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Ethanol Blending from Sugarcane: A Climate Mitigation Strategy for Emerging Economies

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Climate change is one of the most pressing global challenges of the 21st century, driven primarily by the rapid increase in greenhouse gas (GHG) emissions from fossil fuel combustion, land-use change, and industrial activities. The transport sector alone contributes nearly one-quarter of global energy-related CO_2 emissions. Developing countries such as India face a dual challenge: ensuring energy security for a growing population while simultaneously reducing carbon emissions to meet international climate commitments. India is heavily dependent on imported crude oil, with imports accounting for more than 85% of its total petroleum consumption. This dependency exposes the country to global price volatility, geopolitical risks, and rising carbon emissions. In this context, biofuels, particularly ethanol, have emerged as an essential renewable energy alternative. Ethanol blending with petrol is a key component of India's National Bio-Energy Mission. Sugarcane, due to its high biomass productivity and fermentable sugar content, has become the dominant feedstock for ethanol production in India. The Ethanol Blended Petrol (EBP) Programme aims to achieve 20% ethanol blending (E20) nationwide, advancing both energy security and climate mitigation goals. However, while sugarcane-based ethanol is often promoted as a "green fuel," it has generated debate regarding its actual environmental benefits, especially concerning water use, land competition, and lifecycle emissions. This report critically examines the role of sugarcane-based ethanol blending in mitigating climate change, focusing on its environmental, economic, and social dimensions in the Indian context.

Climate Change and the Transport Sector

Greenhouse Gas Emissions from Transport

The transport sector is one of the fastest-growing sources of greenhouse gas emissions globally. Road transport, dominated by petrol and diesel vehicles, is a major contributor to CO_2 emissions, nitrogen oxides (NOx), particulate matter, and other pollutants. In India, rapid urbanization, rising incomes, and increased vehicle ownership have significantly increased fuel consumption. Fossil fuels release carbon that has been stored underground for millions of years, adding "new" carbon to the atmosphere. This accumulation enhances the greenhouse effect, leading to rising global temperatures, extreme weather events, melting glaciers, sea-level rise, and disruptions to ecosystems and agriculture.

Role of Biofuels in Climate Mitigation

Biofuels are derived from biological materials such as crops, agricultural residues, and organic waste. Ethanol, when blended with petrol, partially replaces fossil carbon with biogenic carbon. Since plants absorb CO_2 during photosynthesis, the carbon released during ethanol combustion is considered part of a short-term carbon cycle.

Sugarcane as a Feedstock for Ethanol Production

Characteristics of Sugarcane

Sugarcane (*Saccharum officinarum* L.) is a C_4 photosynthetic plant characterized by exceptionally high photosynthetic efficiency, rapid growth, and superior biomass

accumulation. Due to its efficient carbon fixation mechanism, sugarcane is capable of producing large quantities of fermentable sugars within a relatively short growing period. Under Indian agro-climatic conditions, sugarcane yields typically range from 60 to 100 tonnes per hectare, with sucrose content varying between 10–16%, making it one of the most efficient feedstocks for bioethanol production. One of the significant sugarcane advantages lies in its high ethanol yield per unit area, which surpasses that of most cereal- and tuber-based feedstocks. The crop benefits from well-established cultivation practices, improved varieties, and extensive research support in India. Furthermore, sugarcane-based ethanol production is strongly supported by an existing integrated infrastructure of sugar mills and distilleries, enabling efficient conversion of sugarcane juice, molasses, and by-products into ethanol. Additionally, by-products such as bagasse and press mud can be utilized for cogeneration of energy and organic manure, respectively, enhancing overall resource-use efficiency and economic sustainability of the sugarcane–ethanol value chain.

Sources of Ethanol from Sugarcane

Sugarcane serves as a versatile and renewable feedstock for ethanol production through multiple pathways. The primary source is sugarcane juice, which contains high concentrations of fermentable sugars such as sucrose, glucose, and fructose. Direct fermentation of juice yields high-quality ethanol and is increasingly adopted during surplus sugar seasons. The second major source is molasses, a by-product of sugar manufacturing. Molasses-based ethanol production is well established in India due to its year-round availability, lower cost, and compatibility with existing distillery infrastructure. In addition, bagasse, the fibrous residue left after juice extraction, represents a promising second-generation (2G) ethanol source. Bagasse can be converted into ethanol through pretreatment and enzymatic hydrolysis followed by fermentation, contributing to waste utilization and improved energy efficiency. Emerging sources also include press mud and cane trash, which can be processed for bioethanol production after suitable biochemical or thermochemical conversion. Collectively, these diverse sources enhance the sustainability, flexibility, and economic viability of sugarcane-based ethanol production systems.

Ethanol Blending Programme in India

Evolution of the EBP Programme

The Ethanol Blended Petrol (EBP) Programme in India was launched in 2003 with the objective of reducing dependence on imported fossil fuels, promoting renewable energy, and supporting the sugarcane sector. Initially, the programme mandated 5% ethanol blending in petrol in selected states and Union Territories, but progress remained limited due to irregular ethanol supply and pricing issues. A major push came after 2014, when the Government of India introduced policy reforms such as administered ethanol pricing, long-term procurement contracts, and interest subvention schemes for distillery capacity expansion. In 2018, the National Bio-Energy Mission strengthened the EBP framework, enabling the use of multiple feedstocks, including sugarcane juice, B-heavy molasses, damaged food grains, and agricultural residues. Subsequently, the blending target was advanced from 20% by 2030 to 2025–26, reflecting strong policy commitment (Niti Aayog 2021). The EBP Programme has since evolved into a key component of India's energy transition strategy, contributing to energy security, rural income generation, and greenhouse gas emission reduction.

Policy and Institutional Support

The Government of India has provided strong policy and institutional support to promote ethanol production and blending under the Ethanol Blended Petrol (EBP) Programme. Key initiatives include administered ethanol pricing, assured offtake by Oil Marketing Companies (OMCs), and long-term procurement contracts, which provide price stability to producers. The National Policy on Biofuels (2018, amended 2022) expanded permissible feedstocks and encouraged second-generation (2G) ethanol production. Financial support mechanisms such as interest subvention schemes, viability gap funding, and tax incentives have facilitated distillery capacity expansion. Institutional coordination among the Ministry of Petroleum &

Natural Gas, Ministry of Agriculture, and Ministry of Food ensures effective implementation of ethanol-related policies.

Ethanol Blending and Climate Change Mitigation

Reduction in Greenhouse Gas Emissions

Ethanol blending with petrol significantly contributes to the reduction of greenhouse gas (GHG) emissions by partially replacing fossil fuels with a renewable, plant-based alternative. Sugarcane-based ethanol has a lower life-cycle carbon footprint, as the carbon dioxide released during combustion is largely offset by CO_2 absorbed during crop growth through photosynthesis. Studies indicate that ethanol blending can reduce carbon monoxide, hydrocarbons, and net CO_2 emissions from vehicles. Higher blending levels, such as E10 and E20, further enhance emission mitigation. Additionally, the utilization of by-products and adoption of energy-efficient distillery technologies improve overall emission savings, supporting climate change mitigation and sustainable energy goals.

Carbon Neutrality and Biogenic Carbon Cycle

Sugarcane-based ethanol is often considered carbon neutral due to its involvement in the biogenic carbon cycle. During growth, sugarcane absorbs atmospheric carbon dioxide through photosynthesis and converts it into biomass and fermentable sugars. When ethanol produced from sugarcane is combusted, the released CO_2 is approximately equal to the amount previously absorbed by the crop, resulting in no net addition of carbon to the atmosphere. This closed carbon loop contrasts with fossil fuels, which release long-stored carbon. When combined with efficient cultivation practices and low-emission processing technologies, sugarcane ethanol supports climate mitigation and sustainable energy transitions.

Co-benefits for Air Quality

Ethanol blending in petrol provides significant co-benefits for air quality by reducing emissions of harmful air pollutants from vehicles. Ethanol is an oxygenated fuel, which promotes more complete combustion, leading to lower emissions of carbon monoxide (CO), unburnt hydrocarbons, and particulate matter. Blends such as E10 and E20 also help decrease the formation of toxic compounds like benzene and other aromatic hydrocarbons. Improved combustion efficiency reduces exhaust toxicity, particularly in urban areas with high vehicular density. Consequently, ethanol blending contributes to cleaner ambient air, reduced health risks, and improved overall urban environmental quality.

Water, Land, and Environmental Concerns

Water Footprint of Sugarcane

Sugarcane is a highly water-intensive crop, requiring approximately 1500–2500 mm of water per crop cycle, depending on climate, soil type, and management practices. Large-scale expansion of sugarcane cultivation to meet ethanol demand can exert significant pressure on local water resources. Excessive irrigation often leads to groundwater depletion, declining water tables, and reduced availability of water for drinking and other agricultural uses. Continuous extraction of surface water can also stress river basins, especially in semi-arid regions. States such as Maharashtra and parts of Karnataka have experienced water conflicts due to competing demands from agriculture, industry, and domestic sectors. These challenges highlight the need for efficient irrigation practices and region-specific crop planning.

Land-Use Change and Carbon Debt

The expansion of sugarcane cultivation to meet rising ethanol demand can result in significant land use changes. Productive land traditionally used for food crops may be diverted to sugarcane, potentially affecting food security and crop diversity. Large-scale monocropping can also lead to the loss of biodiversity, disrupt local ecosystems, and reduce habitat availability for flora and fauna. Intensive cultivation practices may further contribute to soil degradation, including nutrient depletion and increased erosion. Moreover, if natural ecosystems such as forests or grasslands are converted into sugarcane fields, substantial

amounts of stored carbon are released into the atmosphere. This initial emission, known as "carbon debt," can offset or even negate the long-term climate benefits of ethanol production.

Pollution from Distilleries

Distillery effluents, particularly spent wash, are highly concentrated organic waste streams with elevated biological and chemical oxygen demand. If discharged without proper treatment, they can contaminate soil, groundwater, and surface water bodies, adversely affecting ecosystems and human health. However, adoption of zero-liquid discharge (ZLD) technologies, including evaporation, incineration, and condensate recycling, significantly reduces pollution. Additionally, bio-composting of spent wash with press mud converts waste into nutrient-rich organic manure, promoting sustainable waste management and minimizing the environmental footprint of ethanol distilleries.

Food vs Fuel Debate

The use of sugarcane juice for ethanol production has intensified the food versus fuel debate, as it may divert agricultural resources away from food and sweetener production. In a country like India, where food security remains a critical concern, prioritizing fuel over food raises ethical and economic questions. However, ethanol production also offers important advantages. It helps manage surplus sugar stocks, stabilizing sugar prices and reducing financial stress on mills. Moreover, molasses-based ethanol utilizes a by-product of sugar manufacturing, thereby minimizing direct competition with food uses. Increased demand for sugarcane can also enhance farmer incomes, strengthen rural livelihoods, and promote agricultural sustainability when managed through balanced and region-specific policies.

Socio-Economic Impacts

Farmer Income and Rural Development

Ethanol blending provides a stable and assured market for sugarcane, reducing price volatility and uncertainty for farmers. Guaranteed procurement by ethanol distilleries and sugar mills improves timely payments, addressing a long-standing issue in the sugar sector. This financial stability encourages farmers to invest in better inputs and sustainable farming practices. Additionally, expansion of ethanol production creates employment opportunities in rural areas, including jobs in cultivation, transportation, processing, and allied services. Increased rural income and local employment help reduce rural distress and seasonal migration to urban areas, thereby supporting inclusive growth, strengthening rural economies, and enhancing overall socio-economic resilience.

Energy Security and Economic Benefits

Ethanol blending reduces India's dependence on imported petrol, thereby saving valuable foreign exchange and strengthening national energy security. Substituting a portion of fossil fuel with domestically produced ethanol enhances energy independence and buffers the economy against global oil price fluctuations. Additionally, the ethanol programme promotes domestic manufacturing, expansion of distillery capacity, and development of supporting infrastructure such as storage, transport, and blending facilities, generating economic growth and employment.

Comparison with Second-Generation (2G) Bioethanol

While sugarcane-based ethanol provides immediate benefits through existing infrastructure and high yields, second-generation (2G) bioethanol derived from agricultural residues such as rice straw, bagasse, and maize stover offers greater long-term sustainability. These feedstocks require significantly lower water inputs, as they are by-products rather than cultivated crops, and therefore avoid additional irrigation demand. Importantly, 2G ethanol does not compete with food crops or arable land, addressing food security concerns. Utilization of crop residues also helps reduce open-field burning, particularly of rice straw. Recognizing these advantages, India's climate mitigation and bioenergy policies increasingly emphasize a gradual transition from first-generation to second-generation biofuels for a more sustainable energy future.

Strategies for Sustainable Ethanol-Based Climate Mitigation

To maximize the climate benefits of ethanol blending, a comprehensive and sustainable approach is essential. Adoption of drip irrigation and other water-efficient practices can significantly reduce the high water footprint of sugarcane cultivation. Restricting sugarcane expansion in water-scarce and drought-prone regions will help prevent groundwater depletion and ecological stress. Greater emphasis should be placed on molasses-based and agricultural residue–based ethanol, which minimizes competition with food crops and land resources. Additionally, strict environmental regulations and monitoring of distilleries, including enforcement of zero-liquid discharge norms, are necessary to control pollution. Finally, integrating ethanol policy with broader climate change and water management policies will ensure balanced resource use and long-term sustainability.

Conclusion

Ethanol blending from sugarcane represents a significant climate mitigation strategy for India's transport sector. It reduces greenhouse gas emissions, enhances energy security, supports rural livelihoods, and contributes to cleaner air. However, its sustainability is conditional. Sugarcane-based ethanol is neither entirely "good" nor "bad" for climate change mitigation. Its effectiveness depends on how it is produced, where it is cultivated, and how it is integrated into broader energy and agricultural policies. While it serves as a valuable transitional solution, long-term climate goals require diversification toward second-generation biofuels, improved water management, and strict environmental safeguards. When implemented responsibly, ethanol blending from sugarcane can play a meaningful role in India's pathway toward a low-carbon and climate-resilient future.

Reference

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