

Techno-economic and environmental assessments of storing woodchips and pellets for bioenergy applications

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ARTICLE INFO

Keywords:

Bioenergy
Woodchips
Pellets
Storage methods
Techno-economic analysis
Greenhouse gas (GHG) emissions

ABSTRACT

Storage is the critical operation within the biomass supply chain to reduce feedstock supply risks and to manage smooth year-around operations of a biorefinery or a bioenergy plant. This paper analyzed the economic and environmental impacts of four different biomass storage systems for woodchips (Outdoor-open, Outdoor-tarped, Indoor, and Silo) and two systems for pellets (Indoor and Silo). Storage cost includes the costs for handling (including ventilation in case of silo storage), infrastructure investment, and dry matter loss (DML) for each system. The estimation of total greenhouse gas (GHG) emissions includes the fugitive emissions from storage piles and emissions due to electricity and fuel consumption for each system. Among four storage systems, the outdoor-tarped (\$15.0 ODMT⁻¹, ODMT: Oven Dry Metric Ton) and silo (\$5.8 ODMT⁻¹) storage were the least-cost options for woodchips and pellets respectively. However, silo-storage could be the most promising option for storing woodchips (\$5.8 ODMT⁻¹) and pellets (\$2.3 ODMT⁻¹), if it is used for short-term (two months) and frequently (at least six times) in a year. The total GHG emissions for six-month storage were 2.8–11.8 kgCO₂e ODMT⁻¹ for woodchips and 8.6–42.0 kgCO₂e ODMT⁻¹ for pellets. During Outdoor-open storage, the lower heating value of woodchips could drop to 37% due to increased dry-matter loss (DML) and moisture content. The initial moisture content, bulk density, DML, and resource required during handling were the most sensitive parameters influenced the storage performances of both woodchips and pellets. This study has demonstrated that a combination of different storage options along the supply chain could reduce the total biomass storage cost for a biorefinery or power plant.

1. Introduction

Forest biomass and short-rotational woody energy crops are typically delivered to a biorefinery or a bioenergy plant in the form of chips, chunks, or logs [1–9]. The primary purposes of comminution are to reduce the particle size, homogenize the composition, and improve bulk density for easy transport, handling, storage, and to meet boiler or other conversion technology requirements [10]. Sawmill residues, shavings, and small diameter logs (less than 6 in.) are often used to densify into wood pellets that can be either used in a boiler to produce power, or produce liquid biofuel using biochemical or thermochemical conversion technologies. Woodchips or pellets are the most commonly-delivered form of woody biomass to biorefineries or power plants and they need to be stored along the supply chain with low material losses (i.e., dry matter loss) while keeping both the storage cost and GHG emissions low [11–14]. Fig. 1 shows the possible storage requirements along the biomass supply chain.

A typical biorefinery or a bioenergy plant requires a reliable, year-around supply of high-quality feedstock with consistent size, moisture content, and homogeneous compositions [13]. The typical moisture content of woodchips is in the range from 40% to 60% wet basis (wb) and high-moisture chips are susceptible to microbial degradation, if not immediately used, leading to high dry matter losses (DML) [12,15]. For a biorefinery producing liquid biofuel through biochemical pathway is unaffected by biomass moisture content [16]. But liquid biofuel production through thermal and biochemical conversion technologies require smaller size particles (< 2 mm) that require biomass (i.e., woodchips) grinding and milling [17]. The high moisture biomass demands higher energy for grinding and poses lower higher heating value (HHV) while increasing the handling and transport costs [18–21]. If a proper storage option is adopted, high moisture content feedstock can be dried naturally or artificially during storage. Therefore a well-designed storage system is required to reduce the dry matter loss (DML) and the feedstock delivered cost.

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<https://doi.org/10.1016/j.rser.2018.08.055>

Received 25 April 2018; Received in revised form 28 July 2018; Accepted 29 August 2018

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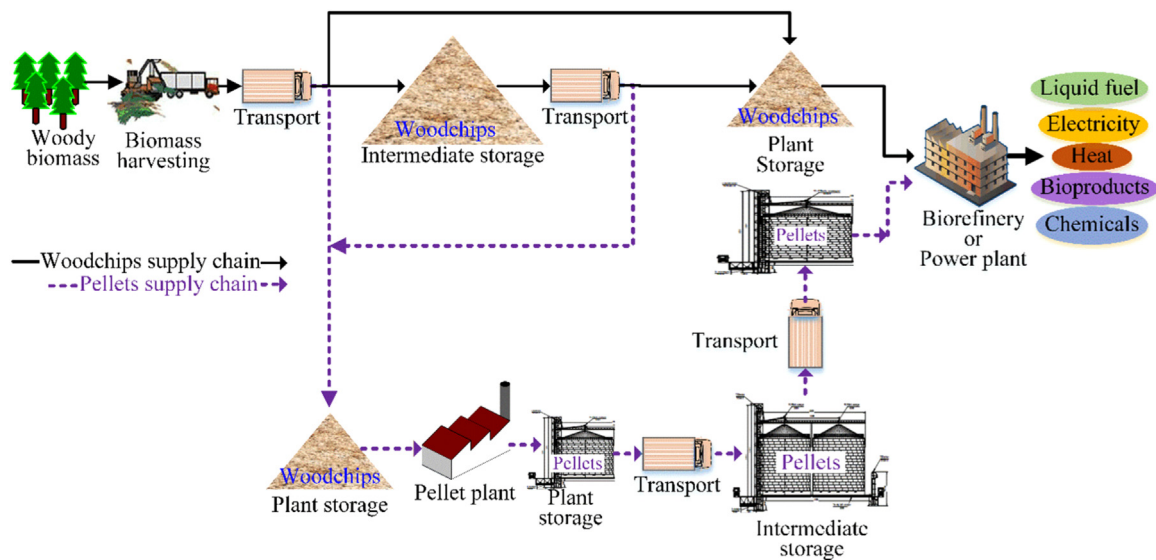


Fig. 1. Bioenergy/biofuel supply chain with potential locations for storing biomass.

Usually, low-bulk density woody biomass such as woodchips and sawdust are densified into high-quality pellets, which reduces the logistics and handling cost for long distance transport, e.g., between counties or sub-continent [18]. Pellet storage at the plants or along the supply chain serves as a buffer to minimize supply and demand uncertainties for consistent operation of a bioenergy plant [11]. Pellet storage costs can be lower than that of other feedstocks due to high bulk density and low DML. Therefore, biomass in the form of pellets can be a suitable option for long-term storage to counter supply disruptions to a biorefinery due to natural disasters such as drought, wildfire, etc.

Woodchips are typically stored in outdoor-open [22,23], outdoor-tarped [24–29] or indoor [30] systems. Pellets can be stored indoors or in silos either at a production facility, or at the point of consumption, or in between supply and demand points along the supply chain [31]. Silo storage can be used to store either woodchips or pellets. Indoor storage of woodchips is not preferred mainly due to high cost incurred for building permanent storage infrastructure. Outdoor-tarped woodchip storage can be preferable due to lower capital cost requirements and the flexibility to change storage locations [13]. However, the long-term storage of outdoor systems could increase the storage cost due to high dry matter losses (DML) [15].

Stored woodchips can emit a number of off-gases due to natural or microbial degradation. In addition to high storage cost, emissions from biomass storage can cause related to health hazards [34,35], the risk of fire [34,36] and greenhouse gas emissions [37]. Woodchips and pellets do emit carbon dioxide (CO_2), carbon monoxide (CO), methane (CH_4), nitrous oxide (NO_x) and volatile organic carbons (VOC) during storage [15,38,39].

There is a multitude of factors that affect the emissions rate of stored biomass. They include the biomass type, initial moisture content, local storage temperature, rain/snowfall, relative air humidity, storage type, pile size, ventilation, location, and many more [14,15]. The GHG emissions may be much higher for outdoor storage compared to that of indoor or tarped storage options due to high biomass degradation exacerbated by high moisture content [37].

In the United States, paper and pulp industries incur millions of dollars lost every year due to the high rate of biomass deterioration/dry matter loss from short-term outdoor pulp-woodchips storage [40]. The financial losses from open storage of woodchips could be huge for bioenergy plants, triggered by dry matter losses and weather risks.

Large-scale bioenergy plants require a large and consistent biomass supplies for year around plant operations and longer-term biomass storage is unavoidable due to seasonal availability [41] and inclement

weather that impedes harvest operations [42]. In Sweden, about 10% of the country's annual woodchip demand is stored for 5–10 months at energy conversion facilities [43]. Although forest biomass is available throughout the year, its accessibility is often limited due to climatic restrictions (i.e., spring breakup in northern states of the United States) [44], extreme weather (i.e., hurricanes, drought, wild fire etc.) [13] and seasonal timber harvesting restrictions (STHRs) [45], which can influence storage duration [8,34]. Therefore, it is important to design and choose appropriate storage systems [13] that offer low storage costs with minimal environmental GHG emissions. However, limited studies on storage of forest biomass, especially for woodchips and pellets are available in the literature. Woodchips and pellets storage costs and GHG emissions with respect to time, capacity, and storage type can be used by scientific communities and stakeholders to design supply chain networks for the biorefinery or power plant and to develop optimal storage strategies to reduce cost along the supply chain [13]. The objectives of this study were (i) to estimate the short and long-term storage costs and GHG emissions for woodchips and pellets using various storage options; (ii) to conduct sensitivity analysis on input parameters affecting the cost and environmental performance of storage systems; and (iii) to recommend appropriate storage systems for woodchips and pellets along the biomass supply chains.

2. Methodology

2.1. Storage methods

In this study, woodchips refer to comminuted forms of forest biomass from logs or forest residues. Pellets refer to densified biomass produced using pelleting technology mainly from sawdust or woodchips. Four primary storage methods were considered to store woodchips: (i) Outdoor-open, (ii) Outdoor-tarped, (iii) Indoor, and (iv) Silo (Fig. 2). Pellets are hygroscopic, that is they absorb moisture from the air, and they could disintegrate into powder, if stored outside. They are also a higher-cost feedstock than woodchips. Therefore, the only wood pellet storage systems considered were indoor bulk storage and silo storage.

In an outdoor-open storage facility, woodchips are in trapezoidal-shaped piles on the well-drained level ground. An outdoor-tarped storage facility uses a tarp [46] to cover an outdoor-open facility's trapezoidal woodchip piles from all sides [22]. An indoor storage facility for woodchips has a permanent roof structure with open sides and a well-drained floor i.e. pole barn [47]. However, an indoor storage facility for

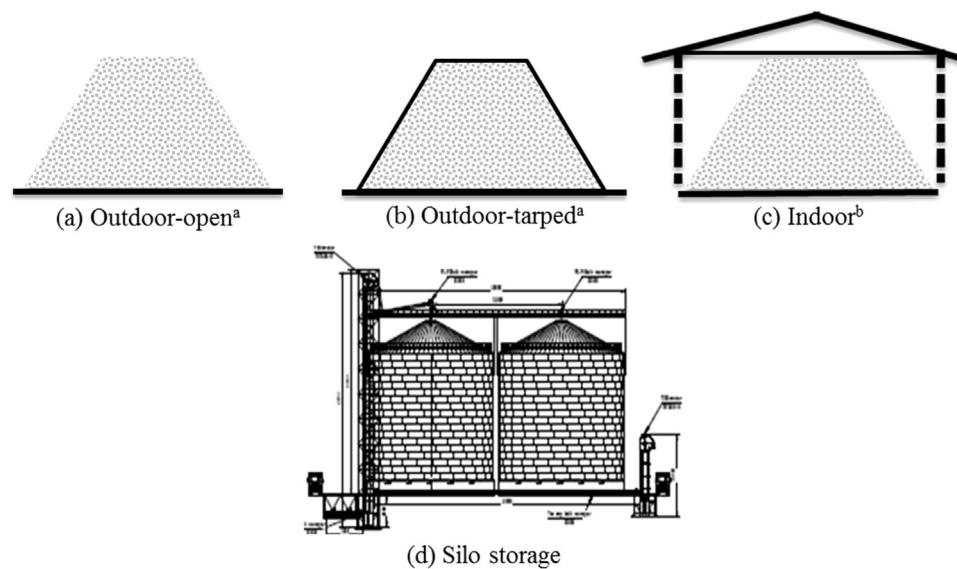


Fig. 2. Types of woodchips and pellets storage systems. (^aOnly woodchips; ^bIndoor structure with all sides open, i.e. pole barn for woodchips and warehouse structure i.e., all sides closed with concrete floor for pellets).

pellets would be similar to a warehouse structure with all sides closed and a concrete floor to prevent entry of rainwater [48]. A silo storage facility would be similar to ones used for storing corn grain or seed but customized for woodchips and pellets (Fig. 2d). Piling of woodchips is performed by a front-end loader except for silo storage where a mechanical handling system is used for loading and unloading woodchips and pellets.

The outdoor and indoor storage facilities' capacities are assumed to be about 20,000 ODMT (Oven Dry Metric Ton) of woodchips/pellets [13]. The silo storage facility's capacity was assumed to be 40,000 m³ for both woodchips (i.e., 8500 ODMT) and pellets (i.e., 28,500 ODMT). Detailed storage facility specifications are presented in Tables 1–3.

A facility's annual capacity is a function of its size, the frequency or

Table 1
General input parameters used in the analysis of storage systems.

Descriptions	Units	Values	Ref.
Daily biomass demand of a plant (biorefinery/power plant)	ODMT day ⁻¹	2000	[13]
Daily supply from a storage facility to a plant	ODMT day ⁻¹	400	[13]
Number of loading docks at the storage facility	nos	2	[13]
Area required to maneuver trucks	m ²	4000	[13]
Number of people handling the storage facility	nos	1	[13]
Higher heating value (HHV)	MJ kg ⁻¹	19.2	[6,31]
Dry bulk density of woodchips/pellets	ODMT m ⁻³	0.209/ 0.711	[6,31]
Initial moisture content of woodchips/pellets	% (wb)	50/7.5	[1,31]
Price of biomass of woodchips/pellets	\$ ODMT ⁻¹	30/135	[49]
EMC for woodchips	%	10/5	[50,51]
Capital Interest rate	%	5.5	[52]
Insurance and repair cost (% of capital cost)	%	2	[52]
Life of indoor storage facility (pole barn, warehouse, and silo)/handling and accessories for silo/tarp	years	20/10/5	[52,53]
Economic scale factor for warehouse and pole barn	unitless	0.84	[54]
Labor for Ag. equipment	\$ h ⁻¹	12	[13]
Labor wage for storage site	\$ h ⁻¹	16	[13]
Labor benefits (% of wage)	%	35	[54]
Land cost or rent	\$ ha ⁻¹	265	[13]

Table 2

Input parameters used in the analysis of outdoor-open, outdoor-tarped and indoor storage systems.

Descriptions	Units	Values	Ref.
Angle of repose	deg.	45	[2]
Pile height (outdoor/indoor)	m	4/7.5	[55]
Pile width (outdoor/indoor)	m	8/50	[55]
Pile length (outdoor/indoor)	m	67/100	[55]
Space between piles	m	9	[13,55]
Wheel loader	kW	55.95	Assumed
Specific fuel consumption	l kW-h ⁻¹	0.20	[56,57]
Bucket volume	m ³	5	[13,56]
Time required to transfer a bucket of woodchips with front-end loader (outdoor/indoor)	min	1.8/2.0	[13,56]
Truck capacity (payload)	MT	26.5	[58]
Trailer volume	m ³	97	[13,56]
Labor required to cover and uncover a pile (only outdoor-tarped, woodchips)	man-h m ⁻²	0.054	[13]
Trap cost	\$ m ⁻²	3	[13]
Pole barn (woodchips only)	\$ m ⁻²	168	[13,47]
Warehouse (pellets only)	\$ m ⁻²	294	[47]
Front-end loader hourly cost for loading chips or pellets to the truck (except Silo)	\$ h ⁻¹	70	Estimated

number of times that biomass is moved into and out of the facility in a year, and the amount of time that woodchips or pellets are held in the facility. It is also possible for a storage facility to be empty for part of the year. For the base case study, the facility use frequency of twice per year was assumed.

2.2. Storage moisture content

Biomass with higher moisture content adversely affects bioenergy supply chains producing either liquid biofuel or heat and electricity [13,41]. Freshly-harvested woodchips often have a moisture content (MC) of about 50% [14]. Previous experimental studies on biomass storage have used wide ranges of input MC (30–60%) [8,41,60]. In contrast, the MC ranges for stored pellets were narrow (5–10%) and consistent [31,61].

If the high-moisture woodchips are stored in piles, the inside pile temperature will increase due to the microbial and chemical degradation [32]. The temperature increase can be sudden and high enough to cause fires [33]. Furthermore, the growth of fungi and spores in the

Table 3
Input parameters used in the analysis of silo storage systems.

Descriptions	Units	Values	Ref.
Storage capacity	m ³ silo ⁻¹	10,000	Assumed
Number of silo	Nos	4	Quotation from vendors
Silo height	m	16.87	Quotation from vendors
Silo diameter	m	18.33	Quotation from vendors
Daily ventilation time	h day ⁻¹	4	Assumed
Moisture removal capacity of ventilated air	g of H ₂ O m ⁻³ of air	2	[59]
Air velocity	m s ⁻¹	0.02	Quotation from vendors
Loading system capacity	MT h ⁻¹	200	Quotation from vendors
Unloading system capacity	MT h ⁻¹	150	Quotation from vendors
Loading system	kW	68	Quotation from vendors
Unloading system	kW	86	Quotation from vendors
Ventilation and control system power consumption	kW	243.35	Quotation from vendors
Silo system	\$	607,447	Quotation from vendors
Dumping equipment	\$	6895	Quotation from vendors
Handling system	\$	327,204	Quotation from vendors
Ventilation system	\$	28,927	Quotation from vendors
Electric control system	\$	13,775	Quotation from vendors
Miscellaneous	\$	2070	Quotation from vendors
Freight	\$	130,346	Quotation from vendors
Installation	\$	335,000	Quotation from vendors
Annual repair and maintenance other than Silo	% of AYI	2	[54]
Insurance and taxes	% of AYI	4	[54]

biomass can pose human health risks. Higher MC biomass also releases less available heat when burned and incurs higher DML during storage [1,62,63]. A safe storage moisture content (less than 10%) could minimize both the fire and health-related risks, while simultaneously providing greater available stored energy in the fuel [64,65].

Theoretically, the temperature increase due to microbial and chemical degradation inside the pile of stored biomass causes a drying effect [66,67]. But external water enters outdoor-open woodchip piles due to precipitation causing increased moisture content during storage [68–70]. Covering of woodchips with tarps could prevent water from entering the piles, so does the moisture content. In silo storage where ventilation is necessary, moisture content reduction depends on the duration of ventilation, the air relative humidity, initial biomass moisture content, temperature, equilibrium moisture content (EMC), and silo height [50,51].

A comprehensive review of available literature was performed to collect experimental moisture variations and dry matter loss with respect to storage time and storage methods. A detailed statistical analysis was performed with those collected data and is presented in the supporting document (Section 2).

Both in outdoor-tarped and indoor storage of woodchips/pellets, biomass moisture content decreased due to transpirational moisture losses. However, the outdoor-open storage method showed two trends: both increasing [30,67,70] and decreasing [26,41,71] moisture content trends with respect to storage time due to local weather conditions.

The moisture content of outdoor storage piles varies by moisture migration due to the drying effect and the external addition of water during precipitation. Therefore, two trends of variations in the moisture content were used to estimate the final energy values in the outdoor-open woodchip storage. The decrease in the moisture content depends on the EMC of biomass [5]. Woodchip moisture content tends to increase (outdoor-open) or decrease faster during initial periods of storage than in later stages. The change in woodchip moisture can be presented as Eq. (1) [70].

$$MC_m(t) = b_0 \pm b_1 \log_{10}^*(t) \quad (1)$$

Where, $MC_m(t)$, b_0 and b_1 represent the final moisture content after storage time (t), initial MC [$MC_m(t = 0)$], and rate of moisture content change respectively. The negative and positive sign represents the decrease and increase in the MC of woodchips during storage. The fitted trends of moisture content and estimated parameters for woodchips in outdoor-open (Fig. S3, Table S5), outdoor-tarped (Fig. S4, Table S6) and

indoor (Fig. S5, Table S7) storage types are shown in the supporting document.

The moisture content of woodchips in a silo depends on the input ventilation parameters such as the amount and the initial condition of air passed through the column of woodchips and their EMC. However, in this study, the moisture removal from silo storage was calculated based on a fixed rate that was estimated by an experimental work for woodchips. It was assumed that two grams of water is removed per cubic meter of air passed through the silo [59].

Compared with woodchips, pellets are considered to be more stable products with very low initial moisture content (~8% wb) [18,72,73] and will experience very small or negligible changes in moisture content during storage (indoor or silo) [74,75]. In this study, no change in the moisture content of wood pellets stored either indoors or in silos was assumed.

2.3. Dry matter loss (DML)

Biological and chemical processes are responsible for physical losses of a certain portion of biomass, i.e., dry matter loss (DML) during storage. Usually, the DML rate is higher during the initial few weeks of storage and is often very high compared with the rest of the storage period [13,25,26]. The DML in woodchip and wood pellet storage systems can be represented as an asymptotical decay path function as described in Eq. (2) [13].

$$DML_{bm}(t) = 1.58 * MDML_{bm} * \left(1 - e^{-\frac{t}{T}}\right) \quad (2)$$

Where $DML_{bm}(t)$ is the dry matter loss of woodchips or pellet (b) for a period (t) in storage method (m).

The maximum dry matter loss ($MDML_{bm}$) for a longer time duration (T), i.e. a year was calculated using a parameter estimation technique [13] and DML data collected from previously-published experimental studies for outdoor-open, outdoor-tarped, and indoor storage methods (see Supporting information, Tables S1–S3). Dry matter loss experimental data along with factors affecting dry matter loss were collected from literature for woodchips and wood pellets. The most significant input factors that influence DML were identified using ANOVA (Analysis of Variance) [76]. These factors were storage time, storage method, type of woodchips, the biomass initial moisture content, and precipitation. However, storage time and storage methods are only key parameters affecting the DML assuming other factors would remain

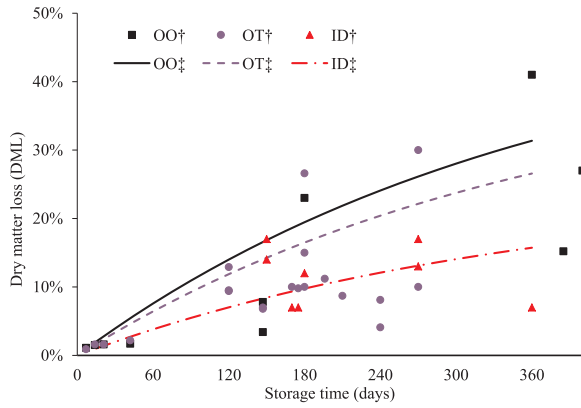


Fig. 3. Experimental (†) and predicted (‡) dry matter loss (DML) vs. storage time for woodchips in outdoor-open (OO), outdoor-tarped (OT), and indoor (ID) storage types.

same for all storage methods in any given location. Asymptotic DML equations were developed for each of the three storage methods with respect to storage duration. The parameters for each equation were estimated by non-linear curve fitting methods using the JMP statistical software package [76]. The detailed analysis and models can be found in the supporting document (Section 2.3).

Fig. 3 shows the DML experimental data published in the literature and predicted DML using the best-fitted models for woodchips with indoor, tarped, and outdoor storage methods. The DML is directly related to loss of carbohydrates or sugars from woodchips and pellets during storage, which needs to be further investigated along with DML and quantification of the economic value loss.

DML for wood pellets during storage (indoor or silo) could be insignificant due to their very low moisture content (~10%). Chemical degradation can be the only cause for DML during wood pellets storage. The DML during storage is transformed into major emissions in the form of carbon dioxide, carbon monoxide, methane, and other emissions. The DML during storage is directly proportional to emissions [77]. Given this relationship, it can be estimated that annually there is about 2.5% DML during storage of wood pellets in a large silo as reported by Yazdanpanah et al. [31].

While experimental information about the DMLs for wood pellets stored for longer duration was not available in the literature, nor was there information on DML for wood pellets in indoor storage, it was assumed that the maximum DML ($MDML_{bm}$) for indoor-stored pellets would be the same as for silo-stored pellets; i.e., about 2.5% in a year. Eq. (2) was used to estimate temporal variations (i.e., asymptotic) in the DML for pellets.

2.4. Energy content variations

The extractable energy from biomass is measured as LHV, which depends on its Higher Heating Value (HHV) and moisture content. The impact of changes in the chemical composition of biomass during storage on the variation in HHV is negligible [59,73]. However, an increase or decrease in the biomass moisture content significantly impacts its LHV [22,46,73]. The LHV of stored biomass (b), i.e., woodchips/pellets can be estimated using Eq. (3) [41].

$$LHV_{bm}(t) = LHV_{bm}(t=0) + E_w [MC_{bm}(t=0) - MC_{bm}(t)] \quad (3)$$

Where, $LHV_{bm}(t=0)$ and $LHV_{bm}(t)$ are the lower heating values (GJ Mg^{-1}) of woodchips/pellets before storage and at the end of storage in storage type (m) respectively. The amount of energy (E_w) needed to evaporate the water in wood is considered to be 2.5 GJ $Mg (H_2O)^{-1}$ [41]. Moisture content of woodchips before storage and after storage is represented as $MC_{bm}(t=0)$ and $MC_{bm}(t)$ respectively.

Energy loss also occurs in a storage facility (Q_{bm} , storage capacity)

due to DML. Eq. (4) represents the energy loss/gain [$EnL/G_{bm}(t)$, GJ $ODMT^{-1}$] from a storage option (m) considering the moisture content change and dry matter loss at the end of the storage period (t).

$$EnL/G_{bm}(t) = \frac{Q_{bm}(t=0) * [LHV_{bm}(t=0) - LHV_{bm}(t) * (1 - DML_{bm}(t))]}{Q_{bm}(t=0) * (1 - DML_{bm}(t)) * (1 - MC_{bm}(t))} \quad (4)$$

2.5. Storage cost

In this study, storage costs were modeled as a function of storage time. Machine rate models were used to estimate costs. The biomass storage includes various costs incurred due to land, infrastructure, dry matter loss, labor required for covering and uncovering woodchip piles with a tarp, ventilating (only in silo storage), handling to unload-load trucks and build piles, and facility management. The loading, unloading, and piling costs at each storage facility were assumed to be part of a storage cost. Eq. (5) shows the estimation of time-dependent storage cost ($SC_{bm}(t)$, \$ $ODMT^{-1}$) by summing fixed cost (FC_{bm} , \$ $ODMT^{-1}$), and variable cost (VC_{bm} , \$ $ODMT^{-1}$) for each biomass type (b) (woodchips or pellets) using storage method (m) considering DML (DML_{bm} , fraction) after a storage time (t).

$$SC_{bm}(t) = \frac{FC_{bm} + VC_{bm}(t)}{1 - DML_{bm}(t)} \quad (5)$$

It was assumed that biomass can be stored for 1–12 months in a storage facility. The storage frequency (that is, the number of times that biomass is moved in and out-biomass turnover) can vary from 1 to 6 per year based on the biomass availability and an associated biomass conversion facility's daily supply requirements [13].

Therefore, the total biomass handled by a storage facility in a year will be a multiple of storage frequency (f_{bm} , Nos yr^{-1}) and the actual storage facility's capacity ($StoCap_{bm}$, $ODMT$). The higher the annual biomass turnover, the lower will be the unit storage cost, especially for indoor and silo storage due to their high initial capital costs that are spread out over the higher throughput.

Eq. (6) consists of two different fixed costs: (i) fixed cost related to a storage facility's annual biomass turnover capacity ($FC1_{bm}$, \$ yr^{-1}); and (ii) fixed cost that is independent of annual biomass turn-over capacity ($FC2_{bm}$, \$) such as the costs incurred during handling in a single storage event, which would include the cost of biomass-in that will be stored for a given time, and the cost of biomass-out from a storage facility, e.g., piling. These fixed costs remain the same for each storage event regardless of storage time or storage frequency.

$$FC_{bm} = \frac{FC1_{bm}}{f_{bm} * StoCap_{bm}} + \frac{FC2_{bm}}{StoCap_{bm}} \quad (6)$$

In Eq. (7), $FC1_{bm}$ includes annual storage facility rent ($Rent_{bm}$, \$ yr^{-1}), the annual capital cost for infrastructure, tarp and handling equipment (ACC_{bm} , \$ yr^{-1}), and annual insurance cost (Ins_{bm} , \$ yr^{-1}). $FC2_{bm}$ includes costs incurred due to piling ($Pile/LoadIn_{bm}$, \$) the biomass in an outdoor-open, outdoor-tarped, or indoor facility, or loading the biomass into a silo. $FC2_{bm}$ also includes costs incurred in loading biomass into a truck ($LoadTruck_{bm}$, \$), labor required to cover piles in outdoor-tarped storage ($LTarp_{bm}$, \$) and labor required to manage the storage facility (Mgt_{bm} , \$) during loading and unloading activities [Eq. (8)].

$$FC1_{bm} = Rent_{bm} + ACC_{bm} + Ins_{bm} \quad (7)$$

$$FC2_{bm} = Pile/LoadIn_{bm} + LoadTruck_{bm} + LTarp_{bm} + Mgt_{bm} \quad (8)$$

In the next set of equations, the annual capital cost (ACC_{bm} \$ yr^{-1}) was estimated using the capital recovery factor [CRF_{bm} , Eq. (10)], total investment (Inv_{bm} , \$) to build infrastructure (i.e., indoor or silo) or to purchase tarp (i.e., outdoor-tarped), salvage value (SV_{bm} , \$), interest rate (r_{int} , % yr^{-1}), and economic life (T , yr) of each component of a

storage facility in Eq. (9). A percent (r_{ins} , %) of average yearly investment (AYI_{bm} , \$ yr⁻¹) in storage infrastructure and other capital investment was considered as annual insurance (Ins_{bm} , \$ yr⁻¹), Eq. (11). Eq. (12) shows the estimation of AYI_{bm} considering total investment for the development of infrastructure and accessories, salvage value, and the storage facility life. Eqs. (13), and (14) were used to estimate the annual cost of piling biomass or loading biomass into a silo ($Pile/Load Bin_{bm}$, \$), and loading biomass to trucks ($LoadTruck_{bm}$, \$) respectively. Front-end loaders are used to pile woodchips or pellets in all storage facilities except silos. The unit cost of piling or loading ($UC(P/L)_{bm}$, \$ ODMT⁻¹) was estimated by multiplying time (h ODMT⁻¹) required to pile or load trucks with a front-end loader by its hiring cost (\$ h⁻¹). Silos are loaded and unloaded by conveyors, so electricity cost was included. The biomass loading and unloading capacities, and the respective electricity usage are shown in Table 3. The unit cost of loading or unloading biomass into or from a silo was estimated as cost incurred due to use of electricity only. Conveyor capital costs are included with a silo system's total initial capital cost and are amortized. Labor is required to cover outdoor-tarped woodchip piles. The tarping cost [Eq. (15)] was estimated considering labor required to install a tarp ($UCLT_{bm}$, \$ m⁻²) and total area of piles (SAP_{bm} , m²) to be covered. $UCLT_{bm}$ was estimated by multiplying labor cost (\$ h⁻¹) and time required to cover a unit area of pile with tarp, i.e. 0.054 labor-h m⁻² (Table 2). Labor is also required to manage a storage facility but only during certain activities such as unloading of biomass from trucks to a storage facility and piling or filling silo, and loading biomass into trucks that supply biomass to a biomass conversion facility. Eq. (16) was used to estimate the annual management cost (Mgt_{bm} , \$ yr⁻¹) for a storage facility considering piling time (PT/LI_{bm} , h) (or time to load silos), unit labor cost (CL , \$ h⁻¹), and a 20% time in excess allowed for delays and miscellaneous activities.

$$ACC_{bm} = CRF_{bm} * \left(Inv_{bm} - \frac{SV_{bm}}{(1+r_{int})^T} \right) \quad (9)$$

$$CRF_{bm} = \frac{r_{int} * (1+r_{int})^T}{(1+r_{int})^T - 1} \quad (10)$$

$$Ins_{bm} = AYI_{bm} * r_{ins} \quad (11)$$

$$AYI_{bm} = \frac{Inv_{bm} * (1 - SV_{bm}) * (T+1)}{2 * T} + SV_{bm} \quad (12)$$

$$Pile/Load Bin_{bm} = StoCap_{bm} * UC(P/L)_{bm} \quad (13)$$

$$LoadTruck_{bm} = StoCap_{bm} * UC(P/L)_{bm} \quad (14)$$

$$LTarp_{bm} = SAP_{bm} * UCLT_{bm} \quad (15)$$

$$Mgt_{bm} = 1.2 * (PT/LI_{bm} + LTT_{bm}) * CL \quad (16)$$

The value loss due to DML in a storage system increases with storage time. Similarly, ventilation is necessary for biomass stored in a silo and it incurs a time-dependent cumulative cost to the system. In Eq. (17), the variable cost ($VC_{bm}(t)$, \$ ODMT⁻¹) includes costs due to DML [$DMLC_{bm}(t)$, Eq. (18)] and ventilation [$Venti_{bm}(t)$, Eq. (19)].

$$VC_{bm}(t) = \frac{DMLC_{bm}(t) + Venti_{bm}(t)}{StoCap_{bm}} \quad (17)$$

$$DMLC_{bm}(t) = DML_{bm}(t) * StoCap_{bm} * P_b \quad (18)$$

$$Venti_{bm}(t) = PowVen_{bm} * DOH_{bm} * C_{elc} * t \quad (19)$$

$DMLC_{bm}(t)$ was estimated by multiplying DML [$DML_{bm}(t)$, %] for a storage time (t), storage capacity, and biomass procurement price (P_b , \$ ODMT⁻¹). Ventilation is considered only in silo storage and its cost was estimated from the power of ventilation units ($PowVen_{bm}$, kW) in the storage facility, daily operating hours (DOH_{bm} , h day⁻¹), the unit cost of electricity (C_{elc}), and storage time (t, days).

Self-ignition can be for a problem in large woodchip piles with higher pile height stored outdoor-open for relatively long time [34]. To avoid spontaneous fire in storage-pile woodchips with bark (for outdoor-open storage for three months or more), the recommended maximum pile volume is 1000 m³ (height × width × length = 4 m × 8 m × 67 m) with a 10 m space between piles [55]. Although, there were no similar recommendations found in the literature for pile dimensions for outdoor-tarped and indoor storage of woodchips and pellets, a similar pile dimensions for other storage types except for silo storage was assumed. To avoid design issues, but to make the storage systems more directly comparable, it was assumed that a larger-capacity silo facility would consist of a series of smaller silos: each 5000 m³ of storage volume.

Additional hidden cost parameters (e.g., quality loss [13], fire insurance, health hazard, a hindrance to the handling of biomass, etc.) were not included in the study, but can be included as the data becomes available for biomass. Also, the costs of feedstock security often included for other commodities, were not considered in the storage costs due to the low value of biomass. The input parameters for storage cost calculations were presented in Tables 1–3. The cost input data were obtained from the published literature and online portals and reported in 2017 US dollars (base year) [78].

2.6. Storage emissions

The major gases emitted during storage of woodchips and pellets are carbon dioxide (CO₂), carbon monoxide (CO), methane (CH₄), nitrogen oxide (NO_x) and volatile organic compounds (VOC) [35,79,80]. The research on storage fugitive gas emissions is scarce and has received little attention from scientific communities compared with other unit processes in biomass supply chains [79]. The main focus of biomass storage research has been on the analysis of carbon monoxide poisoning rather than measuring GHG emissions such as methane and nitrous oxide.

There are multiple factors that affect the emissions rate. These include initial moisture content biomass, temperature, climate, pile size, biomass and storage type and location, ventilation, the storage pile orientation, and many more [81]. Both chemical and biological processes are responsible for these emissions. Emissions from wood pellets storage were predominantly from chemical processes rather than biological processes [35,38].

Experimental studies detected methane emissions during wood pellets storage along with CO₂ and CO [64,82,83]. However, nitrous oxide emissions were either undetected or detected at extremely low levels, [38] but since nitrous oxide is an extremely potent GHG emission agent (1 kg N₂O to 300 kg CO₂e) and its slight emission during storage can have a substantial impact on global warming potential of the system. There are wide and inconsistent variations in off-gas emissions during storage that are presented in the supporting document (Table S 12).

Eq. (20) was used to estimate total GHG emissions ($GHG_{bm}(t)$, kg CO₂e ODMT⁻¹) from storage of woodchips or pellets (b) from each storage option (m) after storage time (t, days). They include methane and nitrous oxide emissions in addition to emissions resulting from fuel/power used during handling in the storage facility.

$$GHG_{bm}(t) = (Q_{CH_4bm} * EF_{CH_4} + Q_{N_2O_{bm}} * EF_{N_2O}) * t + GHG_{Handling_{bm}} \quad (20)$$

$$GHG_{Handling_{bm}} = Q_{fuel_{bm}} * EF_{fuel} + Q_{elec_{bm}} * EF_{elec} \quad (21)$$

The quantity of methane (Q_{CH_4bm} , kg CH₄ ODMT⁻¹ day⁻¹) or nitrous oxide ($Q_{N_2O_{bm}}$, kg N₂O ODMT⁻¹ day⁻¹) emitted was multiplied by respective global warming potential factors ($EF_{CH_4} = 25$ and $EF_{N_2O} = 298$). Further biomass handling ($GHG_{Handling_{bm}}$, kg CO₂e ODMT⁻¹) in a storage facility, such as piling woodchips, loading either woodchips or pellets into a silo and ventilating a silo, produced GHG emissions due to the consumption of fossil fuels or electricity [Eq. (21)].

The fuel ($Q_{fuel_{bm}}$, LODMT^{-1}) and electricity ($Q_{Elec_{bm}}$, kWh ODMT^{-1}) units used during storage were multiplied by respective emissions factors ($EF_{fuel} = 2.7$ and $EF_{elec} = 0.69$). Based on current knowledge, in addition to indirect GHG emissions due to fuel and electricity use during biomass handling, methane fugitive emissions for woodchips ($0.76 \text{ g of CH}_4 \text{ day}^{-1} \text{ ODMT}^{-1}$) and pellets ($0.016 \text{ gm of CH}_4 \text{ day}^{-1} \text{ ODMT}^{-1}$) were included in this study to estimate total GHG emissions from each storage method (Table S 13). The GHG emissions by fugitive nitrous oxide emissions was excluded here due to limited experimental evidence. The GHG emission due to fugitive emissions can be updated with more robust experimental studies at a large scale.

2.7. Sensitivity analysis

A detailed sensitivity analysis was conducted for each storage method and feedstock type to assess the impact of various input parameters on the storage cost and GHG emissions. The storage facility capacity varied between 1000 and 40,000 ODMT for outdoor and indoor storage types [13]. A silo storage facility capacity can vary between $10,000 \text{ m}^3$ ($2 \times 5000 \text{ m}^3$) and $80,000 \text{ m}^3$ ($8 \times 10,000 \text{ m}^3$) [48]. Most other input parameters affecting cost and GHG emissions are varied $\pm 20\%$ to evaluate the variations on the output, with the exception being annual storage frequency – a number of times biomass stored in the storage facility in a year.

A frequent turnover of biomass in a storage facility can reduce the storage cost especially in a pole barn or warehouse or silo – storage methods having high infrastructural capital costs [13]. In this study, it was assumed that woodchips and pellets can be available throughout the year except for few months during severe weather, especially in winter or movement restrictions of heavy vehicles during the spring break-up period in the northern states of the United States [44]. However, at a pellet plant or at a port before export, woodchips, and pellets would be stored for short period of time but multiple times in the same storage facility in a year. Therefore, the effect of storage frequency on the storage cost was evaluated in five scenarios

- storage frequency = 1 and storage time = 6 months or less (i.e., the facility will always be empty for part of the year);
- storage frequency = 2 and storage time = 6 months or less (base case);
- storage frequency = 3 and storage time = 4 months or less;
- storage frequency = 4 and storage time = 3 months or less; and
- storage frequency = 6 and storage time = 2 months or less.

3. Results and discussion

3.1. Storage cost of woodchips and pellets

Fig. 4 shows the storage costs of woodchips and pellets after six months of storage where biomass is turned over twice in a year in a storage facility (base case or scenario 2). Storage costs for woodchips and pellets were about $\$14.34$ – $\$16.10 \text{ ODMT}^{-1}$ and $\$5.78$ – $\$6.30 \text{ ODMT}^{-1}$ respectively. Costs of handling and DML were two major contributors to outdoor and indoor storage costs. The DML of woodchips from outdoor-tarped storage (16.50%) was lower than that of outdoor-open (19.50%). Indoor storage prevents rainwater from entering into the woodchip piles and overall DML was about 50% lower than for outdoor-open storage but indoor storage incurs a high cost of building or infrastructure (i.e., $\$5.08 \text{ ODMT}^{-1}$). Woodchip silo storage experienced the highest cost ($\$16.10 \text{ ODMT}^{-1}$) among all storage types due to high infrastructure cost and additional ventilation cost, while incurring similar DML as indoor storage.

Table 4 presents a comparative storage cost of different storage options and compared with previous studies. In 1979, Springer [20] estimated a $\$16.3 \text{ ODMT}^{-1}$ [adjusted to 2017\$ using PPI (Producer Price Index)] storage cost for polyethylene film-covered woodchips

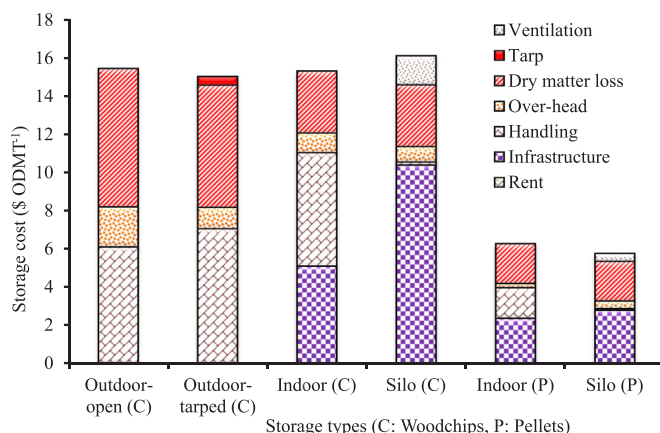


Fig. 4. Woodchips and pellets storage cost (for six months) with selected storage systems.

after six months without considering the DML. Previous studies [24,27] did not consider the costs due to DML, and loading-unloading of woodchips to trucks and reduced cost for making piles. Hence the estimated storage cost for outdoor-open type by previous studies were lower compared with this study. Harris [30] and Springer [20] both advocated storing woodchips indoors and under tarp/cover respectively for long-term storage. They considered the benefits from reduced storage piles rotations to mitigate the fire risk due to self-ignition and gain in LHV due to woodchip drying in indoor or covered storage options compared with outdoor-open. This study also estimated the net gain or loss in LHV due to decrease or increase in the moisture content and DML with respect to time.

After six months, pellet storage costs in indoor and silo storage were about $\$6.00 \text{ ODMT}^{-1}$. Pellets are denser than woodchips and for an equivalent mass (or energy) require less infrastructure for storing and handling. Moreover, pellets have lower moisture content than woodchips and incur very low DML (i.e., 2.5% per year) due to very low biological activity. Indoor pellet storage has higher handling costs compared with silo storage because a front-end loader is used to move indoor-stored pellets into trucks, which is costlier to operate than a conveyor used with silo-stored pellets.

The short-term storage cost of pellets at the port was estimated to be about $\$12.6 \text{ ODMT}^{-1}$ by Mobini et al. [11], which was about twice the cost estimated here. However, the authors did not provide any detailed description of their cost estimation. On the other hand, the $\$0.08 \text{ ODMT}^{-1}$ short-term storage cost of pellets estimated by Mani et al. [18] excluded the handling costs. The estimated unit cost of storing pellets can be reduced drastically with short-term storage if the storage facility can be used multiple times in a year, which is discussed in the later sections of this study.

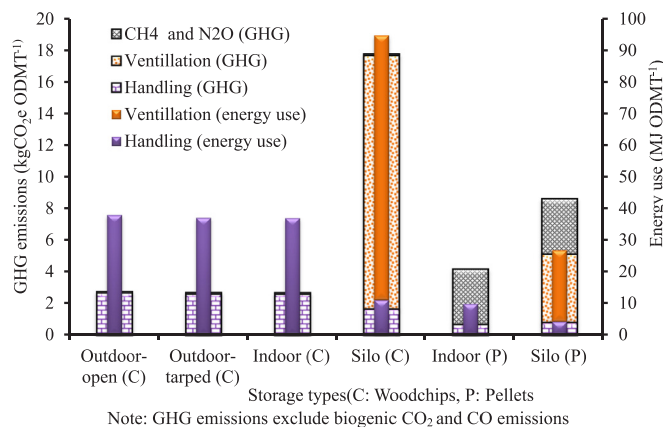
To reduce storage cost, stakeholders such as a biorefinery or power plant and feedstock suppliers will be interested in the selection of suitable storage method to store woodchips or pellets. Fig. 4 illustrates that the base case woodchips storage costs for four storage options are similar. However, storage of high moisture woodchips for heat and power generation could negatively impact the overall thermal efficiency due to low heating value [84,85]. Hence, outdoor-open woodchips storage may not be a suitable option considering storage cost and additional increased downstream costs due to higher biomass moisture content. Other than outdoor-open storage methods, there was a substantial decrease in woodchips moisture content in the outdoor-tarped, indoor and silo storages, which might reduce additional downstream processing costs for grinding, and handling.

Pellet storage costs in indoor and silo are similar (Fig. 4) and there was negligible or no variations in the pellet's moisture content during storage. Moreover, the downstream transportation and handling costs of pellets are similar irrespective of storage methods. Therefore, for the

Table 4

Woodchips and pellets storage costs cost in previous studies and this study.

Biomass type	Storage types	Springer [20]	Balsari and Manzone [24]	Manzone et al. [27]	Kühmaier et al. [23]	Sahoo and Mani [13]	This study (base case)
Woodchips	Outdoor-open	16.3	2.23 ^a	3.17 ^a			15.45
	Outdoor-tarped	5.5	5.66	10.33	9.34	8.19 ^b	15.03
	Indoor		7.06	8.58			15.31
	Silo						16.10
Pellets		Mani et al. [18]	Dhuyvetter et al. [84]	Mobini et al. [11]			
	Indoor						6.27
	Silo	0.08	13.4–18.5 ^c	12.6 ^d			5.76

^a Excluded DML cost and loading/unloading cost in the calculation.^b Cotton residues chops.^c Grain storage.^d Assumed by the authors.**Fig. 5.** Energy usage and GHG emissions in six months storage of woodchips and pellets.

base case, stakeholders can store biomass as pellets either in indoors or in silos.

The total energy use and GHG emissions (i.e., methane and fuel/power used during handling of biomass) from storing woodchips and pellets are presented in Fig. 5. Total energy usage during storage and handling of woodchips and pellets was very low (0.05–0.20% of HHV of wood), although woodchips in silo storage had somewhat higher total energy usage (0.48% of HHV of wood) due to ventilation. Biomass handling procedures, including piling and loading woodchips/pellets to trucks and loading/unloading of biomass into/from silo were one-time processes during the entire storage period. However, in the silo storage system, ventilation was a semi-continuous operation. The total energy use in silo storage was much lower for short duration (~1 months) storage compared with long duration storage (~6 months).

GHG emissions during woodchip storage were lower (~1/10th of silo storage) in outdoor and indoor storage compared with silo storage. These emissions were mainly due to fuel or power use during woodchips handling and ventilation.

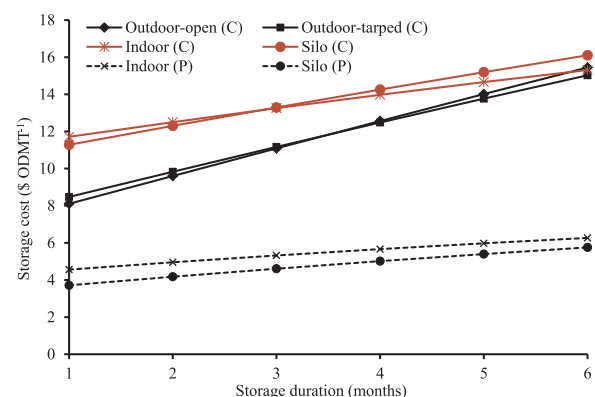
There is conflicting evidence concerning GHG emissions of woodchips during storage. Wihersaari [37] had estimated a large amount of GHG emissions (~60–140 kg CO₂e ODMT⁻¹) during woodchips storage. However, the author had assumed fugitive emissions from the woodchips that were similar to the rate of emissions (methane and nitrous oxide) from composting of woody biomass. However, the later studies reported that the emissions of CH₄ and N₂O during woodchips storage were very low and negligible [81]. Whittaker et al. [81] noted that previous and present experimental setups are not effective to accurately measure the fugitive gas emissions during woodchips storage. Fugitive emissions from biomass storage are very complex and varied with a large number of input parameters including storage method; biomass type, size and shape of comminuted biomass; size and shape of

the pile and its moisture content; climate; and many more. So far, there is no concrete evidence of high fugitive emissions of GHGs from woodchip storage and more research is required to measure the exact amount of fugitive emissions from woodchip storage.

Pellets have consistent properties and are usually stored in a more controlled climate than woodchips. There are many experimental studies that have measured fugitive emissions from pellet storage systems [31,73,83]. A large portion of the emissions from pellet storage was methane (N₂O emission was undetected) due to anaerobic chemical degradation of biomass in indoor storage. GHG emissions from the silo-stored pellets were about twice those of indoor-stored pellets. The former consisted of methane emissions and indirect emissions due to use of power for ventilation. Silo ventilation is very important to maintain the inside storage temperature and to prevent self-ignition. However, the ventilation duration depends mostly on the climate and characteristics of the biomass stored.

3.2. Temporal variations in the storage cost and net energy for each storage system

Storage costs consistently increased with storage time in all storage methods for both woodchips and pellets (Fig. 6). However, for woodchips, indoor storage had a lower rate of increase than that of outdoor storage. For short-term storage (i.e., < 3 months), the outdoor-open storage was the lowest-cost option for woodchips. For intermediate durations (3–6 months), it is cheaper to store woodchips outdoors under a roof. Woodchips can be available throughout the year except during extreme weather or unfavorable climate conditions. Under certain situations, woodchips may require storage for long durations such as during periods of excess production [large biomass volume available due to extreme weather (e.g., hurricanes damage to forests)[85] and extreme insect and pest infestation

**Fig. 6.** Temporal variations in the storage cost with respect to storage time.

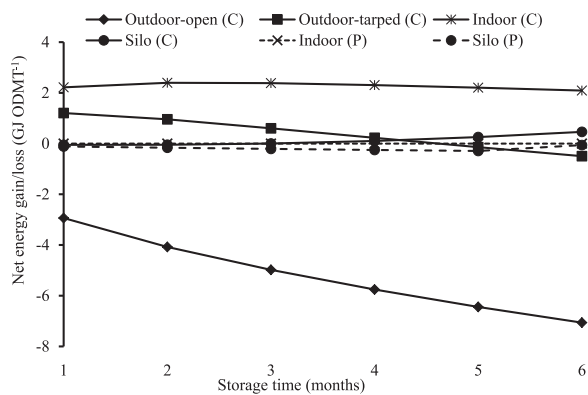


Fig. 7. Combined effect of temporal variation of moisture content and DML on the net energy content of biomass storage systems.

(e.g., pine beetle)] or if forest harvesting equipment and truck movement are restricted during spring break-up especially in northern states of the United States [44,45].

Silo storage of pellets costs less than indoor storage. In spite of lower infrastructure cost and no ventilation cost, the indoor storage cost was higher than that of silo storage cost due to higher handling costs (Fig. 4). However, if pellets require more ventilation time (beyond 4 h daily), then it may be better to store pellets indoors rather than in a silo. Moreover, higher biomass turnover could reduce the unit storage cost drastically by reducing the unit infrastructure development cost. This is especially important for indoor and silo storage.

Lower heating value (LHV) of biomass is very important for heating and power generation from woodchips and pellets. It determines how much biomass must be burned to produce a given amount of heat or to generate a given amount of electricity. Fig. 7 presents the variations in the net energy remaining per unit mass of woodchips or pellets from each storage system due to DML and changes (decrease or increase) in the final moisture content of stored biomass. The higher biomass moisture content significantly reduces the LHV (conversely, lower biomass moisture content increases LHV) and DML reduces the overall energy of stored biomass.

There is mixed evidence relating to changes in biomass moisture content with respect to storage time for woodchips stored outdoors. A number of experimental studies measured a decrease in the woodchips' final moisture content due to drying in outdoor-open storage [14,41,71]. The moisture content fluctuation effect solely depends on the climate such as rainfall, relative humidity, and temperature. Considering net energy output (i.e., LHV) from biomass, if woodchips will dry if stored outdoors, then outdoor-open storage is clearly the most efficient woodchip storage option for power plants.

In areas with higher precipitation and humidity, woodchips stored outdoor-open will increase in moisture and have higher DML the longer that they are stored. Whittaker et al. [15] estimated 21.4% energy loss in outdoor-open stored willow woodchips due to DML over 97 days of storage (and 39.7% in six-months assuming the same DML rate till the end of storage). Among all storage options, the estimated total energy loss in outdoor-open storage system was substantially large (i.e., 84% of initial the value) over a six-month period due to the cumulative effect of high DML (53% of total energy loss) and increased moisture content (47% of total energy loss). Therefore, in such areas, bioenergy plants generating explicitly heat and power should choose outdoor-tarped or indoor storage of woody biomass. Moreover, higher woodchip moisture content in outdoor-open storage will incur additional costs to downstream bioenergy or biofuel supply chain due to the higher cost of grinding, transportation, and handling.

In six-month storage, the total energy loss in woodchips tarped storage was much lower than outdoor-open. Net energy loss in woodchips stored indoors was negligible. But silo-stored woodchips gained

energy due to low DML and a decrease in the moisture content with storage duration. The energy loss in outdoor-tarped and indoor-stored woodchips was reduced by a gain in LHV due to the drying effect.

Pellets stored either indoors or in silos have similar DML and drying effects. That is, DML is low and there is little variation in the MC of the low-moisture pellets when they are stored indoors or in silos. Also, the long-term pellet unit storage costs are similar for both indoor and silo storage. Therefore, either of these two storage methods can be appropriate for longer-term storage, if biomass is stored as pellets.

3.3. Impact of storage frequency on storage cost

The annual demand for biomass by a biorefinery or combined heat and power plant can be very high (i.e., 2000 ODMT day⁻¹) [86] and requires large-scale storage systems to maintain smooth operations by mitigating variations and uncertainties of supply and demand [13]. Large-scale storage structures are necessary at ports to deliver and receive woodchips and pellets in long-distance domestic transport or international export [11,18]. Hence at such facilities, a storage facility is often used multiple times in a year to store biomass but for shorter time durations. This can reduce the fixed unit cost of building storage infrastructure along with ventilation infrastructure and conveyor belts (the latter two being for silo storage only). But the marginal handling cost remains almost the same regardless of storage length, as biomass loading and unloading are required for storage and these associated costs do not change with storage time.

Fig. 8 illustrates the storage cost of both woodchips and pellets for all storage methods assuming that facilities were used over varying frequencies (i.e., 1–6 times in a year) for a short timespan (2 months). As turnover frequency increased, storage costs declined by 74%, 46% and 7% for the silo, indoor, and outdoor-tarped storage types respectively. The storage reduction cost due to increased storage frequency was negligible for outdoor-open storage, as the contribution of infrastructure cost to the total storage cost was very low.

For frequent short-term storage of woodchips, the unit storage cost is much lower in silos than that of other woodchip storage methods. Moreover, indoor or silo storage can maintain a higher quality of woodchips, which can have further additional benefits such as lower energy input for grinding in the downstream bioenergy supply chain. Pellet storage costs (54–66% reduction) also follow a similar pattern to that of woodchips.

3.4. Sensitivity analysis

Figs. 9 and 10 show impacts that variations in the most sensitive input parameters have on storage cost and GHG emissions respectively. For woodchips, most sensitive input parameters were DML, initial moisture content, bulk density, and feedstock procurement price. As the

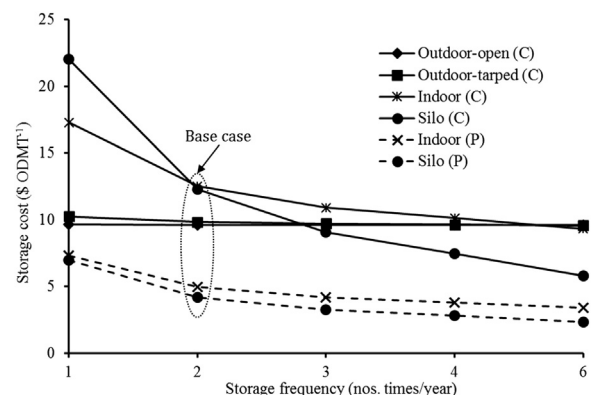


Fig. 8. Potential reduction in storage cost in woodchips and pellets due to frequent use of storage facility in a year.

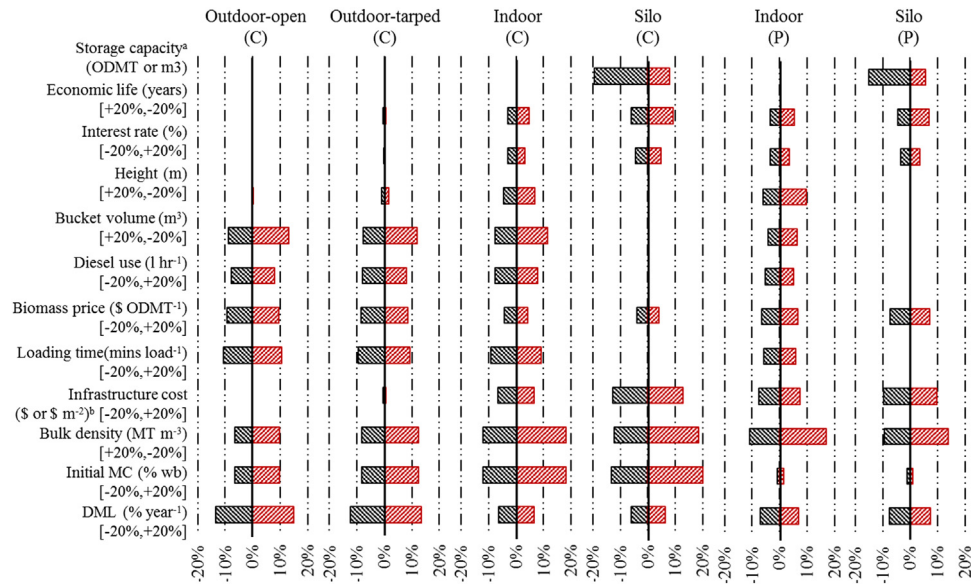


Fig. 9. Variations in input parameters affecting storage cost of woodchips and pellets. ^a Storage capacity of silo were 80,000 m³, 40,000 m³, and 10,000 m³. ^b Infrastructure cost for indoor and silo storage types was in \$ m⁻² and \$ respectively.

initial pellet moisture is very low, a $\pm 20\%$ variation in initial pellet MC did not significantly change the storage cost. Apart from silo storage, handling contributes a significant portion of woodchips and pellets storage costs. Input parameters such as the front-end loader bucket volume and the time required to load feedstock to trucks at the storage facility can increase or decrease the biomass storage cost by 4–13% with $\pm 20\%$ variations in these input parameters. The estimated storage costs in this study can be reduced significantly by optimal usage of handling equipment at the storage facility. Using a front-end loader to pile woodchips or pellets is an expensive option and results in higher handling cost. As an alternative, the use of a conveyor powered by electricity could reduce the cost of piling and loading biomass into the trucks (as demonstrated by low handling cost in silo storage). Further research is required to quantify the economic and environmental tradeoffs involved with using a conveyor compared with a front-end loader at the storage facility. For indoor and silo storage, a large portion of the total storage cost was accounted for by the cost of capital invested to build the required infrastructure.

A 20% increase or decrease in the infrastructure cost in silo storage

can increase or decrease the storage cost of woodchips and pellets by 13% and 10% respectively. Except for silo storage, storage cost was insensitive to a storage type's physical capacity. Doubling a silo's capacity could reduce the costs of storing woodchips and pellets by 20% and 16% respectively.

The most influential factors affecting the GHG emissions were the input parameters associated with fugitive emissions (i.e., CH₄ and N₂O) and fuel or power usage. Fugitive emissions from woodchips storage were very low and did not affect the net GHG emissions. However, with pellet storage, fugitive emissions significantly influenced the net GHG emissions. The most significant input factors affecting the GHG emissions in outdoor and indoor woodchips storage were related to the front-end loaders used to transfer the material. These factors include loading time, bucket volume, and fuel use.

Moisture content is also a key factor affecting the storage cost, especially for woodchips. A 20% decrease or increase in the initial moisture content of woodchips could decrease ($\sim 16\%$) or increase ($\sim 24\%$) the net GHG emissions for both outdoor and indoor storage types. In a silo storage, the combined effect of daily ventilation duration

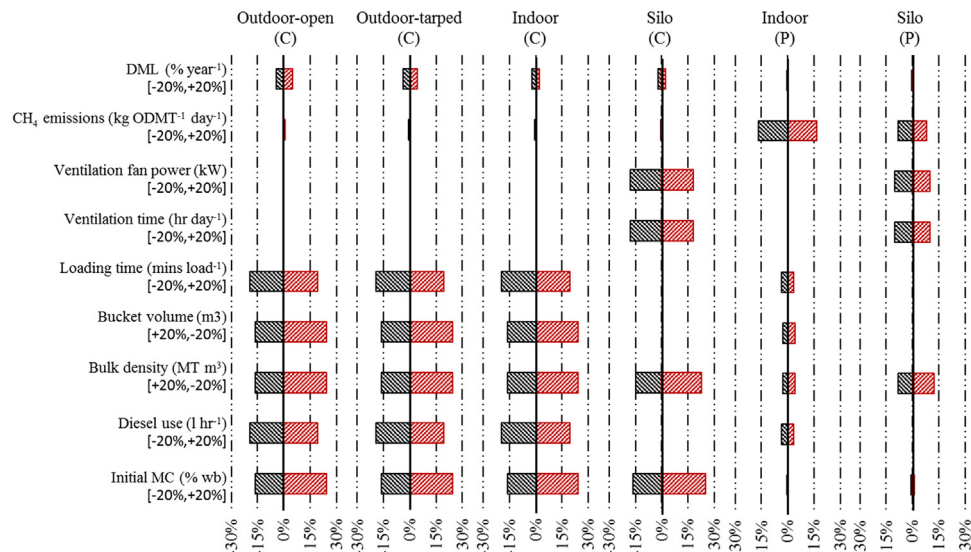


Fig. 10. Variations in input parameters affecting storage GHG emissions of woodchips and pellets.

($\pm 20\%$) and its required power ($\pm 20\%$) on total GHG emissions were higher for woodchips ($\pm 36\%$) than for pellets ($\pm 20\%$).

There is little experimental evidence for significant fugitive GHG emissions in woodchip storage piles [81]. And except for silo storage (both woodchips and pellets), the estimated storage GHG emissions were either small or negligible compared to bioenergy/biofuel cradle-to-gate or cradle-to-grave lifecycle GHG emissions [14]. However, the contribution of storage cost towards total logistics cost is much higher [13] and should be considered with care in the estimation of the total bioenergy supply chain logistics cost.

3.5. Biomass storage strategies

Biomass storage has been envisioned at multiple echelons along the supply chain such as intermediate storage and plant storage. Biomass export, especially pellets may require additional storage, i.e., short-term storage at the ports. The duration of biomass storage depends on its availabilities during the year which is dictated by local policies related to harvesting activities (restrictions for movement of logistics equipment in forest and road). Other influencing factors include its end use (production of electricity, cellulosic bioethanol, etc.) and overall supply chain objective (minimization of cost, carbon footprints, etc.). Table 5 provides the estimated biomass storage cost on monthly basis considering possible storage frequencies.

For long-term biomass storage, the least cost storage options for woodchips and pellets are outdoor-tarped and silo respectively. However, for short-term storage, the silo is the least cost storage option for both woodchips and pellets. Table 5 can be used to decide the storage cost of biomass based on the storage duration and storage frequency. Except for silo, GHG emissions from biomass storage are low (its impact on the supply chain will be less) that may not influence the decision for selecting a storage option.

3.6. Study limitations and future outlook

The data used in this study were derived from previous experimental studies (publications and reports). Not all reports gathered data consistently. Methodologies were inconsistent and the collection errors were not reported. As a result, there were wide variations in reported data that had an impact on the data accuracy.

Although it was suggested in the literature that silos could be used for woodchip storage, and conceptually there seems to be no reason why woodchips could not be silo-stored, there were no experimental studies on woodchips being stored in large capacity silos. It is suspected that higher moisture content of woodchips will require more ventilation than for wood pellets in order to keep the biomass from decomposing and possibly self-igniting. However, without data, attempting to model these interactions was beyond the scope of this study.

Similarly, the impact of local weather and climate on storage systems performance is obvious. The development of a model to measure local climate and weather impacts on changes in biomass moisture content, DML and fugitive emissions require a wide scale storage experiments around the different climatic zones, which was out of the scope of this study due to lack of sufficient availability of experimental studies. But if local experimental data on moisture content variations, DML, and fugitive emissions are available, the developed models in this study can be used to precisely estimate biomass storage cost, energy value and GHG emissions for that storage system.

The impact of local weather on biomass storage is significant and more experimental studies, especially in large-scale should be conducted in multiple climatic conditions to generate consistent data on dry matter loss and fugitive GHG emissions. Therefore, climate-smart storage studies are required for real-time decision making and reducing storage cost for a bioenergy plant. The cost due to dry matter loss is a substantial part of the total storage cost. However, biomass pre-processing such as torrefaction can reduce the dry matter loss as well as emissions. Therefore, the developed storage models in this study to can be used to analyze the benefit of storing torrefied-biomass compared with raw-biomass.

The utilization of storage infrastructure, especially for indoor storage can be very low, which is the main reason for high indoor storage cost. There can be a situation where a storage facility can remain unused for most of the time in a year [12,13]. Storage infrastructure can be leased or shared with any other activity can reduce the cost of storage. For example, using indoor-storage infrastructure for producing solar energy. Indoor storage facility's roof can host solar panels and both storage cost and electricity production cost can be reduced by sharing infrastructure cost between solar electricity production and biomass storage which needs to be studied in the future.

The temporal variations in the storage cost are substantial and the

Table 5

Woodchips and pellets storage costs (\$ ODMT⁻¹) considering storage frequencies in a storage facility.

	Storage duration (months)	Outdoor-open (C)	Outdoor-tarped (C)	Indoor (C)	Silo (C)	Indoor (P)	Silo (P)
Storage frequency = 1; storage time = 6 months or less	1	8.12	8.88	16.41	20.84	6.90	6.48
	2	9.62	10.25	17.29	22.04	7.30	6.95
	3	11.11	11.60	18.13	23.21	7.67	7.39
	4	12.58	12.92	18.93	24.34	8.02	7.80
	5	14.03	14.22	19.69	25.43	8.34	8.19
	6	15.46	15.03	20.41	26.49	8.64	8.55
Storage frequency = 2; Storage time = 6 months or less	1	8.11	8.48	11.71	11.28	4.56	3.72
	2	9.60	9.83	12.50	12.30	4.95	4.18
	3	11.09	11.17	13.26	13.29	5.32	4.61
	4	12.56	12.48	13.98	14.26	5.66	5.02
	5	14.02	13.77	14.66	15.19	5.98	5.40
	6	15.45	15.03	15.31	16.10	6.27	5.76
Storage frequency = 3; Storage time = 4 months or less	1	8.10	8.34	10.15	8.10	3.78	2.79
	2	9.60	9.69	10.91	9.05	4.17	3.25
	3	11.08	11.03	11.63	9.99	4.54	3.68
	4	12.56	12.34	12.33	10.90	4.88	4.09
Storage frequency = 4; Storage time = 3 months or less	1	8.10	8.27	9.36	6.50	3.39	2.33
	2	9.60	9.62	10.11	7.43	3.78	2.79
	3	11.08	10.95	10.82	8.34	4.15	3.22
Storage frequency = 6; Storage time = 2 months or less	1	8.10	8.21	8.58	4.91	3.00	1.87
	2	9.60	9.56	9.31	5.81	3.39	2.33

most suitable storage option (i.e., least cost and emissions) for biomass, especially woodchips is depended on the storage time. For example, outdoor-open and outdoor-tarped woodchips storage methods are the least cost options for a duration up to 3-months and 3-months onwards respectively (Fig. 6). Therefore, a biorefinery should choose different storage methods for storing woodchips that would incur the lowest cost. This study focused on only storage activity in the bioenergy supply chain. However, storage activity has a supply chain scale impacts. Therefore, the storage cost model should be used in supply chain optimization models to make optimal decisions related selection of storage type and its capacity.

4. Conclusions

Large-scale woodchips or pellets storage is necessary to absorb supply and demand risks along the biofuel supply chain and will allow uninterrupted biorefinery operations. Biomass storage can have a substantial influence on the bioenergy or biofuel economic feasibility and environmental benefits.

This study estimated the woodchips and pellets storage costs, energy usage, and emissions from four different storage systems: outdoor-open, outdoor-tarped, indoor, and silo. We concluded that long-term and less frequent biomass storage incurred a considerable cost (\$15 ODMT⁻¹ for woodchips and \$6 ODMT⁻¹ for pellets) but resulted in negligible GHG emissions (3–18 kg CO₂e ODMT⁻¹) and energy usage (10–90 MJ ODMT⁻¹). The storage costs can be reduced drastically (\$6 ODMT⁻¹ for woodchips and \$2 ODMT⁻¹ for pellets) if biomass storage can be more frequent with shorter time spans. Therefore, a biorefinery or bioenergy plant should prefer outdoor-tarp for long-term (and less frequent storage requirement) and silo for short-term (and frequent storage requirement) respectively. A biorefinery with the mixed requirement of storage duration and frequencies can exploit a combination of storage options with minimum annual storage cost and GHG emissions.

The unit cost of storing pellets is about three times less than that of woodchips due to comparatively high bulk density and low moisture content. Considering only the storage cost, it is less costly to store biomass as pellets but there is an additional cost for making pellets. Therefore, a lifecycle costing for the complete supply chain is required including storage.

The storage capacity and infrastructure cost did not affect the outdoor-open and outdoor-tarped storage costs, but it did affect the indoor and silo storage costs. For a silo, about 16–20% reduction in the storage cost could be achieved by doubling its biomass storage capacity. For woodchips, a large portion of the total storage cost was due to DML (20–50%) and handling (25–45%). Further research is required to get in-depth knowledge on the biological and chemical process of DML and potent emissions (e.g. methane and nitrous oxide), which may help to reduce uncertainties and place better limits on the wide range of variations for assessing the storage system performance. A climate-smart storage study is required to exploit the local weather conditions to reduce storage cost for a biorefinery. In the future, biomass storage cost could also be updated to account for qualitative cost factors such as biomass quality loss, fire insurance, and labor health and safety hazard insurances for large-scale biomass conversion facilities.

Acknowledgement

This project was partly supported by the USDA – NIFA Biomass Research and Development Initiative (BRDI) grant (Grant # 2012-1008-2032).

Appendix A. Supplementary material

Supplementary data associated with this article can be found in the online version at [doi:10.1016/j.rser.2018.08.055](https://doi.org/10.1016/j.rser.2018.08.055).

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