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# Life cycle cost analysis of ethanol production from sugarcane molasses for gasoline substitution as transportation fuel in Pakistan

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**Abstract:** The transportation sector is growing rapidly in a developing country like Pakistan and it mostly depends on imported petroleum products**.** To substitute these limited and environment-offending fuels with renewable and more sustainable fuels, ethanol has been recognized as one of the possible solutions**.** However, the economic competitiveness of ethanol against gasoline must be investigated to ensure its economic sustainability**.** The present study has adopted a life cycle costing approach for the economic analysis of sugarcane molasses-based ethanol production**.** The economic feasibility of gasoline substitution by molasses-based ethanol in the form of gasoline-ethanol blends E10 and E20 (10% and 20% blends of ethanol with gasoline, respectively) has been explored**.** The results of cost breakdown analysis showed that the net feedstock cost had the highest contribution followed by operation and maintenance cost, and capital investment cost respectively, in the estimated ethanol production cost**.** Both blends showed comparative economic advantages over gasoline in terms of energy production**.** It is concluded that E20 is the better option because of its lower production cost, better environmental performance and the potential to bring better social reforms as compared to E10.

**Keywords:** Life cycle costing, Molasses, Ethanol, Gasoline, Pakistan.

## 1. Introduction

The world has experienced an enormous increase in energy demand, with the increasing global population [1-3]. To meet these energy needs, fossil fuels, more importantly, petroleum products have been providing most of the energy supplies to the global energy sector [3]. Distribution of these energy resources is uneven around the globe, and a highly dominant portion of these petroleum supplies come from the Persian Gulf where the political situation of some states is quite unpredictable [4-5]. In the last couple of decades, the consumption of petroleum products has increased as compared to their discoverable reserves. The international oil market has also encountered some shortages in the supplies. This can be considered as proof that these natural resources are not endless and depleting rapidly [3]. Due to these global energy crises, the consumers have witnessed an increase in the prices of these petroleum products as well [2-3, 6-11]. The transportation sector has been recognized as the most energy-intensive sector in the world and consumes about 25% of liquid fuels derived from petroleum; that is about 98% of the total energy requirements of this sector [9, 12-15]. Most petroleum products are used to fuel domestic vehicles and carriage trucks [4]. In developing countries like China and Pakistan, the concerned sector is growing rapidly, posing an undesired burden on the supply side [4]. This rapid expansion of the transportation sector has increased the demand for depleting petroleum resources in the developing world creating a problem for global energy security. Moreover, the share of the transportation sector to greenhouse gas (GHG) emissions was 19% in 2015 [9, 14, 16-17]. In addition to carbon dioxide ($CO_2$) emissions, the major emissions from the transportation sector are carbon monoxide (CO) and ozone-forming components that cause smog and air pollution in big cities [5]. The extensive use of fossil fuels in the transportation sector is worsening the situation regarding global energy security and deteriorating the environment leading to global warming [4]. Due to all these problems, many countries have started exploring sustainable energy resources to fuel the world [3].

Substitution of mineral fuels by biofuels such as ethanol has been recognized as a promising solution to tackle the problems such as depleting reserves and rising prices of fossil fuels, and the drastic impacts of burning petroleum products as transportation fuels on the environment [18-20]. Replacement of non-renewable petroleum-based fuels by green, clean and sustainable fuels produced from biomass can empower the developing countries to face the above-mentioned problems. So, the expanding transportation sector in those countries can grow without any hurdle [4, 21]. In the last couple of decades, the production of ethanol for use as transportation fuel has increased all around the world [18, 20]. In 2001 and 2006, the world's total ethanol production was 31 billion liters and 39 billion liters respectively that was reached to a total yield of 85 billion liters in 2010 [18, 20]. In 2018, this production was increased to a record quantity of 154 billion liters, and an increase of 25% in the ethanol production is forcasted till 2024 (International Energy Agency, IEA). Although ethanol production has been increasing over time, it has still not reached the total potential yield. Around 1600 billion tonnes of lignocellulosic biomass is annually available that can potentially be used to produce around 500 billion liters of ethanol. If the total estimated yield of this fuel will be from utilizing lignocellulosic biomass only, about 32% of the total gasoline can be replaced when blended in form of E85 (a blend of 85% ethanol and 15% gasoline by volume) [14]. Ethanol is mostly produced by using food crops like sugarcane, corn, wheat, rice, sugar beet, etc. [3, 11]. Sugarcane comes at the top of the list with a 60% share in the total ethanol production, while the

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remaining 40% is obtained from the other crops [3]. There was a huge debate in recent times that production of ethanol from cereal crops poses direct food to fuel competition and increases GHG emissions due to land-use change, for example, if forest land is turned into farmland, etc. [22-23]. To cope with the dilemma, many non-food feedstocks are being explored [24]. Sugarcane molasses produced as a residue or byproduct in the sugar industry is one of them; it contains a large fraction of fermentable sugars [25-26]. These leftover sugar fractions within molasses cannot be transformed further into edible sugar, which makes sugarcane molasses a strong contender amongst the other feedstocks that directly come from food crops or can be used as food material [26-27]. Ethanol produced from cheap non-food materials such as sugarcane molasses can eliminate the food to fuel competition and other concerned factors. Also, a large portion of gasoline can be substituted [7, 9]. In 2013, about 60% of ethanol was produced from molasses globally [28].

At present sugarcane molasses is the major, in fact, the only source of ethanol production in Pakistan, similar to its neighbor country India [7, 18]. Pakistan is the fifth largest sugar-producing country in the world, after Brazil, India, China, and Thailand [26, 29]. As molasses is produced as a by-product of sugar processing, it is available in bulk quantity in the country [26]. In the year 2018-19, the total molasses production in the country was 2.95 million tonnes (Mt) [30]. If all the available molasses were to be used for ethanol production, an yield of about 0.74 billion liters can be obtained (as 4 kg of molasses yields about 1 liter of ethanol) [18]. Instead of molasses' application in ethanol production, a substantial portion is being exported to earn foreign exchange [18]. In the year 2018, about 0.2 million tonnes of raw molasses was exported. Not only molasses in the raw form, but ethanol produced is also being exported in the undenatured form [30]. According to the Pakistan Sugar Mill Association's (PSMA) annual report 2018, about 700 million liters of undenatured ethanol were exported during the financial year 2018 (FY18) [30]. On the other hand, the country is doomed with severe crises regarding all subdivisions of the energy sector since the last decade [31-32]. Due to these crises, the economy of the country has faced a 2% loss in GDP annually and the rate of unemployment experienced an increase of 6% from 2011-12 [31]. The energy sector of Pakistan mainly depends on oil and gas. Domestic oil production in the country was 24.6 million barrels from July 2018 to March 2019, unable to fulfill the energy demand of the economy that is still in the development phase [32]. The main oil-consuming sector in the country is the transport sector. In FY18, the total oil consumption of this sector was 56% out of the country's total oil consumption. While this consumption was increased to 77% in FY19 [32]. More than 80% of demand for the country is fulfilled by expensive imported oil [31, 29]. The petroleum imports have been increased with a growth rate of 30.5% in FY19 when compared with the previous year. The import bill for FY18 and FY19 was recorded as 9.912 billion US dollars and 12.928 billion US dollars respectively [29]. In the same period, the expenses on petroleum have increased with a growth rate of more than 60% that clearly describes that the increase in petroleum import bill's volume is due to the increase in the international petroleum prices [29]. The substitution of gasoline by fuel ethanol can reduce the heavy burden of petroleum import bills from the shoulders of the economy [26, 33]. The savings from the application of molasses for ethanol production as a transportation fuel will be more than the earnings from the export of raw molasses [33].

The key concern of the ongoing study is to give an insight into various government departments of Pakistan about the cost competitiveness of ethanol as compared to gasoline. The present research investigates the economic advantages of gasoline substitution by ethanol as vehicle fuel in Pakistan. Therefore, the main objective of this study is to perform a life cycle cost (LCC) analysis to explore the economic competitiveness and feasibility of gasoline substitution by sugarcane molasses-based ethanol in the form of gasoline-ethanol blends (E10 and E20). The reason behind selecting E10 and E20 only and not higher order blends is that these blends can be used in the conventional internal combustions engines (ICE) without any alteration. On the other hand, vehicles with specifically modified engines, viz,. flex fuel vehicles (FFV), are required to use gasoline-ethanol blends higher than E20 [34].

## 2. Methodology

The Life cycle cost analysis has been used in many different studies in the past for the assessment of competing alternatives in terms of cost [9, 17, 34]. It is an analytical tool that gives a broader view of the cost structure of fuel production and summarizes all cost components incurred at every stage of the fuel life cycle [35]. The cost breakdown analysis in an LCC study helps to divulge every stage of the product life cycle, where improvements can be done by technological advancements to enhance the product yield and/or better policy reforms that can be brought upon to eliminate the economic barriers [35].

### 2.1 Scope of the study

The scope of the present LCC analysis comprises of ethanol production phase in sugarcane biorefinery. At present, there are a total of 21 ethanol plants operating in the country that only use sugarcane molasses as feedstock. Out of these 21 operational distilleries, only eight plants are producing fuel grade alcohol up to ~99.9% purity [29, 33]. All these eight plants are adjacent to the sugar mills [29]. To serve the purpose, a gate to gate LCC analysis is conducted in this study.

### 2.2 Description of ethanol production system and functional unit

Currently, there are two types of ethanol production technologies that are commercially available. One of these two technologies uses sugar-based feedstocks like sugarcane juice and molasses, etc. To produce ethanol while the other uses starch-based materials such as maize, wheat, cassava, etc. [36]. The technology that uses sugar-based feedstocks, produces ethanol through the fermentation process via microbial conversion [36]. The microorganism that is commonly used in the fermentation process is *Saccharomyces cerevisiae* (baker's yeast). The concentration of alcohol that is produced in the fermentation process is about 5-15% only, while the rest is water. To obtain alcohol with a higher concentration of up to 95-96% (hydrous alcohol), distillation technique is used. Hydrous alcohol cannot be blended with gasoline to use as a transportation fuel in common vehicles. For blending purpose, up to ~99.5% pure alcohol (anhydrous alcohol) is required, which is achieved with the help of the dehydration process. There are three main by-products produced during the whole ethanol production process. These by-products are carbon dioxide ($CO_2$), Fusel oil and Vinasse (stillage). $CO_2$ is produced in almost an equal amount as ethanol during the fermentation process, while fusel oil is another kind of alcohol containing more than two carbon atoms in its molecules that are separated from the ethanol during distillation process in distillation columns. Vinasse, also known as stillage or spent wash, is the wastewater left behind after ethanol extraction in the distillation process [35-37]. All the stages that are included in the ethanol production phase are shown in Fig. 1 within the dotted lines (molasses preparation, fermentation, distillation and dehydration).


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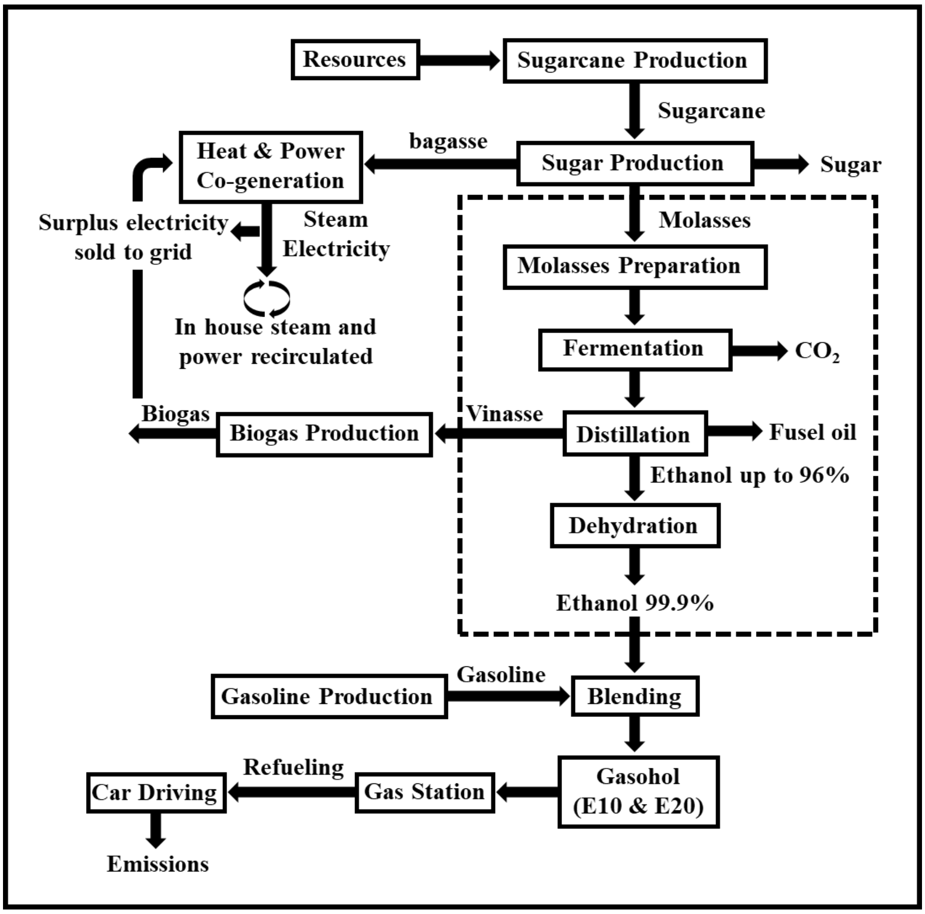


**Figure 1.** Life cycle stages of ethanol production system (in the dotted lines).

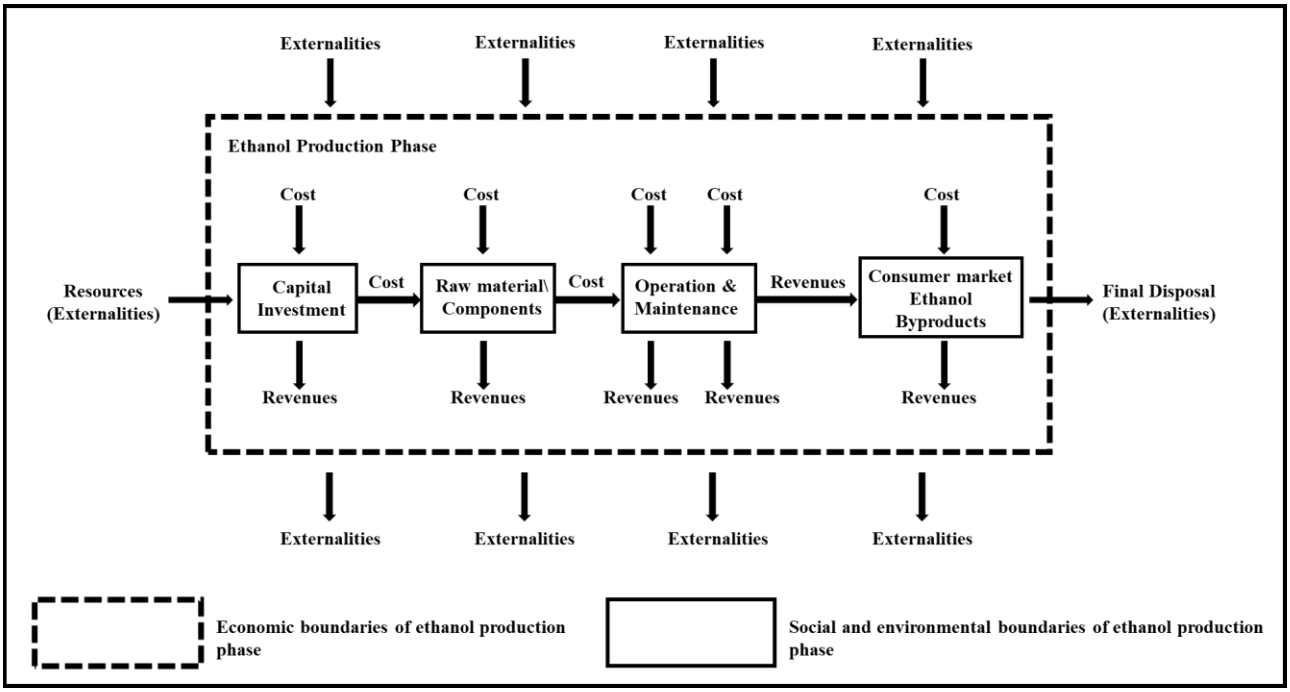


**Figure 2.** Economic boundaries of ethanol production phase for LCC estimation.

In an environmental life cycle assessment, the allocation of environmental impacts is avoided by expanding system boundaries or by dividing the unit process into two or more sub-processes to include additional functions related to co-products. While, in the case of LCC analysis, the costs are directly allocated to the specific activity or process. The decision of assigning costs to particular cost objects depends upon the management and technical judgment of the analysts as there is no theoretical approach for a specific allocation technique in LCC [39]. In the present study, the activity-based costing (ABC) technique is chosen to be followed for cost allocation. According to the ABC approach, costs are directly assigned to the associated activities

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in every stage of a product life cycle. The economic boundaries of the life cycle of a product should also be defined to understand the flow of all the costs related to the production of that particular product for cost allocation. The economic boundaries of ethanol production include all the costs of planning, raw material, investment, operation and maintenance and disposal of the product [39]. The flow of costs and revenues in the economic boundaries of the ethanol production phase is presented and highlighted by dotted lines in Fig 2. Usually, ethanol is blended with gasoline to use as vehicle fuel in the form of different ethanol-gasoline blends, termed as gasohol. In this study, it is assumed that ethanol is used in two different types of blends of gasoline and ethanol by volume. These two blends are E10 which is a mixture of 90 percent gasoline and 10 percent ethanol, and E20 which is a mixture of 80 percent gasoline and 20 percent ethanol. To compare ethanol in the form of E10 and E20 with gasoline, a functional unit is selected as 1 gigajoule (GJ) of energy produced.

### 2.3 Cost breakdown analysis

For the detailed cost breakdown analysis, all the costs associated with the fuel production system at each stage within the ethanol production system are included for the estimation of ethanol life cycle cost [35]. These cost components are mainly divided into four main cost categories such as feedstock cost ($C_{FS}$), operation and maintenance cost ($C_{O\&M}$), capital investment cost ($C_I$) and gains from by-product ($C_G$) [35, 38-40].

#### 2.3.1 Feedstock cost ($C_{FS}$)

Feedstock cost consists of the cost of molasses used for ethanol production. Molasses prices are highly variable, depending on fluctuations in the local market's demand, seasons, and locations, etc. [26]. Pakistan has been exporting cane molasses to the European Union (EU), Saudi Arabia, UAE and Afghanistan [29]. Therefore, the demand and price fluctuations in the international market also have a great influence on the local prices of molasses [35, 39].

#### 2.3.2 Operation and maintenance cost ($C_{O\&M}$)

Operation and maintenance (O&M) cost is an aggregation of costs incurred during the production process due to the inputs of water, labor, chemicals, enzymes (yeast), energy (steam and electricity), maintenance, administration, insurance, and all the other miscellaneous overhead expenditures [35, 38-39].

#### 2.3.3 Capital investment cost ($C_I$)

Capital investment cost consists of the initial cost of all the fundamental equipment, machinery and auxiliaries required for ethanol production. The transportation and installation cost of the machinery etc. is also included. Other than plant machinery and equipment, the land cost and construction cost of the building and other production facilities are also a part of the initial investment. The indirect costs related to plant such as consultancy fee paid to the consultant is accounted for in the capital investment cost as well [35, 38-39].

#### 2.3.4 Gains from by-products ($C_G$)

There are three main by-products of ethanol produced from molasses. These by-products are vinasse, fusel oil, and $CO_2$. If these by-products will be managed properly, they can raise a decent amount of additional income and may reduce the burden on the final cost of ethanol production. The revenue generated from these by-products is considered as by-products gains ($C_G$) in this study [35, 39].

The per-unit production cost of ethanol is a summation of net feedstock cost, operation, and maintenance cost, and capital investment cost. The following equation summarizes the per unit life cycle ethanol production cost ($LCC_E$),

$$LCC_E = (C_{FS} - C_G) + C_{O\&M} + C_I \quad (1)$$

In Equation 1, sub costs $C_{FS}$, $C_{O\&M}$, $C_I$, and $C_G$ represent costs of feedstock, operation and maintenance cost, capital investment cost and gains from by-products respectively. Gains from by-products ($C_G$) in the equation are subtracted from the feedstock cost because it is the income other than the profit earned from the sale of ethanol. By subtracting by-products gains from feedstock cost we obtain net feedstock cost.

### 2.4 Technical assumptions and data collection for $LCC_E$ estimation

In the present study, the life of the ethanol plant is assumed as 30 years and the discount rate is assumed as 10.5% per annum, announced by the State Bank of Pakistan (SBP) for the year 2019. The shutdown period of the ethanol plant is 1 month every year for the maintenance and repairing of the plant equipment. Therefore, the number of operating days is assumed as 330 days per year. The reported capacity of most of the ethanol plants in the selected study area is 125,000 liters per day [26, 30]. Thus, the capacity of an ethanol production plant for this study is assumed as 125,000 liters per day. All the technical assumptions for this study are summarized in Table 1.

For the $LCC_E$ estimation, cost data is required for all the inputs and outputs mentioned in the cost breakdown analysis. At present, there are no life cycle cost inventories available in the country. Therefore, to estimate the life cycle cost of ethanol, the data was collected by applying both bottom-up and top-down approaches. According to the bottom-up approach, cost data was collected from an operational ethanol plant located in the region of central Punjab that is producing fuel-grade ethanol with a per day capacity of 125,000 liters. The data was collected by on-site visits and personal interviews with plant engineers and higher administration. For the top-down approach, the data was obtained from reviewing different reports and literature [29]. The collected data was also corroborated by experts from the Pakistan Agriculture Research Bureau, and Pakistan Ethanol Manufacturers Association (PEMA). The cost data that was used in this study to estimate the production cost of 1 liter of ethanol is presented in Table 2.

**Table 1.** Technical assumptions of ethanol production life cycle cost calculation.

| Sr. No | Type | Assumptions |
|---|---|---|
| 1 | Feedstock | Sugarcane molasses |
| 2 | Plant type | Single feed & adjacent to the mill |
| 3 | Location | Punjab, Pakistan |
| 4 | Annual production (1000 L) | 41,250 |
| 5 | Operating days | 330 |
| 6 | Plant life (years) | 30 |
| 7 | Discount rate | 10.5% |
| 8 | Base year for cost estimation | 2019 |


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**Table 2.** Input-output cost data to estimate per liter ethanol cost.

| Cost Type | Inputs/Outputs | Quantity | Price/Unit | Annual expense PKR/year | Cost PKR/L |
|---|---|---|---|---|---|
| 1. Raw material cost | Molasses | 530 t/d | 12 PKR/kg | 2,098,800,000 | 50.88 |
| 2. Operation & maintenance cost | Labor | 25 Person/d | 72.92 PKR/h | 14,437,500 | 0.35 |
| | Electricity [a] | 1650 kWh/d | 7.91 PKR/kWh | 4,306,995 | 0.1 |
| | Steam [b] | 330 t/d | 1,265 PKR/t | 137,758,500 | 3.34 |
| | Chemicals<br>1). Yeast<br>2). Other | <br>1.67 kg/d<br>0.168 t/d | <br>2,700 PKR/kg<br>22.5 PKR/kg | 2,735,370 | 0.07 |
| | Taxes | - | - | 3,000,000 | 0.07 |
| | Insurance fee | - | - | 4,000,000 | 0.1 |
| | Maintenance [c] | - | - | 2,312,500 | 0.06 |
| | Administration | - | - | 30,000,000 | 0.73 |
| | Miscellaneous | - | - | 7,000,000 | 0.17 |
| 3. Capital investment | Machinery and equipment | - | - | 276,321,204 | 6.7 |
| | Consultant fee | - | - | 14,767,710 | 0.36 |
| | Transportation | - | - | 1,105,285 | 0.03 |
| | Auxiliary | - | - | 7,736,994 | 0.19 |
| | Installation | - | - | 3,315,854 | 0.08 |
| | Land rent | - | - | 2,813,014 | 0.07 |
| | Construction | - | - | 11,052,848 | 0.27 |
| 4. By-products gains | Gains from $CO_2$ | 65 t/d | 7 PKR/kg | 150,150,000 | 3.64 |
| | Gains from Fusel oil | 0.252 t/d | 35 PKR/kg | 2,910,600 | 0.071 |

[a] The cost of electricity is assumed as the electricity tariff introduced by the National Electric Power Regulatory Authority (NEPRA).
[b] The cost of 1 tonne of steam is assumed as the cost of bagasse required to produce it. The cost of bagasse in the approved tariff of NEPRA is PKR 3.2 per kg. 1 tonne of bagasse is reported to produce an average of 2.53 tonne of steam [42].
[c] The maintenance of the plant is done by the plant's own labor and engineers. The duration of maintenance is one month. Therefore, the maintenance cost is assumed as equal to the sum of monthly labor cost and administration cost.

**Table 3.** Average export price and quantity of molasses in Pakistan from FY2005-6 to FY2018-19

| No. | Financial Year | QTY (1000 tonne) | Price/tonne (PKR) | Price/tonne (USD) | Exchange Rate PKR/USD |
|---|---|---|---|---|---|
| 1 | 2005-06 | 1151431 | 3732 | 62 | 59.83 |
| 2 | 2006-07 | 497161 | 5255 | 86 | 60.92 |
| 3 | 2007-08 | 373177 | 4566 | 75 | 61.22 |
| 4 | 2008-09 | 780807 | 4471 | 57 | 79.10 |
| 5 | 2009-10 | 936338 | 7996 | 95 | 84.26 |
| 6 | 2010-11 | 961300 | 8097 | 94 | 85.71 |
| 7 | 2011-12 | 86437 | 10,321 | 115 | 89.97 |
| 8 | 2012-13 | 55608 | 10,394 | 107 | 97.14 |
| 9 | 2013-14 | 225221 | 12,198 | 115 | 105.68 |
| 10 | 2014-15 | 197342 | 12,721 | 127 | 100.46 |
| 11 | 2015-16 | 83229 | 12,139 | 116 | 104.87 |
| 12 | 2016-17 | 73067 | 11,967 | 114 | 104.77 |
| 13 | 2017-18 | 101410 | 12,001 | 114 | 105.46 |
| 14 | 2018-19 | 168962 | 12,515 | 103 | 121.82 |

Source: Pakistan Sugar Mill Association (PSMA)

## 3. Results and discussion

A detailed cost breakdown analysis was performed for a gate to gate LCC analysis to estimate the life cycle cost of ethanol production. The results of the cost breakdown analysis are discussed in detail in the following sections.

### 3.1 Estimation of feedstock cost

For the estimation of feedstock cost, the average export price of molasses for the financial year 2018-19 (FY2018-19) was used. The average export prices of sugarcane molasses from 2005-2019 have been presented in Table 3. For the FY2018-19, the average export price of molasses was PKR 12,000 per tonne or around USD 80 per tonne (as USD 1 = PKR 150.04, the average exchange rate at the end of 2019, International Monetary Fund - IMF) [30]. The feedstock cost per liter of ethanol is estimated as PKR 50.88 or USD 0.34. A huge amount of molasses is being exported in the country. Therefore, the influence of the international market dominates the actual domestic price of molasses [30]. From Table 3, it is clear that throughout the ongoing decade, the molasses price was lowest during the FY2018-19 in the international market. On the other hand, in the domestic market the price of molasses was higher during the FY2018-19 when compared with other years. In 2011, the price of the molasses was PKR 9,000 per tonne of molasses in the domestic market, while this price was increased to around PKR 12,000 for the same quantity in 2019 [33, 44]. These unusual fluctuations in the price of molasses within the country are due to its unstable and low performing currency. Devaluation of the local currency is found as the main reason for these high prices of molasses during the FY2018-19.

**3.2 Estimation of operation and maintenance cost**

Operation cost is an aggregation of all the costs incurred due to consumable inputs or commodities in the operations for ethanol production. These inputs include labor, electricity, steam, chemicals, administration and other miscellaneous expenses such as medical facilities or refreshments for the plant staff and labor. Annual charges like taxes and insurance fees are also included. The data for each input was collected from a representative operational ethanol plant through questionnaires and personal interviews with plant staff and engineers on the cost basis of 2019. The maintenance of the plant is done by plant's own labor and engineers. The duration for plant maintenance and repairing is one month per year. Therefore, the maintenance cost is assumed as equal to the sum of monthly labor cost and administration cost (indirect labor cost). The estimated O&M cost is PKR 6.13 or USD 0.04 per liter of ethanol produced. The share of energy (electricity + steam) cost in the total estimated O&M cost at 75% is the highest among all the inputs. After energy cost, the share of both labor costs (direct and indirect) is the next highest at about 18%. The detailed cost breakdown of the total estimated O&M cost is summarized in Fig. 3.

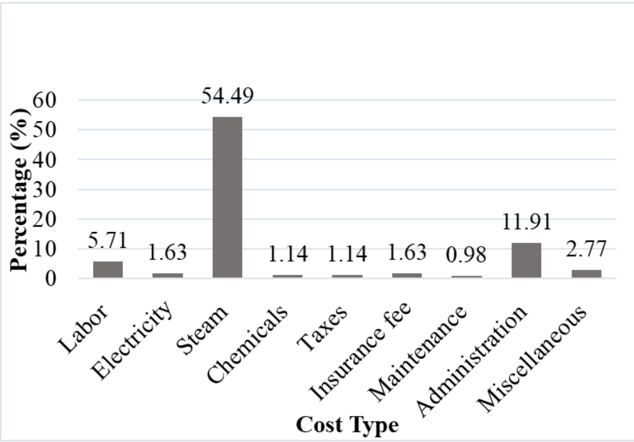


**Figure 3.** Detailed cost breakdown of estimated operation and maintenance cost.

**3.3 Estimation of capital investment cost**

In the present study, the capital investment cost is divided into two different types of costs, viz., direct capital cost and indirect capital cost. The direct capital cost includes initial investment cost on the plant machinery, equipment, auxiliary, building construction, land, storage tanks, and transportation cost, etc. While the indirect cost consists of engineering consultant fees [41]. The historic prices that were paid by the plant owner for the initial acquisition of the ethanol plant are used for the estimation of direct capital cost. The corresponding plant was initiated in 2014, therefore the prices of all the components are adjusted to 2019 as it is assumed as the base, by using consumer price index (CPI) [36, 41]. The indirect capital cost is estimated by assuming a percentage of the direct capital cost, following the approach introduced by Garrett [43]. The total capital investment cost is estimated as PKR 2,869 million or USD 19.12 million.

To calculate capital investment cost per liter of ethanol produced, the initial investment cost is divided across the total number of years of the plant's life. The present value method expressed in the following equation is the commonly used technique for annualizing capital investment cost [36, 41].

$$A = C_I \times \left[\frac{i(1+i)^n}{(1+i)^n-1}\right]$$

Where, '*A*' represents annual payments (PKR per year) while $C_I$, *i*, and *n* represent present worth of the first investment cost (PKR), annual interest rate (%), and plant life (in years) respectively. To calculate the per unit capital cost, the annual capital investment is divided by total annual ethanol production. The estimated capital investment cost per liter of ethanol is PKR 7.69 or USD 0.05. The detailed cost breakdown of the estimated capital investment cost is presented in Fig. 4.

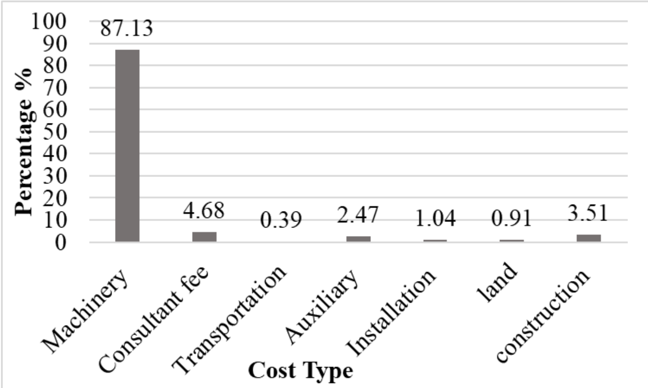


**Figure 4.** Detailed cost breakdown of estimated capital investment cost.

**3.4 Estimation of by-products gains**

From the ethanol production process chain, several by-products are produced such as $CO_2$, fusel oil and vinasse as mentioned earlier in the cost breakdown analysis section. At present, there is no defined market for vinasse in the country. Therefore, only $CO_2$ and fusel oil are selected as income-generating by-products. Fusel oil is produced within the ethanol production cycle and separated from ethanol during the distillation process. On the other hand, $CO_2$ is produced during the fermentation process and then transferred to a compressed $CO_2$ plant where it is converted into liquefied $CO_2$. Both Fusel oil and $CO_2$ are produced within ethanol production system but the burden of all the costs is beared by ethanol only. both of these by-products have some market value when sold, and the value earned from that can be concidered as additional profit [41]. At present, the market prices of fussel oil and $CO_2$ are 35 PKR/L and 7000 PKR/tonne respectively. The estimated gains from the $CO_2$ and fusel oil are PKR 3.64 and PKR 0.07, respectively, per liter of ethanol. Thus, the total estimated by-product gains are PKR 3.71 or USD 0.025 per liter of ethanol produced.

As these gains act as a source of additional income for the ethanol plant, thus this income is subtracted from the feedstock cost. As a result, net feedstock cost per liter of ethanol produced from molasses is obtained as PKR 47.17 or around USD 0.32.

**3.5 Summary of total estimated $LCC_E$**

The estimated LCC of one liter of ~99.9% pure ethanol produced from sugarcane molasses according to the data collected from a single feed ethanol plant adjacent to the sugar mill with a capacity of 125,000 liters per day is 60.99 PKR/L or 0.41USD/L on the cost basis of 2019. The overall estimation of ethanol production cost is summarized in Table 4. In the past, many life cycle costing based studies have been performed for the estimation of ethanol production cost by using several feedstocks. The ethanol costs estimated by Yoosin et al. (2007), Luo et al. (2009), Arshad (2011), Arshad et al. (2016), and Arshad et al. (2019) were 0.58 USD/L, 0.40 USD/L, 0.53 USD/L, 0.40 USD/L and 0.46 USD/L, respectively [24, 26, 33, 36, 44]. The difference between the estimated cost of ethanol production in the above-mentioned studies may occur due to the variation of time and/or space as cost data is very sensitive and highly variable over time and geographical location of the source [39]. However, the estimated LCC of ethanol is 0.41 USD/L, which falls within the


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range of previously estimated ethanol costs i.e. 0.40 USD/L to 0.58 USD/L in the above-referenced studies.

### 3.6 Comparative analysis of economic competitiveness between ethanol and gasoline

The estimated cost of ethanol is 0.41 USD/L while the cost of gasoline used in this study is referenced from the literature and accepted as 0.69 €/kg or 0.51 €/L based on the year 2009 [9, 24, 45]. The gasoline cost is estimated to be 0.63 USD/L or 95.15 PKR/L when indexed according to the base year 2019. The present study is intended to compare the economic competitiveness of gasohol blends (E10 and E20), and gasoline in energy production. Hence, to make such a comparison, the cost of E10 and E20 blends can be calculated by following the approach introduced by Litterman et al. (1978) [46]. According to that approach, the cost of gasohol blends can be estimated by simply summing up the percentage shares of gasoline and ethanol costs according to their volumetric share in each blend [46]. Eq. 2 and Eq. 3 are used to estimate the costs of E10 and E20.

$$C_{E10} = 0.90 \times C_{Gas} + 0.10 \times LCC_E \quad (2)$$

And,

$$C_{E20} = 0.80 \times C_{GAS} + 0.20 \times LCC_E \quad (3)$$

The estimated cost of E10 and E20 are 91.62 PKR/L or 0.61 USD/L and 88.09 PKR/L or 0.59 USD/L respectively. Estimated costs of E10 and E20 show that as the shared volume of ethanol increases in the gasoline-ethanol blends the per-unit cost of the blend decreases. It is because of the lower production cost of ethanol as compared to gasoline. Some of the basic physical and chemical properties of gasoline, E10, E20, and ethanol are presented in Table 5 [12, 47].

However, the cost of higher-order gasohol blends is lower but on the other hand, the heating value decreases, and density increases when more ethanol fraction is added to gasoline. As a result, more quantity of blended fuel is required to produce a specific amount of energy as compared to gasoline. For example, the amount of gasoline that is required to produce 1 GJ of energy is 31.73 L, as 1 L of gasoline produces around 0.0315 GJ of energy. To produce the same amount of energy 32.78 L of E10 is needed, while in the case of E20 the required quantity is 33.86 L. Even if more quantity of E10 and E20 is required to produce 1 GJ of energy, still the blended fuels are economically competitive when compared with gasoline [24]. The percentage decrease in the cost of energy production that can be achieved by replacing gasoline with gasohol blends has been shown in Fig. 5.

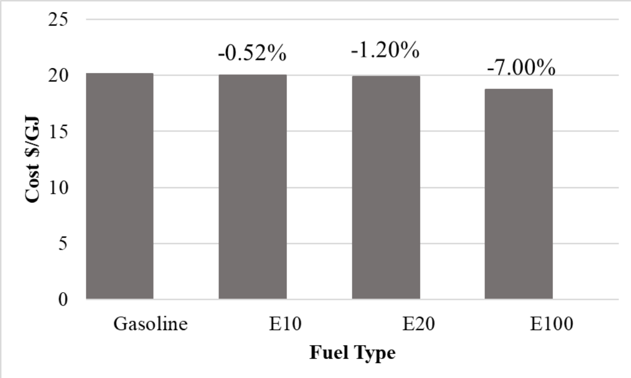


**Figure 5.** Reduction in energy production cost by replacing gasoline with ethanol.

In Fig. 5, the percentage change in the energy production cost by using ethanol and blends as compared to gasoline is presented on the top of all the bars representing different fuels. The negative sign shows the nature of change i.e. the percentage decrease in the cost. In the case of the present study, four different types of fuels including gasoline, E10, E20 and E100 (Ethanol) are examined. The estimated costs, as well as gasoline-equivalent costs of E10, E20, and E100 for 1 GJ of energy produced for each concerned fuel are summarized in Table 6. It can be seen from Table 6., that there is a decrease of USD 0.10, USD 0.24 and USD 1.41 in the cost to produce 1 GJ energy when gasoline is substituted with E10, E20, and E100 respectively.

**Table 4.** Summary of estimated life cycle cost ethanol production.

| No. | Cost Type | Cost PKR/L | Cost USD/L | Cost Million PKR/Yr | Cost Million USD/Yr | Percentage share % |
|---|---|---|---|---|---|---|
| **1** | Net feedstock cost | 47.17 | 0.32 | 1945.72 | 12.97 | 77.34 |
| **2** | Operation & Maintenance cost | 6.13 | 0.04 | 252.86 | 1.69 | 10.05 |
| **3** | Capital Investment cost | 7.69 | 0.05 | 317.21 | 2.11 | 12.61 |
| **4** | $LCC_E$ | 60.99 | 0.41 | 2515.80 | 16.77 | - |

**Table 5.** Physical and chemical properties of gasoline, ethanol and gasohol blends [12, 47].

| Properties | Gasoline | E10 | E20 | Ethanol |
|---|---|---|---|---|
| Density (kg/m$^3$) | 733 | 739 | 746 | 790.9 |
| Density (kg/L) | 0.733 | 0.739 | 0.746 | 0.791 |
| LHV (kj/kg) | 43000 | 41282 | 39591 | 26950 |
| Latent heat of vaporization (kJ/kg) | 350 | - | - | 840 |
| Stoichiometric Air/fuel ratio | 14.49 | 13.89 | 13.31 | 8.87 |

**Table 6**. Gasoline equivalent cost of 1 GJ of energy production.

| Fuel type | Gasoline equivalent ratio | Gasoline equivalent cost (PKR/L) | Gasoline equivalent cost (US/L) | Energy cost (USD/GJ) |
|---|---|---|---|---|
| **Gasoline** | 1 | 95.15 | 0.6342 | 20.12 |
| **E10** | 1.03 | 94.66 | 0.6309 | 20.02 |
| **E20** | 1.07 | 94.01 | 0.6266 | 19.88 |
| **E100** | 1.48 | 88.49 | 0.5898 | 18.71 |

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**3.7 Scenario analysis**

The results of cost break down analysis showed that the cost of energy production is comparatively lower when gasoline is blended with ethanol. Higher the ratio of ethanol in the gasohol blends, lower will the cost of energy production as reported in Table 6. This is because of the lower production price of ethanol than gasoline. For both gasoline and molasses, the cost is quite unstable as referenced in the literature [24, 30]. Therefore, to investigate the impact of these fluctuations on the costs of gasohol blends and ultimately on a specific amount of energy production, the analysis of three different scenarios is conducted for 25%, 50% and 100% increase in gasoline and molasses cost. For the first analysis, it is assumed that there will be 25%, 50% and 100% increase only in the molasses prices while the O & M cost and capital cost for ethanol production remain the same. For the second scenario analysis, only the gasoline cost is assumed to increase by 25%, 50%, and 100%. In the third and last scenario analysis, both gasoline and molasses costs are assumed to increase simultaneously with the same percentages. All three scenarios are denoted as Case 1, Case 2 and Case 3 respectively. The results of Case 1 showed that the cost of energy production from gasoline will be economical as compared to all other kinds of blended fuels. The increase in the cost of ethanol and all other blended fuels due to the increase in molasses costs is presented in Table 7(a). Table 7(a) shows that the cost of both E10 and E20 is less than gasoline, while the cost of E100 is higher due to doubled molasses price. The increase in energy production cost due to the new costs of concerning fuels can be seen in Table 7(b). It can be seen that cost of energy production for all the blends is higher when compared with gasoline in Case 1. The reason behind higher cost of energy production for all the blends is the difference between energy densities of these fuels as mentioned earlier in Table 5. The results of Case 2 and Case 3 found that the cost of energy production is lower when E10 and E20 will be used rather than gasoline. The results of Case 2 and Case 3 are shown in Table 8(a, b) and Table 9(a, b) respectively. It can be perceived from the outcomes of Case 2 and Case 3 that the energy production cost of higher-order blended fuels (like E20 or E100) is economically more competitive despite their lower energy densities and heating values. This is because of the higher production cost of gasoline as compared to ethanol in both of these cases.

**Table 7(a).** Costs of gasoline, E10, E20 and E100 for Case 1.

| Fuel type | Estimated cost | 25% rise in molasses cost | 50% rise in molasses cost | 100% rise in molasses cost | Units |
|---|---|---|---|---|---|
| **E100** | 59.85 | 70.94 | 85.29 | 110.73 | PKR/L |
| **E10** | 91.62 | 92.73 | 94.16 | 96.71 | PKR/L |
| **E20** | 88.09 | 90.31 | 93.18 | 98.27 | PKR/L |
| **Gasoline** | 95.15 | 95.15 | 95.15 | 95.15 | PKR/L |

**Table 7(b).** Costs of 1 GJ energy production for all fuel alternatives for Case 1.

| Fuel type | Estimated cost | 25% rise in molasses cost | 50% rise in molasses cost | 100% rise in molasses cost | Units |
|---|---|---|---|---|---|
| **E100** | 2807.56 | 3327.80 | 4000.95 | 5194.34 | PKR/GJ |
| **E10** | 3003.30 | 3039.66 | 3086.70 | 3170.09 | PKR/GJ |
| **E20** | 2982.73 | 3057.83 | 3155.01 | 3327.29 | PKR/GJ |
| **Gasoline** | 3020.06 | 3020.06 | 3020.06 | 3020.06 | PKR/GJ |

**Table 8(a).** Costs of gasoline, E10, E20 and E100 for Case 2.

| Fuel Type | Estimated Cost | 25% rise in gasoline cost | 50% rise in gasoline cost | 100% rise in gasoline cost | Units |
|---|---|---|---|---|---|
| **E100** | 59.85 | 59.85 | 59.85 | 59.85 | PKR/L |
| **E10** | 91.62 | 113.03 | 134.44 | 177.26 | PKR/L |
| **E20** | 88.09 | 107.12 | 126.15 | 164.21 | PKR/L |
| **Gasoline** | 95.15 | 118.94 | 142.73 | 190.3 | PKR/L |

**Table 8(b).** Costs of 1 GJ energy production for all fuel alternatives for Case 2.

| Fuel Type | Estimated Cost | 25% rise in gasoline cost | 50% rise in gasoline cost | 100% rise in gasoline cost | Units |
|---|---|---|---|---|---|
| **E100** | 2807.56 | 2807.56 | 2807.56 | 2807.56 | PKR/GJ |
| **E10** | 3003.30 | 3705.08 | 4406.86 | 5810.42 | PKR/GJ |
| **E20** | 2982.73 | 3627.08 | 4271.44 | 5560.15 | PKR/GJ |
| **Gasoline** | 3020.06 | 3775.08 | 4530.09 | 6040.12 | PKR/GJ |

**Table 9(a).** Costs of gasoline, E10, E20 and E100 for Case 3.

| Fuel Type | Estimated Cost | 25% rise in both gasoline & molasses cost | 50% rise in both gasoline & molasses cost | 100% rise in both gasoline & molasses cost | Units |
|---|---|---|---|---|---|
| **E100** | 59.85 | 70.94 | 85.29 | 110.73 | PKR/L |
| **E10** | 88.62 | 114.14 | 136.98 | 182.34 | PKR/L |
| **E20** | 85.55 | 109.34 | 131.24 | 174.39 | PKR/L |
| **Gasoline** | 95.15 | 118.94 | 142.73 | 190.30 | PKR/L |

**Table 9(b).** Costs of 1 GJ energy production for all fuel alternatives for Case 3.

| Fuel Type | Estimated Cost | 25% rise in both gasoline & molasses cost | 50% rise in both gasoline & molasses cost | 100% rise in both gasoline & molasses cost | Units |
|---|---|---|---|---|---|
| **E100** | 2807.56 | 3327.80 | 4000.95 | 5194.34 | PKR/GJ |
| **E10** | 2904.96 | 3741.44 | 2795.81 | 5977.20 | PKR/GJ |
| **E20** | 2896.72 | 3702.18 | 4443.72 | 5904.71 | PKR/GJ |
| **Gasoline** | 3020.06 | 3775.08 | 4530.09 | 6040.12 | PKR/GJ |


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In the above performed analysis, in all the selected scenarios (Case 1, Case 2, Case 3), only an increase in the cost of either gasoline or molasses was assumed, and its impacts on energy production cost were examined. Therefore, another analysis is performed for one more scenario termed as Case 4. In Case 4, it is assumed that there will be a decrease of 25% and 50% in the gasoline cost. The reason for only analyzing 25% and 50% fall in gasoline cost, and not 100% is because with 100% decrease the fuel cost will become zero for gasoline which is not reasonable. The results of analysis performed for Case 4 showed that, the per liter cost of gasoline will still remain higher as compared to E10, E20 and E100 in the case of 25% decrease, while the cost of energy production for gasoline will be lower than all considered blends. In the case of 50% fall in gasoline cost both per liter fuel cost, and energy production cost for gasoline will be lower as compared to all considered blends. The outcomes of Case 4 are presented in Table 10(a) and Table 10(b).

### 3.8 Economic, environmental and social benefits of gasoline substitution by molasses based ethanol

The results of LCC analysis can be used for economic, environmental and social evaluation of the gasoline substitution by ethanol in Pakistan. The outcomes of the scenario analysis showed that as compared to E10, E20 is a better substitution for gasoline in terms of cost reduction. Moreover, molasses-based ethanol has a significant potential to reduce the burden of oil imports of the country [29]. The reported molasses production in the country during FY2018-19 was about 3 million tonnes that can be used to produce 0.74 billion liters of ethanol [18, 30]. The overall oil consumption of the country was more than 12.7 million tonnes while 9.74 million tonnes were consumed by the transportation sector only [32]. During the same period, 6.6 million tonnes of petroleum products were imported that added a heavy burden on the economy with an import bill of USD 3.4 billion [32]. According to the current fuel consumption by the transportation sector of the country, if ethanol is used for blending with gasoline in the form of E10 and E20, about 0.70 and 1.42 million tonnes, respectively, of gasoline can be eliminated. This reduction in the dependence on expensive imported oil products can provide help to offset the heavy burden of petroleum import bills with a total of USD 0.35 billion and USD 0.73 billion if gasoline is substituted by E10 and E20, respectively.

Other than economic welfare, ethanol production and its application as vehicle fuel have many other advantages concerning environmental and social aspects [29, 35, 44]. Along with the highest oil consumption, the transportation sector is also responsible for 21% of total GHG emissions in Pakistan. The substitution of gasoline by 1 L of ethanol in the transportation sector, can save GHG emissions equal to around 1.6 kg $CO_2$ eq. (kilograms of $CO_2$ equivalent) [35]. For the potential gasoline substitution of 0.70 and 1.42 million tonnes by E10 and E20, GHG emissions amount to 2.20 Mt $CO_2$ eq. And 4.54 Mt $CO_2$ eq. (million tonnes of $CO_2$ equivalent) can be saved respectively. Therefore, ethanol application as a transportation fuel is a major step towards GHG emission minimization. It also makes biofuel utilization a top-tier option for policymakers to enhance the environmental performance of the country [44].

Along with the GHG emission reduction, the biofuel industry has a great potential to bring social reforms especially to the remote areas of the country [29]. At present, out of 85, only 21 sugar mills have operational ethanol plants [30]. With the proper support of government and appropriate biofuel policy planning, the ethanol industry has a huge potential for development. If the industry expands, it can provide an additional income to farmers producing sugarcane. The profit share of the sugar industry, as well as other industries that are indirectly associated with sugarcane farming such as fertilizers and pesticide industries, will also improve [29, 44]. Most of the sugar mills are located near rural areas or small towns [26]. Ethanol production as a vehicle fuel can enhance job creation opportunities for the locals of these remote areas that the oil imports simply cannot do [29]. The blending and distribution of ethanol will support the development of the country's infrastructure and advancement of the rural economy [26, 44]. The bio-electricity produced from bagasse not only ameliorates the problem of electric power shortage that has been one of the biggest socio-economic challenges over a decade, but it also reduces fossil fuel consumption for power generation in the country [29].

### 3.9 National ethanol policy history and current situation

As the biofuel industry of Pakistan is in its initial stage of development, it requires serious attention from the government. The Pakistani government has tried to oblige the industry in the past but failed to do so because of poor management and inappropriate policy planning. An initiative has been taken by the government in 2006 for blending ethanol with gasoline to use as a transportation fuel. To serve the purpose, Pakistan State Oil (PSO) company with collaboration of Hydrocarbons Development Institute of Pakistan (HDIP) started pilot-scale plants to produce and introduce E10 gasohol (a blend 10% ethanol and 90% gasoline by volume) at retail gas stations in three big cities, viz., Karachi, Lahore, and Islamabad. The project failed due to the lack of coordination between the government and stakeholders, and poor policy planning [29, 33]. In 2009, the Economic Coordination Committee (ECC) of Pakistan's Cabinet manifested to promote the marketing of E10 as vehicle fuel at PSO refilling stations [33]. It was decided to expand the E10 program to other cities including Rawalpindi, Sheikhupura, Gujranwala, Sialkot, Jhelum, and Mirpur Khas in 2010. Later, in 2010 the price of E10 was fixed at PKR 2.5 less than the gasoline price at that time by the Oil and Gas Regulatory Authority (OGRA) to give an economic head start to the scheme [29]. Moreover, the government

**Table 10**(**a**). Costs of gasoline, E10, E20 and E100 for Case 4.

| Fuel Type | Estimated Cost | 25% rise in both gasoline & molasses cost | 50% rise in both gasoline & molasses cost | Units |
|---|---|---|---|---|
| **E100** | 59.85 | 59.85 | 59.85 | PKR/L |
| **E10** | 91.62 | 70.21 | 48.80 | PKR/L |
| **E20** | 88.09 | 69.06 | 50.03 | PKR/L |
| **Gasoline** | 95.15 | 71.36 | 47.58 | PKR/L |

**Table 10**(**b**). Costs of 1 GJ energy production for all fuel alternatives for Case 4.

| Fuel Type | Estimated Cost | 25% rise in both gasoline & molasses cost | 50% rise in both gasoline & molasses cost | Units |
|---|---|---|---|---|
| **E100** | 2807.56 | 2807.56 | 2807.56 | PKR/GJ |
| **E10** | 3003.30 | 2301.52 | 1599.75 | PKR/GJ |
| **E20** | 2982.73 | 2338.37 | 1694.02 | PKR/GJ |
| **Gasoline** | 3020.06 | 2265.05 | 1510.03 | PKR/GJ |

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imposed an export duty of 15% on molasses to promote its use of domestically for ethanol production [29, 33]. Despite all these efforts, the E10 program could not succeed until now due to improper and inconsistent policies [29]. Foreign aid to Pakistan's petroleum sector and extensive investment by different multinational companies in the sector for exploration of domestically available new reserves are the other major reasons behind the failure of biofuels policy in the country [29]. Therefore, biofuel promotion as transportation fuel needs strong governmental support in the form of efficient management and effective and long-term policy planning.

## 4. Conclusion

Sustainability has become the foremost concern for every sector in society. Pakistan's economy highly depends on its energy sector. The application of molasses in ethanol production for gasoline substitution has great potential to introduce sustainability in the energy sector of the country due to its socio-economic and environmental benefits. However, every life cycle stage of ethanol production from sugarcane molasses comes along both with some opportunities and challenges because the biofuel industry of Pakistan is in the rudimentary stage at present. From the results of the present study, we can conclude that ethanol production from sugarcane molasses for gasoline substitution is favorable in terms of economic, environmental and social aspects. According to the detailed cost break down analysis, the feedstock cost poses the heaviest burden to the total ethanol production cost. The burden of feedstock cost can be reduced by increasing per hectare yield of sugarcane at the farm. Although Pakistan is amongst the top sugarcane producing countries, the average sugarcane yield of the country falls between 45-50 tonnes per hectare which is quite low. The main reasons behind low crop yield include conventional farming techniques, inappropriate crop management practices and post-harvest losses. In terms of economic competitiveness, E20 has been found to be a better option for gasoline substitution as compared to E10. These outcomes show that higher-order gasohol blends have greater comparative economic advantages. These blends have the potential to cut down GHG emissions and enhance opportunities for improved social welfare. Hence, the environmental and social pros of ethanol production for gasoline substitution in Pakistan are better for blends having higher concentrations of ethanol. The conclusions drawn are for the specific case of Pakistan in the short term. This is because of the economy's high dependence on imported petroleum products and the fluctuation in the international petroleum prices that manipulate to drive the fuel prices in the country. The results of the study can be useful only if there is sufficient political will considering the benefits that have been shown.

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