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Evaluation of the life cycle of hydrothermally carbonized biomass for energy and horticulture application

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ABSTRACT

Hydrothermal carbonization (HTC) is a promising method to process high moisture biomass into biofuel/biomaterial. The environmental benefits of biomass depend on the processing methods and its end-use. Although life cycle assessment (LCA) of HTC of wet biomass has been conducted, co-processing of peat moss with agricultural biomass (miscanthus) is yet to be reported. This study evaluates the environmental performance of hydrothermally carbonized biomass (peat moss, miscanthus, and a blend of the two) used for energy (S_3, S_5, S_7) or soil amendment (S_2, S_4, S_6, S_8) and compared with untreated biomass (peat moss left on-site: S_1; peat moss used for soil amendment: S_2) to determine the most viable pathway of biomass. Hydrochar produced from miscanthus had a lower global warming potential (GWP) compared with the hydrochar from peat moss or their blend; however, other impact categories were observed to be greater. The environmental impacts from the life cycle of biomass depend on their life cycle pathways. The highest GWP was observed in the case of peat moss used for horticulture application (S_2) followed by S_3, S_5, S_4, S_6, S_7, S_8 and S_1. Hydrochar used in soil amendment was more environmentally benign than the energy application, but the benefits were dependent on the decomposition rate of biomass. Additionally, HTC process required a considerable amount of water even it can process high moisture biomass. Renewable energy and agricultural policy may be needed to encourage hydrochar use/production/integration into soil amendment and energy application in rural communities.

1. Introduction

The concern about climate change and its potential implications led countries or regions to look into renewable resources to replace fossil fuels for energy and power, thus mitigating increased greenhouse gas (GHG) emissions. Ontario has phased out the use of coal and shut down all the coal-fired power plants to combat rising GHG emissions, which contributed to electricity prices [1,2]. Therefore, an alternative renewable fuel is desired, which can replace coal to keep present power plants in operation while abating GHG emissions. In Canada, the major sources of lignocellulosic biomass are agri- and forest residues, purpose-grown energy crops, and municipal solid wastes [3,4]. Solid biofuels can be a potential energy and power resource for remote communities or rural Canadian greenhouse industries. Fuel-grade solid fuel can be produced from biomass or co-processing of biomass or from other renewable resources if properly treated [5–7].

Despite the fact that solid biofuels are being produced from renewable resources through conventional processes, high moisture biomass has a limitation or cannot be converted into solid biofuels in a conventional process. HTC is a thermochemical conversion process where biomass treated at elevated temperature (180–260 °C) and pressure (2–6 MPa) in aqueous medium [6,8–11] producing structured carbon known as fuel-grade hydrochar [6]. HTC process can convert high moisture biomass to fuel-grade solid fuels replacing coal to operate the

Abbreviations: HTC, Hydrothermal carbonization; GWP, Global warming potential; GHG, Greenhouse gas; LCA, life cycle assessment; HBL, Hudson bay lowlands; LDPE, Low-density polyethylene; dLUC, direct land-use change; iLUC, indirect land-use change; MC, Moisture content; CHP, Combined heat and power; HC, Hydrochar; EPA, Environmental protection agency; TRACI, Tool for the reduction and assessment of chemical and other environmental impacts; MJ, Megajule; NSERC, Natural Sciences and Engineering Research Council; OMAFRA, Ontario Ministry of Agriculture, Food and Rural Affairs.

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existing coal-fired power plants which have been shut down. Consequently, these inactive power plants could provide power/electricity to rural greenhouse industries and remote communities using these fuel-grade solid biofuels, which are not connected with grids. In addition, the pretreated (HTC) solid biomass reduces energy consumption during the drying process compared with raw biomass [12].

Peat moss, rich in carbon could be an attractive alternative to coal if properly treated or co-processed with other herbaceous biomass [6]. However, most peat moss harvest in Canada is currently used for non-fuel applications, especially for soil amendment in the horticulture sector [13–15]. The decomposition rate of peat moss is dependent on the carbon-nitrogen ratio, the conditions (e.g., temperature, and availability of water) at the place of application, and the state of biomass [4,16,17]. For example, the decomposition rate of untreated biomass (raw biomass) is greater than that of treated biomass (i.e., hydrochar) [18,19]. Although biomass accumulation exceeds the decomposition rate of organic matter in natural peatlands and becomes a carbon reservoir [20,21], any decomposition of peat moss at natural peatlands resulted in GHG emissions. Peat moss decomposition and its end-use contributed 71% GHG to its life cycle [22]. However, the abundant peat moss can be harvested to produce biofuels or biomaterial for horticultural applications, which can abate GHG emissions from peat moss decomposition.

Canada has about 113.6 million ha of peatland which is scattered in different provinces; however, only about 17,000 ha is harvested [14,23]. In Canadian peatlands, annual accumulation ranges from 0.5 to 1 mm per year [24], and sequestered about 23 million tonnes of carbon per year [25]. Although 70 million tonnes of peat moss is accumulated each year in Canada [14], only 1.3 million tonnes are harvested [26,27]. It is also reported that many existing and new peatland sites can be revegetated with Sphagnum for peat moss harvesting [14]. In addition, Canada has an adequate land base, especially marginal land, for producing energy crops to meeting the viable uses of biomass [28–30]. Miscanthus is a promising energy crop, which can be grown on marginal land without competing with cropland [28–31].

Human activities are not only influencing climate change but also affecting the deposition of nitrogen, thus the dynamics of carbon and the carbon sink capacity of peatlands by changing the decomposition dynamics of peat moss as well as the energy crops. HTC processes known to have a favorable energy balance compared to alternative processes [6,7,12]. In addition, hydrochar can either be used for energy applications or soil amendment, and the nutrient-rich effluent from the HTC process can be used for crop irrigation [12,32,33] as well as a growing media in horticulture [34]. Therefore, it is important to evaluate the various applications of treated and untreated biomass to abate GHG emissions from their life cycle, thus from human activities. Life cycle assessment (LCA) is widely used methodology for evaluating the environmental impacts of bioenergy systems and biomaterials [3,35–42]. Several authors have also conducted LCA of the HTC process of biomass, mainly comparing HTC with other conversion processes [41,43–45] or compared HTC process of various feedstock [46], hydrochar is compared with coal [47] or hydrochar application for either energy or soil amendment [48–51]. Most of these studies deal with agricultural waste, municipal organic waste, sewage sludge, etc.; however, LCA of peat moss and co-processing with agricultural biomass (miscanthus) for various applications are yet to be reported.

Several authors have studied the properties of treated and untreated peat moss, co-carbonization of peat moss [6], hydrothermal carbonization [12], and LCA of peat moss to a limited extent [22]. Cleary et al. [22] noted that peatland emerged as a carbon sink or source depending on the land-use change where the life cycle of untreated peat moss is studied. Contrarily, HTC of wet biomass is reported to be a sustainable system for solid biofuels [12,43]. However, the LCA of hydrothermally pretreated peat moss or co-carbonization of peat moss and miscanthus, as well as comparison with the natural decomposition of peat moss and soil application of harvested peat moss is yet to be reported. Therefore, this study evaluates the environmental performance of hydrothermally treated and untreated biomass applied for energy and soil amendment, comparing it to its counterparts to determine the most viable pathway.

2. Materials and methods

2.1. Feedstocks

Peat moss and miscanthus were selected to evaluate the environmental performance of biomass applications for energy and power or for soil amendment.

2.1.1. Peat moss

Peat is an organic matter resulting from the degradation of sphagnum. Sphagnum (peat moss) biomass can be grown on degraded peatlands. The common harvesting methods are block-cutting and vacuum harvesting [52]. Currently, most peat moss is gathered using vacuum harvesting [24]. In 2000, the average yield of vacuum harvesting was 10×10^3 t/km^2/year [22]. The lifespan of the vacuum harvested peatlands ranges from 20 to 50 years [53]. About 50% of peatlands in Ontario are situated in the Hudson Bay Lowlands (HBL) [54]. Thus, peat moss was assumed to be collected from the HBL, and the lifespan of vacuum harvested peatlands is to be 20 years. Although peat moss collected from the local market was packed in plastics, the packaging material (LDPE: 0.556 kg/m^3 peat moss; peat moss density: 100 kg/m^3) was excluded in this study, assuming that in a large scale hydrochar production unpacked peat moss was directly collected from its production sites. The activities included in the life cycle of peat moss are production, conditioning, and transportation.

2.1.2. Miscanthus

Miscanthus can economically be grown in all regions of Ontario [28,55] and requires very low agrochemicals [56]. Miscanthus stands persist for 15–20 years. Miscanthus yield increases for the first 3 years and then remains constant for the remaining years. Although miscanthus can be grown in all regions (either on prime or marginal land) of Canada except the northern region (because of its short growing period: frost-free days are only 100–145 days) [28,31], the yield varies from region to region and on the types of land [4]. In Canada, typically miscanthus harvesting period is late winter or early spring, consequently contains low moisture (15–20%) [28,31,55,56]. The density of baled miscanthus is 218 kg/m^3 [55]. In this study, miscanthus is assumed to be grown on marginal land to avoid any competition for land with food crops (New Energy Farm, Leamington, Ontario, Canada) and collected for this study. The average annual yield of miscanthus is considered to be 8.35 dry ton (dt)/ha [28]. The carbon dynamics [direct land-use change (dLUC) was determined based on the initial and final carbon content in the soil] of miscanthus cultivated on marginal land (usually used for long-term pasture land) is reported to be 0.03 dt C/ha/year [31]. The inputs in agriculture (raw data for miscanthus cultivation) are collected from literature (personal communication). Miscanthus cultivation may also be associated with indirect land-use change (iLUC) impacts that are caused by the market price of bioenergy crops, or food crops, which are not taken into account in this study. The activities included in the life cycle of miscanthus are rhizome production and transportation, cultivation, harvesting, and dLUC.

2.2. Feedstock processing (hydrothermal carbonization)

Hydrothermal carbonization can convert high moisture biomass into fuel-grade hydrochar, which can be combusted or co-combusted in existing coal-fired power plants [6,57] or can be used for soil amendment [12,58]. Peat moss and miscanthus are hydrothermally carbonized by using a Parr reactor (600 mL benchtop reactor, Moline, IL). The carbonization temperature was controlled to 240 °C for 15 min to produce fuel-grade hydrochar from peat moss, miscanthus or blend of peat moss and miscanthus [6]. The energy consumption in the HTC process was calculated based on the specific heat, mass, and experimental temperature. The unit process models were developed based on the experimental results assuming a continuous HTC reactor capacity of 100 kg dry biomass/day. The mechanical dewatering produces a hydrocarbon that contains about 50% moisture, which can be reduced to 5% through thermal drying [12]. However, the hydrochar was assumed to be dried to 0% MC in the case of energy application, and no drying was employed in the case of soil amendment.

2.3. Goal and system boundaries

Although hydrochar can be used for the same purposes as conventional biochar even though their physicochemical properties differ from variable treatment processes. Their effectiveness in different applications should be evaluated. For example, hydrochar and biochar are commonly produced at 200–300 °C and 300–600 °C (especially in the case of pyrolysis), respectively [32], and may have different physicochemical properties [59,60]. The properties of hydrochar produced from peat moss and miscanthus are reported in the supporting information (SI>, Table 1), which shows that hydrochar can be used for energy application [6,12] or soil amendment [12,58] or water purification [12, 61] or carbon sequestration [62]. Several authors also noted that biochar/hydrochar could be co-combusted in coal-fired power plants [63, 64] or burned directly in Combined Heat and Power (CHP) plant for clean heat and power generation [65], and can also replace coal/light oil in heat generation/combustion applications without any modification [66,67]. Additionally, HTC process water (effluent) rich in nutrients can be used for crop irrigation [12]. Therefore, hydrochar is assumed to be used for either energy application or soil amendment, and process water used for horticulture application/crop irrigation. Cradle to grave scenario is adopted to outline the system boundary (Fig. 1) to evaluate the life cycle of treated and untreated biomass. Table 1 represents the description of different pathways of biomass adopted in this study. The functional unit of this study is assumed to be 1 tonne dry feedstock either left on-site (peat moss) or processed and used for either soil amendment or energy application.

A wide range of product yield of the HTC process is reported in literature (SI, Table 2); the carbon lost during the HTC process is allocated to gaseous and liquid products at an approximate ratio of 5:19 based on the biomass conversion rate during the HTC process [68]. The carbon in the gaseous portion is assumed to be released as CO_2 [69]. The accumulation and decomposition rate of peat moss also varied depending on the moss communities. For example, on-site litter production, accumulation of dead organic matter, and decomposition rate

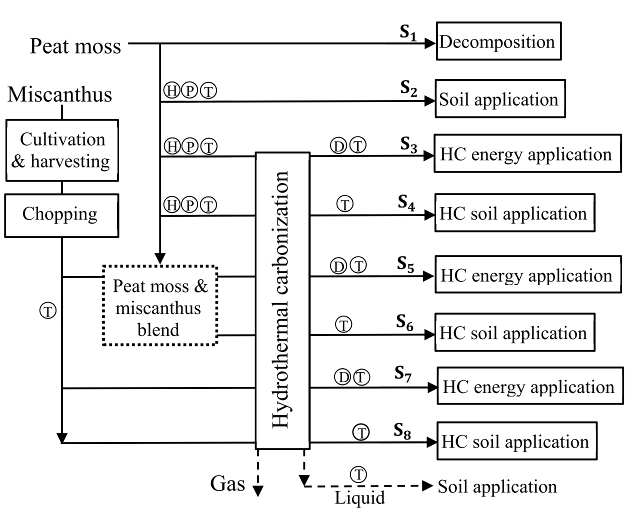

Fig. 1. Process flow diagram and system boundary of this study (HC: hydrochar; H: harvesting; P: processing; D: hydrochar drying; T: transportation).

Table 1
Description of the scenarios of this study.

Scenario	Description	Remarks
S_1	Peat moss remains on the natural peatlands and decomposes over time	Primary business as usual case
S_2	Untreated peat moss used for soil amendment and decomposes over time	Secondary business as usual case
S_3	Peat moss hydrothermally carbonized and used for heat and power in a remote area	Energy application
S_4	Peat moss hydrothermally carbonized and used for soil amendment	Soil application (carbon storage)
S_5	Peat moss and miscanthus blended and hydrothermally carbonized (co-processed) for heat and power	The ratio of peat moss and miscanthus was 1:1 (energy application)
S_6	Peat moss and miscanthus blended and hydrothermally carbonized (co-processed) for soil amendment	The ratio of peat moss and miscanthus was 1:1 (Soil application: carbon storage)
S_7	Miscanthus hydrothermally carbonized and used for heat and power in a remote area	Energy application
S_8	Miscanthus hydrothermally carbonized and used for soil amendment	Soil application (carbon storage)

Note: hydrochar can also be used for replacing coal for heat and power in remote areas.

of moss-turf are 409 g/m^2/year, 33.5 kg/m^2 and 0.017 kg/kg/year, respectively. On the other hand, these decomposition rates for moss-carpet are 0.392 kg/m^2/year, 29.6 kg/m^2 and 0.010 g/g/year, respectively [70]. In the case of soil amendment, peat moss and hydrochar decomposition rates (SI, Table 3) depend on the state of biomass (treated or untreated), soil properties, and climate [16–19,71, 72]. The decomposition rate of peat moss and biochar is reported to be 0.05 to 0.20 [73,74] and 0.003 to 0.049 [18,75], respectively. Peat moss on-site decomposition and horticulture application are assumed to be 0.01 and 0.05, respectively. The biochar decomposition rate is considered to be 0.008.

The carbon remains, and mineralization is determined based on the published methodology (SI, S1). Finally, the carbon balance of the life cycle of biomass is established (SI, S2, and Table 4) based on the carbon content in biomass or hydrochar and the yield of hydrochar and then carbon losses during the HTC process are determined. Based on literature, it is assumed that the aqueous solution contains approximately 19% of dry biomass and 5% in the gaseous medium [9,68,69,76]. In the case of energy application, light fuel oil is assumed to be replaced by the generated energy/heat from hydrochar. The carbon in hydrochar that combusted for heat and energy generation is taken into account to estimate life-cycle emissions for different scenarios. On the other hand, the nutrients in the biomass that can be used by the plants due to carbon mineralization replace chemical fertilizers, and emissions from the nutrients are also taken into account to determine the life cycle emission (SI, S3).

2.4. Data collection and life cycle assessment (LCA)

In this study, both the estimated and literature data are used to evaluate the life cycle environmental impacts. The HTC data are collected from the laboratory scale experiment [6] and converted for the desired HTC plant capacity. Table 2 represents the parameters/processes data and their sources that are used in this study. The ISO standard LCA methodologies are adopted in this study [77]. Environmental impacts are calculated using SimaPro LCA software and the U.S. EPA impact assessment method (TRACI 2.1, v. 1.01; Canada 2005). In addition, the circular economy concept has been used to avoid waste from the system (i.e. aqueous effluent), the main by-product of the HTC process was used for soil amendment. It is assumed that the nitrogen in the effluent

Table 2
Summary of data sources of this study.

Process/parameters	Data	Sources
Peat moss	–	Ecoinvent database
Miscanthus cultivation	SI, Table 5	[31] & (personal communication)
Grinding	30 kWh/t	[78]
HTC process energy	3.06 MJ/kg	[6]
HTC unit	(SI Table 7)	Author-defined
Transportation	Estimated	Author-defined

Note: supporting information (SI).

replaces the chemical fertilizers commonly used in agriculture. The nutrient that can be used to replace fertilizer is also estimated, especially the amount of nitrogen (SI, S3). The raw feedstock may contain a trace amounts of phosphorous and potassium, which is not considered for fertilizer replacement. The aqueous effluent contains about 1–6% acetic acids [69]; however, effluent is assumed to be used in agriculture as a soil amendment, and the carbon mineralization has been calculated based on the decay rate that of hydrochar. The emission factors of fertilizers are used to determine the credit that can be given to the aqueous effluent of the HTC process. The models for each unit processes of the life cycle of the biomass have been developed and then integrated into SimaPro (Classroom 8.0.4.26 Multi-user) to determine the environmental impacts. Some of the unit process models are reported in the supporting information (SI, Tables 5–11).

3. Results and discussion

3.1. Environmental impacts

The environmental impacts from the life cycle of biomass depend on their pathways, i.e., the scenarios adopted in this study (Table 3). The highest GWP is observed in the case of peat moss used for horticulture applications (S_2) followed by S_3, S_5, S_4, S_6, S_7, S_8 and the lowest is S_1. The labor and energy-intensive harvesting and processing may have resulted in the highest impacts for S_2 due to growth patterns of peat moss and limited availability in certain locations [79]. In addition to labor and energy-intensive harvesting of peat moss, GWP may also induced by the higher degradation rate in the case of horticultural application of peat moss [22]. On the other hand, a lower degradation rate in the case of on-site decomposition of peat moss (S_1) leads to lesser environmental impacts compared with other pathways (S_2–S_8). Similarly, treated biomass (S_3–S_8), i.e., hydrochar has a lower degradation rate compared to untreated biomass [19,22,73,80], thus have lower GWP. Other impact categories (ozone depletion, smog, acidification, eutrophication, carcinogenic, non-carcinogenic, respiratory effects, and fossil fuel depletion) are found to be greater in the case of S_6 compared with other scenarios, except ecotoxicity. The greatest ecotoxicity was observed in the case of S_6 might be because of fertilizer application [31,81] during miscanthus cultivation.

Although majority of the applied fertilizer used by plants during cultivation, a portion is released to the air and water because of oxidation/nitrification and leaching [82,83]. In the case of horticulture applications, some of the carbon in the feedstock and effluent remains in the soil. In the case of energy application, burned carbon emits GHGs which can be offset by replacing fossil energy with the generated energy from the system. The biochar remaining in the soil provides an opportunity to store some of its carbon [84–86]. Simultaneously, a portion of carbon in the biochar decomposes over time, emitting GHGs (i.e., CO_2 and N_2O, because of organic matter decomposition) [87,88]. However, the carbon remains in the soil not only offset the emissions due to mineralization of biochar but also emerged as a better option for the environment.

Treated biomass pathways appear to be a better option for abating environmental impacts compared with untreated biomass, except S_1 where peat moss was left on-site. The slower decomposition rate of treated biomass led to store a greater amount of carbon compared to the untreated feedstock (S_2) except peat moss left on-site (S_1) instead of harvesting [18,70,73–75]. Net impacts (GWP) from S_1, S_2, S_3, S_4, S_5, S_6, S_7, and S_8 were −1505.6, 830.5, 824.3, 79.5, 283.3, −320.9–369.8, −830.1 kg-CO_2 eq./t, respectively. The impacts from the life cycle of biomass that are used for energy application seems to be similar with the earlier studies [31,43,44]. The impacts were observed to be dependent on the type of feedstock, replaced energy and the conversion technologies (Table 4). For example, the highest environmental benefits (GWP) is reported in the case of biowaste HTC followed by anaerobic digestion,

Table 4
Life cycle GWP of biomass for different applications.

Feedstock	Conversion technology	Application	GWP/t feedstock (kg CO2 eq)	Reference
Peat moss	–	On-site decomposition	−1505.60	This study
Peat moss	–	Soil amendment	830.52	This study
Peat moss & miscanthus	HTC	Soil amendment	79.51	This study
Peat moss & miscanthus	HTC	Energy	824.34	This study
Miscanthus	HTC	Soil amendment	−320.86	This study
Miscanthus	HTC	Energy	283.30.	This study
Peat moss	–	Soil amendment	714.64	[22]
Food wastes	HTC	Energy	−32.6 to 190	[43]
Green waste (leaves and grass cuttings)	HTC	Energy	51.20 to 372.00	[44]
Green waste	HTC	Energy	0.061–0.112 kg CO2 eq/ kWh	[47]

HTC: hydrothermal carbonization; GWP, global warming potential.

Table 3
Environmental impacts of the different life cycles of biomass.

Impact categories	Unit	Scenario							
		S1	S2	S3	S4	S5	S6	S7	S8
Ozone depletion	kg CFC-11 eq	0.00	1.08E-05	−1.09E-04	5.04E-05	−6.75E-05	5.68E-05	−8.53E-05	4.83E-05
Global warming	kg CO2 eq	−1505.60	830.52	824.34	79.51	283.30	−320.86	−369.81	−830.10
Smog	kg O3 eq	0.48	9.84	23.16	45.07	32.70	50.04	28.21	45.78
Acidification	kg SO2 eq	0.02	0.27	0.50	2.17	1.12	2.44	0.95	2.33
Eutrophication	kg N eq	0.00	−1.42	0.13	0.28	0.24	0.44	0.18	0.30
Carcinogenics	CTUh	0.00	1.11E-06	1.50E-05	1.81E-05	1.65E-05	1.91E-05	1.46E-05	1.71E-05
Non carcinogenics	CTUh	0.00	1.34E-05	2.51E-04	3.66E-04	2.88E-04	3.79E-04	2.81E-04	3.75E-04
Respiratory effects	kg PM2.5 eq	0.00	0.04	0.14	0.28	0.19	0.30	0.16	0.27
Ecotoxicity	CTUe	0.00	75.13	1548.44	2227.02	3176.33	3727.40	4175.88	4733.53
Fossil fuel depletion	MJ surplus	0.00	92.31	−907.45	492.18	−519.11	570.85	−656.80	515.10

incineration, landfilling, and composting [46]. However, the greater environmental benefit is observed in the case of hydrochar used for soil amendment compared with the energy application. The negative value indicates carbon sequestration opportunity from the life cycle of biomass, which resulted mainly because of the benefit from the stored carbon, thus offsets a portion of impacts [31]. In addition, the wide range in results is potentially from differences in LCA modeling choices, HTC processing parameters, product yield, handling of coproducts and end-use of the products.

Several studies have found that 80% of carbon in biochar produced from slow pyrolysis is stable (i.e., mean residence time is 1000 years or longer at 10 °C mean temperature) when applied to soil, while the rest of the carbon is released into the atmosphere [89,90], thus treated biomass applied in soil amendment provided better environmental benefits. Several researchers have also suggested that biochar used for soil amendment act as a carbon storage and provides an opportunity for carbon sequestration [87,91]. In contrast, energetic applications (electricity generation) of HTC of sewage sludge is noted to be beneficial compared with the soil amendment [49]. In the case of energy application, the variation might be induced not only by the difference in system boundary and scope of the study but also the type of fuel replaced and the type of feedstock [43,46,92]. Although biochar/hydrochar used in soil amendment reduces fertilizer demand, improves crop yield and mitigates environmental impacts, it is susceptible to soil dust emissions during agricultural activities, which is hazardous to health [93–95].

Treated biomass tenders lower impacts if applied for energy compared with the horticulture application, except GWP. It also reduces fossil fuel depletion. The fossil fuel depletion varies from −907.45 MJ (negative sign indicates surplus energy that generated from the feedstock) to 554.03 MJ per ton feedstock, depending on the scenarios. It is worth to note that there are no human activities involved in the case of S_1, thus does not deplete any fossil fuel. Although the treated biomass used for energy application replaces fossil fuel and offset a portion of emissions, it stores a lesser amount of carbon compared to horticulture applications, thus proffers greater GWP. Ash generated from energy applications could be used to replace phosphorous if applied in horticulture [12]. Phosphorous substitution from hydrochar ash is not considered in this study as HTC process reduces ash content in hydrochar [57,96] containing negligible amount of phosphorus to be used in horticulture. Although the environmental benefits of HTC have been reported in literature, many of these studies are based on small-scale or pilot-scale data or modeling. There are still gaps in understanding of the optimum application HTC products, biomass decomposition rates, and carbon sequestration potential, and the rebound impacts of biochar use for soil amendment.

3.2. Contribution analysis

The hotspots are identified by analyzing the contribution of different processes in the life cycle of biomass. The feedstock is the main contributor followed by either the use phase or transportation or processing (HTC) in the case of treated biomass (S_3 to S_8). On the other hand, the feedstock is the main contributor in the case of S_2 followed by the use and transportation stage. On-site decomposition/use phase is the main contributor in the case of untreated biomass (S_1). The intensive human activities such as vacuum harvesting of peat moss and processing resulted in greater environmental impacts. It is also important to note that harvested and processed peat moss had greater impacts compared with miscanthus cultivation. Consequently, the blended feedstock had greater impacts compared with only miscanthus (Fig. 2). The contribution of the processing phase varied from 109.1 to 161.2 kg-CO_2 eq/t depending on the scenarios. Carbon emissions in the form of HTC process gas is the main contributor in the processing stage followed by water and energy consumed in the HTC process (SI: Tables 20–22). For on-site decomposition (S_1), the highest amount of stored carbon is observed because of lower decomposition rate compared with the horticulture (S_2, S_4, S_6, and S_8) and energy (S_3, S_5, and S_7) applications. The benefit from stored carbon is 1689.5, 1154.9, 191.5, 1672.2, 369.4, 1550.6, 351.3, 1413.2 kg-CO_2 eq./t for S_1, S_2, S_3, S_4, S_5, S_6, S_7, and S_8, respectively. In the case of energy application, it comes only from the effluent applied to soil (S_3, S_5, S_7); thus it provides lower benefits compared with the feedstock used for soil amendment.

The benefit from fertilizer and energy replacement is only 0.4 to 1.3 kg-CO_2 eq/t and 5.5 to 51.6 kg-CO_2 eq/t, respectively, depending on the scenarios. Other impact categories are also varied depending on the scenarios (SI: Tables 12–19). It is worth to note that no fertilizer replacement is considered in the case of on-site decomposition of peat moss (S_1) since it is not considered as a soil amendment activity. On-site decomposition of peat moss could potentially responsible for methane emission, which is not considered in this study due to lack of data. Therefore, the impacts from S_1 may change if any methane emission is considered. Impact from the transportation phase was dependent on the state of the biomass, treated or untreated. Impact from the transportation phase was higher for treated biomass than untreated biomass. The impact was higher for treated biomass due to the added transportation of effluent generated from the HTC process. Appropriately

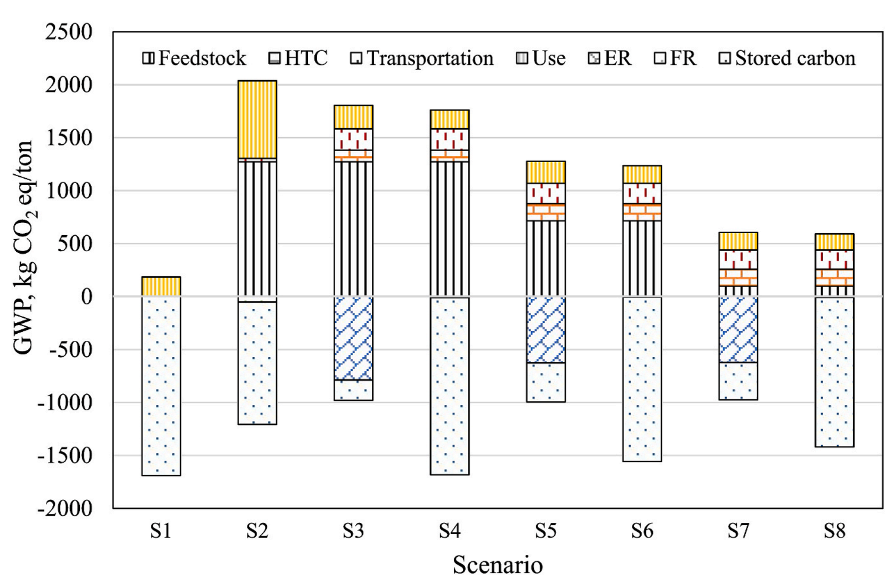

Fig. 2. Contribution of the different unit processes; and stored carbon, energy replacement (ER), and fertilizer replacement (FR).

managed effluent stream of HTC process reduces environmental impacts [43]. In addition, the results also depict that only the treated miscanthus has better environmental benefits compared with peat moss or blend of miscanthus and peat moss.

3.3. Sensitivity analysis

The results of an LCA vary with changes in different parameters of the system being studied. The decomposition rate of treated and untreated biomass varied depending on the type of soil, type of biomass (SI: Table 4), and climate of the location of application [16–18,71,73–75,97,98]. Decomposition rate would be dependent on the location in Canada. In addition, the transportation of biomass is one of the major constraints in a large scale bioenergy industry [99,100]. Therefore, the changes in decomposition rate (±40%) and the transportation distance (±30% and ±60%) on the life cycle impacts are evaluated. Although changes in decomposition rate and transportation distance affect the life cycle environmental impacts, the decomposition rate has greater influence (Fig. 3) compared with the transportation distance (Fig. 4).

The life cycle impact (GWP) varied from −1646.8 kg-CO_2 eq/t to 811.8 kg-CO_2 eq/t when decomposition rate decreased by 40%; however, it varied from −1371.8 kg-CO_2 eq/t to 1180.7 kg-CO_2 eq/t if the decomposition rate increased by 40%. The amount of stored carbon increased with decreasing decomposition rate. Contrarily, a lower amount of carbon can be stored with a greater decomposition rate. Both the carbon in hydrochar and effluent are applied to the soil in the case of soil application (S_2, S_4, S_6, S_8), but only the carbon in the effluent is applied to the soil in the case of energy application (S_3, S_5, S_7). Decomposition rate has a larger effect in horticultural applications as more carbon is applied (effluent and hydrochar) to the soil than in energy applications (only effluent). The GWP varied from 810.9 to 850.1 kg-CO_2 eq/t, 788.5 to 860.2 kg-CO_2 eq/t, 43.7 to 115.4 kg-CO_2 eq/t, 253.1 to 313.5 kg-CO_2 eq/t, −351.1 to −290.6 kg-CO_2 eq/t, −394.5 to −345.6 kg-CO_2 eq/t, and −854.7 to −805.5 kg-CO_2 eq/t for S_2, S_3, S_4, S_5, S_6, S_7, and S_8, respectively. There is no transportation in the case of on-site decomposition of peat moss; thus, the environmental impacts remain unchanged.

4. Discussion

4.1. Environmental implications

The environmental impacts of growing media in the horticulture sectors were observed to be dependent on the components of growing media [101]. Although most of the harvested peat moss is currently used for non-fuel applications in Canada, especially in horticulture as a soil supplement [13–15], the environmental impacts from horticulture sector can be reduced by replacing the peat moss with an alternative product that has lower impacts such as treated peat moss (hydrochar). Several studies have noted that hydorchar/biochar can be used either as a soil amendment to improve crop productivity [85,102] and to store carbon [84,85,103], or for generating heat and energy in the remote areas [104]. However, benefits from soil and energy applications were dependent on the location, climate, source of biomass, and type of energy replaced [31]. For example, HTC of sewage sludge (containing 5% solids) was observed as the least environmentally beneficial when hydrochar was applied as a substitute for nitrogen, phosphorus, and potassium (NPK) fertilizer. Hydrochar was more beneficial in energy applications [50].

In this study, decomposition rates of treated and untreated biomass were taken from literature; as a result, site-specific decomposition rates should be used for determining more realistic environmental impacts in the decision-making process. In addition, the current market price of biochar/hydrochar may restrict its application for either soil amendment or for energy generation which needs to be explored. It is important to have in-depth analysis of the life cycle of biomass, i.e., either naturally grown peat moss or dedicated energy crops grown on the marginal land without competing with food crops for land. Attention also needs to be placed on the selection of feedstock, and application of HTC products to optimize the environmental benefits. Finally, the health impacts of biochar/hydrochar production and application for soil amendment demands in-depth studies to avoid unwanted health problems. Although environmental benefits from HTC were observed in laboratory-scale data, these benefits need to be confirmed with on-site pilot-scale data before pursuing commercial use.

4.2. Practical implications

HTC can process high moisture biomass and reduce ash content of the treated biomass [57,96]; however, drawbacks (substantial amount

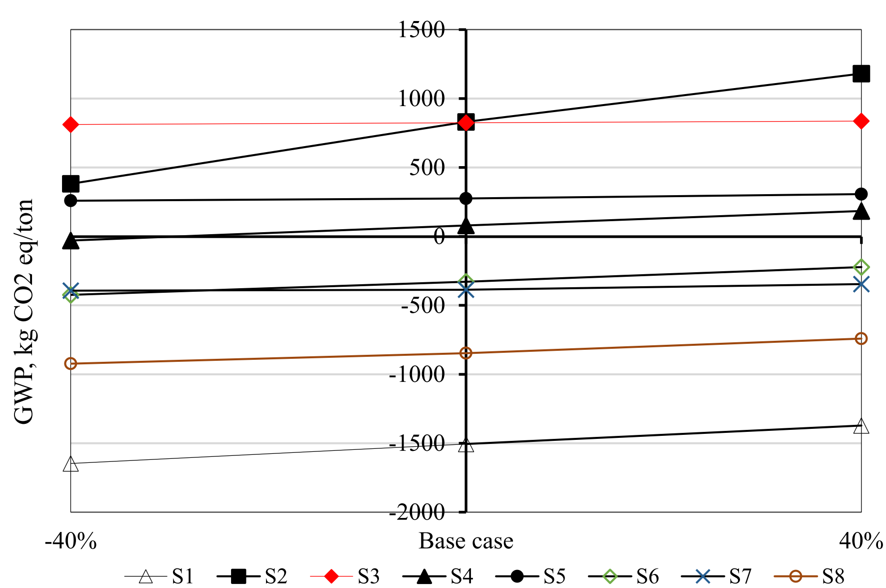

Fig. 3. Effect of decomposition rate of biomass (GWP).

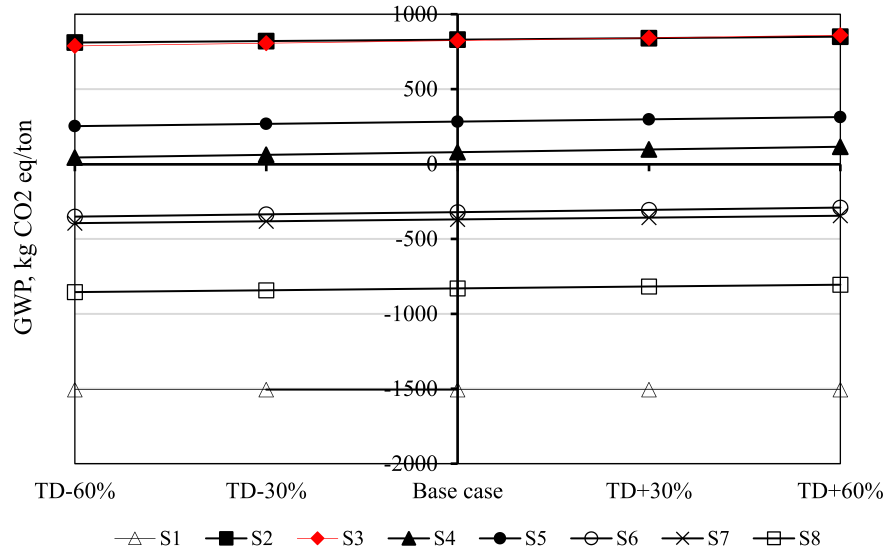

Fig. 4. Effect of transportation distance of feedstock (GWP).

of water consumption) need to be considered. A wide range of biomass and water ratios have been reported in the literature [6,105–107]. It is important to minimize water consumption to reduce energy consumption in the HTC process. Water consumption can be reduced by reusing the HTC process water and implementing a continuous system, it would further reduce water and energy consumption. Although HTC process is recognized as a cost-effective approach to producing hydrochar from wet biomass, the industrial symbiosis approach can also play an important role to minimize the feedstock as well as the hydrochar transportation distance. In addition, reduce environmental impacts from the life cycle of biomass and improve economic benefits.

On-site decomposition, i.e. peat moss left on-site instead of harvesting was observed to have the highest environmental benefits compared with treated and untreated biomass pathways that were applied in energy or soil applications. Although the LCA results depict that leaving peat moss on-site was environmentally beneficial, there would be no economic activities and may affect the rural economy. However, the use of either treated or untreated peat moss and blend of peat moss and miscanthus would lead to more activities and contribute to rural development and create rural employment opportunities, which need to be taken into account for a complete LCA study. The results of this study suggest biomass used in soil amendment is more environmentally beneficial than using it in energy applications. However, integrating biomass into energy applications would reduce fossil fuel depletion. Consequently, the renewable energy policy or agricultural policy may be needed to enhance the application of treated biomass either for energy or for soil amendment and reduce the environmental impacts from the life cycle of biomass. The laboratory-scale batch process data has been used in evaluating the life cycle impacts of biomass. Commercial or pilot-scale as well as the on-site data from a continuous HTC process are required to avoid technical and geographical effects in LCA results. Additionally, the environmental benefit of HTC found to be dependent on the type of feedstock [92], the way it is cultivated or harvested; thus, sources of feedstock have to be considered carefully to avoid any competition with food crops for land and carbon impact on crop growth to abate GHG emissions.

5. Conclusions

This study presents an LCA of biomass (peat moss, miscanthus, and a blend of the two), either untreated or treated in the HTC process. The results reveal that the environmental benefits from the biomass were dependent on its life cycle pathways. Treated biomass would be an environmentally friendly option if not left on-site (untreated peat moss); however, miscanthus emerged as a better option compared with peat moss or blend of peat moss and miscanthus. Treated biomass used as a soil supplement provided more environmental benefits than energy applications; however, higher fossil fuel depletion is observed and requires a considerable amount of water.

Environmental benefits of the HTC process were dependent on the biomass sources and the end-use of HTC products. There should be a strong focus in feedstock selection and application to abate environmental consequences/impacts. Additionally, more research is required in developing a continuous HTC process to pursue commercial applications. A robust renewable or agricultural policy may need to be enforced to enhance the application of treated biomass in soil amendment and energy production to displace the use of chemical fertilizers and fossil fuels, especially for the remote communities, which would create market for hydrochar and green jobs. However, any investment in commercial HTC process needs to be supported by its economic benefits to avoid business risk.

Authors contribution

The authors declared that this study is conducted and compiled by Poritosh Roy who was guided and supervised by Animesh Dutta and Jim Gallant.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.rser.2020.110046.

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