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Designing Harvesting and Hauling Cost Models for Energy Cane Production for Biorefineries

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Abstract: The harvesting and hauling operations of bioenergy feedstock is an important area in biofuel production. Production costs can be minimized by maintaining optimal machinery units for these operations. The objective of this study is to design an optimal harvesting unit for bioenergy refinery and estimate harvesting and hauling costs of energy cane. A biorefinery with the annual capacity of processing twenty-five million imp. gallons of ethanol were considered. Given the efficiency of harvesting, a two-row soldier system was considered. Considering the year-round supply of energy cane to the refinery, the optimal machinery unit was designed, and the combined operation costs were derived. The average estimated ownership, repair, labor and fuel and lubricant costs of biomass harvest unit were calculated to be $0.50, $0.54, $1.78 and $1.51/mt, respectively. The costs distribution generated showed harvesting and hauling costs could range between $5.47–$9.23/mt of energy cane. The methodology and the research output will provide guidelines for investors in designing harvesting and hauling units and estimating costs for different scales of operation.

Keywords: bioenergy; biorefinery; cost modelling; harvesting and hauling unit; energy cane; machinery; simulation

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1. Introduction

Biomass resources have greater potential to increase energy security in regions with inadequate fossil fuel reserves, improve the supplies of fuel transportation and maintain a stable environment by decreasing net emissions of carbon into the atmosphere [1–4]. The availability and potentiality of biomass are dependent on a wide range of factors, such as land availability, technological conversion, environmental changes, and competition with food production [5]. Among a variety of candidate crops, energy cane has recently gained popularity as a bioethanol feedstock [6–10]. Energy cane has a stronger energy balance than other competing crops due to its low input requirements, adaptability, and exceptional biological productivity [11,12]. Energy cane (*Saccharum* spp.) is a hybrid between commercial sugarcane lines and wild sugarcane (*Saccharum spontaneum* L.) that has been developed and cultivated primarily for the purpose of using biomass as a fuel [13,14]. It has a lower sugar concentration than commercial sugarcane cultivars but a higher cold tolerance, allowing for a broader growing zone in the southeastern United States [15–18]. Energy cane dry matter yields have ranged from 8 to 53 Mg/ha year^{-1} in the southeastern United States, depending on location, cultivar, years after planting, number of annual cuttings, and input amounts [19–21]. When grown in the tropics and subtropics, energy cane is a promising feedstock for biomass production and could play a significant role as a bioenergy crop, even though there are environmental interactions between biomass production and risks that must be assessed [10,16].

The southeastern Regional Biomass Research Center (RBRC) is working to produce high-performing herbaceous feedstocks such as energy cane and other subtropical/tropical perennial grasses [22–24]. The recent use of biomass for energy production has grown in the past years, specifically in developed countries as well [25–27]. Global interest is shown in the opportunities that bioenergy presents, especially in the sustainable development of more modern and efficient bioenergy production systems. However, this has increased the forecasts and energy needs in many developed countries even though all evidence points to the biomass potential, and domestic biofuel production capacity will be insufficient to meet the energy needs of these countries [28].

Agricultural input use and production costs are important for biomass production decisions as well as a research tool to analyze the farm economy [29]. One of the major challenges facing industrial biofuel production is the production costs of feedstock [30]. Harvesting and transportations operations are important in maintaining the economic viability of bioenergy production [31–33]. Due to operational risk, high input costs, price fluctuations, etc., producers find it difficult to increase profit and to remain sustainable. Among the agricultural production costs, machinery is a major cost item. For example, development of new machineries, technological development, and fluctuating energy prices have caused farm machinery and power costs to increase in recent times. The operators need to make smarts decisions about acquiring, operating and maintaining machinery to minimize costs. An accurate estimate of the costs of owning and operating farm machinery is helpful in making best decisions. Therefore, a development of a methodology to estimate machinery costs for harvesting and hauling operations would be useful for producers in estimating costs in the absence of detailed farm survey data. The objective of this paper is to design a harvesting and hauling unit for a representative biorefinery and estimate the associated costs. The structure of the paper is designed as follows. In the next section, the data and the estimation procedures are described, then the estimated results are presented, and, finally, the conclusions of the research are highlighted.

2. Materials and Methods

Biomass production from energy cane was considered for the analysis. There are two types of herbaceous biofuel feedstocks, namely thick-stemmed species such as energy cane and thin-stemmed species, hence different types of machines are required for harvesting. Basically, two methods are available for handling high moisture crops, namely a direct cut system and a wilting system [34]. The harvesting and hauling designed for costs estimated here are for feedstock supply for an ethanol plant with a 25-million-gallon annual capacity.

It is assumed that harvesting and hauling operations of thick stem biomass such as energy cane are similar to sugarcane. For example, sugarcane harvesting is done by two types of mechanical harvesters, namely combine harvesters and whole stalk harvesters. The combine harvester is popular in Australia and the states of Florida and Texas in the USA. The whole stalk harvesting system is the predominant method of harvesting in Louisiana [35]. However, in a combine harvester, the hours of combine operations needed to harvest a given amount of acreage is about twice the time required for a soldier harvester [36]. Therefore, a two-row soldier harvester was considered for efficient harvesting of energy cane. A soldier harvester can harvest around 90–140 mt [35]. The two-row loader machine was taken for loading the harvested biomass for both systems. The average capacity of the two-row loader is 75 mt/h. There are two choices for transporting harvested biomass. Biomass can be directly transported to the processing facility using direct wagons. The other option is to bring the harvested biomass to the on-farm facility using transfer wagons. The average capacity of transfer or direct wagon is 10 mt. The stored biomass is loaded into truck trailers using a transloader and transported to the refinery. A transloader has the capacity to load around 100 mt/h, while truck trailers have the capacity of 28 mt (Figure 1).

The following assumptions [35,36] were made in estimating applicable costs. The average annual biomass yield of energy cane was 66.12 mt/ha. For energy cane, line up time in the field for transfer and direct wagon is assumed to be 8 min. Distance to the transfer site and to the processing site was assumed to be 0.5 and 5 km, respectively. Waiting time to unload for transfer and direct wagon at the loading site was assumed to be 8 min. Queuing time at the loading site was assumed to be 8 min, while queuing and unloading time at the mill was assumed to be 15 min. The number of working hours per day was assumed to be 8 h. It is assumed that half of the daily harvested biomass is directly transported to the processing plant while the rest of the harvested product is transported to the transloading site at the farm.

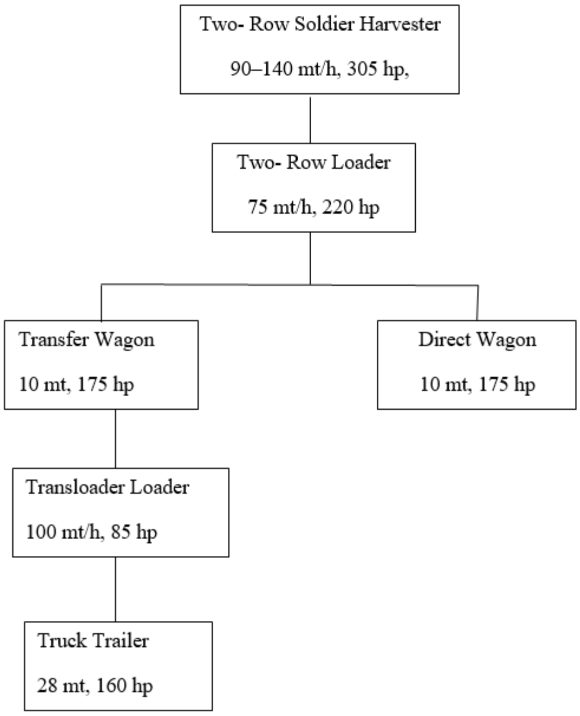


Figure 1. Energy cane harvesting and hauling unit (adopted from sugarcane harvesting system, 36).

Details of machine specifications (hp, purchasing costs, age, salvage value factor, fuel and lubrication factors, etc.) needed for the analysis were gathered from published data [37–40]. The harvesting and hauling cost model were based on the economic engineering approach [39].

Energy cane Harvesting and Hauling Costs (HHC_i) is a function of Ownership Cost of Machinery (*OCM*), Fuel Cost (*Fuel)*, Lubrication Cost (*Lubri*), Repair Cost (*Repair*), and Operating Labor Cost (*OL*).

$HHC_i = OCM_i + Fuel_i + Lubri_i + Repair_i + OL_i$
$OCM_i = capital\ recovery + TIH$
$capital\ recovery = (total\ depreciation \times capital\ recovery\ factor) + (salvage\ value \times interest\ rate)$
$total\ depreciation = initial\ costs\ of\ machinery - salvage\ value$
$capital\ recovery\ factor = 0.13$
$salvage\ value = initial\ costs\ of\ machinery \times salvage\ value\ factor\ (0.3)$
$TIH = Taxes,\ Insurance\ \&\ Housing = 0.01 \times purchase\ price$
$Fuel_i\ (Average\ diesel\ consumption\ per\ hour) = diesel\ consumption\ factor\ (0.044) \times maximum\ horsepower$
$Lubri_i = lubrication\ factor\ (0.15) \times Average\ cost\ for\ fuel\ consumption$
$Repair_i = repair\ cost\ factor\ (0.03) \times purchase\ price$

The labor cost include costs for harvesting and hauling.

$Labor_i = labor\ cost\ for\ the\ harvest\ unit + labor\ cost\ for\ transportation$

Specific data and the estimation procedures are elaborated under the respective tables under the results and discussion for better visualization.

3. Results

3.1. Energy Cane Feedstock Requirement

The estimated farm size and the total feedstock requirement for the continuous supply of energy cane for the operation of a biorefinery with an annual capacity of 25 million gallons is given in Table 1. Based on the assumption that there are 300 operational days of the plant, the daily ethanol production was 83,333 imperial gallons (imp gal). The annual supply of feedstock for the ethanol plant with the above capacity requires 4726 ha of energy cane field. The total energy cane requirement and area needed to be harvested on a daily basis were 1042 mt and 15.75 ha, respectively.

Table 1. Minimum area needed for daily harvesting for continuous supply of energycane for biorefinery.

Category	Value
Yield (MT/ha)	66.12
Ethanol yield (imp gal/mt)	80.00
Ethanol yield (imp gal/mt/year)	5289.80
Total Ethanol yield per farm (imp gal)	25,000,000
Plant Capacity (imp gal)	25,000,000
Days of operation per year	300
Daily capacity	83,333
Total cane yield needed (mt)	312,500
Energycane needed per day (mt)	1042
Farm size (ha)	4726
Minimum area needed to harvest (ha/day)	15.75

3.2. Harvesting Unit

Table 2 shows the number of machines needed per day for harvesting and loading. The estimated numbers of machines needed were based on the total hours needed for daily harvest and the number of working hours/days. Accordingly, two harvesters are needed to harvest the biomass yield to be harvested daily assuming an 8-h workday schedule. To load the harvested biomass, two two-row loaders are needed. Also, a single transloader is needed to handle the daily biomass arriving at the transloading center.

3.3. Hauling Unit

The total number of wagons and trucks with trailers needed to effectively transport daily harvested biomass was estimated based on total daily travel time needed to transport the biomass. Based on an 8-h working day, approximately three transfer wagons, five direct wagons, and four trucks with trailers are needed to transport the daily harvested energy cane to the biorefinery (Tables 3 and 4).

3.4. Ownership and Operation Costs of Harvesting and Hauling

The details of estimated costs are presented under several sub-categories namely machinery ownership, accumulated repair and maintenance, machinery operating labor, fuel and lubricant.

3.4.1. Machinery Ownership

The breakdown of ownership costs for harvesting and hauling units is given in Table 5. In order to estimate the ownership costs, salvage values were estimated based on current list price of each piece of machinery and the remaining value factor [21]. The estimated salvage value was used to estimate the depreciation cost of each machine. Total ownership costs were based on estimated total depreciation, capital recovery, and taxes. Accordingly, the estimated total ownership costs of machinery were $0.50/mt of energy cane. The most ownership costs occur for two-row soldier harvesters and two-row loaders due to higher initial costs.

Table 2. Estimated number of harvesters and loading machine requirements for energycane.

Machinery	Capacity (mt/h)	Av.Capacity (mt/h)	Average Farm Yield (mt/ha)	Harvest Capacity (ha/h)	Max. Potential Daily Harvest ha [1]	Actual Daily Harvest Area	Actual Machine Hours Needed per day	Total Daily Harvest (MT)	Total Farm Size (ha)	Total Machine Use h/year [2]	Total Hours for Harvesting per Day	No of Machines Needed per Day [3]
Two-row soldier harvester	90–140	81.82	66.12	1.24	9.90	15.75	12.73	1042	4726	3819	12.73	2
Two-row loader	75.00	68.18	66.12	1.03	8.25	15.75	15.28	1042	4726	4583	15.28	2
Transloader loader	100.00	90.91	66.12	1.37	11.00	15.75	11.46	1042	4726	3437	11.46	1

[1] Based on 8 h/day schedule. [2] Machine h/day × 300 working days/year. [3] Rounded to the nearest integer.

Table 3. Estimated number of wagons for transportation of harvested biomass.

Machinery	Waiting Time to Unload (min)	Total Trips	Total Waiting Time	Waiting Time(h)	Overall Waiting Time in the Field and Loading Site	Total Travel Time (h)	Total Time (Q&T): h	Working hour/day	Wagons Needed [1]
Transfer wagon	8.00	95.49	763.89	12.73	20.69	4.37	25.05	8.00	3
Direct wagon	8.00	95.49	763.89	12.73	20.69	27.28	47.97	9.00	5

[1] Rounded to the nearest integer.

Table 4. Estimated number truck trailers for transportation of harvested biomass.

Machinery	Queuing Time (min) [1]	No of Trailer Loads	Total Queuing Time (h) [2]	Total Round Trip km [3]	Time per Round Trip (h) [4]	Total Travel Time (h)	Queuing/Unloading at Mill (min)	Total Unloading Time (h) [5]	Total Operation Time (h) [6]	Daily Work Hours	Total Truck Tailor Needed [7]
Truck with tailor	8.00	40.9	5.5	409.23	0.40	16.37	15.00	10.23	32.06	8.00	4

[1] Queuing time at the loading site. [2] Total queuing time = queuing time × no of trailer loads = 327.4 min = 5.5 h. [3] Total round trip travelled = no of trailer loads × round trip per load (10 km) = 409 km. [4] Time per round trip = distance for a round trip (10 km)/tractor speed (25 km/h). [5] Total unloading time = total trips (40.9) × queuing and unloading time (15 min/trip) = 614 min (10.23 h). [6] Total operation time = total queuing time + total travel time + unloading time. [7] Rounded to the nearest integer.

3.4.2. Accumulated Repair and Maintenance

The estimated accumulated repair costs are given in Table 6. Estimated hours used by each machinery are the total machinery hours to be used during the life cycle of the machine. Accumulated repair cost/h of machine use was based on the total accumulated repair cost during the life of the machine and the estimated hours used for the machine during its lifetime. Accordingly, the repair costs account for \$0.37/mt of energy cane.

3.4.3. Operating Labor

The estimated total labor costs for harvesting and transportation of each machine is given in Table 7. Annual use hours per machine were based on the total days for harvest and working h/day. Total machine h/ha was based on estimated total machine hours and the area to be harvested. Accordingly, the estimated total labor costs were \$2.31/mt of energy cane.

3.4.4. Fuel and Lubricants

The estimated fuel and lubricant costs were \$0.97/m and \$0.15/mt, respectively. Accordingly, the total estimated costs for fuel and lubrication were \$1.11/mt of energy cane (Table 8).

The summary of the estimated costs of harvesting and the hauling unit is given in Figures 2 and 3. Figure 2 shows annual costs, while Figure 3 shows costs/mt. The ownership costs can be categorized as fixed costs, while repair, labor and fuel & lubricant costs can be classified under variable costs. Accordingly, variable costs incur higher costs (\$3.82/mt) compared to the ownership costs (0.50/mt) which is the case in crop production. The total estimated costs of machinery for harvesting and hauling units were \$4.32/mt of energy cane.

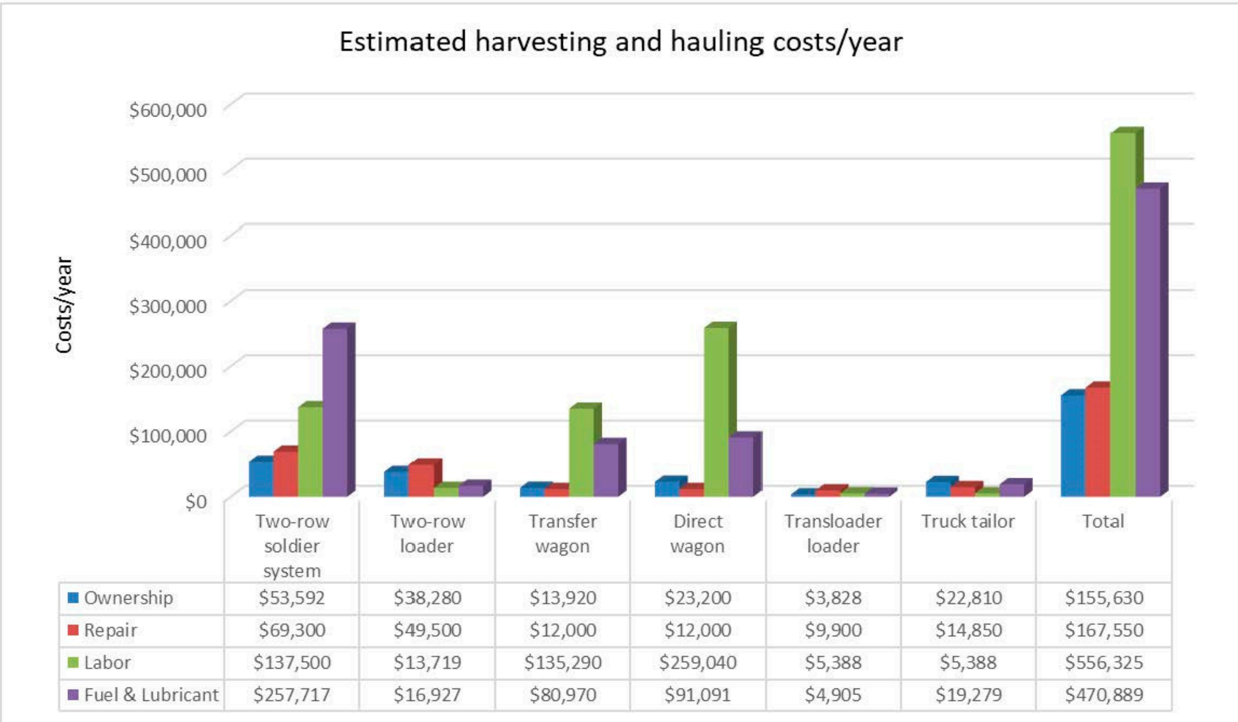


Figure 2. Summary of costs to operate a harvesting and hauling unit/year of energycane.

Table 5. Estimated ownership costs of machinery in harvesting and hauling unit.

Machinery	HP	Initial Cost	Salvage Value Factor	Salvage Value [1]	Total Depreciation [2]	Capital Recovery Factor	Interest Rate	Capital Recovery [3]	Total Taxes [4]	Total Ownership Costs ($/Year) [5]	Total Ownership Costs/mt
Two-row soldier system	350	$231,000	0.3	$69,300	$161,700	0.13	0.05	$24,486	$2310	$53,552	$0.17
Two-row loader	220	$165,000	0.3	$49,500	$115,500	0.13	0.05	$17,490	$1650	$38,280	$0.12
Transfer wagon	175	$40,000	0.3	$12,000	$28,000	0.13	0.05	$4240	$400	$13,920	$0.05
Direct wagon	175	$40,000	0.3	$12,000	$28,000	0.13	0.05	$4240	$400	$23,200	$0.07
Trans loader loader	85	$33,000	0.3	$9900	$23,100	0.13	0.05	$3498	$330	$3828	$0.01
Truck trailer	160	$49,500	0.3	$15,345	$34,155	0.13	0.05	$5207	$495	$22,810	$0.07

[1] Salvage value = initial costs of machinery × salvage value factor. [2] Total depreciation = initial costs of machinery − salvage value. [3] Capital recovery = (Total depreciation × capital recovery factor) + Total depreciation × (interest rate). [4] Total taxes = initial costs of machinery × 1%. [5] Total ownership costs = (capital recovery + taxes) × no of machines needed.

Table 6. Estimated repair costs of machinery.

Machinery	HP	Initial Cost	Annual Use (h)	Age (Year)	Repair Costs Factor	Accumulated Repair Cost [1]	Repair Cost/Year	Repair Costs/h	Repair Costs/mt
Two-row soldier system	350	$231,000	3819	12	30%	$69,300	$5775	$1.51	$0.0185
Two-row loader	220	$165,000	399	10	30%	$49,500	$4950	$12.40	$0.0158
Transfer wagon	175	$40,000	2400	13	30%	$12,000	$923	$0.38	$0.0030
Direct wagon	175	$40,000	2700	10	30%	$12,000	$1200	$0.44	$0.0038
Transloader loader	85	$33,000	299	8	30%	$9900	$1237	$4.13	$0.0040
Truck trailer	160	$49,500	625	10	30%	$14,850	$1485	$2.38	$0.0048

[1] Accumulated repair cost = Initial cost of machinery (from Table 4) × repair costs factor.

Table 7. Total labor costs for harvesting and transportation unit.

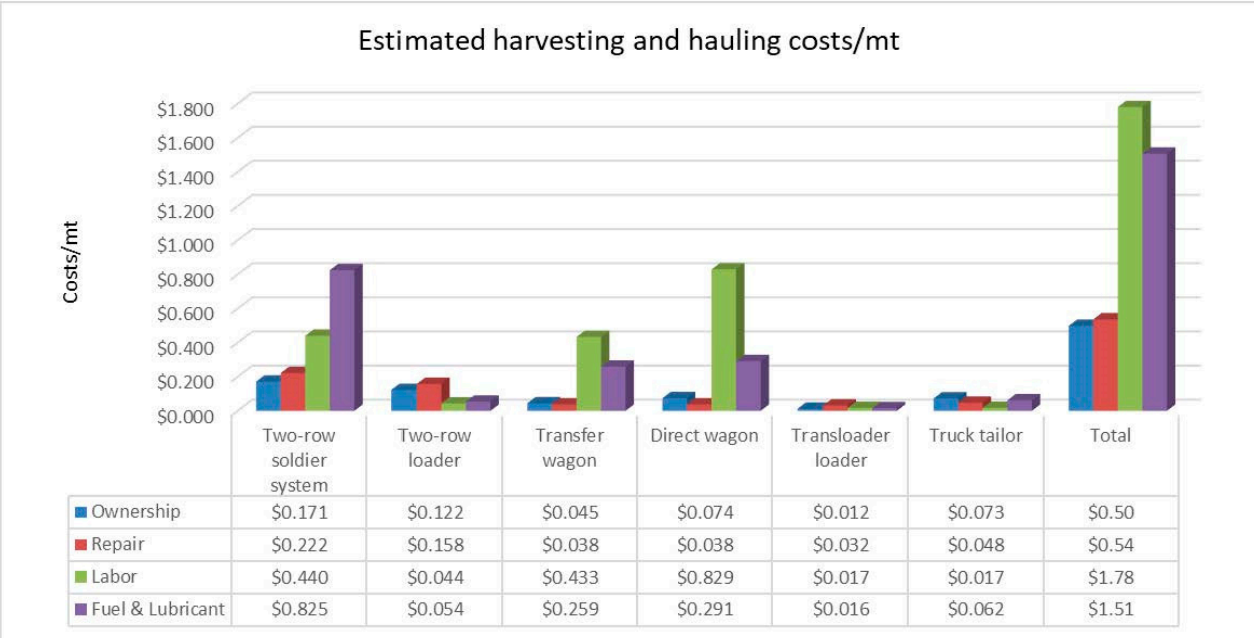
Machinery	No of Machines Needed	Annual Use Hours per Machine [1]	Total Machine Hours	Total Area(ha)	Machine Hours per ha [2]	Labor Cost $/h	Total Labor Costs	Total Energycane Yield (MT)	Cost/Mt
Two-row soldier system	2	3819	7639	4726	1.62	$18	$137,500	312,483	$0.44
Two-row loader	2	399	762	4726	0.16	$18	$13,719	312,483	$0.04
Transfer wagon	3	2400	7516	4726	1.59	$18	$135,290	312,483	$0.43
Direct wagon	5	2700	14,391	4726	3.05	$18	$259,040	312,483	$0.83
Transloader loader	1	299	299	4726	0.06	$18	$5388	312,483	$0.02
Truck with trailer	4	2400	9617	4726	2.03	$18	$173,103	312,483	$0.55

[1] Annual use hours per machine = total days for harvest × working h/day. [2] Total machine h/ha = area to be harvested/estimated total machine hours.

Table 8. The estimated fuel and lubricant costs for harvesting and transportation unit.

Machinery	Diesel Consumption Factor	Av. Fuel Consumption (imp gal/h)	Diesel Cost/imp gal	Av Fuel Cost per Hour	Fuel Cost/year	Total Lubrication Cost/h [1]	Total Lubrication Cost/year	Total Fuel and Lubrication Cost/year	Fuel and Lubrication Costs/mt
Two-row soldier system	0.044	15.4	$3.81	$58.67	$224,102	$8.80	$33,615	$257,717	$0.82
Two-row loader	0.044	9.68	$3.81	$36.88	$14,718	$5.53	$2207	$16,926	$0.05
Transfer wagon	0.044	7.7	$3.81	$29.34	$70,408	$4.40	$10,561	$80,970	$0.26
Direct wagon	0.044	7.7	$3.81	$29.34	$79,209	$4.40	$11,881	$91,091	$0.29
Transloader loader	0.044	3.74	$3.81	$14.25	$4265	$2.14	$639	$4905	$0.02
Truck with trailer	0.044	7.04	$3.81	$26.82	$16,764	$4.02	$2515	$19,279	$0.06

[1] Total lubrication costs on most farms average about 15% of fuel costs (lubrication factor of 0.15). Lubrication costs = 0.15 × average fuel costs/h.



	Two-row soldier system	Two-row loader	Transfer wagon	Direct wagon	Transloader loader	Truck tailor	Total
Ownership	$0.171	$0.122	$0.045	$0.074	$0.012	$0.073	$0.50
Repair	$0.222	$0.158	$0.038	$0.038	$0.032	$0.048	$0.54
Labor	$0.440	$0.044	$0.433	$0.829	$0.017	$0.017	$1.78
Fuel & Lubricant	$0.825	$0.054	$0.259	$0.291	$0.016	$0.062	$1.51

Figure 3. Summary of costs to operate a harvesting and hauling unit/mt of energycane.

3.5. Distribution of Harvesting and Hauling Costs

To better visualize the potential range of costs, we reviewed the harvesting and hauling costs of sugarcane which is a comparable crop for energy cane. Previous estimates on sugarcane harvesting [36] showed harvesting costs range from $3.92–$9.42 range with mean costs of $6.67. We considered our estimated costs as minimum costs and generated the cost distribution based on assumptions from previous work (Figure 4). According to 90% confidence level, the harvesting and hauling costs could range from $5.47–$9.23/mt of energy cane.

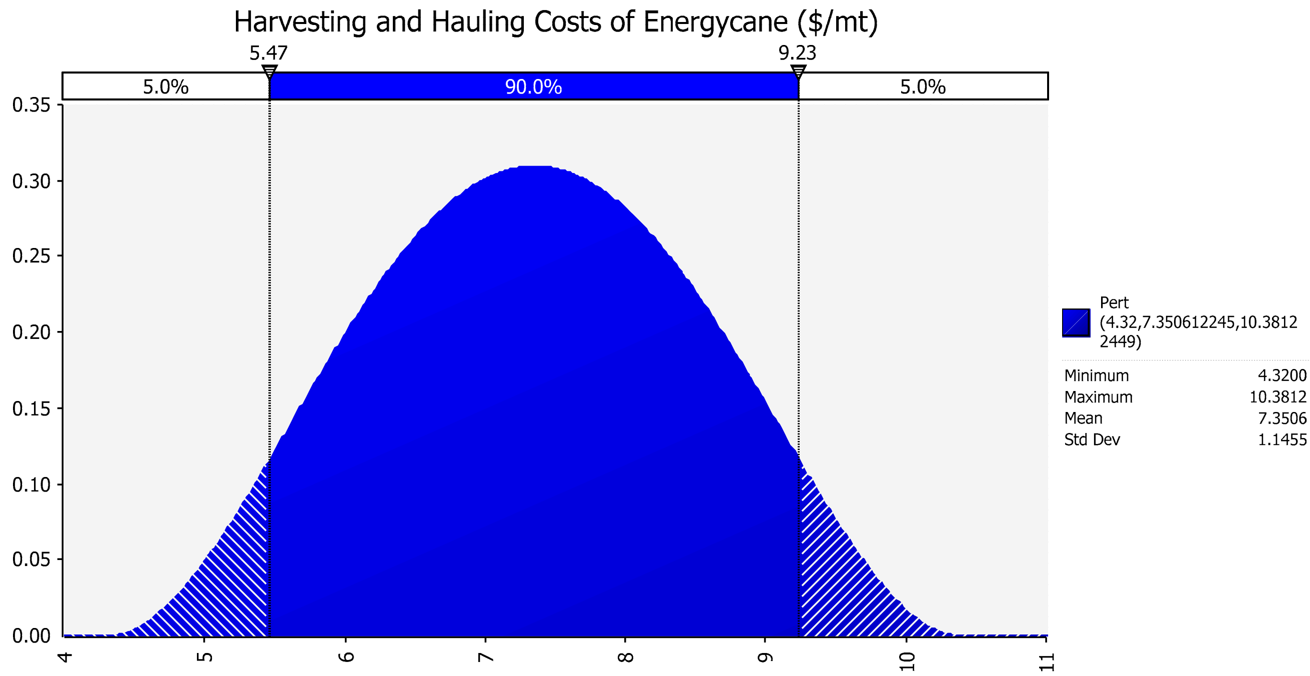


Figure 4. Distribution of transportation and hauling costs of energycane.

4. Discussion

The results generated from this study will be useful for supply chain development for supply of biomass for ethanol biorefineries. Biorefineries can evaluate options for maintaining one's own harvesting unit for their field operations or considering custom harvesting for biomass supply. The results will be useful for harvesting companies to determine initial capital investment, annual expenses for operation and production costs based on timing of operations. The estimated harvesting and hauling unit is specific to a biorefinery with a selected capacity, and the required machinery units may change with biomass yield, ethanol yield/mt of biomass and the days of operation annually along with the capacity of machine. A study of this nature is based on assumptions, hence any changes in assumptions may affect the estimation. The harvesting and hauling costs are sensitive to a wide range of stochastic factors including type of machinery (capacity, power, initial costs etc.), travel time and distance, working hours, waiting time, labor wages, fuel and lubricant prices etc. We generated the potential distribution of costs by analyzing sugarcane harvesting and hauling costs. However, a detailed sensitivity analysis is useful in evaluating costs under various scenarios given risk and uncertainty, hence we highlight the importance of performing a sensitivity analysis in a similar study. A sensitivity analysis would be useful to identify how the results can be applicable to other scenarios such as different local/economic situations.

5. Conclusions

A supply of feedstock to an industrial bioenergy refinery with the processing capacity of 25 million imp gal of ethanol was considered in this research. To supply energy cane, an area of 4746 ha is needed. The machinery units required for the continuous harvest and supply of energy cane were assessed, and the cost analysis was performed. The average estimated ownership, repair, labor and fuel and lubricant costs of biomass harvest units were calculated to be $0.50, $0.54, $1.78 and $1.51/ mt, respectively. The simulation results show that costs distribution (95% CI) could range between $5.47–$9.23/mt of energy cane. Currently, the commercial production of biomass sorghum in the southeastern region is at early stage, hence the research output will provide vital information for the feedstock development initiative. The research findings may help to identify and design machinery units for harvesting biomass with lower costs. The study findings can also be used in evaluating investment costs for designing harvesting and hauling units for different scales of operation. The new investment opportunities in the biomass harvesting and hauling operations will likely provide new revenue generation and employment opportunities that would bring additional economic impact to local and the regional economies.

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