Biological Evidence 2024, Vol.14, No.1, 1-10
http://bioscipublisher.com/index.php/be

Review and Progress Open Access

The Application of Ethanol Fuel: Taking the United States as An Example

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Biological Evidence, 2024, Vol.14, No.1 doi: 10.5376/be.2024.14.0001
Received: 25 Dec., 2023
Accepted: 27 Dec., 2023
Published: 01 Jan., 2024

Preferred citation for this article:
Green Y., 2024, The application of ethanol fuel: taking the United States as an example, Biological Evidence, 14(1): 1-9 (doi: 10.5376/be.2024.14.0001)

Abstract In recent years, with the increasing awareness of global environmental protection, the development of new energy has gradually become a focus of national policies and research. Ethanol fuel, as a renewable energy source, has been widely used worldwide due to its environmental, economic, and safety advantages, and has become an effective way to address national energy security and environmental protection issues. This review aims to explore the application of ethanol fuel in the United States, as well as its related policies, environmental and social impacts, and future development trends. Firstly, an overview of ethanol fuel is introduced, including its raw materials, production process, and common types of ethanol fuels. Next, the application of ethanol fuel in the United States is analyzed, including its historical and current development trends. Policies related to ethanol fuel are also discussed, including legislation and regulation, tariffs, and tax incentives. In addition, the environmental and social impacts of ethanol fuel are analyzed, including its demand for land and water resources and its impact on food prices. Finally, this review looks at the future development trends of ethanol fuel, including its future prospects and development trends, as well as competition and integration with other renewable energy sources.
Keywords Ethanol fuel; United States; Application; Policy; Market demand

Ethanol (CH_3CH_2OH) originated in the early 20th century and is currently the most popular biofuel on the world market. In the 1930s, fuel ethanol emerged as a gasoline additive in the United States, but it was not widely used at that time for various reasons. The impacts of two oil crises in the 1970s led to a global surge in oil prices and a slowdown in economic growth in industrialized nations, prompting increased emphasis on alternative energy sources that could reduce dependence on petroleum (Zhang et al., 2023; Zhou et al., 2023). During the first oil crisis of 1973, many countries recognized the strategic importance of fuel ethanol and began vigorously supporting the industry, especially in nations rich in biomass resources but lacking in petroleum reserves. Environmental concerns played a significant role in shaping policies and regulations favoring fuel ethanol. Currently, global fuel ethanol production stands at nearly 27 billion gallons, with the United States being the largest producer and consumer. In 2017, the United States produced nearly 15.8 billion gallons, accounting for 58% of the global production, surpassing the combined output of all other countries (http://www.las.hitech.cas.cn/cygs/201810/t20181015_453076.htm).

Henry Ford used the term "fuel of the future" to describe ethanol. It is used as an alternative fuel for two primary reasons: it is produced from renewable agricultural products like corn, sugar, and molasses rather than non-renewable petroleum products, and it is less toxic than other alcohol-based fuels. The byproducts of incomplete oxidation of ethanol, such as acetic acid and acetaldehyde, are less toxic than those formed by other alcohol-based fuels. Ethanol fuel, as a novel clean energy source, has garnered widespread attention and research. It is considered a significant alternative to traditional petroleum fuels, capable of reducing greenhouse gas emissions, promoting sustainable development, and simultaneously fostering the growth of agriculture and industry.

This review will use the United States as an example to explore and analyze the application of ethanol fuel. Firstly, an overview of ethanol fuel, including its raw materials, production process, and common types, will be introduced. Subsequently, the review will provide a detailed account of the application of ethanol fuel in the United States, discussing its historical development and current trends. It will also cover policies and regulatory measures related to ethanol fuel, such as legislation, regulations, tariffs, and tax incentives. This review will also delve into the environmental and social impacts of ethanol fuel, such as reducing greenhouse gas emissions and promoting sustainable development. Additionally, it will explore the advantages and disadvantages of ethanol fuel, including its impact on food supply and lower energy density issues. Finally, the review will analyze the future prospects and development trends of ethanol fuel, discussing its role and challenges in the energy transition. This comprehensive review aims to provide readers with valuable information and insights to promote the broader application and development of ethanol fuel. It will offer a holistic analysis of the application and development trends of ethanol fuel in the United States, examining its environmental, social, and economic impacts and advantages, while also addressing the issues and controversies it faces. We hope to contribute to the readers' understanding and stimulate further adoption and growth of ethanol fuel.

1 Ethanol Fuel Overview

1.1 Raw materials

Ethanol fuel, also known as ethanol gasoline or bioethanol, is a green energy source that can replace traditional petroleum fuels. It finds wide applications in the fields of transportation and industry. The primary source of its raw materials is biomass and waste materials, which are converted through biotechnology and fermentation techniques. The selection and utilization of raw materials for ethanol fuel production may vary across different regions and countries. To promote the sustainable development of ethanol fuel, research and development of various biomass materials, as well as the enhancement of conversion efficiency and reduction of production costs, will be crucial directions for the future development of the ethanol fuel industry.

In the United States, corn is the primary raw material for ethanol fuel production (Figure 1). According to data from the U.S. Energy Information Administration (EIA), in 2019, over 90% of the ethanol fuel produced in the United States came from corn. Additionally, data from the U.S. Grains Council indicates that the corn production in the United States reached nearly 13.4 billion bushels in the 2019-2020 period, with approximately 38% of it being used for ethanol fuel production. This highlights the significant role that corn plays in ethanol fuel production in the United States. Furthermore, corn is one of the major staple crops in the United States, extensively used in food and animal feed production.

Figure 1 Corn is the main feedstock for the production of ethanol fuel (Photo by Bing)

Cellulose is also one of the main raw materials for ethanol fuel production. Cellulose is a potentially renewable, cleaner-burning, and carbon-neutral gasoline alternative. Materials considered for cellulose biofuels include plant substances from agricultural residues, yard waste, sawdust, and paper (Sun et al., 2003). Professors R. Malcolm Brown Jr. and David Noble Jr. at the University of Texas at Austin developed a type of blue-green algae that has the potential to produce cellulose, glucose, and sucrose, with the latter two being easily converted into ethanol. This provides the possibility of ethanol production without the need for plant materials.

Sugar is also a common raw material for ethanol fuel production. Producing ethanol from sugar is simpler than converting corn into ethanol. Converting sugar only requires a yeast fermentation process, whereas converting corn requires additional cooking and enzyme application. Furthermore, the energy required for sugar conversion is about half that of corn, and the energy produced by sugarcane is sufficient to cover the conversion energy. A report from the U.S. Department of Agriculture in 2006 found that, at market ethanol prices, converting sugarcane, sugar beets, and molasses into ethanol would be profitable. By mid-2009, the first three sugarcane-based ethanol production facilities were operational in Louisiana.

Other materials such as cheese whey, barley, potato waste, beverage waste, brewery, and distillery waste can also be used as raw materials for ethanol fuel, but their scale is significantly smaller compared to corn and sugarcane ethanol, as facilities using these materials can produce only 3 to 5 million gallons (11×103 to 19×103 cubic meters) annually.

1.2 Production process

Ethanol fuel, as a renewable energy source, involves several processes in its production, including raw material handling, fermentation, separation, additives, storage, and distribution. It encompasses critical steps such as biomass conversion, fermentation, and distillation, making it an environmentally friendly and sustainable alternative energy source. In the future, with continuous technological innovation and optimization, the production process of ethanol fuel will further enhance efficiency and reduce costs, contributing more to the development of sustainable energy.

The primary raw materials for ethanol fuel are derived from biomass, including various plant materials such as corn, wheat, sugarcane, and wood. Before the production process begins, biomass needs to be collected and pretreated. The collection process involves crop cultivation and harvesting, as well as the logging and processing of wood. Pretreatment includes activities like chopping and grinding biomass to increase its surface area, facilitating subsequent enzyme action and saccharification reactions.

Biomass conversion is one of the core steps in ethanol fuel production. During this stage, pre-treated biomass is heated and processed to convert polysaccharides such as starch and cellulose into fermentable sugars. Saccharification reactions are achieved by adding enzymes or other catalysts to convert starch into glucose and cellulose into xylose and glucose, providing raw materials for subsequent fermentation. The resulting sugar solution is introduced into a fermentation tank, where, under the action of microorganisms, sugars like glucose and xylose are converted into ethanol and carbon dioxide. Common fermentation microorganisms include brewer's yeast (Saccharomyces cerevisiae) and Escherichia coli. The fermentation process typically requires controlling parameters such as temperature and pH to ensure optimal fermentation outcomes.

After fermentation, ethanol forms a mixture with fermentation by-products, and separation of ethanol is achieved through distillation and purification. Ethanol has a lower boiling point, allowing it to be extracted from the mixture through distillation. This process also involves further purification to remove impurities, ensuring ethanol's purity meets fuel standards.

Dehydration is a critical step in ethanol fuel production because ethanol and water form an azeotrope, and a series of separation and dehydration techniques are necessary to remove water from ethanol to obtain high-purity ethanol fuel. Common dehydration methods include molecular sieve adsorption and steam dehydration. Once high-purity ethanol is obtained, it needs special additives to enhance the stability and longevity of ethanol fuel. These additives include preservatives, antioxidants, and detergents.

Following dehydration and purification, the obtained ethanol fuel meets fuel standards and can be used in transportation, industrial production, and other applications. Ethanol fuel is typically stored in sealed containers to prevent contamination by water and impurities. Ethanol fuel distribution commonly involves pipeline transport or tanker truck delivery to terminal sales points such as gas stations. The final product of ethanol fuel can be of different blends, such as E10 (containing 10% ethanol), E85 (containing 85% ethanol), and so on. Its application is continually expanding, making a positive contribution to achieving clean energy and sustainable development.

1.3 Classification of ethanol fuel

Ethanol fuel production and types are diverse, and ethanol fuels can be classified into various categories based on their ethanol content. In the United States, the most common ethanol fuel is E10, which is a blend of 10% ethanol and 90% gasoline. E10 fuel holds a market share of over 90% in the United States, and most gas stations offer E10 fuel.

In addition to E10, there are other types of ethanol fuels, such as E15 and E85. E15 refers to a fuel blend containing 15% ethanol and 85% gasoline, and it currently has a lower market share in the United States. According to data from the U.S. Energy Information Administration (EIA), as of the end of 2019, E15 was only permitted for sale at selected gas stations in a few states, with a market share of less than 1%. Among them, the largest sales market was in Minnesota, where over 360 gas stations sell E15 fuel.

E85, on the other hand, is a fuel blend composed of 85% ethanol and 15% gasoline, primarily used in some flexible fuel vehicles (FFVs). These vehicles can use E85 while also being compatible with gasoline. According to data from the U.S. Grains Council for the 2019/2020 period, the total production of E15 fuel in the United States was only about 150 million gallons, while the total production of E85 fuel was approximately 1.38 billion gallons. Additionally, there are flexible fuel vehicles (FFVs) that can use various ethanol fuel blends, including E10, E15, E85, and more, making them adaptable to different ethanol fuel ratios. While this type of vehicle has gained some level of promotion in the United States, its market share remains relatively low.

2 Ethanol Fuel Application in the United States

2.1 Historical development of ethanol fuel in the United States

In 1826, Samuel Morey conducted experiments with an internal combustion chemical mixture, using ethanol (combining turpentine with the surrounding air, then vaporizing it) as fuel. At that time, his discovery was largely overlooked, primarily due to the success of steam power. It wasn't until 1860 when Nicholas Otto began experimenting with internal combustion engines that ethanol fuel gained attention. In 1859, the discovery of oil in Pennsylvania provided a new fuel source decades later. Before the use of oil, a popular fuel mixture in the United States was a combination of alcohol and turpentine, known as "camphene," also referred to as "burning fluid." The discovery of oil and unfavorable taxation on burning fluid made kerosene a more favored fuel.

In 1896, Henry Ford designed his first car, the "Quadricycle," which ran on pure ethanol. In 1908, the revolutionary Model T car (Figure 2) designed by Ford could run on gasoline, ethanol, or a mixture of fuels. Even during the Prohibition era, Ford continued to advocate for ethanol fuel, but lower prices favored gasoline.

Figure 2 Ford Model T (Photo by Bing)

In the late 1970s, gasoline with ethanol content as high as 10% began a decades-long growth in the United States. The discovery of methyl tert-butyl ether (MTBE) contaminating groundwater stimulated the demand for ethanol production from corn. Due to the 1992 Clean Air Act Amendment that mandated the reduction of carbon monoxide emissions, MTBE was widely used as an oxygenate additive. By 2006, the use of MTBE in gasoline had been banned in nearly 20 states. Suppliers were concerned about potential lawsuits and a 2005 court ruling denying legal protection for MTBE. The fall from favor of MTBE opened a new market for its primary alternative, ethanol. At that time, corn prices were around $2 per bushel. Farmers saw a new market and increased production. This shift in demand occurred amid rising oil prices.

The rapid growth in ethanol consumption in the 21st century was driven by federal legislation aimed at reducing petroleum consumption and enhancing energy security. The Energy Policy Act of 2005 required the use of 7.5 billion gallons of renewable fuel by 2012, and the Energy Independence and Security Act of 2007 raised this standard to 36 billion gallons of renewable fuel per year by 2022. Within this demand, 21 billion gallons had to be advanced biofuels, which are renewable fuels that reduce greenhouse gas emissions by at least 50%.

2.2 Ethanol fuel production capacity and output in the United States

The United States is currently the world's largest producer and consumer of automotive ethanol gasoline. The use of ethanol fuel in the United States has a history spanning several decades, gradually gaining popularity since the 1970s. Ethanol fuel has a significant market share in the United States, with 50 states already utilizing ethanol gasoline for vehicles (Figure 3). The application of ethanol fuel in the United States is also very diverse, primarily used in the transportation sector, including automobiles, trucks, and public transportation. Additionally, ethanol fuel can find applications in power generation, heating, and other fields (Xu and Fang, 2007).

Figure 3 Ethanol fuel concept (Photo by Bing)

In 2010, the ethanol production in the United States reached 13.2 billion gallons (49.95 billion liters), accounting for 57.5% of the global production. Brazil was the second-largest producer with 6.92 billion gallons (26.19 billion liters). Together, the United States and Brazil contributed to 88% of the world's total ethanol production, which amounted to 22.95 billion gallons (86.85 billion liters). As of December 2010, the ethanol production industry in the United States consisted of 204 operational plants in 29 states, with nine additional plants under construction or expansion, adding a capacity of 560 million gallons. This brought the total installed capacity in the United States to 14.6 billion gallons (55.25 billion liters). By the end of 2010, over 90% of all gasoline sold in the United States was blended with ethanol.

The current ethanol fuel production and consumption in the United States have been steadily increasing year by year. In 2017, there were 211 corn-based ethanol biorefineries in operation and six under construction in the United States, spread across 28 states, with a total production capacity of 16.2 billion gallons. Since the early 1980s when the United States began promoting the use of ethanol fuel, production and consumption have steadily increased. In 2017, records were set with 15.8 billion gallons of ethanol fuel, 4.14 million tons of animal feed, and 3.6 billion pounds of distillers' oil (source: http://www.las.hitech.cas.cn/cygs/201810/t20181015_453076.htm).

2.3 The import and export situation of ethanol fuel in the United States

In 2017, the United States exported nearly 1.4 billion gallons of fuel ethanol, surpassing the previous record set in 2011 at 1.2 billion gallons. During the same year, the import of ethanol into the United States increased compared to 2016, but the relative quantity was much lower, standing at 77 million gallons, marking the country's eighth consecutive year as a net exporter of ethanol. With corn production and ethanol capacity surpassing domestic ethanol consumption, the United States maintained an upward trend in fuel exports for eight consecutive years. By 2017, the U.S. exported fuel ethanol to 35 countries, with over half of the exports going to Brazil and Canada.

The fuel ethanol exports to Brazil from the United States have seen a continuous four-year growth, reaching 450 million gallons in 2017, constituting nearly one-third of the total U.S. fuel ethanol. Canada stands as the second-largest destination market for U.S. fuel ethanol exports, importing nearly 33 million gallons in 2017, marking a 5% increase from the previous year. In 2016, China became the third-largest importing country for U.S. fuel ethanol.

3 Policies and Regulations of Ethanol Fuel

3.1 Legislation and regulation

In 2007, the Energy Independence and Security Act instructed the Department of Energy to assess the feasibility of using mid-level ethanol blends in existing vehicles. The National Renewable Energy Laboratory (NREL) evaluated the potential impacts on legacy vehicles and other engines. In October 2008, NREL released a preliminary report describing the effects of E10, E15, and E20 on exhaust and evaporative emissions, catalyst and engine durability, vehicle drivability, engine operability, and vehicle and engine materials. The report found that no vehicles displayed fault indicator lights, no symptoms of fuel filter plugging were observed, no cold-start issues were observed under laboratory conditions (24 °C (75°F) and 10 °C (50°F)), and all test vehicles exhibited fuel economy losses proportional to the lower energy density of ethanol. For instance, compared to natural gas (E0) test vehicles, E20 showed an average fuel economy reduction of 7.7%.

The Obama administration set a goal to install 10,000 blender pumps across the country by 2015. These pumps can dispense various blends, including E85, E50, E30, and E20, which can be used by E85 vehicles. In May 2011, the U.S. Department of Agriculture (USDA) issued a regulation that included flex-fuel pumps under the Rural Energy for America Program (REAP). This ruling provided financial assistance to gas station owners for installing E85 and blender pumps through grants and loan guarantees.

In May 2011, with bipartisan support, the Open Fuel Standard Act (OFS) was introduced to Congress. This bill required that by 2014, 50% of vehicles produced, by 2016, 80% of vehicles produced, and by 2017, 95% of vehicles produced must be manufactured and warranted to run on non-petroleum fuels. These fuels include flexible fuels, natural gas, hydrogen, biodiesel, plug-in electric vehicles, and fuel cells, among other existing technologies. Considering the rapid adoption of flexible-fuel vehicles in Brazil and the relatively low cost of making a vehicle flexible-fuel (approximately $100 per vehicle), the primary goal of this bill was to promote the widespread adoption of flexible-fuel vehicles capable of running on ethanol or methanol fuels.

In November 2013, the U.S. Environmental Protection Agency (EPA) sought public opinions on reducing the volume of ethanol required in the U.S. gasoline supply, in accordance with the 2007 Energy Independence and Security Act. The agency pointed out the challenges of increasing ethanol blend percentages to above 10%. This limitation is referred to as the "blend wall," signifying the practical difficulties in introducing increasing amounts of ethanol into the transportation fuel supply, exceeding the quantity achieved by selling almost all gasoline as E10.

3.2 Tariffs and tax incentives

From the 1980s to 2011, U.S. ethanol producers were protected by a 54-cent-per-gallon import tariff primarily aimed at restraining the import of Brazilian sugarcane ethanol. Starting in 2004, blender pumps received a tax credit for every gallon of ethanol blended into transportation fuels. Historically, the tariff was designed to offset the federal tax credits applicable to ethanol, regardless of the country of origin. Several countries in the Caribbean

Basin import and further process Brazilian ethanol, typically converting hydrated ethanol to anhydrous ethanol before exporting it to the United States. They benefited from the Caribbean Basin Initiative (CBI) and free trade agreements, avoiding the 2.5% tariff and tax credits. This process was limited to within 7% of U.S. ethanol consumption.

As of 2011, blender pumps received a tax credit of 45 cents per gallon, regardless of the feedstock used. Small producers received an additional 10 cents on the first 15 million gallons, while cellulosic ethanol producers were eligible for credits of up to $1.01 per gallon. The tax credits aimed at promoting biofuel production and consumption can be traced back to the 1970s. In 2011, these credits were based on the 2005 Energy Policy Act, the 2008 Food, Conservation, and Energy Act, and the 2008 Energy Improvement and Extension Act.

The Congressional Budget Office (CBO) conducted a study in 2010 and found that in the 2009 fiscal year, biofuel tax credits reduced federal revenue by approximately $6 billion, with corn ethanol and cellulosic ethanol accounting for $5.16 billion and $50 million, respectively. The CBO estimated that the cost to taxpayers for reducing one gallon of gasoline consumption was $1.78 for corn ethanol and $3.00 for cellulosic ethanol. Similarly, without considering the potential indirect land use effects, the cost to taxpayers for reducing greenhouse gas emissions through tax credits was approximately $750 per metric ton of CO_2 equivalent for ethanol and about $275 per metric ton for cellulosic ethanol.

On June 16, 2011, the U.S. Congress passed an economic development bill amendment, which eliminated tax credits and tariffs. However, this bill did not advance further. Nevertheless, the U.S. Congress did not extend the tariffs and tax incentives, allowing both to expire on December 31, 2011. Since 1980, the ethanol industry had received approximately $45 billion in subsidies (Khanna et al., 2008).

3.3 Sustainable development strategies

Sustainable development of the U.S. ethanol fuel industry is an important issue, and for this purpose, the government has implemented a series of strategies to ensure sustainable management of biomass resources and sustainable production of ethanol fuel. By enhancing biomass resource management and establishing sustainable production standards, the U.S. government is committed to promoting the sustainable development of the ethanol fuel industry. The implementation of these strategies will help ensure the sustainability of ethanol fuel's feedstock sources and improve the sustainability and resource utilization efficiency of the production process. This not only aligns with environmental protection and sustainable resource utilization requirements but also contributes to driving the transition to clean energy and reducing dependence on traditional fossil fuels.

The government strengthens the management of biomass resources to promote their sustainable utilization. Through the formulation of relevant policies and regulations, the government strives to ensure the responsible development and utilization of biomass resources, thus preventing over-harvesting and ecological damage. The government also encourages farmers and forestry sectors to adopt sustainable agricultural and forestry practices to ensure a sustainable supply of biomass resources. This not only helps protect biodiversity but also reduces reliance on traditional energy sources.

The government also establishes production standards for ethanol fuel to enhance sustainability and resource utilization efficiency. These standards include environmental protection requirements and energy efficiency criteria, encouraging production enterprises to adopt sustainable production technologies and processes. The government may provide financial and tax incentives to encourage businesses to invest in environmentally friendly facilities and energy-saving equipment, reducing water, energy, and raw material consumption. Furthermore, the government may incentivize businesses to engage in research and development activities to drive innovation in the ethanol production process, thus improving resource utilization efficiency and reducing environmental impacts.

4 Ethanol Fuel's Environmental and Social Impact on the United States

Ethanol fuel, as a renewable energy source, has wide-ranging effects on the environment and society in the United States. Its production and usage involve various stages such as biomass harvesting, production processes, transportation, and consumption, which have significant impacts on aspects including the environment, energy security, and the economy.

4.1 Environmental impact

Regarding the environment, the application of ethanol fuel can reduce petroleum use, consequently lowering greenhouse gas emissions. Studies have shown that ethanol fuel can reduce the emissions of harmful substances such as carbon dioxide, carbon monoxide, and nitrogen oxides into the atmosphere (Farrell et al., 2006). However, the use of ethanol fuel also poses certain environmental challenges.

The primary feedstock for ethanol fuel is corn, and the cultivation of corn and the production of ethanol fuel require significant land and water resources. According to data from the U.S. Environmental Protection Agency, producing one gallon of ethanol fuel consumes between 2,500 and 29,000 gallons of water, potentially putting pressure on local water resources (Dominguez-faus et al., 2009). If these resources are acquired and utilized improperly, it can have consequences on water and energy supplies and, in turn, lead to irreversible effects on ecosystems (Searchinger et al., 2008). Furthermore, the application of ethanol fuel can result in excessive land clearing and loss of biodiversity (Fargione et al., 2008). The production and transportation of ethanol fuel require substantial energy and chemical substances, which can also have adverse environmental impacts.

4.2 Food impact

The production of ethanol fuel requires substantial amounts of food and water resources, which can lead to food supply shortages and price increases, thereby having adverse effects on agricultural production and food security. The production of ethanol fuel heavily relies on crops such as corn, which can affect food prices. According to data from the United States National Agricultural Statistics Service and the U.S. Energy Information Administration (EIA), ethanol fuel production in the United States has shown significant growth. Since 2000, U.S. ethanol fuel production has increased from approximately 1.7 billion gallons to about 16 billion gallons in 2019. Since 2005, ethanol fuel production has become a major consumer of U.S. corn, which has had an impact on the corn market. According to the U.S. Department of Agriculture's data, the proportion of U.S. corn used for ethanol production has increased from about 15% in 2000 to approximately 38% in 2019. This means that a significant amount of corn is being used for ethanol production rather than as food or animal feed. As the demand for ethanol fuel production continues to rise, there may be pressure on corn supplies, potentially leading to higher corn prices. This can be a challenge for both farmers and consumers, especially those who rely on corn as a primary food source.

Furthermore, because food resources are used for ethanol production, this can have negative consequences for agricultural production and food security. Farmers may face greater pressure to plant crops, while the prices of other agricultural products may also be affected. Additionally, food supply shortages can have global implications for food security and result in rising food prices.

4.3 Energy use impact

The production and transportation of ethanol fuel consume significant amounts of energy, which can also have negative environmental impacts. According to data from the U.S. Energy Information Administration, in 2019, the production of ethanol fuel in the United States consumed over 150 million tons of corn and 22 million tons of natural gas, among other resources. The production process also results in substantial greenhouse gas emissions.

Additionally, ethanol fuel has a lower energy density compared to traditional fuels, which means that more fuel is needed to provide the same amount of energy. This results in relatively shorter driving ranges for vehicles. There are also issues related to heterogeneity and compatibility among different types of ethanol fuels, which can lead to certain vehicles being unable to use specific types of ethanol fuel, limiting their applicability.

4.4 Social impact

In the realm of society, the application of ethanol fuel can create employment opportunities and boost agricultural income in the United States. The production of ethanol fuel requires substantial quantities of corn, sugar beets, and other crops, providing American farmers with a new market. However, the use of ethanol fuel also presents some social issues. For instance, ethanol fuel production may lead to an increase in the prices of crops, which can have adverse effects on consumers. Overreliance on crops such as corn for ethanol production, along with resource mismanagement, could potentially result in food shortages and increased food prices, thus affecting social stability.

Furthermore, ethanol fuel is typically more expensive than traditional fuels, imposing a certain economic burden on the lives of U.S. residents. The production and utilization of ethanol fuel can also impact the agricultural and energy sectors, potentially leading to changes in employment and income. According to data from the U.S. Department of Agriculture, in 2019, the American ethanol fuel industry created over 300,000 employment opportunities locally.

5 Outlook

The future development trends of the United States, as a significant producer and consumer of ethanol fuel, are under close scrutiny. Ethanol fuel, as a renewable and environmentally friendly energy source, holds broad prospects for application. With the growing awareness of sustainable energy and environmental protection, the ethanol fuel industry will play an even more vital role in the future.

As government environmental policies continue to strengthen, ethanol fuel will gradually replace traditional petroleum fuels, becoming a significant alternative in the U.S. transportation sector. Government subsidies and incentive programs will encourage more people to purchase and use ethanol-fueled vehicles, especially those capable of using various ethanol-gasoline blends such as E10, E15, E85, reducing vehicle carbon emissions and lessening environmental impact.

The ethanol fuel industry in the United States will continue to experience steady growth, with technological innovation and research and development investment serving as essential drivers for industry development. Ongoing improvements in biomass conversion technologies will enhance ethanol production efficiency and yield, while research into advanced ethanol fuels like cellulosic ethanol will broaden the sources of ethanol production and enhance sustainability. Additionally, the intelligent and digital transformation of ethanol fuel will further increase the industry's competitiveness and adaptability in the market.

The production and application of ethanol fuel will also drive the development of urban and rural economies in the United States. Biomass harvesting and fuel production processes will create employment opportunities in rural areas, thereby increasing farmers' income. Simultaneously, the consumption of ethanol fuel will promote the development of ethanol processing plants and sales outlets, driving the expansion and enhancement of related industry chains and stimulating economic growth in urban areas. As a leading nation in the ethanol fuel industry, the United States will actively promote international cooperation and technological exchanges with other countries. Amid the global wave of energy transformation, international collaboration in the ethanol fuel industry will facilitate technological innovation and dissemination, promoting the sustainable development of global energy.

Of course, the development of ethanol fuel in the United States will also face some challenges. For instance, ethanol fuel competes with new energy sources like electric vehicles, which have a broader range of applications and established charging infrastructure. Furthermore, the production and consumption of ethanol fuel must overcome various technical and market difficulties. In the future, the United States will continue to invest more resources and efforts to promote the sustainable development of ethanol fuel, seeking increased cooperation and innovation while addressing technical and market challenges.

As one of the representatives of renewable energy in the United States, ethanol fuel holds a promising outlook. In the future, ethanol fuel will find broader applications in the automotive fuel sector, contributing to the green transformation of the U.S. transportation industry. Additionally, the development of the ethanol fuel industry will stimulate economic growth and sustainability, bolstering the United States' leading position in the global energy sector. Achieving the sustainable development of the ethanol fuel industry requires joint efforts from the government and the industry. Increased focus on technological innovation and policy support is essential to drive the healthy development of the ethanol fuel industry, contributing to a greener energy landscape in the future.

Author's contributions

Yolanda Green conceived and led this research, conducted extensive literature reviews, designed and executed survey analyses, wrote the initial draft of the paper, and thoroughly organized and edited the paper to ensure its quality and accuracy.

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