. Ozturk (2015) analyzed the role of biofuel production in the sustainable development of 12 countries over the period of 2000–2013, utilizing four sustainable indicators with significant impact on biofuel production: carbon dioxide emissions, energy intensity, renewable energy generation, and total population. The results confirmed that all the sustainable indicators studied link dynamically with biofuel production. The study concludes that biofuel production can optimize economic growth and bolster sustainable development. Additionally, the author states that future research should focus on broadening the range of countries by income level and using a more extensive data series and indicators to examine biofuels' relationship to sustainable development further. In a follow-up study, Ozturk 2016 investigates the linkages between biofuel production and sustainable indicators in 17 developed and developing countries between 2000–2012. The study used: carbon dioxide emissions, energy intensity, renewable energy generation, and total population. It found that carbon dioxide emissions increase along with biofuel production. In addition, renewable electricity generation also increases biofuel production. The results confirmed that all sustainable indicators significantly affect biofuels production, as total primary energy consumption increases biofuels production, while total population significantly decreases biofuels production in the analyzed countries.

SDG 2: Zero Hunger

In the existing literature, biofuels often come under fire for their perceived negative impacts on SDG 2 and the related SDG 6, which encompass sustainable agriculture and food access, and clean water and sanitation, respectively. Many papers point to biofuel feedstock's competition with land that could otherwise be used for food supply, as well as the broader ethical concern of using food crops as a fuel source. Some papers acknowledge that biofuels can advance other sustainable development indicators through advances in agriculture.

Msangi et al. (2009) indicated that increasing demand for food and energy from first-generation biofuels would put stress on food systems and surrounding ecosystems. The authors point out that rising household incomes, along with rising populations, in many countries contribute to this increased energy demand. Subramaniam et al. (2019) econometrically investigated the connection between food security and biofuel production in 56 developing countries and found the coefficient for biofuel production and food security was negative for all 56 countries, indicating biofuels' adverse impacts on food security. The paper notes that Research & Development (R&D) is a factor that could improve the efficiency of biofuels' land usage and production processes, and lead the process of advancing third and fourth-generation biofuels, which have not been found to have impacts on food security. Renzaho et al. (2017) also analyzed biofuel production and its impact on food security in low and middle-income countries, concluding that biofuel production could raise food prices and threaten food and nutrition security in low and middle-income countries, which could impede the attainment of SDG 2. The authors also point to the evidence that in countries' with established commercial biofuel production systems, increase in biofuel production did contribute to an overall increase in food prices since 2000. Using data from 51 developing countries, Subramaniam et al. (2020) found that the association between various indicators of environmental quality and biofuel production, overall, has a positive and significant impact on food security, meaning that while in the short-term, biofuels may create competition with crops used for food production, in the long term they may lead to an overall increase in food production. The authors note that biofuels' adverse effects on food security decline as indicators of an environmental quality in countries increase. Research by Rulli et al. (2016) concluded that the volume of agricultural land available in the world may not be sufficient to meet the current human demand for food and energy. The authors argue that the global reliance on fossil fuels cannot be met by first-generation biofuels without undermining the food security of human societies. The study concluded that the competition between food and biofuels is expected to become even more intense in the future. De Fraiture et al. (2008), however, note that some biofuel crops like corn are mainly used to feed animals to produce meat and milk, thereby challenging the ethical concern that the dilemma related to biofuels is between producing energy and feeding people. Alsaleh et. al (2020) concluded that expanded biofuel production could contribute to sustainable development if feedstock is grown using sustainable agriculture methods and are traded on equitable terms.

SDG 6: Clean Water and Sanitation

Another topic of debate is whether biofuels, because they are produced from crops using conventional agricultural practices, will lead to an increase in use of water for agriculture, which is the major source of water pollution. Across the globe, energy and agriculture are the two top sectors for water withdrawals. Many studies recognize that increased biofuel production will exacerbate stresses on water supplies and water quality.

Arshad and Abbas (2014) note that because biofuel production processes rely on freshwater collected from surface water or groundwater reservoirs; agricultural drainage to the surface after production is often contaminated with fertilizers, pesticides, and sediments. The authors also point out high water intensity of biofuel production, with 10-17 liters of water needed to produce one liter of ethanol. Gerbens-Leenes et al. (2009) give an overview of the water footprints of bioenergy from 12 crops that contribute the most to global agricultural production, noting that ethanol has an overall lower water footprint than biodiesel. Hoogeveen et al. (2009) discuss the connection between agriculture and water use in the context of biofuel sustainability. According to the authors' estimates, at the time of their research, 1% of all water withdrawn for irrigation is used to produce biofuel feedstocks. They projected that this number would rise by 74% by 2017, however no actual data was found to support or refute this projection through their own review of more recent literature. The authors also state that though water withdrawals for biofuels will likely continue to remain modest on the global scale and overall water resources will not be depleted as a result of biofuel feedstocks, local water scarcity issues in certain areas may be more pronounced, especially in middle-income countries with rapidly developing economies, where there is already competition for scarce water resources. Further, in conjunction with climate change and land use, Delucchi (2010) argues that methods to increase the sustainability of biofuel feedstock agriculture, namely no fossil fuel inputs, cannot yet be performed commercially. In terms of industrial water use for biofuel processing Yeh et al. (2011) found that in some areas, water usage in the industrial sector has steadily decreased since the 1990s, primarily due to the introduction of new environmental policy. Dominguez-Faus et al. (2009) also note that water consumption during biofuel production could adversely impact the availability of water, noting that as biofuel production increases, there is a need to better understand and mitigate potential impacts on water resources. Given that most studies regarding biofuels and water use and quality found through this extensive literature review were published over ten years ago, this paper will use more recent data.

SDG 7 - Affordable and Clean Energy

The energy sector contributes about 60% of the world's GHG emissions, most of which are attributed to fossil fuels. According to data from the most recent IEA report on bioenergy, by 2019 (the last year of this paper's study period), bioenergy makes up about 6% of the global energy supply, and liquid biofuels only make up about 7% of bioenergy use. By increasing the availability of the fuel itself, which can then be used to generate energy, expansion in biofuel production can have a positive impact on rural communities in developing countries. The lack of access to reliable energy negatively impacts the quality of life in rural communities across the developing world. Biofuel production can lead to the creation of reliable rural jobs and overall economic growth. Access to energy services allows people to have jobs that provide them with income which they can use to improve their living conditions, including by having access to quality health and education, leading to a reduction in poverty. Data from the report suggests that by 2030, liquid biofuel production will contribute 20% of bioenergy.

Acheampong et al. (2017) assess whether biofuels are a reliable source of energy to support targets in SDG 7, concluding that the challenges with large scale adoption of the first-generation biofuels must be carefully managed while developing third and fourth generation biofuels which are thought to address most of negative aspects of the biofuels used presently. Jha and Schmidt (2021) support the point that before selecting feedstocks for household- or industrial-scale biofuel production, it is essential to assess how biofuel feedstock cultivation affects local or regional socioeconomic conditions. Using data from Sub-Saharan Africa (SSA), they conclude that appropriate initiatives can promote local biofuel production and trigger the establishment of effective biofuel markets while supporting local populations. In addition, biofuel import dependencies and the environmental footprint could be improved.

One of the main applications of biofuels is in the transport sector, with IEA (2020) predicting that biofuels will account for 5.4% of road transport energy demand in 2025, up from just under 4.8% in 2019. Debnath et al. (2019) note that emissions from gas-powered vehicles in the transportation sector have been growing over the past few decades, and while the prospect for electric vehicles (EV) is growing, the widespread deployment of EVs will likely continue to be constrained due to vehicle range limitations and insufficient infrastructure availability, under current policies. Liquid biofuels can serve as a substitute to power gasoline vehicles (GV). Currently, the most commercially available form of biofuels are biofuel-gasoline blends. Chang et al. (2017) simulated the effects of replacing gasoline with biofuel from different feedstocks and in different concentrations on the overall GHG emission and energy consumption. The authors found that the combination that has the most substantial lowering of GHG emissions by about 59.4%, the total energy consumption for production was more than double that of gasoline, at about 101.3%; this indicates that there is a tradeoff between the GHG reduction and energy efficiency with biofuels. In addition to lifecycle and net GHG emissions, Aron et al. (2020) evaluated the energy efficiency of each of the four generations of biofuels, concluding that first-generation biofuels currently have the highest energy efficiency and that third-generation biofuels require the highest energy input and least economically competitive, mainly because this generation is still in the research stage.

SDG 13: Climate Action

One of the critical overall benefits and motivations of increased production of biofuels is the fact that they are considered to be net zero because in their growing stage, by photosynthesis, feedstocks sequester the CO2 that is later released upon combustion. However, in connection to SDG 2 and SDG 15, many authors point to the need to consider the indirect CO2 emissions in biofuel production through land use change.

Garcia-Franco et al. (2021) state that production of first- and second-generation ethanol (which is not widely commercially viable yet) overall reduces GHG and decreases the demand for crude oil and other fossil fuels. Elshout et al. (2015) note that land use transformation driven by increase in biofuel production could alter natural carbon cycles in ecosystems, which could initially contribute to biofuels' GHG emissions. They proposed using the greenhouse gas payback time (GPBT) to measure the number of years it would take to realize the GHG savings of biofuels compared to fossil fuels, with the initial emissions caused by land use change. The authors found that the global GPBTs for five different biofuel crops range from 1 to 162 years, noting that the location of the crop cultivation was the primary driver of GPBTs, with the highest GPBTs occurring in tropical regions. Cherubini et al. (2009) discuss how the cultivation of biofuel feedstock can reduce the oxidation of methane in soil, which would increase the concentration of methane in the atmosphere; they also note that the conversion of tropical peat into agricultural land for feedstocks like palm, would lead to even greater methane emissions. Pillai (2016) found that biofuels may contribute to nitrous oxide (N2O) emissions especially in agriculture, depending on the efficiency of crops' uptake in of nitrogen fertilizer. Hallgren et al. (2013) note that an expansion of biofuel production could lead to pressures on land supply and alter land use. The authors examined the effects of land use changes attributed to biofuel production and found that land clearing, especially forest clearing for biofuel production overall, could warm tropical regions but cool extratropical regions. However, Hallgren et al. (2013) conclude that on the global scale, the impact of biofuel production on climate change is negligible because "the warming associated with increases in GHG concentrations is offset by a cooling from changes in albedo." Jeswani et al. (2020) note that the estimates of biofuel's environmental and climate-related impacts vary widely across many studies. Based on the available data, the authors argue that if no changes in land use are involved, first-generation biofuels can—on average—have lower GHG emissions than fossil fuels. Khan et. al (2018) notes that increasing the use of biofuels in business operations, especially in countries with high GHG emissions, could have a positive impact in sectors like health. Aron et al. (2020) evaluated the net GHG emissions from the four different biofuel generations, finding that commercialized first-generation biofuels contribute the highest amount of GHG emissions, while the third generation promises the lowest net GHG emissions. The authors acknowledge that developing second-generation biofuels will take time and that, at the present state of development, third-generation biofuels from algae are unlikely to contribute to the transport sector as their overall GHG emissions are higher than those from fossil fuels.

SDG 15: Life on Land

This target encompasses protecting, restoring, and promoting sustainable use of land and forests and stopping and reversing land degradation and biodiversity loss. Many papers that touch on this SDG have examined the association between biodiversity and expanded biofuel production, with a vast majority finding that biofuel production negatively impacts biodiversity, primarily due to land use changes, which were discussed in the section regarding SDG 2.

As some papers mentioned above, Verdade et al. (2015) argue that the expansion of biofuel crops often results in direct habitat loss in addition to other agricultural impacts like soil and biotic contamination and water eutrophication. However, the authors also note that there are circumstances in which biofuel crops can increase biodiversity compared to other agricultural crops. Trudge et al. (2021) used data from 116 instances of the potential impacts of different biofuel crops on species richness and total abundance, which are two key indicators of biodiversity. The authors discovered that species richness and abundance, especially for plant species, was 39-49% lower in areas with first-generation biofuel crops planted instead of native vegetation, leading them to suggest that biofuel crops overall reduce local biodiversity. Notably, Trudge et al. (2021) acknowledge that the degree of biofuels' influence on biodiversity is determined by the crop yield per unit of bioenergy generated as well as geographic effects, which other papers have similarly indicated. They found that tropical regions growing biofuel feedstocks suffer the highest biodiversity declines. Dale et al. (2014) investigated the impacts of biofuels on biodiversity compared to those of traditional fossil fuels, finding that petrol production can affect more than 5.8 billion ha of land and water, whereas biofuels would affect only 2 billion ha. They emphasize that much of the natural area impacted by fossil fuels would be found in more remote and fragile terrestrial ecosystems that would otherwise remain untouched, while areas needed for biofuel production would already most likely have been altered by human activity. Overall, the authors make the point that while all energy supply options are likely to negatively impact species richness and threaten species, biofuels' negative effects would be smaller in extent and duration than those of fossil fuels and that they have the unique potential to be reduced. Keles et al. (2018) used data from 112 low and middle-income countries to determine the association between biofuels and deforestation, finding a positive relationship between the two variables, corroborating Dale et al. (2014) view that biofuel expansion does not spread to the densest forest areas. Bessou et al. (2011) point out that the main limiting factor for biofuel development is land availability noting that given the available land areas, population growth rate and consumption behaviors, it would be possible to considerably increase biofuel share in the critically important transport sector, provided that the right policies are implemented worldwide.

SDGs and Biofuel Policy

Ebadian et al. (2020) evaluated the effectiveness of technology-push and market-pull policies in encouraging the production and use of biofuels in 15 countries including major biofuels producers. The paper concludes that countries with a mixture of policy instruments have been most successful at increasing biofuels production and use and also developing and deploying less mature advanced biofuels. The policies have primarily promoted the production and use of biofuels for road transport with key long-distance transport sectors (aviation and shipping). While older policies promoted energy security, more recent ones, such as low carbon fuel standard, have reduced the carbon intensity of transportation fuels as a primary goal. The research finds that while policies have helped grow the biofuels sector, they have not been sufficient to drive the level of development needed to produce fuels that can decarbonize the transport sector. They did help expand biofuels markets, which is considered a good outcome.

From the literature review, it can be determined that even the most robust studies had examined only a small number of sustainable development indicators across a limited number of countries. This paper aims to calculate the association between biofuel production on economic growth and sustainable development using data for a larger group of different income and development-level countries, explore changes on a more extended data series, and analyze a more comprehensive set of variables to quantify the association between various indicators of certain SDGs in biofuel-producing and consuming countries between 2009 and 2019.

Data and Methods

Data

For this study, the correlation between biofuel production data and 23 indicators of sustainable development relating to five UN SDGs was analyzed for 34 countries that were engaged in biofuel production over the period 2009-2019. Upon examination of a worldwide data set of biofuel production, these countries were found to be among the greatest in either or both areas. Countries' biofuel and production data were obtained from the United States Energy Information Administration. Data on the sustainable development indicators were obtained from the World Bank Sustainable Development and ESG databases. Sustainable development indicators were broadly grouped according to which SDG they are most directly related to in order to create an idea of how biofuel production is associated with the advancement or hindrance of each of the selected goals. As discussed in the literature review, the SDGs most related to biofuels are SDG 2 (zero hunger), SDG 6 (clean water and sanitation), SDG 7 (affordable and clean energy), SDG 8 (decent work and economic growth), SDG 13 (climate action), and SDG 15 (life on land). The indicators relate to several targets of each SDG. It is important to note that the database used in this study does not contain data on all indicators tied to the selected SDGs and their respective targets.

Methods

Pearson correlation coefficients spanning SDG indicator data over the 11-year period were determined with respect to a country's ethanol production, biodiesel production, and total biofuel production, which were each divided by the country's GDP for each year in order to compare data relative to the size of a country's economy. The software Google Sheets was used to perform the calculations. Directionality was considered for each correlation in the context of the literature review, with relationships determined as either unidirectional or bidirectional Additionally, scatter plot diagrams with trendlines were generated to provide a visual aide to the relative correlation between each indicator and the six biofuel data sets. Based on the grouping of correlations for each group of indicators attributed to an SDG, an overall assessment of biofuels' effect on each considered SDG was determined. This study will not make any causal statements.

A key limitation to this methodology that must be acknowledged, is that the existence of a correlation or no correlation alone, cannot necessarily be attributed to a causation linkage. Additionally, due to the multitude of other interrelated and unrelated factors that can impact the SDG indicators.Therefore, the overall goal of this study is to observe and analyze the affinity between the derived SDG-biofuel correlations and draw conclusions about this relationship based on the existing literature.

Results

Correlation Analysis: SDG 2

Four indicators from the World Bank database relating to agricultural production, food insecurity, and agricultural land area, were analyzed to measure the association between biofuel production and SDG 2.

A key aspect of target 2.4 is increasing agricultural efficiency production, in a sustainable manner. Table 4 shows there is no correlation between biofuel production and the percentage of agricultural land observed, which could be attributed to different countries' agricultural land practices. As discussed in the literature review, increased demand for biofuel could require additional agricultural land; however, in some countries, agricultural efficiency has increased, meaning that less land area may be used to generate the same or greater crop yields, whereas in other countries, the percentage of agricultural land is still increasing. The crop production index measures the agricultural production of all crops, whereas the food production index measures the agricultural production of all crops considered edible and have nutritional value. Table 4 shows no correlation between biofuel production and the crop production index, suggesting that increases in biofuel production do not affect the production of the share of all crops. Target 2.1 envisions stable food access for all. However, a very small positive correlation between total biofuel production and the food production index was found, per Table 4, which supports certain predictions observed in the literature review that demand for biofuels may lead to an increase in agricultural food production. These results, in the context of the literature review, suggest a bidirectional relationship between these variables, wherein a country's food production levels could determine how much is allocated for biofuels, and biofuel production levels may influence levels of food production. The correlation analysis in Table 4 and the positive slope of Figure 2.d. also shows a moderate positive correlation between ethanol and biodiesel production and a small positive correlation between total biofuel production and moderate to severe food insecurity. This discrepancy could suggest that the levels of food insecurity in countries mainly producing ethanol versus biodiesel may differ. Studies on the relationship between food insecurity and biofuels share similar notions that a boost in biofuel production could increase food scarcity and food prices in many countries due to food crops getting allocated for biofuel production rather than human consumption, thereby worsening food insecurity. Therefore, there is likely a unidirectional relationship between biofuel production and food insecurity, wherein biofuel production could exasperate food security in countries. Available data from the World Bank related to food scarcity and prices were inadequate to examine for the scope of this study. Overall, the correlations between the four SDG 2 indicators and biofuel production data suggest that there is more likely to be a negative association of advancing targets 2.1, 2.2, 2.3, and 2.4 because analyses suggest that while there is no or weak correlation between biofuel production and crop and food production, respectively, there is a moderate positive correlation between biofuel production and food insecurity, which is a key focus of SDG 2.

Correlation Analysis: SDG 6

Three indicators from the World Bank database relating to water usage and scarcity were analyzed to measure the association between biofuel production and SDG 6. In the context of biofuel feedstock production, the indicators selected for SDG 6 are related to those of SDG 2 surrounding agricultural production.

Target 6.4 concerns improving water-use efficiency, ensuring sustainable freshwater withdrawals across industries, and mitigating levels of water stress. Researchers have explored whether increased biofuel production could lead to an increased demand for freshwater at the regional or country level. Results in Table 6 and a slight positive slope in Figure 3.a. partly support this notion with a weak positive correlation between biodiesel production and annual freshwater withdrawals from agriculture. The findings in the literature review could point to a unidirectional relationship wherein increased biofuel production will require more feedstock to be harvested, which could require more water to be withdrawn for this purpose. The small negative correlation between annual freshwater withdrawals in industry and the separate ethanol and biodiesel production datasets, in Table 6 along with the slightly negative slope in Figure 3.b., could suggest that ethanol and biodiesel processing consumes less freshwater than other industrial processes requiring freshwater. The total biofuel production data sets for agricultural and industrial freshwater withdrawals show no correlation to the indicator data, suggesting that different countries are withdrawing water for ethanol production than for biodiesel. The results in Table 6 and the slightly negative slope in Figure 3.c., also show a weak negative correlation between ethanol and biodiesel production and the level of water stress supporting findings by other authors that increased biofuel production may not lead to shortages of water on a global scale. Overall, the correlations between the three SDG 6 indicators and biofuel production data suggest that there is a positive association of advancing target 6.4 because analyses suggest that while there is a positive association between agricultural freshwater withdrawals, there is a negative association with levels of water stress and industrial water withdrawals, which could demonstrate water-use efficiency.

Correlation Analysis: SDG 7

Seven indicators from the World Bank database relating to energy access, renewable energy, energy investment, and fossil fuel energy were analyzed to measure the association between biofuel production and SDG 7.

Target 7.1 focuses on ensuring universal access to energy services. The small positive correlation between total biofuel production and access to electricity in rural areas, in Table 8, suggests that total biofuel production is associated with improved electricity access in rural areas. The weak association of this correlation could be attributed to the fact that the average percentage of rural electricity access across the country dataset is already very high (96.4%). There is likely a unidirectional relationship between rural electricity access and biofuel production, wherein countries with high electricity access, including in rural areas, tend to have higher levels of biofuel production. A key component of target 7.a is promoting research and investment in clean energy infrastructure technology. Table 8 shows a significant positive correlation between ethanol and biodiesel production and investment in energy with private participation and Figure 4.d. shows a positive slope. An increase in the production of biofuels may encourage more private investments in the energy sector for energy infrastructure projects, possibly related to biofuels. While most biofuels are used as transportation fuels, they may also be used for heating and electricity generation. Table 8 shows a very small positive correlation between transport investment and ethanol and biodiesel production, and Figure 4.c.. The associations between investment by private participation in energy and transportation and biofuel production are likely unidirectional: countries in which the private sector is already engaged in sustainable technologies may also be investing in biofuels. Since investment in biofuels relating to applications in energy and transport represent only a portion of the total amount of annual investment, more precise data of investments related to biofuel in the energy and transport sectors would be conducive to determining a more direct association between the data, especially given that the correlations between ethanol and biodiesel production and total biofuel production support opposite notions. Target 7.2 involves increasing the share of renewable energy in the global energy mix. The strong positive correlation between ethanol and biodiesel production and renewable energy consumption, in Table 8, and the positive slope in Figure 4.e., supports the notion expressed by researchers that more biofuel production could add to renewable energy generation (and consequently consumption) through applications in transport, heating, and electricity generation. Building on this assumption, a moderate negative correlation between ethanol and biodiesel production and fossil fuel energy consumption, in Table 8 and the negative slope in Figure 4.f., supports the conclusions made by past papers that increases in biofuel production may lead to decreases in fossil fuel consumption, for example through adding biofuel into gasoline. There is likely a bidirectional association between renewable energy and fossil fuel consumption and biofuel production, wherein countries engaging in more sustainable technologies are also producing biofuels, and an increase in biofuel production can increase renewable energy consumption. Target 7.3 concerns improving global energy efficiency; energy intensity is a measure of the energy inefficiency of an economy. The weak negative correlation between the total biofuel production and country energy intensity level, in Table 8, suggests that increased biofuel production over the 11-year period could be associated with an overall improvement in energy efficiency. Because biofuels can be produced using, for the most part, countries' existing infrastructure, they could reduce countries’ dependence on imported energy. Findings in Table 8 partly support this idea by showing a weak negative correlation between biofuel production and energy imports. There is likely a bidirectional association between energy imports and biofuel production, wherein countries seeking to become more energy independent are producing biofuels to achieve this goal, and biofuels can contribute to lessening energy imports. Overall, the correlations between the seven SDG 7 indicators and biofuel production data suggest that there is a positive association of advancing targets 7.1, 7.2, 7.3, and 7.A, because analyses suggest that biofuel production is associated with improved electricity access and energy and transport investment, as well as increased consumption of renewable energy and decreased consumption of fossil fuels.

Correlation Analysis: SDG 13

Three indicators from the World Bank database relating to GHG emissions and air pollution were analyzed to measure the association between biofuel production and SDG 13.

Target 13.2 concerns integrating climate change measures into policies, a key indicator of which is the total GHG emissions per year. A weak negative correlation between ethanol and biodiesel production and CO2 emissions t/per capita in Table 10 and negative slope in Figure 5.a., suggests that increases in ethanol production not only do not increase overall CO2 emissions but may lead to minimal decreases in their levels, which support some previous researchers’ findings. As discussed in the literature review, biofuel production may lead to initial indirect CO2 emissions, primarily due to land use change; however, biofuels are believed to be carbon neutral as feedstock photosynthesis offsets the emissions upon combustion. As discussed in section 4.3., the correlation analysis seems to support the notion that if biofuels are integrated into the energy mix, possibly replacing fossil fuels, then per capita CO2 emissions could decrease. Since methane emissions may be generated from various sources coupled with the fact that in the literature review for this paper, no information establishing linkages between biofuels and methane was found, more precise data of methane emissions related to biofuels would be conducive to determining a more direct association between these variables, especially given that the correlations between ethanol and biodiesel production and total biofuel production support opposite notions. Results in Table 10 and a positive slope in Figure 5.c. point to a very small positive correlation between N2O emissions and ethanol and biodiesel production, which supports the notion discussed in the literature review that N2O may be emitted from various sources related to biofuels, primarily through industrial and agricultural processes. The association, in the context of the literature review, seems to be bidirectional, wherein countries keen on reducing GHG emissions are implementing policies to do so through many means, which may include biofuel expansion, and as discussed, biofuel at the time of final usage itself is associated with lowered emissions. Overall, the correlations between the three SDG 13 indicators and biofuel production data are inconclusive regarding target 13.2 because analyses suggest that emissions of CO2, the primary greenhouse gas leading contributor to climate change, are negatively associated with biofuel production; in contrast, emissions of methane and N2O, which are less prevalent but more potent greenhouse gasses, are positively associated with biofuel production.

Correlation Analysis: SDG 15

Five indicators from the World Bank database relating to terrestrial areas and biodiversity were analyzed to measure the association between biofuel production and SDG 15.

Target 15.2 focuses on ensuring sustainable management of forests and curbing deforestation. The moderate positive correlation between ethanol and biodiesel production and annual deforestation, in Table 12 and the positive slope in Figure 6.a., supports concerns expressed by some researchers that expanding biofuel production may lead to the loss of forest area. When coupled with the result from section 3.1 that the percentage of agricultural land is negligibly associated with biofuel production, the correlation analyses suggest that deforestation may occur in certain countries for other reasons, related to biofuels or not, then for agricultural land. Therefore, according to the literature review, there could be a bidirectional association between biofuel production and deforestation, wherein countries with already high deforestation rates are pursuing biofuels, and biofuels are positively associated with deforestation in manners other than agriculture. Target 15.5 concerns reducing degradation of natural habitat, threats to biodiversity, and the number of threatened species. Results in Table 12 and positive slopes in Figure 6.b., Figure 6.c., and Figure 6.d., show a significant positive correlation between biofuel production and threatened mammal species and bird species, thereby supporting concerns expressed by some researchers that an expansion of biofuel production could pose risks to wildlife diversity. Further, Table 12 shows a weak positive correlation between biofuel production and plant species threatened, indicating that biofuel expansion could also threaten plant diversity. Overall, these three sets of positive correlations suggest that increased biofuel production could threaten biodiversity; aspects discussed in the reviewed literature, such as monocropping, land use change, and deforestation, could be contributing factors. As with the indicator of deforestation, the existing literature coupled with the correlation analysis suggests a bidirectional association between biofuel production and threats to biodiversity, wherein countries already experiencing threats to biodiversity could also be producing biofuel, and the expansion of biofuel itself could threaten biodiversity. Overall, the correlations between the four SDG 15 indicators and biofuel production data suggest a negative association of advancing targets 15.1, 15.2, and 15.5 because analyses suggest that biofuel production is positively associated with deforestation and the number of threatened wildlife and plant species. While there was no data in the dataset used for this study on soil degradation, given the discussed potential effects of increasing the production of biofuel feedstocks on soil degradation, further data analysis on this topic would be required.

Conclusion

The papers reviewed for this research offered a rich knowledge base related to the impact the first-generation of biofuels have had on various indicators of sustainable development. This study focused on a diverse group of countries of different income levels which are the world's biggest biofuel producers; utilized longer data series and more variables than previous research, in an effort to investigate the impact of biofuels on various internationally recognized indicators of sustainable development. The study utilized correlation analyses of 23 indicators relating to specific targets within several Sustainable Development Goals to suggest whether biofuel production advances or hinders these goals in a scope representing large segments of the world. Subjected to this analysis were targets within SDG 2, 6, 7, 13, and 15 and their relationship to biofuel production for 34 of the largest biofuel-producing countries. The directionality of the observed associations was also proposed. Special attention was given to connecting with the existing literature on biofuel production and the SDGs.Due to the dynamic relationship between agriculture and biofuel production, this study has yet to reach a definitive conclusion as to whether biofuel production advances or hinders a number of related targets for SDG 2 (2.1,2.2,2.3, and 2.4). Notably, it was observed that biofuel production is positively associated with levels of moderate to severe food insecurity. Concerning SDG 6, this study suggests that on a global scale, biofuel production would not hinder target 6.4 because there is a negative association with levels of water stress, despite the positive association with freshwater withdrawals for agriculture. Nevertheless, the dynamic relationship between these two indicators should be further researched to determine how they may influence one another. When it comes to SDG 7, associations between biofuel production and targets 7.1, 7.2, 7.3, and 7.a found by this research suggest that expanded biofuel production could advance these targets. Notably, moderate positive associations were observed between biofuel production and private investments in energy and renewable energy consumption, coupled with a moderate negative association with fossil fuel energy consumption. With regards to emissions, this study suggests that biofuels may be beneficial to lowering overall CO2 emissions, despite initial emissions due to land use change. In terms of CH4 and N2O emissions, which have been less studied, analysis in this paper suggests that biofuel production could increase emissions of these more potent greenhouse gasses. Lastly, regarding SDG 15, this study suggests biofuel production may hinder targets 15.2 and 15.5, with moderate positive correlations between biofuel production and deforestation rates and threatened plant and animal species.

Given the variety of environmental effects, mainly involving feedstock agriculture, it is difficult to quantify and generalize the impact of biofuels on sustainable development on a broader scale. A fundamental limitation in this study was the extensive scope of the available data regarding SDG indicators, which encompasses individual data that may or may not be material to biofuel production. Therefore, to more precisely determine the associations between biofuel production and the SDGs, future research should seek to obtain and analyze data on the indicators analyzed in this paper as well as indicators even more directly related to biofuel production. Similar analyses utilizing more precise SDG-related data may allow for the establishment of causality between SDG indicator data and biofuel production. In order to establish a more holistic view of how biofuel production affects sustainable development around the world, an additional layer of data that should be considered is the areas in which feedstock is grown, for oftentimes, the feedstock utilized for biofuel production is imported to countries in which the processing of biofuel takes place.

Tables

Table 1. Summary statistics table of biofuel datasets

Dataset	Mean	Median	Standard Deviation	Minimum	Maximum
Ethanol production	22748747	4015000	68143753	0	427415000
Biodiesel production	16928213	1095000	62602493	0	383250000
Total biofuel production	5750453	2190000	8224375	0	50370000
Ethanol production as share of country GDP (%)	0.0015661684	0.0009135818	0.0019433916	0	0.0128574592
Biodiesel production as share of country GDP (%)	0.0008121087	0.0002249668	0.0017629700	0	0.0108516153
Total biofuel production as share of country GDP (%)	0.0007413375	0.0005595770	0.0007627017	0	0.0048002048

Table 2. Summary statistics table for selected sustainable development indicators

Indicator	Mean	Median	Standard Deviation	Minimum	Maximum
Access to electricity, rural (% of rural population)	96.44	100.00	8.48	50.96	100.00
Annual deforestation (% of change)	-0.01	-0.06	0.66	-1.26	2.12
Annual freshwater withdrawals, agriculture (% of total freshwater withdrawal)	41.99	46.30	34.22	0.48	91.95
Annual freshwater withdrawals, industry (% of total freshwater withdrawal)	37.37	24.05	30.00	1.27	91.69
CO2 emissions (metric tons per capita)	6.02	5.21	4.07	0.74	18.22
Energy intensity level of primary energy (MJ/$2017 PPP GDP)	3.91	3.65	1.27	1.70	8.95
Investment in energy with private participation (current US$)	3488118651	1641600000	6171125536	9710000	34474510000
Investment in transport with private participation (current US$)	4363650133	1872070000	6736371808	2500000	33749230000
Level of water stress: freshwater withdrawal as a proportion of available freshwater resources	21.47	15.71	23.21	1.18	160.03
Mammal species, threatened	30.09	11.50	39.39	1.00	191.00
Bird species, threatened	45.24	20.50	46.90	8.00	175.00
Crop Production Index (2014-2016=100)	96.78	97.89	10.08	53.05	132.87
Plant species (higher), threatened	1591	66	203	0	727
Renewable energy consumption (% of total final energy consumption)	20.97	16.45	14.04	0.47	65.36
Terrestrial protected areas (% of total land area)	19.83	19.20	8.97	2.44	39.74
Agricultural land (% of land area)	39.74	44.13	16.75	0.92	72.42
Energy imports, net (% of energy use)	10.42	28.99	76.62	-294.76	97.93
Fossil fuel energy consumption (% of total)	73.79	76.34	16.45	25.12	97.93
Methane emissions (metric tons of CO2 equivalent per capita)	1.35	0.97	1.06	0.46	7.15
Nitrous oxide emissions (metric tons of CO2 equivalent per capita)	0.66	0.46	0.54	0.09	4.69
Prevalence of moderate or severe food insecurity in the population (%)	12.05	8.35	10.21	2.80	47.80
Food production index (2014-2016 = 100)	97.60	98.33	8.63	57.92	135.53

Sourced from US EIA and biofuel data sets divided by country GDP, for 34 countries from 2009-2019. Note: values are derived from multiplying the thousands of gallons per day metric in the original set by 365 and then dividing by 1000 to obtain a more comparable value to the magnitude of the GDP values.

Includes 23 sustainable development indicator datasets for 34 countries over 2009-2019 that were sourced from the World Bank Sustainable Development database.

Table 3. Selected sustainable development indicators and related SDG 2 targets

Selected Indicator	Related SDG Target(s)
Agricultural land (% of land area)	2.4
Prevalence of moderate or severe food insecurity in the population (%)	2.1
Crop production index (2014-2016 = 100)	2.4
Food production index (2014-2016 = 100)	2.1, 2.4

Table 4. Pearson correlation coefficients between biofuel production data and four indicators related to SDG 2

Indicator	Ethanol Production	Biodiesel Production	Total Biofuel Production
Crop production Index (2014-2016 =100)	0.03	0.01	0.04
Food production index (2014-2016 = 100)	0.08	0.01	0.14
Agricultural land (% of land area)	-0.09	-0.08	-0.03
Prevalence of moderate or severe food insecurity in the population (%)	0.26	0.24	0.18

Highlighted are statistically significant correlation coefficients. Note: the raw biofuel production and consumption data was divided by a country's GDP for a given year.

Table 5. Selected sustainable development indicators and related SDG 6 targets

Selected Indicator	Related SDG Target(s)
Annual freshwater withdrawals, agriculture (% of total freshwater withdrawal)	6.4
Annual freshwater withdrawals, industry (% of total freshwater withdrawal)	6.4
Level of water stress: freshwater withdrawal as a proportion of available freshwater resources	6.4

Table 6. Pearson correlation coefficients between biofuel production data and four indicators related to SDG 6

Indicator	Ethanol Production	Biodiesel Production	Total Biofuel Production
Annual freshwater withdrawals, agriculture (% of total freshwater withdrawal)	0.18	0.20	0.07
Annual freshwater withdrawals, industry (% of total freshwater withdrawal)	-0.17	-0.18	-0.01
Level of water stress: freshwater withdrawal as a proportion of available freshwater resources	-0.24	-0.25	-0.14

Highlighted are statistically significant correlation coefficients. Note: the raw biofuel production and consumption data was divided by a country's GDP for a given year.

Table 7. Selected sustainable development indicators and related SDG 7 targets

Selected Indicator	Related SDG Target(s)
Access to electricity, rural (% of rural population)	7.1
Energy intensity level of primary energy (MJ/$2017 PPP GDP)	7.3
Investment in energy with private participation (current US$)	7.A
Investment in transport with private participation (current US$)	7.A
Renewable energy consumption (% of total final energy consumption)	7.2
Energy imports, net (% of energy use)	7.3
Fossil fuel energy consumption (% of total)	7.2

Table 8. Pearson correlation coefficients between biofuel production data and four indicators related to SDG 7

Indicator	Ethanol Production	Biodiesel Production	Total Biofuel Production
Access to electricity, rural (% of rural population)	0.08	-0.01	0.22
Energy intensity level of primary energy (MJ/$2017 PPP GDP)	-0.06	0.01	-0.16
Investment in energy with private participation (current US$)	0.41	0.49	-0.11
Investment in transport with private participation (current US$)	0.13	0.18	-0.14
Renewable energy consumption (% of total final energy consumption)	0.38	0.45	-0.06
Energy imports, net (% of energy use)	0.03	-0.07	0.24
Fossil fuel energy consumption (% of total)	-0.26	-0.31	0.07

Highlighted are statistically significant correlation coefficients. Note: the raw biofuel production and consumption data was divided by a country's GDP for a given year.

Table 9. Selected sustainable development indicators and related SDG 13 targets

Selected Indicator	Related SDG Target(s)
CO2 emissions (metric tons per capita)	13.2
Methane emissions (metric tons of CO2 equivalent per capita)	13.2
Nitrous oxide emissions (metric tons of CO2 equivalent per capita)	13.2

Table 10. Pearson correlation coefficients between biofuel production data and three indicators related to SDG 13

Indicator	Ethanol Production	Biodiesel Production	Total Biofuel Production
CO2 emissions (metric tons per capita)	-0.29	-0.23	-0.20
Methane emissions (metric tons of CO2 equivalent per capita)	0.24	0.32	-0.11
Nitrous oxide emissions (metric tons of CO2 equivalent per capita)	0.12	0.14	-0.05

Highlighted are statistically significant correlation coefficients. Note: the raw biofuel production and consumption data was divided by a country's GDP for a given year.

Table 11. Selected sustainable development indicators and related SDG 15 targets

Selected Indicator	Related SDG Target(s)
Annual deforestation (% of change)	15.2
Mammal species, threatened	15.5
Bird species, threatened	15.5
Plant species (higher), threatened	15.5

Table 12. Pearson correlation coefficients between biofuel production data and four indicators related to SDG 15

Indicator	Ethanol Production	Biodiesel Production	Total Biofuel Production
Annual deforestation (% of change)	0.39	0.36	0.18
Mammal species, threatened	0.28	0.14	0.45
Bird species, threatened	0.48	0.42	0.29
Plant species (higher), threatened	0.28	0.24	0.21

Highlighted are statistically significant correlation coefficients. Note: the raw biofuel production and consumption data was divided by a country's GDP for a given year.

Conflict of Interest

The author has no conflicts of interest to disclose.

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