The United States currently consumes approximately 140 billion gallons of gasoline per year,¹ and produces approximately 8.8 billion gallons of ethanol from corn kernels.² There is no U.S. commercial cellulosic ethanol production plant yet in operation, but last year, the U.S. Department of Energy selected six demonstration projects to produce more than 130 million gallons of cellulosic ethanol per year once fully operational. This article addresses potential environmental impacts and future challenges of the production and use of ethanol as a transportation fuel.

Ethanol

Biomas is an inexpensive, renewable, and abundant source of carbon. Ethanol can be relatively easily produced from carbohydrates, which are abundant in starch crops such as corn and sweet sorghum with the help of fermenting micro-organisms. However, these resources are limited and bioethanol has accounted for recent rising food prices. The non-food-based biomass feedstocks include lignocellulosic agricultural residues such as corn stover and cereal straws, industrial plant waste like sawdust and paper pulp, and energy crops grown specifically for fuel production like switchgrass and algae. It is estimated that the United States can utilize approximately 368 and 998 million dry tons of sustainably removable biomass (total over 1.3 billion dry tons) annually from forestry and agricultural resources, respectively, which is enough to meet more than one-third of the current demand for transportation fuel.³ The production of liquid fuels from biomass sources is particularly attractive as the nation’s transportation infrastructure would require little or no modifications to handle and distribute these fuels. In

Diminishing petroleum resources along with increased demand for petroleum by emerging economies are driving our society to search for new liquid transportation fuels. The Energy Independence and Security Act of 2007 calls for a four-fold increase in the amount of biofuels, such as ethanol, currently produced. This increase, when added to gasoline, is to total 36 billion gallons by 2022. It requires the production of 15 and 21 billion gallons of ethanol from corn kernels and non-food-based biomass, respectively.

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addition, the use of biomass as feedstock would not result in increased atmospheric carbon dioxide (CO₂) emissions as the carbon content of the biomass is part of the active carbon cycle.³⁴

Technical Challenges and Barriers
Cellulosic ethanol production is more difficult than corn ethanol production primarily due to the recalcitrant nature of lignocellulose. Pretreatment is an important process required to alter the recalcitrant structure of cellulosic biomass to make cellulose more accessible to the enzymes used for subsequent hydrolysis process, as shown in Figure 1. Some of the important technical challenges and barriers to overcome are listed below.

- **Biomass Variability.** Biomass characteristics vary widely in terms of physical and chemical composition, size, shape, and bulk density. These variations make it more difficult to supply biorefineries with consistent feedstocks.
- **Biomass Recalcitrance.** Lignocellulosic biomass is inherently resistant to chemical and biological degradation.
- **Pretreatment Chemistry and Costs.** Pretreatment (prehydrolysis) chemistry is not well understood, and the reactors typically require to be constructed with expensive materials to resist acid and alkali attack at elevated temperatures.
- **Enzyme Biochemistry, Loading, and Cost.** Cost-effective and efficient enzymes for C₅ (five-carbon sugars; e.g., glucose) and C₆ (six-carbon sugars; e.g., xylose) with high thermostability and resistance to inhibitory compounds need to be developed.
- **Separation.** Low-cost separation technologies that can selectively remove non-sugar impurities inhibitory to enzymatic hydrolysis and fermentation need to be developed. This will provide concentrated and clean sugar feedstocks to the downstream fermentation process.

Potential Environmental Impacts
Air Quality
Ethanol has been mainly used as an oxygenated fuel additive. Blending ethanol with gasoline increases the octane number due to the high octane number of ethanol (96–113) and reduces the need for toxic octane-enhancing additives such as methyl tertiary butyl ether (MTBE), which has generated many groundwater contamination problems. The oxygen content in ethanol will lead to the reduced emissions of carbon monoxide (CO) and noncombusted hydrocarbons.

Although there is no biorefinery plant for cellulosic ethanol production in the United States, there are many corn-derived fuel ethanol plants available in the country. The Minnesota Pollution Control Agency conducted emissions tests for total and speciated volatile organic compounds (VOCs) with combined U.S. Environmental Protection Agency (EPA) Reference Methods 5 and 18 from corn kernel-derived fuel ethanol plants in the state.⁵ Generally, a large volume of VOC emissions was detected across most plants and emission units, particularly from fermentation scrubbers and fluid-bed coolers (i.e., located after a dryer used to convert residual wet cake into distillers dried grains). Ethanol, acetaldehyde, acetic acid, and ethyl acetate were the pollutants emitted at the highest rates.

Another discussion point regarding ethanol fuel use is whether ethanol burns cleaner than gasoline. During
Brazil’s big ethanol push in the 1970s, Brazil’s air quality worsened and the reason is still unclear. With respect to air pollution, a previous combustion emission study reported that ethanol blending increased acetaldehydes and nitrogen dioxide (NO₂) emissions, but decreased most carbonyls, except formaldehyde and acrolein; compounds derived from aromatics, such as benzaldehyde and tolualdehyde; and CO and NO emissions, compared to gasoline. The major human carcinogens emitted during gasoline and E85 (a mixture of 85% ethanol and 15% gasoline by volume) combustion are formaldehyde, acetaldehyde, 1,3-butadiene, and benzene. Ethanol tends to produce less benzene and butadiene, but more acetaldehyde and formaldehyde than gasoline when combusted. A recent atmospheric modeling study predicted the future air pollution of the continental United States in the year 2020 based on the E85 and 100% gasoline scenarios from automobiles, and evaluated their potential impacts on public health. The study suggested that E85 may increase ozone-related mortality, hospitalization, and asthma by 9% in Los Angeles and/or 4% in the United States as a whole, compared to 100% use of gasoline.

Net energy return and greenhouse gas emissions have been important metrics in evaluating the energy and environmental implications of bioethanol from corn grain and lignocellulosic feedstocks. Appropriate evaluation of these two metrics has been a very contentious issue (especially for corn ethanol) due to different raw materials (e.g., corn grain or lignocellulosic feedstocks), different process configurations (e.g., the use of lignin as a fuel to power the ethanol biorefinery), fossil fuels required to produce bioethanol and fertilizers, and immeasurable quantities such as soil erosion and climate change. However, it is generally accepted that cellulose ethanol can offer very high energy return (> 8:1) and large reductions in greenhouse gas emissions (e.g., 11 and 94 kg CO₂-equivalent per MJ from cellulose ethanol and gasoline, respectively). A recent study based on field trials of switchgrass production on 10 farms in the Great Plains indicated that cellulose ethanol derived from switchgrass could produce a very high energy return (an estimated average of 13.1 MJ of ethanol per 1 MJ of petroleum input for the production, refining, and distribution phases) and approximately 94% lower net CO₂ emissions than gasoline.

**Water Quality**

It has been reported that the reuse of the stillage water coming from the bottom of the distillation column would be limited by various inhibitory compounds generated from the degradation of sugars and the lignin component over the course of various biomass pretreatment technologies. Those inhibitory compounds are divided into three main groups: weak acids, furan derivatives, and phenolic compounds. Weak acids and furan derivatives are derived from hemicellulose/ cellulose, while phenolic compounds are derived from lignin. Inhibitory effects of such compounds on the subsequent fermentation process are known to depend primarily on the combination of biomass materials, pretreatment technologies, and/or hydrolytic/ fermenting microorganisms. In the long term, the development of inhibitor-resistant and robust microorganisms will be required; however, such robust and versatile strains resistant to various compounds have not yet been reported. Therefore, either a separation or detoxification process will need to be developed to recycle the stillage water stream, which will minimize both replacement water consumption and wastewater production.

Different biomass sources for biofuel production have unique implications for water resources. A recent report released by the National Academies’ National Research Council (NRC) warns that corn-based ethanol production will considerably increase degradation of water resources and water quality. It predicts that increased soil erosion and the use of pesticides and herbicides would create low oxygen dead zones in water bodies from fertilizer runoff and more frequent and localized water shortages for drinking and irrigation. The study also suggests that cellulose ethanol is likely to have less impact on water quality per unit of energy gained because corn requires more fertilizer inputs per unit area than lignocellulosic feedstocks and thus generates more severe soil erosion problem. Therefore, the NRC report suggests that policies...
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should promote the development of cellulosic biofuels. Furthermore, the current estimates of consumptive water use by ethanol biorefineries are 4 and 9.5 gallons of water per gallon of ethanol produced from corn kernels and cellulosic feedstocks, respectively. An additional 0.7 billion gal/day of freshwater are likely to be required to meet the annual production of 36 billion gallons of ethanol by 2022, and the estimated amount of freshwater required for the ethanol production would be much less than that required for irrigation and thermoelectric power generation (approximately 305 billion gal/day in 2005). However, it could be regionally problematic, representing an incremental withdrawal from already unsustainable sources. For example, current withdrawals in the High Plains Aquifer (more than 1.5 billion gal/day) are greater than the aquifer’s recharge rate (approximately 0.02–0.05 ft/yr in south central Nebraska) and the loss of this resource is irreversible.

In addition to salt buildup in cooling towers and boilers, wastewater is generated from the processing of byproducts such as stillage and distillers’ grains at corn ethanol facilities. This wastewater potentially contains high biochemical oxygen demand (BOD), and discharge of this high BOD water to rivers and lakes could consume most of the dissolved oxygen in the receiving waters. Cellulosic ethanol plants would have similar water requirements and discharge characteristics as the current corn ethanol plants. Two additional steps of pretreatment and hydrolysis could also produce wastewater streams containing high BOD and would require on-site or off-site treatment.

Accidental fuel spills that may occur at gas stations or during transportation could also generate a negative impact on water quality. While ethanol is completely soluble in water, and rapidly biodegraded under most conditions, the rapid biodegradation of ethanol in blending fuels such as E85 may inhibit the biodegradation of more toxic gasoline compounds, and enable the compounds to migrate farther off site.

Future Challenges and Opportunities

There are currently no full-scale plants for the production of cellulosic ethanol. However, several technical challenges need to be resolved if cellulosic ethanol is to achieve its potential as a renewable alternative fuel. The main challenges and opportunities for environmental professionals are to:

- conduct and obtain extensive combustion performance and emissions data with different ethanol blends using existing and modified combustion engines;
- obtain more emission inventories of existing food-derived and future non-food-derived ethanol production facilities;
- construct projected new emission inventories from ethanol production facilities and automobiles with respect to different blending scenarios;
- conduct rigorous air quality studies based on the new emission inventories and its associated impacts on public health;
- further develop performance metrics for life-cycle assessments of bioethanol such as greenhouse gas emissions, soil erosion, and fossil fuel inputs;
- increase process integration to reduce the number of process steps, the energy demand, and to re-use process streams to minimize the use of freshwater and reduce the amount of waste streams;
- construct a water resources database to be used for future site selection of cellulosic ethanol plants along with future plans for wastewater treatment; and
- establish a protective protocol for accidental spills and develop remediation technologies.

References