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Supply Cost and Life-Cycle Greenhouse Gas Footprint of Dry and Ensiled Biomass Sorghum for Biofuel Production

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Abstract

Biomass sorghum is a promising feedstock for cellulosic biorefineries because of its high yield and drought tolerance. However, the difficulty of effectively drying sorghum in some regions means it may require different handling than previously studied grassy feedstocks. This study compares the delivered cost and life-cycle greenhouse gas (GHG) footprint of field-drying and baling, module storage (wrapped, densely packed biomass), pelletizing, and ensiling. Ensiling has not been widely considered for use in bioenergy production. For farms within 66 km of the biorefinery, ensiled biomass is the lowest- cost and GHG strategy despite additional cost and energy demands for hauling wet biomass. Field-drying and baling, if feasible, is the most cost-effective option for sorghum between 66 km and 104 km, beyond which pellets are preferable. A

2000 bone-dry-metric ton (bdt)/day biorefinery can source sorghum with 18 bdt/ha yield cultivated on 5% of surrounding land at costs range from $122 (silage) to $167 (pellets)/bdt and a life-cycle GHG footprint of 111 (silage) to 179 kg CO_2e/bdt (pellets). With 28 bdt/ha biomass yield, 10% cultivation of surrounding land, and low fertilizer application, costs can range from $66 (silage) to $85 (pellets)/bdt and GHG footprint of 43 (silage) to 96 kg CO_2e (pellets)/bdt.

Keywords: Bioenergy, silage, sorghum, biomass, technoeconomic analysis, life-cycle assessment, greenhouse gas emissions

Introduction

Bioenergy sorghum (also referred to as biomass sorghum) is an important potential feedstock for future biorefineries in the United States. Sorghum [*Sorghum bicolor* (L.) Moench] is one of the few crops that can fit into all of the current bioenergy frameworks: grain-to-ethanol; sweet sorghum sugar into fuels; and as a biomass feedstock for lignocellulosic and cellulosic conversion. Sorghum lines typically considered most promising for lignocellulosic biofuel production are photoperiod-sensitive (PS), meaning they remain in a vegetative state for longer than photoperiod insensitive varieties and develop little or no grain. Brown midrib (BMR) mutants can provide additional advantages because of their relatively low lignin content and high digestibility.[1] Because biomass sorghum is an annual crop with an existing market as a forage, it may be considered a less risky dedicated bioenergy crop for farmers to cultivate relative to perennials like *Miscanthus* spp or switchgrass (*Panicum virgatum*) that have high upfront establishment costs and limited alternative markets.[2] Alternative markets are important to the stability of biofuel feedstock supply chains, given the limited cellulosic biorefinery capacity developed to date. Other key features of biomass sorghum are: (i) a high carbohydrate content of >70 wt%;[1] (ii) average biomass yield of 17.9 ± 3.3 bone dry tonne (bdt)/ha (Mg/ha, 0% moisture),[1,3-9] which is roughly 4-fold more than a typical harvest rate of corn stover collected following grain harvest; [10] (iii) potentially high soil carbon sequestration of -0.04 to -0.8 MgC/ha/year [11] (iv) tolerance to drought, disease, and heat; [12,13] and (v) relatively high nitrogen and water use efficiencies.[14,15]

Despite sorghum's advantages, the 60-80% moisture content[16,17] (all moisture content values reported as a fraction of total wet weight), prior to senescence is a serious challenge for the biomass sorghum dry feedstock supply system. Stable long-term storage of biomass under aerobic conditions generally requires a moisture content around 15-20% and, for lignocellulosic biorefineries to operate at or near capacity year-round, these facilities must store feedstock for as long as one year.[7] Many commercial sorghum varieties have been bred for delayed senescence (the stay-green phenotype) and even for non-stay-green varieties, delaying harvest until complete senescence can result in additional dry matter losses and weather-related complications.[18] Ensiling wet chopped biomass, which runs counter to the conventional bioenergy strategy of dry storage, may be a viable alternative. In current practice, forage sorghum is commonly collected and chopped with a forage harvester and stored wet in a covered pit or pile (often inoculated with an organic-acid producing bacteria such as *Lactobacillus*), or in plastic tubes ('AgBags'), or anaerobic wrapped bales (baleage). Silage relies on a reduced pH and anaerobic conditions to ensure stability and quality. [18,19] This is a common strategy in the dairy industry and farmers are familiar with silage production practices. Forage sorghums are difficult to dry in the field (especially in rainy areas), and ensiling is the most common storage method. Ensiling also enables greater flexibility with harvest timing and could be beneficial for biomass deconstruction[16] if it is stored for a long period of time. However, the question remains as to how ensiling sorghum compares to more conventional strategies, such as baling, and how the farm-to-biorefinery distance impacts the least-cost, lowest-carbon strategy. The goal of this study is to evaluate a range of alternatives for efficient and cost-effective year-round bioenergy sorghum supply to biorefineries.

The U.S. Department of Energy *Billion Ton Study* recommends a strategy for sorghum that has similarities to ensiling, and is modeled after practices in the cotton growing industry: the wet material can be chopped as it is harvested and subsequently consolidated anaerobically into densely-packed plastic-wrapped modules (without inoculate).[7] The direct transportation of the loose chopped-biomass (as in the case of silage) or densely-packed modules diminishes the eventual size reduction (milling) cost relative to bales but increases drying cost and energy (if downstream processing/conversion requires dry biomass). [7,19] A rigorous technoeconomic analysis (TEA) and life-cycle greenhouse gas (GHG) inventory are essential to quantify the tradeoffs of these different approaches and identify the key cost and emissions drivers. A deeper understanding of costs and emissions is particularly crucial given the aggressive targets for delivered feedstock costs established by the U.S. Department of Energy at the pretreatment reactor throat of $78.6/bdt ($71.26/bone-dry short ton) to achieve biofuel prices of less than $2.5/gallon gasoline equivalent (gge) by 2030.[20] A limited number of previous studies have estimated biomass sorghum supply cost in the form of bale,[21,22] module,[7,22] and silage,[22] although these studies are limited to single point analysis and did not consider the entire supply chain including biomass production and delivery to the biorefinery gate or to the pretreatment reactor throat.

In this study, we performed a stochastic analysis of both costs and life-cycle GHG emissions for cultivating, harvesting, storing, and delivering bioenergy sorghum to biorefineries considering two different supply routes (with and without a preprocessing depot) and four different feedstock forms including chopped and ensiled biomass, modules, bales, and pellets. Any drying and densification of biomass adds cost, with the expectation that it will achieve savings in transportation and in reduced biomass losses during storage. Thus, this study provides results as a function of transportation distance from farm to biorefinery for these potential feedstock collection and handling strategies. We also provide potential avenues to achieve the targeted feedstock supply cost at the reactor throat of $78.6/bdt.[20]

Methods

Bioenergy sorghum production and supply systems

Three potential supply strategies are considered in which bioenergy sorghum is delivered directly from the field to the biorefinery in the form of either chopped wet biomass (for ensiling at the biorefinery), densely packed modules, or dry bales (Figure 1). An alternative pelleting system is also considered, which is designed to accommodate longer distances between the farm and biorefinery. In the pelleting case, bioenergy sorghum is first transported from the field to the preprocessing depot (storage depot) and then pelletized[23] before being transported to the biorefinery. This analysis is based on the particle size requirements for biochemical conversion pathways. Once the biomass arrives at the biorefinery, some forms require further size reduction and others do not. Chopped ensiled biomass (particle size can be controlled by changing the knife configurations in the forage harvester) and pellets can be directly fed to the pretreatment reactor (Supporting Information (SI)-S1.2.1 and S1.5). Baled dry sorghum requires size reduction before pretreatment,[24] whereas modules[7] only need to be broken apart from their compacted form.

Our analysis is based on the use of a shredder to reduce the particle size of baled biomass to <38 mm (1.5 in.) at the biorefinery, [24,25] which is similar to the typical maximum particle size of chopped biomass produced by forage harvesters [26,27] on the field. The resulting particle sizes will not be uniform, and forage choppers or shredders set to deliver 34 mm particles will produce many particles under 10 mm. [27] Modules must be broken apart with a combination of impact and shearing actions. The expected module-braking machine is not available at present; thus, energy consumption of such machine is assumed to be 5 kWh/metric ton (half of the bale shredder), throughput is increased from 28 to 40 metric ton/h (same as the stover shredder [28]), and the purchase cost is assumed to be the same as the bale shredder of $302,000 (originally reported in year 2000 dollars).[24]

Although the impact of particle size distribution on sugar yields and downstream costs need to be further investigated at pilot or larger scales, there is evidence that many promising pretreatment processes, including steam explosion,[29] ammonia fiber explosion,[30] deacetylation and mechanical refining,[31] and ionic liquid,[30] can handle these larger particle sizes without appreciable reductions in sugar yield. Biomass used to produce pellets must be milled to a smaller size than biomass supplied directly to the biorefinery. We modeled a two-stage milling process at the depot to achieve a mean particle size of 6.35 mm (¼ in.) for the optimal densification.[23,32,33] All the feedstock forms considered in this study require a feedstock handling process prior to entering the pretreatment reactor that includes conveyors (belt/screw) and short-term storage.[34]

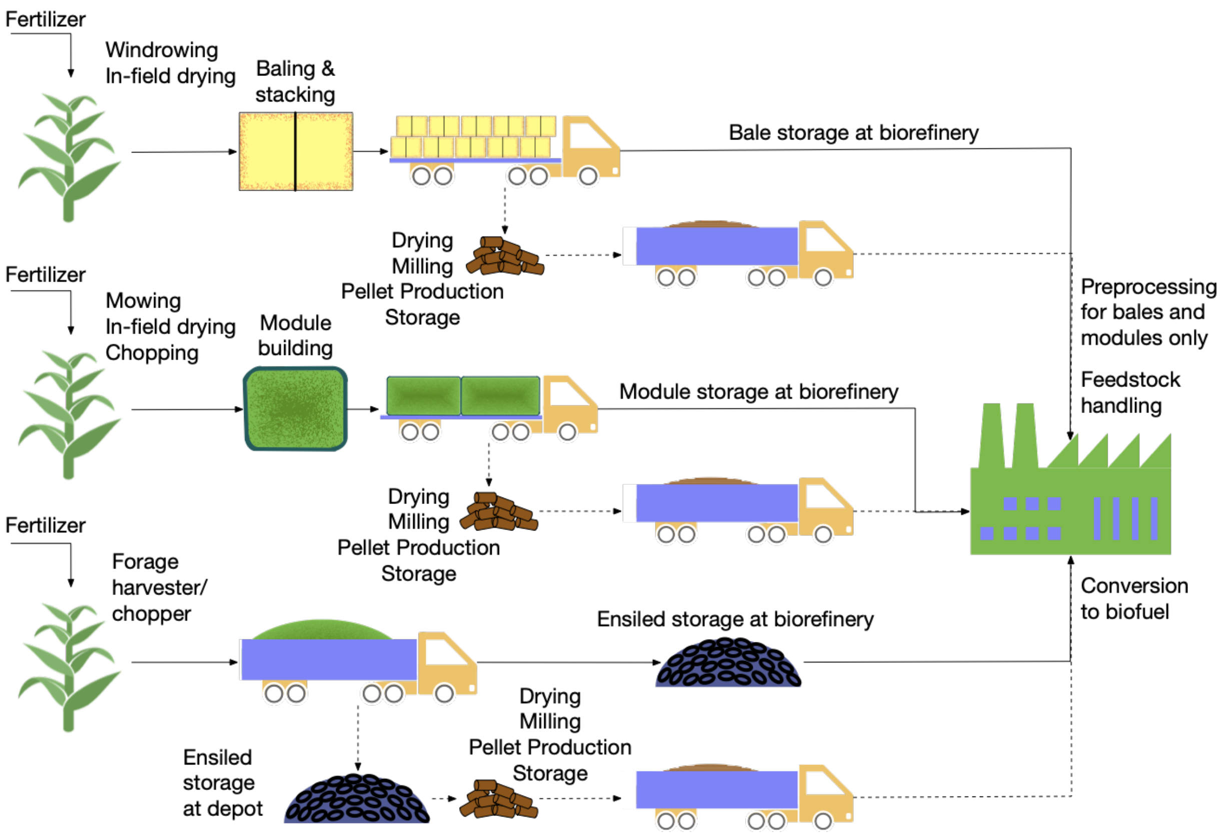

Figure 1. An overview of biomass sorghum supply systems considered for analysis in this study. Pellet production at the depot requires a series of unit operations including feedstock handling, primary milling (only required for module and bale), drying, secondary milling, conditioning and pelletizing, and steam generation units (SI-S1.5).

The logistics model was developed by using macro-enabled Microsoft Excel sheets. The process models for the preprocessing (pellet production at the storage depot) and handling at the biorefinery are developed in process modeling software (SuperPro Designer V10.2 [35]). Visual Basic code was used to integrate these modeling and analysis tools. Feedstock supply models and assumptions are consistent with previous logistics models developed for chopped biomass [22,36,37], module [38,7,22], bale,[10,22,23,36,37,39,40], and pellets[10,23,36,37,39,40] of different herbaceous lignocellulosic biomass feedstocks, including sorghum, corn stover, Miscanthus, and switchgrass. Previous studies[10,22,33,41] provided a detailed discussion about the different stages of the feedstock supply system. Recognizing that similar operations are required for biomass sorghum,[7,21,22] this study provides detailed discussion of these different components/stages of the biomass supply chain (Figure 1) and associated data inputs in the SI (S1.1 to S1.6 and Tables S1 to S6). We consider a standard biorefinery sized to take in 2000 bdt biomass sorghum to the pretreatment reactor throat per day in every scenario. This biorefinery size was selected based on the economies of scale achievable for ethanol, although this size is commonly used to model a wide range of biochemically-produced fuels and products.[24,40]

The optimal biorefinery size is dependent on a number of factors, including the specifics of the conversion process and scaling factors for capital equipment, which must be weighed against the increased feedstock transportation costs for larger facilities.[40] The biorefinery is assumed to be operated 330 days per year and 24 hours per day. We allocate 12.5% of additional feedstock (for 45 days) as a safety stock to mitigate the risk of stock-outs due to inclement weather, unexpected biomass losses, and any transportation delays.[42] Therefore, the logistics model developed in this study delivered the bone-dry biomass feedstock of 2250 t/day for the baseline scenario. Table 1 summarizes the major input parameters associated with biomass sorghum production and supply chain, including dry matter loss, harvest window, dry-down time on the field, and the fraction of land cultivated with sorghum around the biorefinery (land utilization) (Table 1). In addition to the biorefinery supply scenarios detailed in Table 1, we analyzed delivered sorghum biomass cost per bdt as a function of distance from the farm-to-biorefinery, which is independent of biorefinery scale and land utilization factor.

Dry matter loss, particularly during storage, is an important parameter for both cost and emissions, and these losses are well documented for herbaceous biomass bales.[10,23,43] Prior work [42] collected data from several studies and found the dry matter loss of the bale supply system in the range of 4.2 to 25% with the mean value of 11.6%. Dry matter loss in bales increases with moisture content and storage duration, [43] whereas the ensiling process uses anaerobic conditions and a low pH to control decomposition. Easily accessible carbohydrates (e.g. soluble starch) are converted to organic acids during the ensiling process and some initial degradation takes place before the ensiled biomass reaches a stable pH of 3.5- 4.5 and again during the feed out phase where material will again be exposed to oxygen.[44] A meta-analysis considering 43 peer-reviewed studies found the forage dry matter loss during the ensiling process in the range of 0 to 28.6% with the mean value of 6.2% and median value of 14%.[44] Wendt et al.[19] found dry matter loss of 5.75% after 110 days of anaerobic storage of corn stover. Another recent study[17] found 11 wt% organic acids in the ensiled biomass sorghum and 13.5% loss of total carbohydrates, although the easily accessible carbohydrate content will depend on whether the forage sorghum has a grain head. Modules systems, because they have not been widely implemented or studied for sorghum, are not well understood in terms of dry matter loss. Because relative differences in dry matter losses across different supply systems are uncertain and dependent on local conditions, we use a consistent loss factor across all scenarios and include a range of 2-30% in the uncertainty analysis (Table 1).

The sorghum harvest window impacts equipment and labor costs, and is dependent on local climate conditions. The active harvest window of sorghum for silage in the U.S. is in the range of 15 to 75 days, with the average value of 31.5 days (average of 13 different states).[45] Ensiling or module building could allow for a wider harvesting window because these strategies do not require dry-down in the field, but extending the harvest window into the rainy season can result in soil erosion from the use of field machinery and trucks/loaders in the wet field. Therefore, we conduct our analysis using the 31.5-day average harvest window (Table 1). Dry down time on the field is also dependent on the local climate and effectiveness of biomass conditioning. Conditioning (crush and/or split the biomass sorghum stem) reduces the stiffness of the biomass, accelerates field drying, and facilitates the production of uniform and compact bales. A prior study[46] explored the impacts of using a "V" impeller, chisel impeller, and fluted roll conditioner on thin-layer drying time and found that the fluted roll conditioner reduced drying time by nearly 80% relative to the unconditioned material. Researchers at Oklahoma State University[47] have indicated that dry-down time in the field can be as low as 5 days with good conditioning and favorable weather conditions, while less effective conditioning results in 10 or more days required for dry-down. We use a minimum dry-down time of 5 days, a maximum of 21 days based on data reported by Khanchi et al.[48], and an average duration of 10 days.[38]

The availability of biomass sorghum fields around the biorefinery (land utilization) is another important parameter because it impacts transportation costs to satisfy the facility's needs. For the baseline scenario, we assume 5% of land surrounding the biorefinery is actively growing sorghum (meaning more land may include a sorghum rotation, but 5% of total land is producing sorghum in any given year). For comparison, the U.S. currently utilizes 1.7% of the total cropland for sorghum farming, typical land utilization for corn crops in corn-dominated regions is considerably higher (35%) whereas typical assumptions for other bioenergy crops such as switchgrass and Miscanthus are 5-10%.[3] The land utilization factor could increase well beyond

5% in some regions if biomass sorghum becomes a widely used bioenergy crop.[7] In the pelletization scenarios, preprocessing (storage) depots are assumed to be uniformly distributed around the biorefinery. With 5% land utilization, we estimated an optimal number of 13 preprocessing depots to achieve the lowest possible delivered biomass cost. This results in an average field-to-depot supply distance of 16 km (9.9 miles). Additional assumptions made in this study, descriptions of each stage in the supply chain, and the data sources used to develop the process model are provided in SI-Tables S1 to S6.

Table 1. Major input parameters for biomass sorghum supply chain

Parameter	Unit	μ	a	b	σ	Probability distribution
Biorefinery size (assumed)	bdt/day	2,000	-	-	-	None
Biorefinery working days (assumed)	days/year	330	-	-	-	None
Biomass yield[1,3–9,49]	bdt /ha	17.9	5.2	27.6	5.4	Lognormal
Moisture content at harvest[7,16,17]	%	59.7	40.0	70.0	10.7	Triangular
Safety stock [42]	%	12.5	8.0	25.0	8.8	Triangular
Dry matter loss (supply chain) [19,23,42]	%	11.6	4.2	25.0	6.6	Lognormal
Dry matter loss (forage harvester) [38,50]	%	2.4	0.8	4.0	-	Triangular
Harvest window [45]	days/year	31.5	15.0	75.0	14.6	Triangular
Harvesting hours[λ]	hours/day	16.0	8.0	24.0	8.0	Triangular
Fraction of land surrounding biorefinery cultivated with sorghum[ω,Φ]	%	5.0	2.0	10.0	-	Triangular
Road winding factor [10,28,51,52]	-	1.5	1.1	3.5	0.4	Normal
Direct land use change impact [11]	tCO_{2e}/ha	-0.46	-0.04	-0.8	-	Triangular

Note: ***μ*** = average value; **a** = minimum value; **b** = maximum value; **σ** = standard deviation; bdt = bone dry tonnes

[λ]Assumed based on the current harvesting practices of biomass sorghum.

[ω]Percentage of the total area (including land, water bodies, and others) around the biorefinery.

[Φ]Assume the biomass sorghum field is uniformly distributed around the biorefinery.[10,51]

Biomass sorghum production and supply costs, and greenhouse gas emissions estimates

We estimate the biomass sorghum production and supply costs using cash flow analysis, including capital investments, ownership costs (including depreciation, interest, taxes, insurance, and housing), and operating costs (including repair and maintenance, fuel, lubrication, labor, and consumable materials, such as string, tarp, and plastic wrap). For non-grain biomass feedstock, such as biomass sorghum, biomass production cost and associated GHG emissions should be allocated entirely for biomass. We calculated biomass production cost including cultivation (except fertilizer), fertilizer, and herbicides costs. Cultivation includes such factors as land rent, establishment labor and fuel inputs, seed costs, and herbicides. Data inputs used to determine these different cost components are documented in SI-Tables S1 and S2. Detailed methods and equations used to estimate biomass production and supply costs are documented in previous studies.[10,41,53]

In addition to the feedstock supply cost, life-cycle GHG emissions were calculated for each stage of the supply chain using a hybrid process-based/physical units input-output model as documented in our previous work.[54] The emission factors were gathered from widely used LCA databases, including GREET, Ecoinvent, and U.S. LCI database.[55–57] Net emissions/sequestration of GHGs resulting from conversion of arable land for sorghum production is an important contributor and has not been well documented in previous life-cycle emissions studies for bioenergy sorghum, so we have used net GHG fluxes from direct land use change documented in recently-completed DAYCENT modeling [11,58,59] by taking an average of net SOC impacts across all arable land in the U.S. of -0.46 tCO_{2e}/ha/year. To estimate N_2O emissions resulting from microbial nitrification and denitrification processes in the soil, we employed the standard practice of assuming 1.15% of nitrogen applied as fertilizer is released as N_2O, with a global warming potential of 298. [11] Further details on methods and assumptions are discussed in the SI-S2.

To capture uncertainty, we conducted a single-point sensitivity analysis for cost and GHG emissions to highlight the impacts of specific individual parameters, and separately ran stochastic simulations to develop probability distributions for the results. For the single-point sensitivity, minimum and maximum values of influential input parameters were gathered from published literature (Table 1 and SI-Tables S1-S7). Additionally, we developed heat maps for cost and GHG emissions considering direct transportation of chopped ensiled biomass from the field to the biorefinery as a representative case, with the goal of illustrating the combined effect of varying various sets of two selected input parameters on the feedstock supply cost and GHG emissions. The stochastic Monte Carlo simulations were conducted using best-available probability distributions, including uniform, normal, triangular, and lognormal (Table 1 and SI-Tables S1-S7). The field-to-biorefinery distance is varied during two-point sensitivity analysis and Monte Carlo simulation; it is a function of biomass yield, land utilization fraction (% of surrounding land cultivated for sorghum), dry matter loss, and the road-winding factor (Table 1). The process of defining the probability distribution is consistent with the authors' recent study.[60] The simulations were run for 10,000 Monte Carlo trials.

Results and discussion

Biomass sorghum supply cost

Figure 2a shows the delivered cost of biomass sorghum at the pretreatment reactor throat for silage, modules, and bales, with a comparison for each between direct supply versus pelletization at a storage depot. For the baseline biorefinery size of 2000 bdt/day around which 5% of land is cultivated with biomass sorghum, modules are the most expensive form of feedstock ($146/t), followed by bales ($125/t), and chopped ensiled biomass ($121/t) when these are directly delivered from the field to the biorefinery. The sum of machinery, seed, herbicides, land rent, labor, and fuel, [4,6] is responsible for, on average, 24% of the overall supply cost. While this study considered an average biomass sorghum production cost, it should be noted that these costs will vary by location. Fertilizers account for, on average, 19% of the overall feedstock supply cost. Although not incorporated into the baseline case, sustainable farming practices, such as low- or no-till strategies and crop rotation, can reduce costs by minimizing nutrient inputs, irrigation, and use of machinery.

The major differences among the modules, bales, and silage are in the field operation and transport costs. The field operation cost is, respectively, responsible for 31%, 23%, and 9% of the overall delivered cost for modules, bales, and silage. Biomass transportation accounts for 18%, 22%, and 32% of the overall delivered cost for modules, bales, and silage, respectively. While a forage harvester can be used for harvesting and loading the chopped biomass on the truck all in a single step,[22] the module-building process requires multiple field operations[7,22] including mowing, on-field drying (to reduce moisture to 40%), chopping, module building and wrapping (using a plastic wrap), and on-field transportation or stacking at the field edge. These series of operations required for modules result in a 4X increase in field operations costs relative to the chopped ensiled biomass. The baling process also requires multiple field operations, including windrowing or mowing, on-field drying and raking (to reduce moisture to 20%), baling, and stacking at the field edge, which results in a 2.5X increase in field operations costs relative to the chopped ensiled biomass. Importantly, the time requirement for field drying entails greater risk from rain damage. However, the chopped ensiled biomass requires 49% and 43% greater transportation costs from the field to the biorefinery relative to modules and bales, respectively. This large transportation cost is mainly due to a low bulk density and high moisture content (Table 1 and SI-Table S3) relative to bales and modules.

Delivering pellets (as part of the depot system) produced from chopped ensiled biomass, modules, and bales to the biorefinery reduces the overall transportation cost by 42, 34, and 30 %, respectively, relative to their direct field-to-biorefinery transportation costs. This reduction is primarily due to the full utilization of truck payload capacity and reduction in required truck trips due to a low moisture content of pellets (10%).[23] However, the additional cost of pellet production is substantial, accounting for 20-25 % of the overall feedstock supply cost. Differences in pellet production cost depend on the level of milling and drying required, which is dependent on the form of the delivered sorghum (SI-Figure S1). Chopped ensiled biomass has already been processed in a forage harvester/chopper and thus only requires a single-stage milling process to achieve the required particle size for pelletizing of 6.35 mm, [23] whereas biomass bales require a two-stage milling process. The cost associated with the rotary steam dryer, including the onsite steam generation (using natural gas as the fuel) is responsible for 43% of the total pellet production cost from silage (Figure 2a and SI-Figure S1). Modules (40% moisture) and bales (20% moisture) require less steam for drying; the drying process makes up 37% and 15% of their pellet production cost, respectively (Figure 2a and SI-Figure S1). Despite the increased drying costs and higher field-to-depot transportation costs, the delivered cost of pellets produced from chopped ensiled biomass is lowest ($136/t) followed closely by bales ($147/t) and modules ($167/t) (Figure 2a). Our results indicate that the additional drying cost, including onsite steam generation, required for the chopped ensiled biomass at the depot is offset by its lower field operation and size reduction costs relative to modules and bales (SI-Figure S1).

For comparison, the overall biomass sorghum supply costs determined in this study are comparable to the market price of biomass sorghum bales (after adjusting preprocessing cost at the biorefinery (SI-Figure S2)) in the range of $123 to 161/t.[61] One notable difference between this study and prior work is in the estimated preprocessing cost for bales at the biorefinery ($7/bdt), which includes material handling, size reduction, and short-term storage costs. Prior studies on corn stover bales estimated $10.9/bdt with grinding[28] and $14.3/bdt with two-stage milling [10] (mean particle size of 4 mm). Our lower preprocessing costs are based on use of a shredder (consumes about 10-fold less energy than grinding [24,28]) and larger maximum particle size (length of 38 mm, which is consistent with the module and silage systems). Recent studies indicate that these larger particle sizes do not appreciably impact performance for many commonly studied pretreatment processes including ionic liquid,[30] steam explosion,[29] and ammonia fiber explosion[30] pretreatment processes.

The biomass sorghum supply costs modeled in this study are, in addition to aligning with sorghum market values, comparable to other potential biomass feedstocks costs at the pretreatment reactor throat, including corn stover costs ($86-132/t [23,33,40,63]), Miscanthus ($127-155/t [23,40]) , and switchgrass ($79-139/t [23,33,40]). These wide ranges are due to regional variations in on-farm resource requirements, biomass yield, land utilization surrounding the biorefinery/depot, and moisture content. Biomass yield per unit cultivated land area is a particularly key parameter because biomass yield directly alters both the costs associated with farming (e.g. land rent, fertilizer, labor, fuel, harvesting costs) and the average farm-to-biorefinery distance to deliver 2000 bdt of feedstock per day.

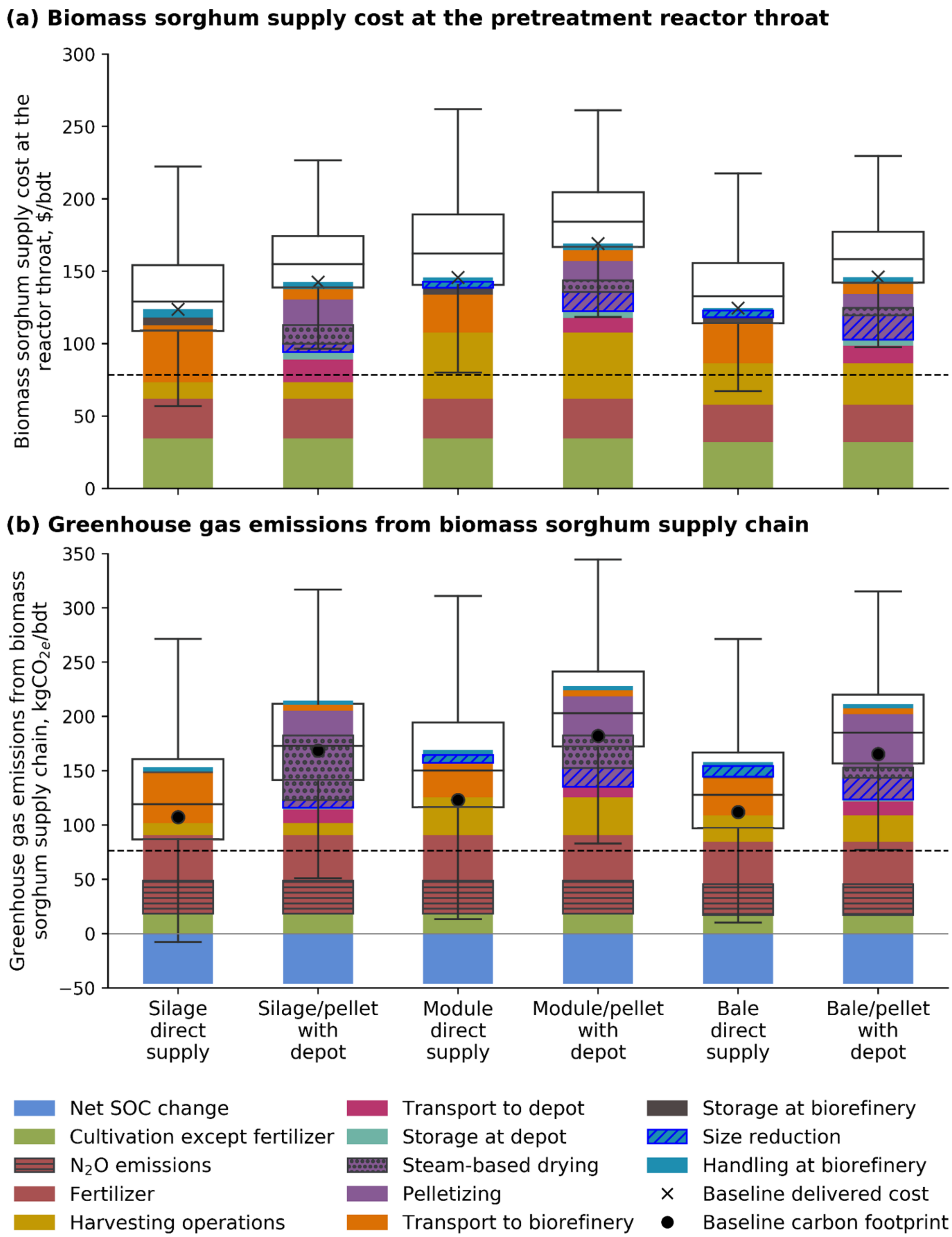

Figure 2. Delivered cost of biomass sorghum feedstock at the pretreatment reactor throat (a) and associated greenhouse gas emissions (b). For the baseline analysis, the estimated farm-to-biorefinery distances are 57.8 km for silage and module, and 55.9 km for bale, which are dependent on the biomass yield, land utilization, dry matter loss, and the road-winding factor (Table 1). The detailed cost and carbon footprint contributions from different unit

operations associated with preprocessing at the depot and the biorefinery are documented in the SI-Figures S1 and S2. The box and whisker plots show uncertainties in costs and GHG emissions. The horizontal dashed lines represent (a) the targeted feedstock supply cost at the pretreatment reactor throat of $78.6/bdt,[20] and (b) an average GHG emissions from corn stover supply chain[42,63,64] of 76.3 kgCO_{2e}/bdt.

Greenhouse gas footprint of biomass sorghum supply system

Across all scenarios, we use an average estimated soil organic carbon (SOC) sequestration of -0.46 tCO_{2e}/ha/year for production in the U.S. (local SOC sequestration values range from 0.04 to 0.8 tCO_{2e}/ha/year[11]). This net SOC sequestration factor reduces the GHG footprint by an average of 25% (Figure 2b). The SOC sequestration potential of biomass sorghum depends on site-specific biomass yield, nutrient application, irrigation, soil type, management history, and local climate, which we account for in the uncertainty analysis,[11,58] but warrants further in-depth study. On-farm activities required for sorghum cultivation, excluding nutrient inputs, is responsible for an average 10% of the gross GHG emissions, comprised primarily of diesel fuel combustion in field machinery. GHG emissions associated with fertilizer application (18-27%), biomass transportation (8-30%), and pellet production (38-40%, required for the depot options) are other major contributors to the gross GHG emissions (Figure 2b). N_2O emissions resulting from nitrogen fertilizer application are responsible for, on average, 16% of the gross GHG footprint. Chopped ensiled biomass requires fewer operations for harvesting (because it is a single-pass system) and handling at the biorefinery, resulting in 4-5% lower net GHG emissions relative to the module and bale systems, respectively. Notably, many of the factors driving module-building costs do not translate into similarly elevated GHG emissions. Similar to the biomass supply cost, GHG emissions associated with biomass transportation can be cut in half by switching from the direct supply to the depot option. However, this reduction does not compensate for the increased emissions associated with drying, milling, conditioning, and pelletizing. Steam for drying the biomass can be generated onsite using natural gas and we account for the electricity required for milling and pelletizing using the U.S. average electricity mix. Apart from drying (58% of the total preprocessing carbon footprint), carbon footprints of other preprocessing stages, specifically milling and pelletizing, are also significant (Figure 2b and SI-Figure S1). A shift toward renewable sources of electricity can reduce these emissions.

For comparison, the net GHG footprint for the baseline scenario (Figure 2b) determined in this study is similar to the GHG footprint of biomass sorghum reported in previous studies ranging from 19 kg CO_2e/bdt[57] (only includes GHG emissions associated with sorghum farming) to 132 kg CO_2e/bdt[65] (includes sorghum farming, fertilizer, N_2O emissions, and transportation). The GHG emissions from the biomass sorghum supply chain are also comparable with other biomass feedstock, including corn stover [42,63,64] in the range of 66-97 kg CO_2e/bdt, Miscanthus [66,67] in the range of 47-93 kg CO_2e/bdt, and switchgrass[33,63] in the range of 52-245 kg CO_2e/bdt (high upper end due to unusually large fertilizer application during establishment). These wide ranges are due to variations in fertilizer application, biomass yield, N_2O emissions, and impacts from land use change.

Sensitivity of costs and GHG emissions to key parameters

Biomass yield is the single most influential parameter on the basis of delivered feedstock cost because it alters the land requirements, on-field operations, and average transportation distances from the farm to biorefinery (see SI-Figures S3-S8 and Figures S21-S26 for additional details). To further explore the impact of biomass yield in combination with other parameters, Figure 3 provides cost and GHG emissions results for chopped ensiled biomass across a range of biomass yields, in combination with nitrogen application, dry matter loss, and land utilization (% land cultivated around the biorefinery). Each subset of this analysis shows an opportunity to reduce the biomass sorghum supply cost at the pretreatment reactor throat below \$100/t. A more optimistic but achievable case with biomass yield of 25 bdt/ha [4,5,7] could reduce feedstock supply cost below \$100/t under any of the following conditions: (1) nitrogen application <100 t/ha; (2) dry matter loss of supply chain <11 wt%; (3) land utilization >5%. Achieving \$100/bdt is very challenging at lower biomass yields (Figure 3a-c). The paths to reaching a GHG footprint at or below 50 kg CO_{2e}/bdt require similarly high yields, low dry matter losses, and higher land utilization factors (Figure 3d-f). The most important difference to note is the influence of nitrogenous fertilizer application, which has a greater impact on GHG emissions than it does on delivered feedstock cost. Dry matter loss is also important, and highly uncertain for silage and modules.[44] SI-Figures S27 shows the impact of varying dry matter losses from 2 to 30% on delivered cost and carbon footprint. Similar to bales,[43] the dry matter losses of silage and modules can be reduced by applying the best management practices. The relative impact of additional input parameters on the delivered biomass costs and GHG emissions are presented in the SI-Figures S3 to S9 and S21 to S26, respectively.

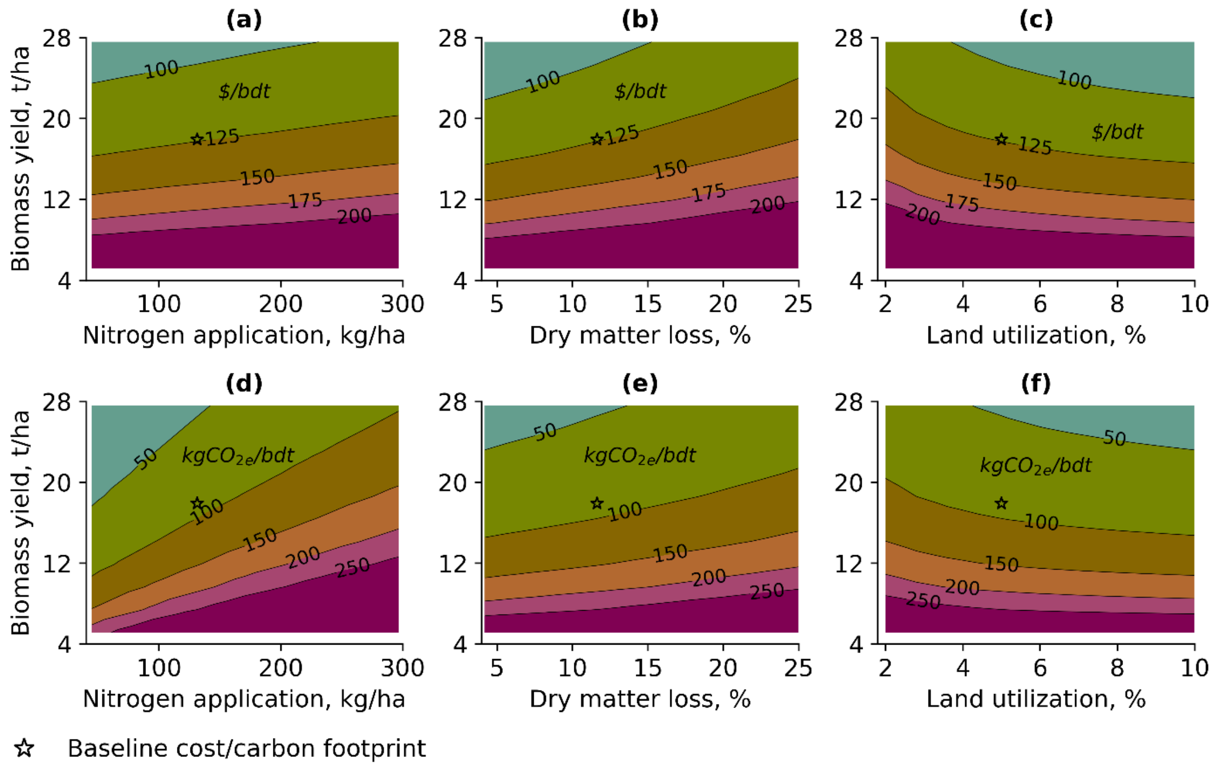

Figure 3. Combined impacts of a set of two most influential input parameters on the biomass sorghum supply cost at the pretreatment reactor throat (a, b, and c) and greenhouse gas emissions (d, e, and f). This is a representative case considering the direct supply of chopped ensiled biomass from the field to the biorefinery.

Because logistics decisions may be made on a farm-by-farm basis, this study also explores variations in cost and GHG emissions for each supply system as a function of farm-to-biorefinery distance (Figure 4). It is most economical for biorefineries to source chopped biomass directly from the field and ensile the material next to the biorefinery if the sorghum field is located within 66 km (41 miles). Chopped ensiled biomass supply is also the least carbon-intensive option if the field-to-biorefinery supply radius is less than 80 km (50 miles). If the sorghum field is located between 66 km and 105 km (65 miles) from the biorefinery, the direct transportation of bales from the field to the biorefinery is the most economical option, assuming dry-down in the field and baling is feasible in the local climate (Figure 4). Direct supply of bales is the least GHG-intensive option between 80 km and 248 km farm-to-biorefinery distance (Figure 4-b). Two factors drive transportation costs and emissions from the farm to biorefinery: bulk density and moisture content. The maximum payload capacity (Federal weight limits) of a five-axle flat-bed tractor-semitrailer of 22.7 t [22] is still at least 7% underutilized (limited by volume) with large rectangular bales (2.42 m long, 1.17 m wide, and 0.98 m high) at a bulk density of 168 kg/m^3.[10,42]

For farm-to-biorefinery distances of 105 km or greater, we find that transportation savings justify the additional cost of pellet production and the silage/pellet system is roughly equivalent to the bale/pellet system (Figure 4-a). In terms of GHG emissions (Figure 4-b), direct supply of ensiled biomass is preferable up to 80 km, at which point direct supply of bales becomes the lowest-carbon choice. The depot system does not become the lowest-emission option until a distance of 248 km, at which point the bale/pellet system has an advantage. Figures S3 to S8 provide the results of single-point sensitivity analysis for each scenario to capture each parameter's impact on costs. Biomass yield, fertilizer application, dry matter loss, land utilization (percent land cultivated with sorghum around the biorefinery), and the road winding factor prove to be key cost drivers. For GHG emissions, the key parameters are direct land use change impacts, fertilizer application, the road winding factor, land utilization factor, moisture content at harvest, yield, fuel for cultivation and field machinery, and dry matter losses.

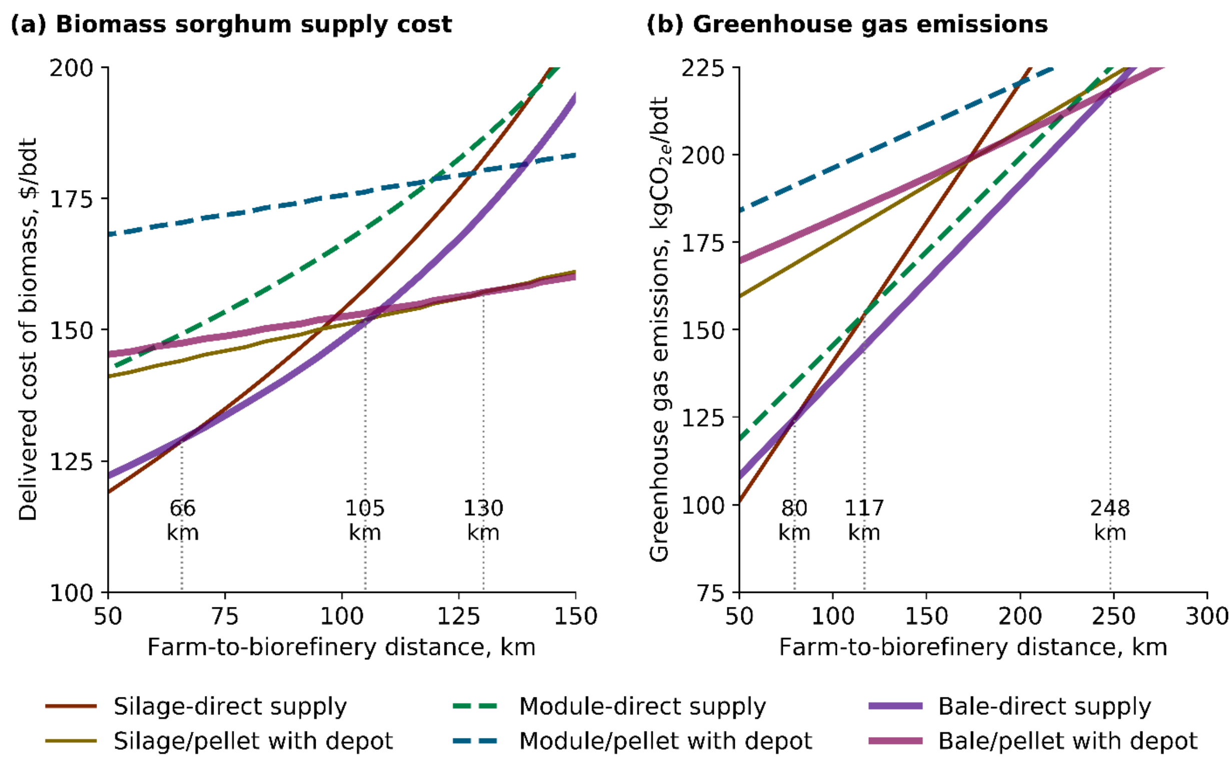

Figure 4. Delivered sorghum biomass costs (a) and greenhouse gas emissions (b) as a function of farm-to-biorefinery distance. Beyond 130 km, the bale/pellet depot with depot system is most economical and its advantage increases further beyond 150 km.

Potential for feedstock supply cost and GHG emissions reductions

Both the cost and GHG emissions results from our analysis suggest that ensiled sorghum warrants wider consideration as a potential bioenergy feedstock, particularly given that this system is already familiar to farmers who grow sorghum as a forage crop. An obvious extension of this work would be to model the conversion of each feedstock to biofuel and report results on a per-gallon gasoline equivalent (gge) or MJ of fuel basis. However, until experimental research can elucidate the impact of the ensiling process on downstream processing and conversion, any results reported on a per unit fuel basis may not be accurate. Previously published results do suggest that the module and ensiling systems are both effective at retaining the quality of the moist biomass feedstock (moisture content of >20%) for further biochemical conversion.[19]

If sorghum becomes a more widely produced crop for bioenergy and other fiber markets, it is possible that supply systems can be improved to reduce costs and emissions. For example, the current theoretical estimate of the biomass module building process based on the existing cotton module building process[7,38] is expensive, but a consolidated module building process could be developed in the future, combining harvesting, chopping, module building, and wrapping operations in a single pass. Field drying and baling is less likely to change substantially, and its attractiveness will remain reliant on uncontrollable natural factors such as local precipitation, relative humidity, and field conditions during the weeks following harvest. Additionally, the multi-pass harvesting techniques considered for bales and modules gather more dirt/sand[33] when compared to single-pass harvests, such as loose chopped ensiled biomass, considered in this study. These operating trade-offs and key areas of improvement among the selected biomass sorghum feedstock supply chain options show opportunities for further process optimization and intensification.

Aggressively optimizing biomass production, field operations, and biomass transportation can result in dramatic reductions in delivered cost and GHG emissions. In the most optimistic scenario, average harvested biomass increases from 17.9 to 28 bdt/ha, the road winding factor is reduced from 1.45 to 1.2, land utilization for sorghum around the biorefinery doubles from 5% to 10%, fertilizer application is minimized (see SI- Figures S31-S36), dry matter loss is cut from 11.6% to 5%, and the harvest window expands from 31 to 75 days. The result of all these factors combined (referred to as an "optimal" case) would be a reduction in the delivered cost at the reactor throat to \$66, \$79, and \$70 per bdt as well as GHG emissions to 43, 66, 62 kg CO_2e per bdt for the direct supply of chopped ensiled biomass, modules, and bales, respectively. The combination of all these improvements should be thought of as a theoretical best-possible outcome, and unlikely to be achieved in most locations. These step by step reductions in the delivered cost and GHG emissions are presented in the SI- Figures S15-S20 and Figures S33 to S38, respectively. Our results highlight the importance of the location of biorefineries for achieving the targeted biomass supply cost at the pretreatment reactor throat of \$78.6/bdt. The optimal delivered cost of chopped ensiled biomass and bales of \$66/bdt (SI-Figure S15) and \$70/bdt (SI-Figure S19), respectively, for the improved future case overshoot the targeted cost of \$78.6/bdt. If the biomass is pelletized for longer-distance transportation, switching to the solar drying can reduce GHG emissions by 30-33% (SI-Figure S16 and S35).

Our findings suggest that, although no single logistics strategy will reliably reduce delivered biomass cost to the U.S. Department of Energy target, different systems will be preferable depending on the location of production; biomass yield, local conditions, and farm-to-biorefinery distances will be determining factors. The value of selecting strategies that are familiar to farmers must not be underestimated. Ensiling of bioenergy sorghum requires only existing equipment and is widely practiced by farmers today. The delivered cost and GHG emissions of the chopped ensiled biomass prove to be competitive in the baseline and optimal scenarios and the recent encouraging sugar yield results[17] with ensiled biomass indicate that ensiled material may generate further reductions in costs per unit of biofuel produced. A combination of the strategies presented in this study will be needed to deliver the flexibility in biomass supply needed to produce a consistent supply of competitively-priced, low-carbon biofuels.

Disclosures

The authors declare no competing financial interest.

Supporting Information

Supporting information includes detailed methods, data inputs, single-point sensitivity analysis results, detailed uncertainty results for each stage of supply chain, and optimal biomass supply cost and greenhouse gas emissions for the selected scenarios.

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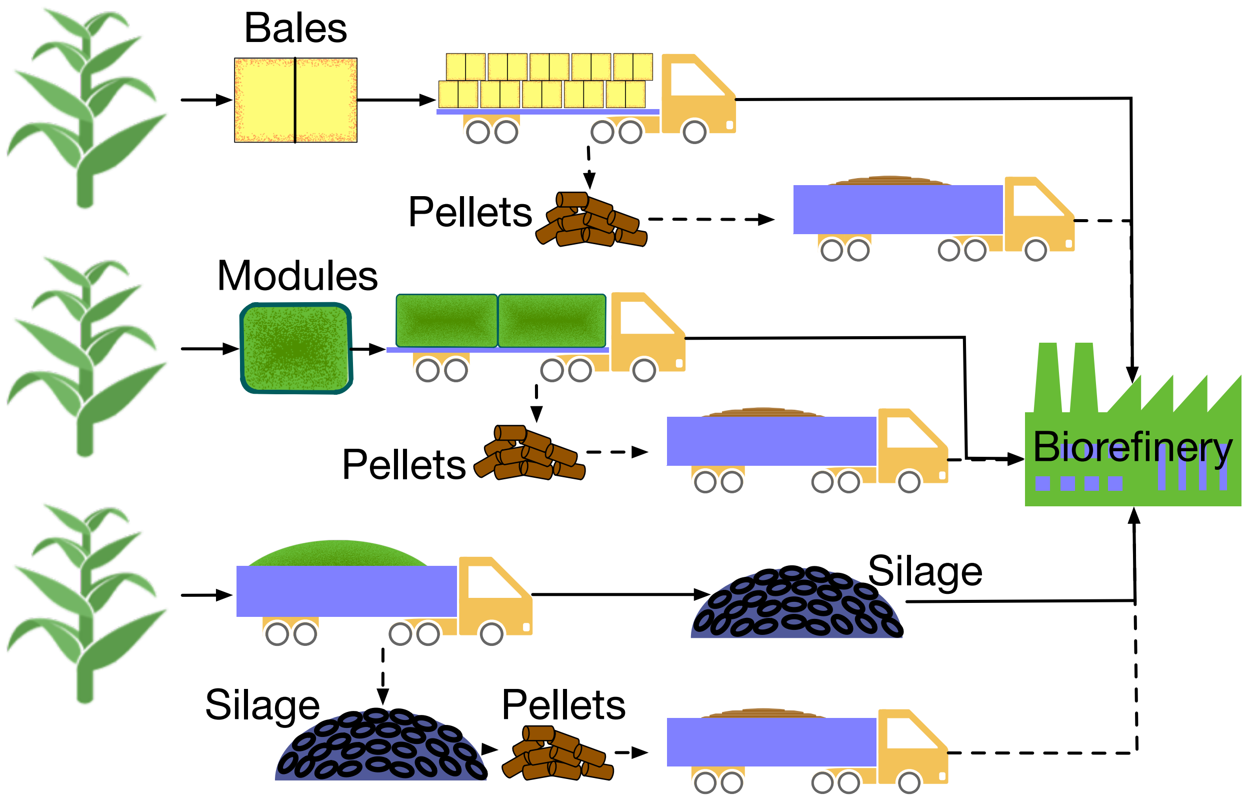
Table of Contents (TOC) graphic (For Table of Contents Use Only)



A cost and life-cycle greenhouse gas comparison of baling, module-building, and ensiling for direct-transport and depot-based biomass sorghum supply systems.