



A life cycle assessment of *Agaricus bisporus* mushroom production in the USA

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Abstract

Purpose Stakeholders across the food product supply chain are increasingly interested in understanding the environmental effects of food production. Mushrooms are a unique food crop, grown in the absence of sunlight and in climate controlled environments. Few life cycle assessment (LCA) studies have been conducted previously on mushrooms and none in the USA. This study assesses the cradle-to-gate life cycle environmental impacts of mushroom production in the USA from cultivation to harvest and preparation for bulk packaging.

Methods This process-based LCA uses primary data from mushroom producers to define the foreground system. Primary data for operations were collected from compost and mushroom producers in the USA, representing approximately one third of US mushroom production. Secondary data were collected from life cycle inventory databases and other published resources to define background systems and process emissions from the foreground system. The study uses a functional unit of 1 kg mushrooms and applies the Institute of Environmental Sciences (CML) impact analysis method, supplemented with additional impact categories for energy use, freshwater use, and 20 and 100-year global warming potentials (GWPs) with and without carbon-climate feedback.

Results and discussion Results show that GWP₁₀₀ impacts range from 2.13 to 2.95 kg CO₂e/kg of mushroom product, slightly lower than previous mushroom LCAs conducted for Australian and Spanish production systems. Electricity and fossil fuels were the most impactful inputs, not just for GWP, but most other impact categories as well, followed by compost materials, compost emissions, and transportation. Transport of peat, a key input to the mushroom production substrate, and compost materials contributed to 60 and 36% of the total transportation impacts, respectively. The co-product generated by the system, spent mushroom substrate (SMS), was handled using the displacement method. SMS generated very small credits to the system, less than 1% in every impact category.

Conclusions Recommendations to improve the commercial mushroom production process include reducing electricity and fossil fuel use through on-site renewable energy generation. This recommendation is primarily relevant to mushroom producers in the Eastern region of the USA, where the electricity grid is the most coal and fossil fuel-intensive. Future work should contextualize the results of this study in the context of nutrition, meal, or diet-level assessments to enable informed food choices.

Keywords Carbon footprint · Compost · Environmental impacts · Food LCA · Mushroom · Sustainability

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1 Introduction

Global mushroom production has grown dramatically since the late 1990s, increasing more than fivefold to approximately 34 million t in 2013, with average per-capita consumption growing significantly as well (Royse et al. 2016). Of produced mushrooms, cultivated edible varieties constitute just over half of economic value, with the balance of production attributable to wild harvest (8%) and medicinal use (38%). China is the world's largest producer of edible mushrooms, supplying over 30 million t, or 87% of global supply (Royse et al. 2016).

Agaricus bisporus, commonly known as the white or brown button mushroom and hereafter referred to simply as mushrooms, is the most common edible mushroom in the United States (US), which is the second largest producer of the genus after China. The US mushroom supply was approximately 440,326 t of mushrooms in 2016, with 12% imported and 1% exported, leading to approximately 1.4 kg of mushrooms consumed annually per capita (USDA 2017). Mushrooms contain all of the essential amino acids and have a very low fat content, which has led to efforts to increase consumption as part of healthier diets (USDA Mushroom Council 2013); nevertheless, while US per-capita consumption has steadily increased over the last few decades, it remains well below the global average, which exceeds four and a half kilogram per annum (Royse et al. 2016).

As with all food products, mushrooms require energy, material, and water inputs for their production. There has been increasing awareness and demand for information on the energy and environmental implications of the food system (National Academies of Sciences, Engineering, and Medicine 2016). An increasing number of crops and food products have been evaluated using “footprinting” methods or life cycle assessment (LCA) (Hoekstra and Mekonnen 2012; Roy et al. 2009). Mushrooms present an interesting LCA case to study because they are grown under unique conditions, using specially formulated compost in dark, climate controlled environments.

Few LCAs or environmental footprints have been conducted previously for mushrooms, and none for US production. Gunady et al. (2012) completed a streamlined LCA from cradle-to-retail in Australia, and Leiva et al. (2015) completed an LCA for mushroom production in Spain. Both studies evaluated *Agaricus bisporus*, and comparison of their results shows great variability in estimates of impact; for example, their carbon intensity estimates, 2.76 kg CO₂ equivalent (CO₂e) and 4.41 kg CO₂e/kg mushroom, differed by 60%. These differences are a function of both real variability in production processes and background systems, and methodological differences in the implementation of LCA. One additional study was found in the published literature that undertook an LCA of shiitake mushrooms (*Lentinula edodes*) in Thailand (Tongpool and Pongpat 2013), finding that transport and incineration processes, both functions of local conditions and practices, were important in determining environmental impacts. Shiitake are cultivated quite differently than *Agaricus bisporus*, but as a point of comparison to Gunady et al.’s (2012) and Leiva et al.’s (2015) findings, Tongpool and Pongpat estimated carbon intensity at 1.87 kg CO₂e/kg mushroom.

Mushroom production occurs across the continental US, including Western, Central, and Eastern regions. The Eastern US dominates production, supplying 71%, while the West produces 19% and the Central US produces 9% (United

States International Trade Commission 2010). Each region has different environmental and climatic conditions, electricity grids, and costs and availability for compost materials and heating fuels, all of which lead to unique LCA results for each region.

This study conducts a cradle-to-gate LCA of mushroom production in the US based on a production-weighted average for the three regions to assess the environmental impacts from cultivation to harvest and preparation for bulk packaging. The study results provide a baseline estimate of the environmental impacts of mushrooms, which will facilitate improved understanding of the environmental impacts of different steps in mushroom production and the impacts of diets that include mushrooms.

2 Methodology

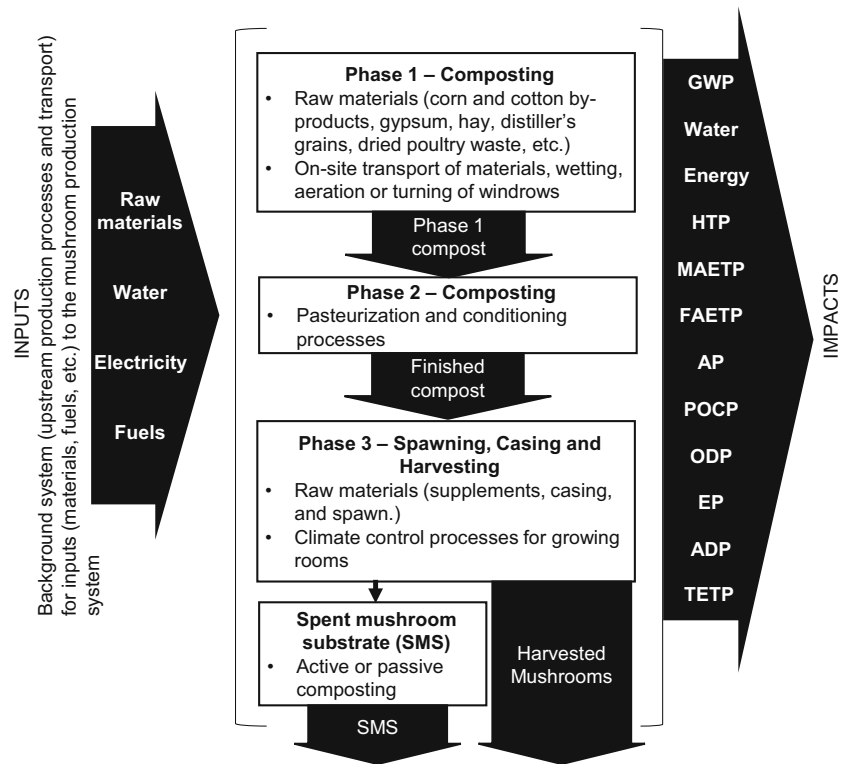
2.1 Goal and scope definition

The goal of this study is to characterize a typical commercial mushroom production system in the US using process-based LCA that largely conforms to the International Organization for Standardization (ISO) guidelines for LCA, ISO 14040 and 14,044 (ISO 2006). Mushroom production is typically divided into three distinct phases: composting and composting operations (phase 1), pasteurization and conditioning to finish the compost (phase 2), and growing and harvesting of mushrooms (phase 3). In phase 1, the compost is created by wetting and mixing bulk ingredients, nitrogen supplements, and gypsum, and then composted using processes such as aeration, turning, and watering for 6–14 days. In phase 2, the compost is pasteurized to kill pests and fungi and is conditioned to remove ammonia, all of which can damage the mushroom crop (Beyer 2017).

Unlike most crops where seed is planted, the mushroom is introduced to the compost through spawn. In phase 3, spawn is created by propagating mycelium on a grain material, and then the spawn and additional supplements are mixed into the finished compost. Mushrooms are grown in sealed, insulated rooms where the temperature, humidity, and carbon dioxide (CO₂) concentration are carefully controlled. Once the compost, spawn, and supplements are in place, casing (mostly comprised of peat moss) or casing inoculum (casing seeded with mushroom spawn) is applied over the top of the mixture. Mushrooms can be harvested 18–21 days after casing in 7–10-day cycles for 35–60 days (Beyer 2017). After the final harvesting, the remaining material, referred to as spent mushroom substrate (SMS), can be used for other applications, for example, as a soil amendment.

The scope of the LCA is from cradle-to-facility gate with a functional unit of 1 kg (wet basis 92% moisture content) of bulk mushroom product (USDA 2016). Figure 1 illustrates the

Fig. 1 System diagram for LCA of US Mushroom Production. GWP global warming potential, HTP human toxicity potential, MAETP marine aquatic ecotoxicity potential, TETP terrestrial ecotoxicity potential, FAETP freshwater aquatic ecotoxicity potential, AP acidification potential, POCP photochemical ozone creation potential, ODP ozone layer depletion potential, EP eutrophication potential, ADP abiotic depletion potential



modeled system, showing each of the three phases, as well as the production of SMS. Material and energy inputs such as pesticides, cleaning products, compost materials, peat, electricity, and fuels; outputs of emissions from fuel combustion and off-gassing; and transport processes are all included in the system boundary. The construction, repair, and decommissioning of facility structures and equipment are excluded.

2.2 Life cycle inventory

The foreground system, which is comprised of the processes directly involved in production, is characterized using survey data as described in Sect. 2.2.1, and emission rates and factors for processes such as off-gassing are drawn from literature (Sects. 2.2.3 and 2.2.4). The background system, comprised of the upstream processes (upstream with reference to the supply chains) that produce the inputs or provide the services consumed by the foreground system, is characterized by secondary data, namely reference life cycle inventory (LCI) datasets sourced from the GaBi software tool (Thinkstep 2016) as described in Sect. 2.2.2.

The SMS co-product has no economic value but does have a use as a soil amendment; thus, co-product allocation is handled two ways, first through economic allocation where no production-related impacts are attributed to SMS because of its zero economic value to producers and, second, through a

displacement calculation assuming that it is used as a soil amendment, as described in Sect. 2.2.6.

2.2.1 Primary data collection

Two different surveys were administered to US mushroom producers in 2015: one administered by Sureharvest and one by the University of California Davis LCA research team. Both surveys generated data used in this study. Primary data were gathered from 22 mushroom compost and mushroom production facilities nationwide, accounting for approximately one third of total national mushroom production (USDA and National Agricultural Statistics Service 2016). The Sureharvest survey consisted of 285 questions on the on-site use of water, energy, fuel, labor, detailed raw material inputs, composting timelines, the composition of finished compost, recycling and shrink data, growing facility data, yield data, and SMS information. The UC Davis survey was administered as a follow-up survey and contained another 43 questions on spawn, recycling of finished products, co-products, on-site electricity generation, transport of raw materials and interim products, and the uses of insecticides, fungicides, microbicides, and sanitizers. Meetings with facilities were conducted to query certain data points and verify data. The LCIs generated based on the data collected for this study are presented in weighted and unweighted averages/kg of mushroom product (Table S1, Electronic Supplementary Material).

2.2.2 Reference life cycle inventories

The GaBi Professional database (Thinkstep 2016) and the Ecoinvent database (Ecoinvent Center 2016) provided the LCI datasets used in the model. Where available, LCIs based on US conditions were selected. Combining LCIs from two databases was necessary as neither database could provide all the needed LCIs. Table S2 in the Electronic Supplementary Material reports the dataset used for each input. With one exception, the same dataset is used regardless of the location of a mushroom producer. Electricity is the exception, as LCIs differ based on the regional electricity grid of each producer as defined by the North American Electric Reliability Corporation (NERC). Each grid uses different fuels and technologies to produce and deliver electricity, and thus their life cycle impacts are different.

Some inputs to mushroom production do not have existing LCI datasets, such as some pesticide, fungicide, insecticide, and sanitizer inputs. When unavailable in either of the two databases, LCIs were created based on the active ingredients reported in the respective material's material safety data sheet. Table S2 (Electronic Supplementary Material) also describes the LCIs created for this project.

2.2.3 Transport of materials

The average transport distances for material inputs are based on the material manufacturer and location information reported in facility survey data. For all materials, the transport distances from manufacturer to facility (one-way transport) are averaged separately for each material type (Table S9, Electronic Supplementary Material). The distance for each input is multiplied by the mass of material input and then multiplied by the GaBi reference LCI for US freight truck transport, based on units of freight intensity. Freight intensity units account for average backhaul rates, meaning only one-way transport distances need to be modeled. Transport within facilities is accounted for using reported annual fuel use data.

2.2.4 Compost production

Compost may be produced on site at the mushroom growing facility or may be produced at a compost-only facility and transported to mushroom growers. For facilities that do not produce mushrooms, a calculated ratio is used to equate emission values to a per-mass of mushroom basis (Eqs. (1) and (2)).

$$\frac{\text{mass (tons) of phase 1 compost}}{\text{mass (tons) of phase 2 (finished) compost}} = 1.40 \quad (1)$$

$$\frac{\text{mass (tons) of phase 2 (finished) compost}}{\text{mass (tons) of mushrooms produced}} = 3.63 \quad (2)$$

These calculated ratios are based on average mass flow at each phase in the production system. The calculated mass of phase 1 compost relative to phase 2 finishing compost equaled 1.40 ± 0.14 , and the mass of phase 2 compost to mushroom produced equaled 3.63 ± 0.69 .

Compost emissions are released during the composting process, and these emissions include methane (CH_4), nitrous oxide (N_2O), and ammonia (NH_3). Composting emissions can vary based on composting practices (e.g., aeration and turning) and conditions (e.g., temperature, moisture content). Phase 1 may occur either in windrows or tunnels; phase 2 always occurs indoors, in spaces often referred to as tunnels. Emission factors for composting are taken from a peer-reviewed study of a windrow system conducted by Saer et al. (2013): 4.06×10^{-4} kg (NH_3)/kg compost, 1.83×10^{-3} kg CH_4 /kg compost, and 7.50×10^{-5} kg N_2O /kg compost.

Tunnel-based composting emits approximately twice the ammonia emissions than windrow-based composting (Cadena et al. 2009). A source for peer-reviewed literature values for tunnel-based compost emissions was not identified. As such, the Saer et al. (2013) windrow-based compost emissions values are used for both windrow and tunnel composting systems. Given the variability in the emissions generated from windrow and tunnel composting systems, this may lead to an underestimation of the tunnel-based composting emissions. It is also important to note that tunnel-based composting emissions can be captured in biofilters which would reduce or eliminate this difference (Cadena et al. 2009; Sánchez et al. 2015); however, the surveys administered for this study did not query biofilter use, and thus filter use and related emissions abatement are not accounted for in the assessment.

2.2.5 Peat emissions

Peat is a carbon-rich soil-like material that is used as casing in mushroom production. Peat forms in bogs and other similar environments where plant matter accumulates, rather than degrading, and accrues and stores carbon for periods of centuries or millennia. Peat begins to degrade upon exposure to oxygen and in doing so releases fossil carbon dioxide (CO_2). The peat emission factor for CO_2 (0.3726 kg CO_2 /kg of peat per year) is based on peer-reviewed literature values from a peat study that sourced peat from regions across Canada including Quebec, Ontario, and Manitoba (Moore and Dalva 1997). Moore and Dalva (1997) measured emissions from peat samples held in a controlled environment (i.e., temperatures 15–20 °C (59–68 °F) and aerobic conditions. These environmental conditions are similar to the mushroom growing environment (i.e., ambient temperature ≈ 18 °C (65 °F)) and aerobic conditions. Because, according to the survey data collected for this LCA study, US mushroom producers mainly

source peat from Canada, and the environmental conditions (temperature and oxygen levels) in mushroom production are comparable with the environmental conditions in the Moore and Dalva (1997) study, the measured emissions values from that study are assumed adequate for estimation of peat emissions in this study.

2.2.6 SMS co-product and allocation

SMS is the used portion of the growing medium from mushroom production that no longer has all the nutrients needed for growing mushrooms but retains nitrogen (N) and phosphorus (P) content which may have value for other cultivation systems. SMS also contains carbon (C), with a C/N ratio of 9–15:1 (Roy et al. 2015), and could contribute to soil C. The primary use of SMS is as a soil amendment in agricultural systems.

Based on survey data, SMS has no value to the mushroom producer (survey respondents indicated that they received no payment for the SMS), but they also incur no cost of disposal as SMS users pick up the SMS at no cost to the mushroom producers. Two options for considering how to conduct co-product allocation are considered: First, allocation can be applied based on economic value, which leads to no impacts attributed from mushroom production to the SMS because the producer receives no value for SMS generation; second, a displacement calculation can be used to estimate the environmental value of SMS production assuming that it displaces substitutable products. Both approaches are used in this article. In all results, SMS credits are reported separately, along with total results with and without SMS credits. By doing so, both the economic allocation results (which allocate no production-related impacts to SMS) and the results of displacement calculations are reported.

N and P nutrients are typically provided to agricultural soils through synthetic and mineral sources. As such, when SMS is used on agricultural soils, it can displace these nutrient sources and SMS can receive a credit for avoiding their production. While additional C may be beneficial to a soil, SMS is modeled to displace soil amendments that provide nutrients only. It is important to note that the C content in SMS is a labile form that does not contribute to soil aggregate formation nor long-term soil C sequestration (Peregrina et al. 2014); as such, this study applies no C sequestration credits for the C content of SMS. This assumption errs on the side of undervaluing the C content of SMS from a carbon accounting standpoint.

Based on the N and P content of SMS, LCIs for two common fertilizers, an N fertilizer (urea ammonium nitrate; 30% N content) and a P fertilizer (triple superphosphate; 45% P content), are used to estimate avoided impacts due to the production of these fertilizers. The LCIs (sourced from GaBi) are used to calculate the value of SMS as a substitute for the

synthetic and mineral fertilizers. The average nutrient content for SMS is 1.12% nitrogen and 0.29% phosphorus on a wet weight basis (Fidanza et al. 2010), and this information is used as described in Eq. (3) to estimate a co-product credit.

$$\begin{aligned} \text{Credit per kg SMS} = & (0.0112 \text{ kg } N_{\text{SMS}}) \times (N_F \text{ LCI}) \\ & + (0.00029 \text{ kg } P_{\text{SMS}}) \times (P_F \text{ LCI}) \quad (3) \end{aligned}$$

where SMS refers to spent mushroom substrate, N_{SMS} refers to nitrogen content of SMS, $N_F \text{ LCI}$ refers to the nitrogen fertilizer LCI (assuming a functional unit of 1 kg N), P_{SMS} refers to the phosphorus content of SMS, and $P_F \text{ LCI}$ refers to the phosphorous fertilizer life cycle inventory (assuming a functional unit of 1 kg P).

Impacts for other material inputs (e.g., wheat straw) that are produced from multi-product systems are calculated using economic allocation and averaged market prices for 2016–2017. All allocation calculations are documented in Table S2 in the Electronic Supplementary Material.

2.3 Life cycle impact assessment

LCAs can select from among many life cycle impact methods. These methods provide the means to translate the tracked environmental flows into indicators of impact. Each impact category represents specific environmental issues that can be quantified. These categories define the impacts of an assessment and are evaluated and interpreted to develop conclusions based on the results of the study. This study applies the CML impact analysis method, supplemented with additional impact categories for energy use, freshwater use, and 20- and 100-year global warming potentials (GWPs) with and without carbon-climate feedback. In addition, the Tool for Reduction and Assessment of Chemicals and Other Environmental Impacts (TRACI) 2.1 methodology is used for a comparison of results and presented in the online resource materials (Tables S7 and S8, Electronic Supplementary Material).

The Intergovernmental Panel on Climate Change (IPCC) Fifth Assessment Report GWPs are used in this study (IPCC 2014). Both the 20- and 100-year GWPs are evaluated with and without climate-carbon feedback mechanisms, in units of carbon dioxide equivalents (CO₂e). Primary energy use from renewable and non-renewable sources is calculated and reported in units of megajoule. Non-renewable energy sources include coalbed CH₄, crude oil, hard coal, lignite, natural gas, oil sand, peat, pit CH₄, shale gas, tight gas, and uranium. Renewable energy sources include geothermic, hydropower, solar, wave, and wind power, as well as resources from primary forests. The total primary energy metric is the sum of the renewable and non-renewable sources. Total freshwater use reported in kilogram of water is the life cycle water use metric used in this assessment. It includes rainwater use, surface

water (lakes and rivers), and ground water use. In addition, the CML methodology impact categories and characterization factors developed by Leiden University Institute of Environmental Sciences (2016) are used to assess a suite of environmental impacts including human toxicity potential (HTP), marine aquatic ecotoxicity potential (MAETP), terrestrial ecotoxicity potential (TETP), freshwater aquatic ecotoxicity potential (FAETP), acidification potential (AP), photochemical ozone creation potential (POCP), ozone layer depletion potential (ODP), eutrophication potential (EP), elements abiotic depletion (elements ADP), and fossil abiotic depletion (fossil ADP) per kilogram of mushroom product. Though the CML impact analysis method includes GWP, it is modeled and discussed separately from the other CML impact categories.

3 Results

The production-weighted average LCA results are presented in the body of this article and are based on the regional production volumes for Eastern, Central, and Western regions. The regional production (percent) is calculated based on the regional production per the total national production and then multiplied by the total average impacts per category (e.g., GWP, eutrophication, etc.). The unweighted average results (the simple mean of all production facilities' impact results) are reported in the online resource material (Tables S3, S4, S5, and S6 in the Electronic Supplementary Material 1). In addition, TRACI methodology results are reported in the online resource materials in production-weighted (Table S7, Electronic Supplementary Material) and unweighted (Table S8, Electronic Supplementary Material) averages. The complete LCI results, both weighted and unweighted averages, are also provided in the online resource materials, as Electronic Supplementary Material 2.

Figure 2 shows summary results for total primary energy, GWP₁₀₀ (without climate-carbon feedback) and freshwater use and demonstrates the significant contribution of electricity to all three impact categories, the importance of fuel use to both electricity and GWP, and the particular contribution of compost, dominated by emissions from the composting process, to GWP. SMS credits are very small, contributing between −0.3 and −0.4% to each category. More detailed results are provided in Sects. 3.1 to 3.4 for these and other impact categories.

3.1 Global warming potential

Total GWP impacts range from 2.13 to 2.95 kg CO₂e/kg of mushroom product depending on the GWP metric selected (Table 1). The results from the current study are comparable in magnitude to the other mushroom (*Agaricus bisporus*)

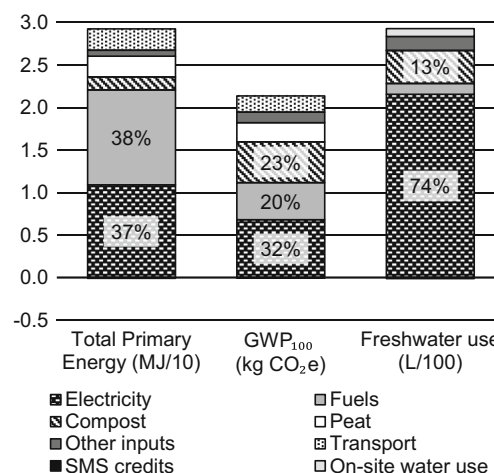


Fig. 2 Total primary energy and GWP for 1 kg mushroom based on the US production-weighted average

LCA studies completed. Gunady et al. (2012) found that 2.76 kg of CO₂e is released for every kilogram of mushroom produced, and Leiva et al. (2015) found 4.41 kg CO₂e released per kilogram of mushroom. In addition to differences in background systems, including electricity grid fuel mixes, differences in cultural practices, and differences in climate, the difference in CO₂e between studies may also be partly explained by the streamlined approach taken by Gunady et al. (2012) and the GWP conversion factors used by each study. Gunady et al. (2012) used GWPs published in the IPCC's Second Assessment Report (IPCC 1996), Leiva et al. (2015) used GWPs published in the IPCC's Fourth Assessment Report (IPCC, 2007), and this study used the most recent GWP estimates from the IPCC's Fifth Assessment Report (IPCC 2014). In addition, the carbon accounting methods in Leiva et al. (2015) may contribute to differences between its results and those of this study and Gunady et al.'s (2012). For example, they seem to account for a CO₂ credit rather than emission for peat use, which does not conform with accepted practice for estimating emissions caused by peat harvesting and decomposition (Cleary et al. 2005), and it is not clear how global warming emissions from the growing process, which they find to be the largest contributor to GWP, were modeled and accounted for.

For all GWP metrics calculated in this study, electricity, compost, and fuels are the largest contributors in descending order (Table 1 and Fig. 2). Combustion of coal and natural gas are the two largest contributors to GWP from electricity consumption, and CH₄ emitted from anaerobic decomposition is a dominant factor in composting GWP. The GWP of CH₄ is much higher for the 20-year time horizon than the 100-year time horizon because its atmospheric lifetime is only about 12 years. Because compost emissions are a significant source of CH₄ emissions, GWP₂₀ results are higher than GWP₁₀₀ results. Total transport emissions contribute 6–9% of GWP impacts with the higher range of emissions generated from

Table 1 Global warming potential in kilograms CO₂e per kilogram of mushroom product by input or process

Inputs	GWP ₂₀	GWP ₂₀ with climate change feedback	GWP ₁₀₀	GWP ₁₀₀ with climate change feedback
Electricity	7.41×10^{-1}	7.43×10^{-1}	6.81×10^{-1}	6.86×10^{-1}
Diesel	1.59×10^{-1}	1.59×10^{-1}	1.44×10^{-1}	1.45×10^{-1}
Natural gas	1.46×10^{-1}	1.46×10^{-1}	1.10×10^{-1}	1.13×10^{-1}
Heating oil	1.80×10^{-1}	1.80×10^{-1}	1.63×10^{-1}	1.65×10^{-1}
LPG	1.87×10^{-2}	1.87×10^{-2}	1.70×10^{-2}	1.72×10^{-2}
Compost materials	1.27×10^{-1}	1.28×10^{-1}	1.15×10^{-1}	1.20×10^{-1}
Spawn, supplements	4.22×10^{-2}	4.23×10^{-2}	3.84×10^{-2}	3.95×10^{-2}
Compost emissions	8.91×10^{-1}	9.11×10^{-1}	3.65×10^{-1}	4.34×10^{-1}
Peat	8.21×10^{-2}	8.18×10^{-2}	9.71×10^{-2}	9.60×10^{-2}
Growing materials	4.94×10^{-3}	4.94×10^{-3}	4.98×10^{-3}	4.98×10^{-3}
Refrigerants	2.10×10^{-1}	2.14×10^{-1}	8.23×10^{-2}	9.73×10^{-2}
Pesticides	2.70×10^{-4}	2.71×10^{-4}	2.27×10^{-4}	2.32×10^{-4}
Sanitizers	3.02×10^{-4}	3.02×10^{-4}	2.66×10^{-4}	2.69×10^{-4}
Total transport	2.01×10^{-1}	2.01×10^{-1}	1.88×10^{-1}	1.89×10^{-1}
SMS credits	-7.94×10^{-3}	-8.00×10^{-3}	-6.75×10^{-3}	-7.13×10^{-3}
Peat emissions	1.29×10^{-1}	1.29×10^{-1}	1.29×10^{-1}	1.29×10^{-1}
Total	2.92	2.95	2.13	2.23

the 100-year GWP. Refrigerants, spawn and supplements, and peat impacts contribute 1 to 8% of total impacts.

3.2 Energy use

Energy consumption in the mushroom production system is reported in three ways: renewable, non-renewable, and total primary energy (Table 2). The total primary energy consumed is 29.1 MJ (27.8 MJ from non-renewable sources and 1.3 MJ from renewable sources) per kilogram of mushroom product. Non-renewable energy use is 20 times greater than renewable energy use. While electricity comprises 37% of energy consumption, fuel use is the dominant cause of energy consumption (38%). Combined, diesel and heating oil alone comprise 26% of total primary energy. In contrast, pesticides and sanitizers account for less than 1% of energy for either renewable or non-renewable energy use.

3.3 Total freshwater use

Freshwater use is dominated by the background system, and in particular electricity production, which consumes 74% of total freshwater used in mushroom production (Table 3 and Fig. 2). Water is used throughout the electricity supply chain for fuel mining, production, and refinement, but mostly, it is used in thermoelectric power plants for cooling. In fact, thermoelectric power is the single largest non-consumptive use of freshwater in the US. On-site water use consumed 9 kg freshwater per kilogram mushroom, or 3.1% of total freshwater consumption.

Table 2 Non-renewable, renewable, and total primary energy use in megajoule per kilogram of mushroom product

Inputs	Primary energy from non-renewable resources (MJ)	Primary energy from renewable resources (MJ)	Total primary energy (MJ)
Electricity	1.02×10	6.21×10^{-1}	1.09×10
Diesel	3.48	2.85×10^{-2}	3.51
Natural gas	3.30	1.06×10^{-3}	3.31
Heating oil	3.93	3.22×10^{-2}	3.96
LPG	3.92×10^{-1}	6.33×10^{-4}	3.93×10^{-1}
Compost materials	9.28×10^{-1}	5.80×10^{-1}	1.51
Spawn and supplements	5.83×10^{-1}	4.72×10^{-2}	6.31×10^{-1}
Compost emissions	0	0	0
Peat	2.45	1.75×10^{-2}	2.46
Growing materials	3.83×10^{-2}	1.61×10^{-3}	3.99×10^{-2}
Refrigerants	4.58×10^{-3}	1.88×10^{-4}	4.77×10^{-3}
Pesticides	3.20×10^{-3}	1.30×10^{-4}	3.33×10^{-3}
Sanitizers	3.69×10^{-3}	2.52×10^{-3}	6.21×10^{-3}
Total transport	2.51	0	2.51
SMS credits	-7.65×10^{-2}	-2.76×10^{-3}	-7.92×10^{-2}
Peat emissions	0	0	0
Total (with SMS credits)	2.78×10	1.33	2.91×10
Total (without SMS credits)	2.79×10	1.33	2.92×10

Table 3 Total freshwater use in kilograms of water per kilogram of mushroom product

Inputs	Total freshwater use (kg)
Electricity	2.16×10^2
Diesel	5.59
Natural gas	4.53×10^{-1}
Heating oil	6.31
LPG	3.71×10^{-1}
Compost materials	3.88×10
Spawn and supplements	1.53×10
Compost emissions	0
Peat	2.85×10^{-1}
Growing materials	7.40×10^{-1}
Refrigerants	8.83×10^{-2}
Pesticides	1.07×10^{-3}
Sanitizers	1.21×10^{-1}
Total transport	0
On-site water use	9.00
SMS credits	− 1.18
Peat emissions	0
Total (with SMS credits)	2.92×10^2
Total (no SMS credits)	2.93×10^2

3.4 CML impact categories

The CML impact categories considered in this study are presented in Table 4. Electricity has the largest impact of any single input on TETP, comprising 43% due to the mercury, arsenic, and chromium released during the combustion of fuels, particularly coal. Electricity also comprises 30% of fossil ADP as a result of fossil fuel consumption and contributes to AP and POCP mostly through combustion-related sulfur dioxide and nitrogen oxide emissions.

When fuels (diesel, heating oil, natural gas, and LPG) are viewed as one category, they dominate many of the impact categories. They contribute to HTP by emitting barium and carcinogenic PAH emissions during combustion and cause MAETP impacts due to barium and hydrogen fluoride emissions, also mostly emitted during combustion. FAETP impacts are due almost entirely to barium emissions. POCP impacts are caused by nitrogen oxides, NMVOC, and carbon monoxide emissions, also emitted during combustion.

Transportation has the largest single impact on marine and freshwater aquatic ecotoxicity categories. Composting causes approximately 48 and 68% of AP and EP, respectively, with composting emissions contributing more than half to both categories. Compost materials have the largest impact of any single input for elements ADP. However, compost materials provide a 12% credit to TETP due to chromium uptake in hay production. SMS credits are less than 0.3% in all impact categories except elements ADP (2.7%) and MAETP (5.8%).

Leiva et al.'s (2015) study also used CML and were similar, but somewhat higher, for many impact categories. It is difficult to determine the source of these differences given real differences in each growing region's practices and background systems, and modeling differences, such as system boundary decisions and the choice of emission factors.

4 Discussion

4.1 Opportunities for improvement

Analyzing the inputs or processes of mushroom production that cause the greatest impacts can elucidate opportunities for reducing impacts with the least disruption and cost to producers.

4.1.1 Energy use

Energy consumption either in the form of electricity or direct use of fuels is a significant cause of many impacts of concern. As evident in the results, electricity is the largest contributor to total primary energy, GWP, freshwater use, fossil, and elements ADP, and is also the second largest contributor to TETP and POCP. In mushroom production, electricity is used for climate control or pumping depending on the phase (phases 1, 2, or 3), so increasing energy efficiency or on-site renewable energy generation could reduce impacts, which is further explored through sensitivity analysis in Sect. 4.4. For example, data collected from US mushroom producers for this assessment show that a facility can offset 10% of their electricity demand with an on-site biomass gasifier.

During mushroom production, diesel is used mostly for large trucks, tractors, and machinery used to mix compost inputs and move compost and peat. Heating oil is used primarily in colder regions that rely on generators and diesel-based heat or electricity production. One strategy for reducing emissions could be fuel switching for boilers and other equipment. For example, low NO_x natural gas boilers could replace heating oil in boilers or heaters and significantly reduce many combustion-related emissions (U.S. EPA 2010). Replacing old equipment with more efficient equipment can also reduce the amount of diesel and heating oil used and the consequent emissions from combustion.

4.1.2 Compost emissions

Opportunities for reducing impacts from compost operations include management practices and, where practical, control technologies. Turning and aerating compost frequently will prevent anaerobic conditions and can reduce the CH₄ and N₂O emissions created by the process (Saer et al. 2013). The use of biofilters can also substantially reduce compost

Table 4 CML impacts per kilogram of mushroom product

Inputs	HTP (kg DCB eq.)	MAETP (kg DCB eq.)	TETP (kg DCB eq.)	FAETP (kg DCB eq.)	AP (kg SO ₂ eq.)	POCP (kg C ₂ H ₄ eq.)	ODP (kg CFC-11 eq.)	EP (kg PO ₄ eq.)	Elements ADP (kg Sb eq.)	Fossil ADP (MJ)
Electricity	4.08×10^{-2}	2.85×10^{-1}	3.62×10^{-4}	1.11×10^{-3}	2.37×10^{-3}	1.37×10^{-4}	3.04×10^{-10}	1.23×10^{-4}	8.17×10^{-8}	7.55
Diesel	1.85×10^{-1}	1.42×10^{-2}	1.79×10^{-5}	3.80×10^{-2}	1.39×10^{-3}	1.43×10^{-4}	5.65×10^{-12}	3.07×10^{-4}	1.83×10^{-8}	3.46
Natural gas	4.51×10^{-2}	3.40×10^{-1}	9.90×10^{-6}	9.08×10^{-3}	9.15×10^{-4}	4.89×10^{-5}	8.81×10^{-14}	1.63×10^{-5}	3.87×10^{-8}	3.30
Heating oil	1.38×10^{-1}	1.61×10^{-2}	9.56×10^{-5}	4.28×10^{-2}	4.81×10^{-4}	8.11×10^{-5}	6.37×10^{-12}	6.39×10^{-5}	2.07×10^{-8}	3.90
LPG	1.48×10^{-2}	1.54×10^{-1}	2.09×10^{-6}	4.13×10^{-3}	5.02×10^{-5}	8.29×10^{-6}	6.01×10^{-13}	6.42×10^{-6}	2.06×10^{-9}	3.90×10^{-1}
Compost materials	4.86×10^{-2}	4.04×10^{-1}	-9.67×10^{-5}	3.43×10^{-3}	2.56×10^{-3}	5.23×10^{-5}	5.17×10^{-9}	7.82×10^{-4}	3.30×10^{-9}	8.16×10^{-1}
Spawn, supplements	1.40×10^{-1}	1.44×10^{-1}	4.11×10^{-4}	3.75×10^{-3}	3.19×10^{-4}	2.06×10^{-5}	1.05×10^{-11}	7.47×10^{-5}	6.95×10^{-9}	5.34×10^{-1}
Compost emissions	2.08×10^{-4}	0	0	0	3.33×10^{-3}	5.64×10^{-5}	0	8.33×10^{-4}	0	0
Peat	8.33×10^{-4}	3.50×10^{-1}	1.11×10^{-5}	1.58×10^{-5}	9.41×10^{-6}	-4.07×10^{-7}	2.34×10^{-10}	2.82×10^{-6}	5.37×10^{-9}	2.44
Growing Materials	2.47×10^{-4}	6.82×10^{-2}	1.12×10^{-5}	7.42×10^{-6}	1.93×10^{-6}	1.24×10^{-7}	2.16×10^{-12}	3.73×10^{-7}	2.21×10^{-10}	3.72×10^{-2}
Refrigerants	3.07×10^{-5}	1.28×10^{-2}	2.95×10^{-7}	1.17×10^{-6}	1.13×10^{-6}	7.65×10^{-8}	1.51×10^{-6}	6.98×10^{-8}	1.24×10^{-8}	4.23×10^{-3}
Pesticides	6.29×10^{-4}	1.17×10^{-1}	1.64×10^{-6}	1.05×10^{-5}	3.94×10^{-6}	2.73×10^{-7}	3.59×10^{-11}	4.53×10^{-7}	1.89×10^{-9}	2.86×10^{-3}
Sanitizers	2.19×10^{-4}	5.13×10^{-2}	1.15×10^{-6}	1.70×10^{-6}	1.21×10^{-6}	1.25×10^{-7}	4.49×10^{-12}	2.80×10^{-7}	3.11×10^{-9}	3.28×10^{-3}
Total transport	1.50×10^{-1}	2.00×10^{-2}	9.32×10^{-6}	5.27×10^{-2}	9.24×10^{-4}	1.11×10^{-4}	6.63×10^{-12}	1.65×10^{-4}	4.50×10^{-11}	2.49
SMS credits	-3.30×10^{-4}	-1.08×10^{-1}	-2.17×10^{-6}	-1.70×10^{-5}	-1.20×10^{-5}	-9.37×10^{-7}	-3.82×10^{-13}	-4.22×10^{-6}	-5.19×10^{-9}	-7.26×10^{-2}
Peat emission	0	0	0	0	0	0	0	0	0	60
Total (SMS credits)	7.64×10^{-1}	6.36×10^2	8.34×10^{-4}	1.55×10^{-1}	1.23×10^{-2}	6.57×10^{-4}	1.52×10^{-6}	2.37×10^{-3}	3.49×10^{-6}	2.49×10
Total (no SMS credits)	7.65×10^{-1}	6.36×10^2	8.36×10^{-4}	1.55×10^{-1}	1.24×10^{-2}	6.58×10^{-4}	1.52×10^{-6}	2.38×10^{-3}	3.50×10^{-6}	2.49×10

emissions such as ammonia (Park et al. 2002; Rosenfeld et al. 2004; Sánchez et al. 2015). Some composters have implemented biofilter technology, reducing their compost emissions impacts. However, biofilter technology is best implemented with enclosed compost operations; thus, outdoor windrow composting cannot benefit from this technology.

4.1.3 Transportation

The transport of peat accounts for 60% of all transport as quantified in units of tonne-kilometers. Waste products that are used for compost materials account for 12% of transportation emissions. Peat is such a large portion of transportation impacts because of its transport from the Quebec region of Canada to locations in the US. Waste product transportation shows significant variability, from an average of 5 mi (for hardwood tree leaves) to 413 mi (for sugar beet lime) away. Straw comes from an average of 206 mi away from facilities and is used in such large quantities that it is the third largest contributor to transportation. The most effective way to reduce these impacts is to reduce the distance traveled by inputs or to use more efficient modes of transport—namely moving from truck to rail when possible. The sources of peat may be limited, so mode-switch is likely the most effective way to reduce impacts. Straw and waste materials used in compost may provide some opportunities for producers to reduce transport distances by selecting local suppliers when possible.

4.2 Regional variance: Eastern, Central, and Western regions

The Western region has the lowest GWP impacts and primary energy use, followed by the Central and Eastern regions. The lower GWP intensity in the Western region resulted from differences in electricity and fuel use. For electricity, two factors influenced the lower GWP. First, and more influential, is the difference in the electricity grid fuel mix in each region. The Western region mix has more renewables and less coal leading to lower GWP per megajoule generated (Western Electricity Coordinating Council 2016). In terms of fuel use and types, the Eastern region consumes heating oil for heating, which no other region consumes, and the Western region uses more natural gas and less diesel than any other region. Second, the average electricity use for the Western region was affected by on-site renewable energy production at one of the Western region facilities. The facility uses an on-site biomass gasification unit to generate electricity, thus reducing the grid electricity demand. Peat transport to the Western region (from Canada) contributed to double the environmental impacts than peat transport to the Central region and more than four times the impacts than the Eastern region. Total freshwater use is greatest in the Western region, followed by the Central region (more than three times lower) and the Eastern region (more

than five times lower). These differences are due to differences in water use for grid electricity generation. Regional differences in the types and quantities of compost materials used, e.g., corn was only used in the Eastern region, are influential and are explored through scenario analysis in Sect. 4.3.

4.3 Differences in compost materials: mulch hay versus wheat straw

Impacts of GWP, primary energy, and the CML categories differ for compost materials between regions. These differences are mostly due to the use of hay as a compost input in the Eastern region, while the Western and Central regions use wheat straw, a co-product from wheat production. Hay is a purpose-grown crop, usually grown for animal feed, so all the impacts of hay production are attributed to the hay. However, mulch hay, the type of hay used for compost, has only a portion of these impacts due to its lower quality. Wheat is grown primarily grain, so wheat straw is a less economically valuable co-product of production, which causes most wheat production impacts to be attributed to the grain instead of the straw. As an illustration of the difference between these two compost materials, hay is expected to emit 0.122 kg CO₂e/kg hay, while wheat straw is estimated to emit 0.005 kg CO₂e/kg wheat straw.

4.4 Sensitivity analysis: on-site renewable energy production in the Eastern region

Although the Eastern region uses less electricity than other regions on a per kilogram of mushroom basis (0.26 kWh/kg mushrooms for the Eastern region, 0.56 kWh/kg mushrooms for the Central region, and 0.38 kWh/kg mushrooms for the Western region), the total GWP impacts from electricity in the Eastern region are two times larger than the Western region on a per kilogram of mushroom basis, because of the electricity grid mix in the Eastern region. Because of this, a facility in the Eastern region avoids a greater amount of pollution by adopting on-site renewable sources of electricity than a facility in the Western region. A sensitivity analysis comparing varying percentages (10, 15, and 20%) of renewable energy produced on-site in the Eastern region is shown in Table 5 for impacts of primary energy and GWP.

Table 5 Impact reduction from renewable energy use in the Eastern region

Percent renewable energy use	Primary energy reduction	GWP ₂₀ reduction
0%	0%	0%
10%	3.53%	2.57%
15%	5.29%	3.85%
20%	7.06%	5.14%

5 Conclusions

Based on the study results, recommendations are provided to suggest where improvements can be made within the mushroom production system, from resource extraction to facility gate. Most processes within the US mushroom production system are fairly optimized for water and waste recycling. Pesticide and sanitizer production for the mushroom growing facility are small contributors to total impacts. Energy consumption, comprised of electricity and fuel use, is the most impactful process, and reducing energy consumption is a lever for reducing emissions and upstream water consumption. One potential way to reduce energy-related impacts is implementation of alternative on-site energy technologies, e.g., photovoltaic solar power or biomass power, to reduce dependency on grid-based electricity.

A primary goal of this study was to provide a comprehensive LCI of US mushrooms to be used in other LCA studies, such as studies examining meal or diet-level comparisons. As is common for reference LCIs, results are reported based on a functional unit of mass. However, a mass basis is not a sufficient or satisfactory functional unit for comparative or integrative studies. Foods serve many functions, as sources of nutrition, or as elements in a single meal or complex diet (both of which are mediated by cultural preferences). Understanding these functions and creating appropriate comparisons will make interpretation of these results more useful to consumer and retail audiences, and will provide insights on the dual goals of improving nutrition and reducing impacts from the food system. Thus, future work should contextualize the mushroom LCA on a nutrition, meal, or diet basis.

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