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Life Cycle Assessment of Oat Flake Production with Two End-of-Life Options for Agro-Industrial Residue Management

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Abstract: Canada is one of the world's largest producers of oat (*Avena sativa* L.) grains and their derivatives, such as oat flakes. During oat flake production, considerable amounts of residue are generated, which constitutes a major issue for producers. We applied life cycle assessment (LCA): (1) to quantify the environmental impacts of oat flakes production in northeastern Canada and (2) to compare two agro-industrial symbiosis scenarios applied to agricultural residues (transformation of residues into feed for farm animals vs. composting). LCA results indicated that the environmental impacts of oat flake production are largely dominated by the production and use of synthetic fertilisers (contributing to at least 50% of the impact of each evaluated category). Regarding end-of-life scenarios, an environmental advantage is observed for the scenario of residue transformation into animal feed in the provinces of Quebec and Manitoba. However, this recommendation may change depending on the electricity mix used and the assumptions made for the avoided products. The choice of industrial symbiosis chains must take into consideration the economic characteristics of the region where they will be implemented and the methodological parameters that can influence the decision-making process.

Keywords: LCA; agro-industrial ecology; circular economy; waste management; grain production; oat flakes; animal feed; composting

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1. Introduction

The development of industrial network symbioses can lead to the optimisation of the flow of energy and materials. The latter are exchanged by actors within a network to preserve biotic and abiotic resources and, consequently, to reduce the environmental impacts of economic systems [1]. Changing the logic of linear production is a prerequisite for meeting UN Sustainable Development Goals (SDGs) [2] and climate-related agreements [3]. From this perspective, agri-food industries could use this resource management approach to reduce the environmental impacts of their activities. Indeed, food production annually generates a large quantity of residues, which are not always valorised [4]. In North America, for example, it is estimated that 4–16% of cereal production is lost during agricultural production, storage, and processing stages [5]. The production of residues is even more important for certain cereal products, such as oat flakes, i.e., flat-rolled oat (*Avena sativa* L.) grain. Beyond the losses that are linked to the treatment processes, oat hulls represent up to 36% of grain weight and generate a considerable quantity of residues to be treated, which constitutes a major challenge for oat flake producers [6]. To address this issue, oat flake producers can set up agro-industrial symbiosis chains to reduce environmental impacts that are linked to the high production of residues from this activity.

The main limitation to the sale of oat hulls is their high transportation costs. Indeed, oat hulls are low-density residues, which prevents their transport at a competitive price. Oat hulls also easily disperse in the air, which constitutes an additional challenge for the end-of-life management of these residues. In most cases, oat hulls are used as farm animal bedding or compost. Potentially, to improve the end-of-life of these residues, one may consider oat hull incorporation into animal feed, thanks to their high fibre content. Hulls could partially replace dehydrated alfalfa (*Medicago sativa* L.) or other sources of fibre that are used in animal diets, for example, those of broiler chickens [7], swine [8], and ruminants (beef cattle) [9]. There are many advantages to replacing a portion of agricultural crops that are intended as animal feed with agricultural co-products, such as the reduction of environmental impacts and increases in socio-economic benefits [10]. According to the FAO [11], 41% of greenhouse gas (GHG) emissions from livestock are related to the production of animal feed, which illustrates the need to find alternatives that would reduce the pressure of livestock farming on the environment.

Theoretically, valorisation of residues is a sound strategy for reducing the environmental impacts of economic systems. Yet, the construction and operation of recycling systems consume resources and energy and require significant up-front investments. In the case of oat flake residues that are intended as animal feed, the hulls must be recovered and pelletised to reduce costs that are associated with their storage and transport and to facilitate their use. Further, the reduction of environmental impacts that are related to residue recovery depends strongly on production and market parameters, including the quality of the co-product, the efficiency of recycling processes, the products that are replaced, the composition of the energy mix that is used, and transport distance, among others [12]. Therefore, it is important to conduct detailed evaluations according to the region in which the waste will be assigned a value (valorised).

In the present study, we applied life cycle assessment (LCA): (1) to quantify the environmental impacts of oat flake production in northeastern Canada; and (2) to verify whether the implementation of a processing system valorising oat hulls into animal feed would improve the environmental balance of oat flake production compared to another agricultural waste end-of-life management strategy, namely composting. Canada is the second-largest producer of grain oats in the world, with a production area of 1.3 Mha and a yield of 4.5 Mt yr^{-1} in 2020 [13]. Valorising the residues of this agricultural sector could help reduce the impacts of the production of oats and their derivatives, as well as the production of food for animals.

LCA is an environmental accounting method that scrutinises a product throughout its life cycle to inventory the inputs (resources) and outputs (emissions in water, air, and soil) that are exchanged between the technosphere (or anthroposphere) and the ecosphere (biosphere) [14]. Today, LCA is a well-established and widely-used method that is used to identify the most appropriate solutions for reducing the environmental impacts of agricultural production [15] and waste management [16]. So far, many LCAs have been applied to quantifying the environmental impacts of cereal crops in Canada [17] and in other countries [18–20], including oat production [21,22]. To our knowledge, very few LCA studies exist that are specific to the transformation of agro-industrial residues from oat flakes, or more broadly, converting cereal products into food for farm animals. On the one hand, McDevitt and Milà i Canals. [23] quantified the impacts of porridge oat production in the UK, but no residue recovery system was addressed. On the other hand, several LCAs, or carbon footprints, have been conducted to assess the potential benefits of valorising food waste into animal feed [24–27]. For example, Vandermeersch et al. [27] assessed the environmental impacts of two food waste valorisation scenarios from a company in the Belgian retail sector. Their analysis showed that processing food residues for animal feed was preferable to biogas production, but only for food waste fractions with low water content. Results that are presented by Moult et al. [25] pointed in the same direction. They quantified the GHG emissions of eight UK food waste management options. According to the authors, when food is unfit for human consumption, converting food waste into animal feed is the best option available. Yet, as highlighted by Kim and Kim [24], the results of these LCAs are highly dependent upon local conditions and methodological choices, which are specifically considered in the present study.

2. Materials and Methods

The main steps of the LCA conceptual framework [28] are discussed in the following sections: Section 2.1, Goal and Scope Definition; Section 2.2, Life Cycle Inventory Data; and Section 2.3, Life Cycle Impact Assessment Methodology.

2.1. Goal and Scope Definition

2.1.1. Goal

This study aims at comparing the environmental impacts of oat flake production with two end-of-life scenarios for oat hulls. In the baseline scenario, oat hulls are sent for industrial composting. In the alternative scenario, the production of oat flakes is associated with a system for processing oat hulls into animal feed.

The results of this study would provide relevant information to farmers regarding the benefits of setting up systems for residue recovery from cereal products. Various jurisdictional governments would also be able to assess whether it is appropriate, and under what conditions, to consider financing part of the investments that are necessary to establish systems for residue recovery from cereal production and to encourage the implementation of a circular economy in agriculture.

2.1.2. Farm Selection

Data that were used in this study had been collected from the Olofée farm (48°38′06.3″ N, 72°29′37.5″ W), which is located in Saint-Félicien, Saguenay–Lac Saint Jean region of Quebec (Canada). The farm harvests 240 ha of oats annually. The average pedo-climatic characteristics of the farm are summarised in Table S1.

The Olofée farm was selected for several reasons. First, it is the largest producer of oat grains in Quebec, with 14,500 tonnes of oat grains processed in 2021. This production volume accounted for 7.5% of the total production of oat grains in the Province of Quebec in 2021 [13]. Second, the farm is the largest producer of oat flakes in the province. Beyond its own oat production, the farm sources its supplies from local producers. Finally, the farm is equipped with a system that allows oat hull recovery. The co-product that is generated, and which is hereafter referred to as feed grade oat pellets (FGO), is intended for animal feed. Thanks to the farm's processing volume, the collected data can be considered representative of most farms in eastern Canada.

2.1.3. Functional Unit

As proposed in the Product Category Rules (PCR) for the environmental performance assessment of arable and vegetable crops, the functional unit (FU) of this study is based upon product mass [29]. The production of one tonne of oat flakes with a maximum of 13.5% humidity and without packaging was retained as the FU.

2.1.4. System Boundaries

The present study considered the main processes that are involved in oat flake production, from the extraction of raw materials that are required to produce oat grains (agricultural phase) to the production of oat flakes and the end-of-life management of oat hulls (cradle-to-mill or farm-gate approach, see Figure 1). Due to a lack of data, a number of processes were excluded, such as wastewater treatment and other minor sources of solid waste that had been generated by the oat flake production mill. Packaging of co-products was not included in the analysis. The infrastructure that is required for sorting, drying, storage, and grain processing was also excluded. Only energy data were included for each of these operations.

The structure of the inventory has been divided into three stages: (a) field operations, viz., from preparation of agricultural fields to harvesting of oat grains); (b) operations that take place in the farm infrastructure, from transport of grain that is produced in the fields to oat flake production; and (c) end-of-life management of oat hulls. We have expanded the system to account for avoided products in oat hull end-of-life management scenarios. In the baseline scenario, we assume that oat hulls are sent for industrial composting, which is a strategy to replace synthetic fertilisers [30]. In the alternative scenario, we consider that FGO replaces dehydrated alfalfa and other agricultural co-products in farm animal diets (for more details, see Section 2.2.2).

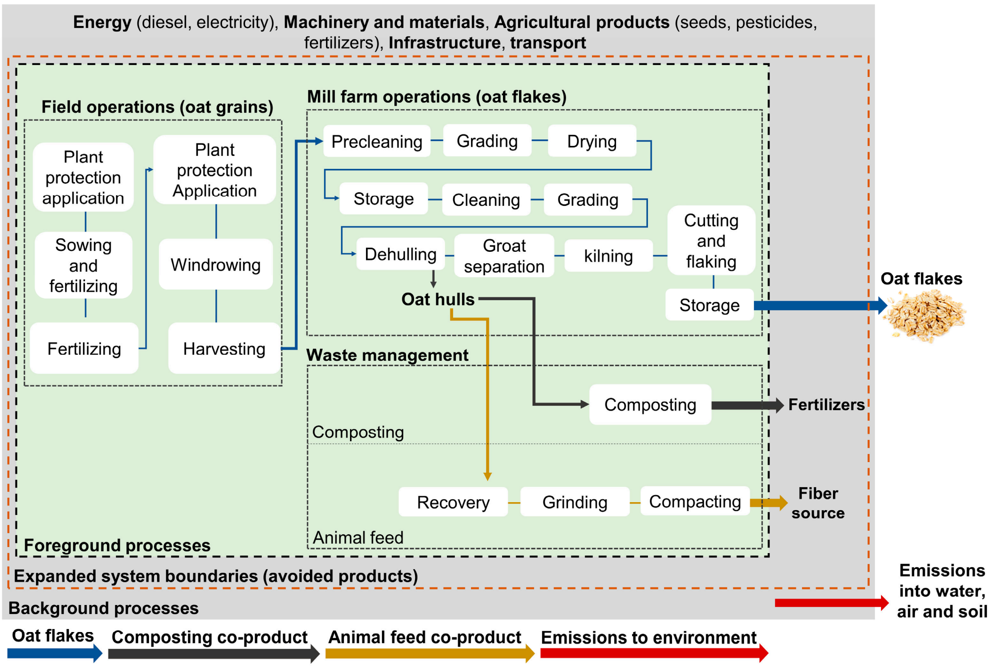

Figure 1. System boundaries for oat flake production and oat hull waste management.

2.2. Life Cycle Inventory Data

In order to quantify the environmental impacts of the oat grain production stage, life cycle inventories (LCI) that were developed by Viana et al. [22] were adapted to this study (Tables 1 and 2). They conducted a LCA of conventional and organic grain oat production with primary data provided by the same farm. Analyses include the main processes for the production of grain oats (i.e., field work, use and emissions of fertilisers and pesticides, manufacture of agricultural machinery, among others).

Data that were related to the production of oat flakes and oat hulls were collected using a questionnaire and from discussions with employees who were responsible for data management and grain processing operations.

To our knowledge, no life cycle inventory (LCI) is available for industrial composting in Quebec. Therefore, we used generic data to quantify the environmental impacts of composting. Only energy data (e.g., electricity, propane, heating oil) and emissions to the environment were included for the production of oat flakes, FGO, and compost. In other words, the infrastructure of the composting plant and the production of oat flakes and oat hulls were beyond the boundaries of the study. The data were collected in 2020, and the inventory was completed with average data over the period 2015–2020 for production of oat flakes and FGO (yields, losses, and agricultural operations).

The ecoinvent V3.4 database "allocation, cut-off by classification" [31] was used to model background production inventories of the evaluated systems (diesel, lubricants, seeds, chemical materials, etc.). The ecoinvent data also served as a basis for modelling the avoided products.

Table 1. Agricultural products and transport that are required for the production of 1 tonne of oat grains.

Products/Processes	Transport (km) [e]	Amount ($kg\ t^{-1}$) [f]
Seeds	500	33
Glyphosate (herbicide) [a]	500	0.2
Ag surf (herbicide) [b]	500	0.05
Refine SG (herbicide) [c]	500	0.007
MCPA ester 600 (herbicide) [d]	500	0.08
Urea (46-0-0)	500	28.6
Mono-ammonium phosphate (MAP) (11-52-0)	500	14.3
Potassium chloride (0-0-60)	500	14.3

[a] 1.5 L ha^{-1} (540 g L^{-1}). [b] 0.25 L ha^{-1} à (920 g L^{-1}). [c] 30 g ha^{-1}. [d] 0.58 L ha^{-1} (600 g L^{-1}). [e] From the port of Montreal to the farm. [f] For an agricultural yield of 4.2 t ha^{-1}.

Table 2. Agricultural operations required for the production of 1 tonne of oat grains.

Processes	Tractor Power (kW) and Mass (kg)	Agricultural Machinery Mass (kg)	Diesel Consumption ($L\ h^{-1}$)	Operating Rate ($h\ ha^{-1}$)	Amount ($L\ t^{-1}$) [a]
Plant protection application (glyphosate)	125 and 8000	6500	28	0.040	0.27
Sowing and fertilising (urea and MAP)	268 and 16,000	8000	52	0.083	1.03
Fertilising (potassium chloride)	115 and 6800	4500	25	0.050	0.30
Plant protection application (Refine SG and MCPA ester 600)	125 and 8000	6500	28	0.040	0.27
Windrowing	105 and 5000	1800	23	0.200	1.10
Harvesting	298 and 16,800	-	70	0.200	3.33

[a] For an agricultural yield of 4.2 t ha^{-1}.

2.2.1. Production of Oat Flakes

Detailed information on the oat grain production stage can be found in Viana et al. [22], such as the average yield of the Olofée farm for the period 2015–2020 (4.2 t ha^{-1}), for example.

Following harvest, the grain was transported to the oat flake production plant, which was located on the farm. The grain was then sorted, dried, and stored. The following steps are necessary to process oat grains into flakes: cleaning, sorting, hulling, separation of groats, kilning, cutting, and flaking. Overall, the sequential processes that are involved in turning oat grains into flakes are cleaning and sorting of the grains (removal of weed seeds, chaff, stones, metal particles, dust, etc.), hulling (isolating the hulls), kilning the grain (to develop the taste, prevent the development of rancidity, bad flavours, and bad odours, and inactivate endogenous enzymes), and, finally, reducing the cooking time (cutting and flaking) [6,32]. According to production managers, the production of one tonne of oat flakes requires 1.54 tonnes of oat grains. These losses must be added to the inventories that are presented (Tables 1–3) for the modelling of environmental impacts. To do so, the values that are presented in the previously mentioned tables are multiplied by 1.54.

Table 3. Farm mill operations that are required to process one tonne of oat grain into oat flakes.

Phase	Process	Input	Unit	Amount
Oat grain production	Grain transport (from field to mill)	Diesel	L	2.5
	Grading and pre-cleaning	Electricity	kWh	6
	Drying	Propane	L	8
	Transport to storage	Diesel	L	2.5
	Storage	Electricity	kWh	3
Oat flake production	All processes	Electricity	kWh	158
	All processes (including building heating)	Heating oil	L	12.7

2.2.2. Waste Management of Oat Hulls

The efficiency of processing grains into oat flakes varies depending on the variety of oats and the efficiency of the mill. According to estimates by mill managers at the grain processing plant, the production of one tonne of oat flakes results in the production of 540 kg of oat hulls. On average, 5022 tonnes of oat hulls must be managed per year on the Olofée farm. We present the details of two end-of-life scenarios for oat hulls below.

Baseline scenario. In the baseline scenario, oat hulls are sent for composting (63 km from the farm). Due to the lack of specific data, the data of Martínez-Blanco et al. [30] were used to model the impacts of industrial composting (Table 4). Based upon data from Parent and Gagné [33], we consider the amount of total nitrogen per tonne of compost (7.3 kg $tonne^{-1}$ of compost) and the mineralisation efficiency rate (25%) to quantify the benefits that are associated with replacing synthetic N fertilisers. Overall, 1.83 kg of N are available per tonne of applied compost. For phosphorus (P) and potassium (K), their quantities are 2.7 kg and 7.2 kg, respectively, per tonne of applied compost [34]. Nitrous oxide (N_2O) emissions from the application of compost and synthetic fertilisers to agricultural fields are considered equivalent and, therefore, are excluded from the analysis. Data that were used to model the benefits associated with synthetic fertiliser substitutions are presented in Table S2. We also consider that the use of one dry tonne of compost allows storage of 0.15 t CO_2 [35] on average with a time horizon of 100 years. We consider the dry matter content of the compost to be 35% [34].

Animal feed. The oat flakes and feed-grade oat pellets (FGO) are integrated. The oat hulls that are collected during the hulling process of the oat grains are finely ground and compacted to create FGO for animal feed. FGO is mainly composed of hulls but also includes endosperm, small grains, and sieve dust. Nutritional characteristics of FGO are presented in Table S3. According to the mill manager, almost 100% of the residues are converted into FGO. Finally, it is estimated that the processes involved in the production of one tonne of FGO consume 136 kWh of electricity.

According to information that was provided by the Ministry of Agriculture, Fisheries, and Food of Quebec (MAPAQ; P.Y. Vachon, personal communication, 3 October 2022), FGO is competing in Quebec with dehydrated alfalfa and other fibrous agricultural co-products, including wheat grits, malted germ, and soy hulls. In the scenario where oat hulls are processed into animal feed, we consider that FGO replaces alfalfa production. Yet, it is highly likely that FGO also replaces other agricultural co-products. In the case where FGO replaces another agricultural co-product, fewer avoided products would be associated with the use of FGO. For this reason, we assume that one tonne of FGO avoids only the production of 100 kg (10%) of alfalfa. A sensitivity analysis was performed on this parameter.

Table 4. Life-cycle inventory for the production of one tonne of industrial compost. The figures that are presented are estimated from the processing of 14,461 tonnes of organic waste. At the end of the composting process, 2094 tonnes of compost are produced. Additionally, 2823 tonnes of non-compostable solid waste (e.g., plastics and metal) are removed from the composting process. Note that biogenic CO_2 is not included in the calculation of environmental impacts.

	Unit	Amount
Processes		
Electricity	kWh t^{-1}	32.2
Diesel oil	L t^{-1}	4.4
Water	L t^{-1}	272
Emissions to air		
CO_2 biogenic	kg t^{-1}	165
COV	kg t^{-1}	1.21
CH_4	kg t^{-1}	0.38
NH_3	kg t^{-1}	0.11
N_2O	kg t^{-1}	0.02

2.2.3. Emissions Related to Nitrogen, Phosphorus, and Pesticides

To quantify emissions of nitrogen, phosphorus, and pesticides into the environment (air, water, and soil), we employed the emission factors that were used in Viana et al. [22] (Table S4). The authors used study region-specific data for direct emissions of nitrous oxide (N_2O) and phosphorus to water. For direct N_2O emissions, we used emission factors proposed by Rochette et al. [36], which are adapted for the application of fertilisers to annual crops that are located in eastern Canada. Phosphorus emissions were calculated using the agricultural management tool PEDT (phosphorus export diagnostic tool), which was adapted to the agricultural context of Quebec [37]. Phosphorus emissions are calculated by taking into account annual forecasts of runoff, drain runoff, and sediment and phosphorus exports at the plot scale.

Due to the lack of specific data for nitrate (NO_3^-), ammonia (NH_3), and nitrogen oxide (NO_x) emissions, several models were used. For example, the model that was proposed by Roy et al. [38] was used to calculate the proportion of nitrate (NO_3^-) that was leached to groundwater. Thus, this model distinguishes N application-derived nitrate emissions from nitrate emissions that are derived from soil organic matter N [39]. The model considers soil clay content, rainfall, irrigation, and nitrogen input to the crop.

NH_3 emissions were quantified using the EFE-So software (Estimation of Fertilisers Emissions-Software) [40]. It is possible to enter several parameters, such as average temperature and precipitation, type of crop, and amount of ammonia in the fertilisers that were applied, among others. Taking specific parameters into account is important because, for example, NH_3 emissions tend to increase in environments that are characterised by low concentrations of hydrogen ions (alkaline) and high temperatures [41]. For indirect N_2O and nitrogen oxide emissions, we used generic data that were proposed by the IPCC [42].

Finally, the distribution of pesticide emissions in air, water, and soil was assessed following the guidelines that were proposed by Audsley et al. [43]. Accordingly, 88.4% of the active ingredient penetrates the soil and 2% is released to the air, with 1.6% entering surface water. The remaining 8% is absorbed by plants and is not inventoried as an emission. All N, P, and pesticide emissions are presented in Table 5. To recap, the values presented in Table 5 must be multiplied by 1.54 (losses) to quantify the environmental impacts associated with the production of one tonne of oat flakes.

2.3. Sensitivity Analyses

Replacement of animal feed. The sensitivity of results to the substitution of FGO for alfalfa was assessed through pessimistic (0%) and optimistic (50%) scenarios. As a reminder, when FGO replaces another agricultural co-product, no avoided product is attributed to the former.

Electricity production. Canada has a very heterogeneous electricity generation landscape. The carbon intensity of electricity generation ranges from 0.02 kg CO_2 eq. kWh^{-1} for Quebec to 0.9 kg CO_2 eq. kWh^{-1} for Alberta [31]. Quebec has a low-carbon intensity electricity mix because 94% of the electricity that is produced in the province comes from hydroelectric dams [44]. Knowing that the production of FGO consumes 136 kWh t^{-1}, it is important to carry out a sensitivity analysis to determine whether FGO production is also relevant with other electricity mixes. To do so, we tested the effects of three electricity mixes that differed from those in Quebec, viz., those in the Prairie Provinces of Alberta, Manitoba, and Saskatchewan. These provinces are among the top grain producers in Canada [13]. It should be noted that the ecoinvent database provides inventories for the electricity production of each Canadian province. The inventories take into account the electricity losses during transmission and transformation, electricity imports/exports, and grid maintenance [31].

Table 5. Overview of direct and indirect emissions to water, air, and soil from agricultural activities per tonne of oat grain.

Pollutants	Unit	Amount
Emissions to air		
NH_3	kg t^{-1}	2.49
N_2O	kg t^{-1}	0.55
NO_2	kg t^{-1}	0.51
Glyphosate	g t^{-1}	3.86
Thifensulfuron-methyl	g t^{-1}	0.05
Tribenuron-methyl	g t^{-1}	0.02
2,4-D 2-ethylhexyl ester	g t^{-1}	1.50
Nonylphenol	g t^{-1}	0.001
Emissions to water		
NO_3^-	kg t^{-1}	8.79
PO_4^{3-}	kg t^{-1}	0.35
Glyphosate	g t^{-1}	3.09
Thifensulfuron-methyl	g t^{-1}	0.04
Tribenuron-methyl	g t^{-1}	0.02
2,4-D 2-ethylhexyl ester	g t^{-1}	1.20
Nonylphenol	g t^{-1}	0.001
Emissions to soil		
Glyphosate	g t^{-1}	170
Thifensulfuron-methyl	g t^{-1}	2.08
Tribenuron-methyl	g t^{-1}	1.05
2,4-D 2-ethylhexyl ester	g t^{-1}	66.3
Nonylphenol	g t^{-1}	0.05

2.4. Life Cycle Impact Assessment (LCIA)

Agricultural practises have diverse effects on the environment. For example, excessive application of synthetic or organic fertilisers disturbs the biogeochemical cycles of nitrogen (N) and phosphorus (P), causing eutrophication of aquatic and terrestrial ecosystems, acidification of waters and soils by ammonia (NH_3) emissions, and ozone pollution resulting from nitrogen oxide (NO_x) emissions [45]. Emissions of NH_3 and NO_x are gaseous precursors of fine particulates and acid precipitation. Furthermore, the production of synthetic fertilisers is very energy-intensive [46] and contributes to the depletion of both mineral and fossil fuel resources [47].

Based on the work of Viana et al. [22], four mid-point indicators were selected: global warming, fine particulate matter formation, terrestrial acidification, and mineral resource scarcity. We used characterisation factors that were proposed by the ReCiPe (H) midpoint hierarchist (problem-oriented) approach to quantify environmental impacts [48]. These emission factors were used to convert elementary flows into environmental impacts. ReCiPe is a recognised LCIA that is used in agricultural LCA studies [49]. The methodology is a combination and harmonisation of two other impact methodologies, viz., CML 2001 (mid-point indicators) and Eco-indicator 99 (endpoint indicators). SimaPro 8 software (PRé Sustainability, Amersfoort, NL, The Netherlands) was used for the compilation of the inventories and the assessment of environmental impacts. This software is widely used in LCA studies due to its flexibility, compatibility with many LCA databases, and ability to generate transparent results.

3. Results and Discussion

3.1. Midpoint Impacts

The environmental impacts of oat flake production are largely dominated by oat grain production (agricultural processes) and, to a lesser extent, by oat flake production (agro-industrial processes) (Table 6, Figure 2). Depending on the impact category, end-of-life management of oat hulls represents <1–18% of the total impact.

Table 6. Characterisation results for the production of one tonne of oat flakes.

Impact Category	Scenario	Oat Grain Production	Oat Flake Production	Oat Hull End-of-Life	Avoided Impacts	Total
Global warming	Compost	449	115	36.6	6.9	594
(kg CO_2 eq)	Animal feed (10%)	449	115	1.7	20	566
Fine particulate matter formation	Compost	1.5	0.1	0.1	<0.01	546
(kg PM2.5 eq)	Animal feed (10%)	1.5	0.1	<0.01	<0.01	466
Terrestrial acidification	Compost	9	0.3	0.2	<0.01	608
(kg SO_2 eq)	Animal feed (10%)	9	0.3	<0.01	0.2	582
Mineral resource scarcity	Compost	0.9	0.1	0.2	<0.01	562
(kg Cu eq)	Animal feed (10%)	0.9	0.1	<0.01	<0.01	482

The environmental impact of oat flake production varies little with the oat hull end-of-life scenario (Table 6 and Figure 2), but an environmental benefit is nevertheless observed for the scenario in which oat hulls are used as animal feed. This performance is mainly due to the renewable energy source of electricity (hydro) used in the province of Quebec. Composting results in high GHG emissions associated with residue transport to composting centres and the operations at the compost facility [30]. Further, the decomposition of organic matter emits GHGs (i.e., CH_4 and N_2O) and contributes to the formation of fine particulates (e.g., NH_3 and N_2O) and soil acidification (e.g., NH_3). For composting, the processes that contribute the most to the climate change indicator are, in order of importance, composting operations (52%), decomposition of organic matter (28%), and transport (16%).

Implementation of a feed processing solution for oat hulls would improve the climate change indicator by reducing GHG emissions by 35 kg of CO_2 eq. per tonne of flakes compared to the reference scenario. This figure represents 6% of the total impact of oat flake production.

Considering that an average 5022 tonnes of oat hulls need to be managed each year on the study farm, 175 tonnes of CO_2 eq. can be avoided annually by transforming oat hull wastes into animal feed (excluding avoided products). In the composting scenario, GHG emissions that are associated with the end-of-life management of oat hulls are greater than the benefits that are provided by the production of synthetic fertilisers that are avoided in this scenario (Table 6 and Figure 2). When considering the avoided impacts of each end-of-life scenario, the processing of oat hulls into animal feed achieves an annual reduction of 242 tonnes of GHGs compared to the composting scenario. Therefore, processing oat hulls into animal feed is a better option than sending them for composting. This result is consistent with several studies that have compared the environmental impacts of food waste valorisation scenarios [24,25,27]. Indeed, producing animal feed has significant environmental impacts [11], which makes the use of such alternative food sources relevant to reducing the pressure of livestock farming on the environment.

To our knowledge, this is the first LCA comparing oat flake production with several end-of-life management options for oat hulls. McDevitt and Milà i Canals [23] quantified the impacts of porridge production in the UK (a product made from oat flakes), but the authors presented the results as a percentage, which prevents the comparison with the raw results that were obtained here. Although McDevitt and Milà i Canals [23] did not consider end-of-life management of oat hulls, the observed impacts that were associated with oat grain production were higher than those of the oat flake production phase, which is consistent with our results.

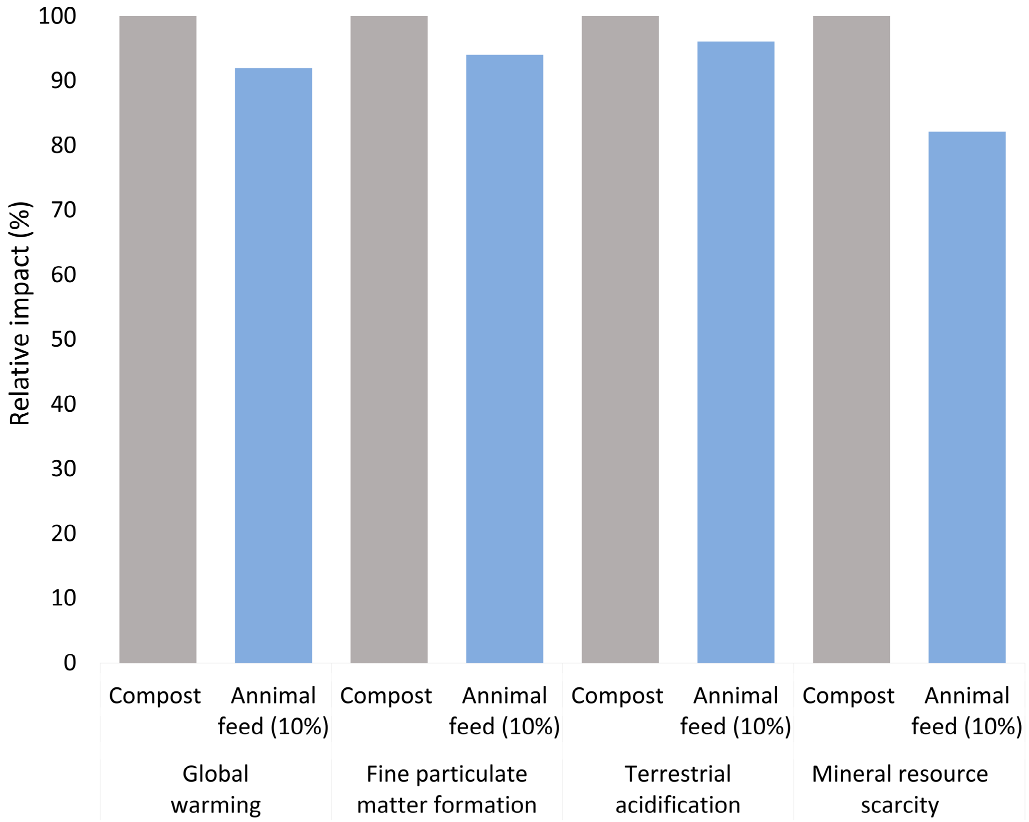

Figure 2. Relative impact (expressed as %) of the production of one tonne of oat flakes according to end-of-life scenarios for oat hulls.

3.2. Hotspots

Depending upon the impact category and the end-of-life scenario for oat hulls, the agricultural phase (grain production) represents 76–97% of the impact of oat flake production (Table 6, Figure 2). All the mid-point impact categories that were assessed are strongly affected by the production and use of N fertilisers. This significant contribution stems mainly from ammonia production and significant N_2O and NH_3 emissions from fertiliser applications, thereby emphasising the importance of using techniques that promote soil health and that limit the use of synthetic fertilisers [22]. Furthermore, the production of ammonia, which is the precursor to almost all nitrogenous mineral fertilisers (e.g., urea and mono-ammonium phosphate), is very energy (Haber–Bosch process) and infrastructure intensive [46]. This is due especially to the use of natural gas as both a source of energy and a substrate (hydrogen) for the production of ammonia.

The global warming category is largely dominated by the manufacture (16–18%) and application of fertilisers (42–46%) and, to a lesser extent, by the heat requirements for building heating and oat flake production (13–14%). CO_2 and N_2O emissions account for a similar share of GHG emissions over the entire life cycle of oat flake production (49–50%

and 46–48%, respectively). The application of nitrogen fertilisers is also responsible for most of the impacts associated with the formation of fine airborne particles (62–66%) and terrestrial acidification (83–86%). NH_3 emissions are responsible for 60–62% and 84–85% of emissions that are associated with fine particle formation and terrestrial acidification, respectively. Finally, the mineral resource scarcity category is largely dominated by the manufacture of fertilisers (45–56%). The use of iron (21–26%) for the production of steel (e.g., infrastructure and agricultural machinery), nickel (15–16%), which is used as an alloying element, and phosphorus (8–12%), one of the main mono-ammonium phosphate manufacturing raw materials, are the resources that contribute the most to the total impact of oat flake production.

3.3. Sensitivity Analyses

The environmental performance of oat flake production changes considerably with the electricity mix and the quantity of alfalfa that is replaced by FGO (Table 7 and Figure 3). Given that the results point in the same direction for all impact categories, we present only the results for the climate change indicator in this section. The results that were obtained for the other impact categories can be found in Table S5.

Table 7. Global warming impact of producing one tonne of oat flakes in four Canadian provinces with different substitution rates of a main agricultural product by feed grade oat pellets (FGO). Oat grain production impacts are not presented in the table given that they were not affected by the sensitivity scenarios.

Impact Category	Scenario [a]	End-of-Life Scenario	Oat Flake Production	Hull End-of-Life	Avoided Impacts
Global warming (kg CO_2 eq)	Québec	Compost	115	37	7
		Animal feed (0%)	115	1.7	0
		Animal feed (10%)	115	1.7	20
		Animal feed (50%)	115	1.7	101
	Manitoba	Compost	128	37	7
		Animal feed (0%)	128	5.4	0
		Animal feed (10%)	128	5.4	20
		Animal feed (50%)	128	5.4	101
	Saskatchewan	Compost	290	49	7
		Animal feed (0%)	290	54	0
		Animal feed (10%)	290	54	20
		Animal feed (50%)	290	54	101
	Alberta	Compost	334	52	7
		Animal feed (0%)	334	68	0
		Animal feed (10%)	334	68	20
		Animal feed (50%)	334	68	101

[a] Impacts of grain production (Table 6) must be added to quantify the total impact of each scenario.

Electricity production. The production of oat flakes, FGO, and the composting of oat hulls are the foreground processes that use the most electricity in our model. In Quebec and Manitoba, where the electricity mix is based on hydroelectricity [44], the carbon performance of oat flake production is considerably better than in Saskatchewan and Alberta (Table 7 and Figure 3), where electricity generation is based on coal and natural gas [50]. Producing oat flakes in Quebec, for example, has a 28–34% lower impact than in the Province of Alberta. Given that on average 8691 tonnes of oat flakes are produced annually on the study farm, a difference ranging from 2041 to 2479 tonnes of GHGs can be observed between Quebec and Alberta (Table 7 and Figure 3). Alberta and Saskatchewan are major agricultural regions in North America [51], which highlights the potential benefit of increasing the share of renewable energy in their electricity mix.

Considering only the end-of-life scenarios for oat hulls, the deployment of a feed milling system for oat hulls is preferable using the electricity mix of the provinces of Quebec and Manitoba. Conversely, in the provinces of Saskatchewan and Alberta, the reference scenario (composting) has a similar or slightly lower impact than the processing of oat hulls into animal feed. The benefit, not accounting for avoided products, of using granulated hulls as animal feed was 35 kg CO_2 eq. per tonne of oat flakes in Quebec. In Alberta, the composting scenario produces 16 kg CO_2 eq. less emissions than the FGO scenario. (Table 7 and Figure 3).

Replacement of animal feed. The environmental performance of oat flake production improves considerably with the amount of alfalfa that is replaced by FGO. In the optimistic scenario (50% replacement), the production of FGO reduces GHG emissions from 9% (Alberta) to 22% (Quebec) (from 726 to 1196 t CO_2 eq. yr^{-1}) compared to composting (Table 7, Figure 3). In the pessimistic scenario (0% replacement), processing oat hulls into animal feed remains preferable to composting in the provinces of Quebec and Manitoba, contrary to what is observed in the provinces of Saskatchewan and Alberta. As discussed in several studies, e.g., [12,24,52], the environmental relevance of a waste treatment pathway is highly dependent upon methodological choices and market characteristics, such as the quality of the co-product, the efficiency of the recycling processes, the type of product being replaced, the composition of the electricity mix, and the transport distance, among others. Our results are consistent with this statement. In our study, the mix of electricity and avoided products was an important driver for the final outcomes.

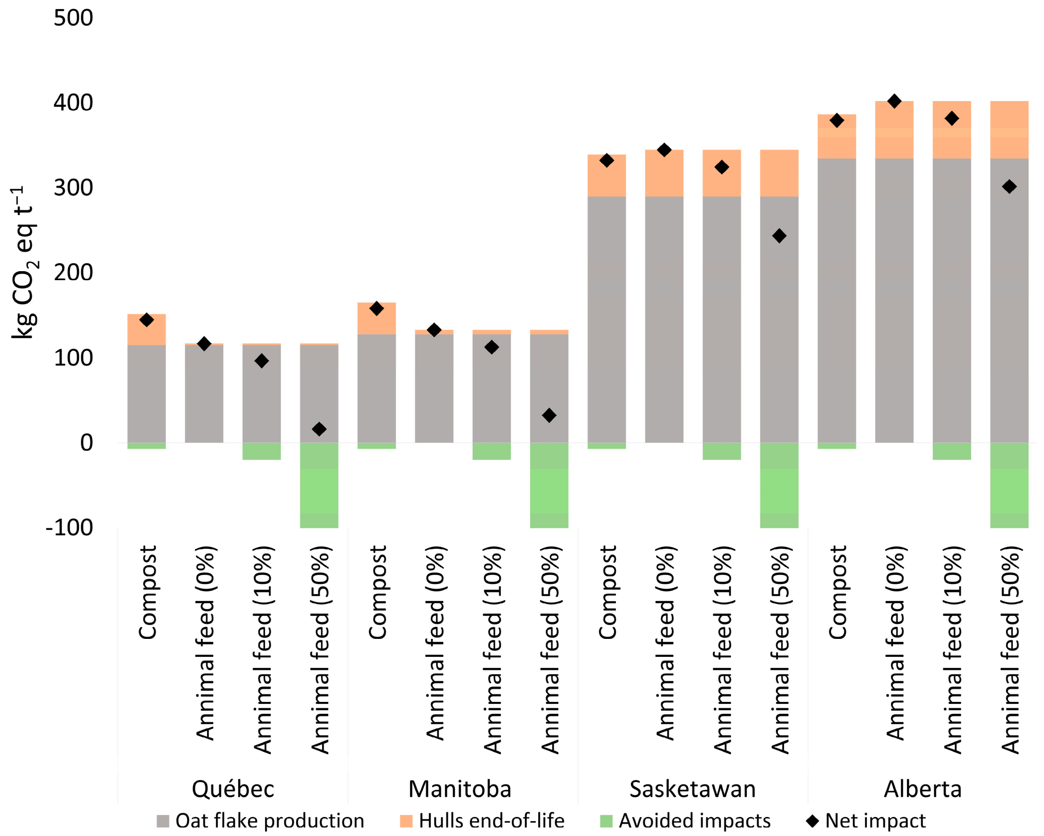

Figure 3. Global warming impacts of oat flake production (excluding grain production) under different sensitivity scenarios.

3.4. Study Limitations and Future Research

Choice of avoided products. The choice of avoided products is an intensely debated topic in LCA studies [53]. For some products, such as compost, it is difficult to determine which products they can replace. Since compost has much less NPK than other organic fertilisers, such as manures [54], its ability to replace synthetic fertilisers is low and, as observed in this study, does not offset the impacts of composting. Yet, composts can perform several functions when used in agricultural production, such as increasing resilience to droughts (increased water-holding capacity) and improving soil structure (increased aggregate formation and soil porosity), which are not considered in LCAs [55]. Based upon its NPK content, compost frequently replaces only synthetic fertilisers in LCA studies [30,34,56]. Several further reasons make it difficult to consider the benefits of composting. The products that are replaced by compost change according to the type of agricultural crop for which it is used. For instance, using compost in organic farming will have a limited environmental benefit, given that compost replaces other organic fertilisers instead of synthetic fertilisers. From a functional perspective, compost must also ensure the same agricultural yield as synthetic fertilisers for a specific crop, which can hinder the role of composts in replacing synthetic fertilisers.

In the case of agricultural residues that are intended as animal feed, some studies rely upon their protein content or other nutritional content to determine the rate of replacement of agricultural crops being avoided [57]. Although this approach appears to be methodologically correct, it is still not known whether animal feed derived from residues would replace main agricultural crops or other agricultural co-products. This is the reason why we used several replacement scenarios in our study (0%, 10%, and 50%). The consequential life cycle assessment (C-LCA) is a way of improving the consideration of avoided products [58]. Indeed, C-LCA uses market (economic) data to determine the marginal products that would be replaced by the marketing of co-products [59]. Further research using C-LCA should be conducted to quantify the large-scale consequences of the deployment of agro-industrial symbiosis chains.

Limits of environmental indicators. Environmental indicators are important for choosing among various waste management scenarios, but they do not cover other dimensions that are equally important, such as economic, social, and technical feasibility aspects [60,61]. For example, FGO have been in high demand over the last few years according to data obtained from the study farm, indicating the economic potential of this co-product for farmers. Depending upon the market conditions, the composting scenario could imply significant management costs for farmers, especially due to the transportation of the oat hulls to the industrial composting centres. Moreover, from the perspective of its technical feasibility, the equipment that is used to transform oat hulls into animal feed is integrated with the production of oat flakes, which simplifies the management of these residues. Therefore, it is strongly recommended that several dimensions be considered to select the most appropriate agricultural residue management scenarios. Given that it is difficult to make objective decisions based on a large set of indicators, the use of multi-criteria decision analysis (MCA) methods can be applied to help in the decision-making process. MCA methods make it possible to deal with complex problems involving data of different natures, multiple interests, and multiple perspectives, together with the interaction between biophysical and socio-economic systems [62,63].

Other agro-industrial symbiosis options. In this study, we have compared only two scenarios of industrial symbioses. Yet, other scenarios could be considered. Oat hulls may also be used as a source of feedstock for the production of bioethanol [64] and biogas [65] and can replace sawdust or wood shavings as an alternative bedding material for farm animals, such as dairy cattle [66], sources of activated carbon used in leachate treatment [67], furfural [6], and highly cellulosic fibrous materials [68], as well as serving as fuel to produce steam [6]. As we have seen, the ability of a co-product to improve the environmental performance of oat flake production also depends on the environmental performance of the waste management route and the products that are being replaced. Therefore, it would be useful to evaluate the environmental performance of other end-of-life scenarios for oat hulls.

4. Conclusions

The purpose of this study was to quantify the environmental impacts of oat flakes production in northeastern Canada and to compare two agro-industrial symbiosis scenarios that were applied to agro-industrial residues.

In order to reduce the environmental impacts of oat flake production, farmers should focus on the agricultural phase of grain production, particularly those aspects that are related to the use of synthetic fertilisers, which strongly contribute to all impact categories (at least 50% of the impact of each category). Thus, it is important to use techniques that promote soil health and limit the application of synthetic fertilisers. When it comes to the agro-industrial step of oat flake production, producers have little latitude in reducing environmental impacts. Indeed, most of the losses that are associated with this step are related to the composition of the oat grains, not to the production process. In Quebec and Manitoba, where the electricity mix has a low carbon intensity, most of the impact of the production of oat flakes (the agro-industrial phase) is associated with the heating of buildings. In this sense, oat flake producers can substitute fossil fuel-based heating for renewable sources such as biomass. In Saskatchewan and Alberta, the impacts of oat flake production are mainly centred around the use of electricity. Thus, it is also necessary to focus on the energy efficiency of the processes that are involved in the production of oat flakes.

Regarding the end-of-life scenarios with the Quebec and Manitoba electricity mixes, it is still preferable (even in the pessimistic scenario) to transform the oat hulls into animal feed. However, the environmental benefits of the FGO scenario are substantially lower in the provinces of Saskatchewan and Alberta. The choice of an end-of-life scenario in these two provinces will depend on the benefits associated with the avoided products. In a scenario where FGO does not replace any agricultural products (a pessimistic scenario), composting the oat hulls is preferable. LCA is demonstrated to be a relevant tool for identifying hotspots in oat flake production and choosing the most appropriate end-of-life scenarios for oat hulls. The results also highlight the important role that is played by local characteristics on the environmental impacts, which prevents us from proposing universal solutions for the management of agricultural residues. The implementation of industrial symbiosis chains without a prior study could even increase the environmental impacts compared to a reference scenario. This finding is important for the development of public policies that aim to encourage the implementation of agro-industrial symbiosis chains. Future studies may evaluate other end-of-life scenarios for oat hulls to improve the environmental performance of oat flake production. Certain methodological aspects, such as better consideration of avoided products, must also be improved. Finally, the inclusion of socio-economic indicators in the analysis, which are of primary importance for the agri-food industry, would help in choosing the best management strategy.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/su15065124/s1; Table S1: Average characteristics of the study farm's fields; Table S2: Data used to replace synthetic fertilisers with industrial compost; Table S3: Features and specifications of feed grade oat pellets expressed in %; Table S4: Sources and values used to quantify nitrogen and phosphate emissions to air and water for oat grain production; Table S5: LCA results of oat flakes production according to selected sensitivity scenarios. References [36–38,41,42] are cited in the Supplementary Materials.

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