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Environmental Profile of the Swiss Supply Chain for French Fries: Effects of Food Loss Reduction, Loss Treatments and Process Modifications

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Abstract: The production of food is responsible for major environmental impacts. Bearing this in mind, it is even worse when food is lost rather than consumed. In Switzerland, 46% of all processing potatoes and 53% of all fresh potatoes are lost on their way from field to fork. Our study therefore compares the environmental impacts of losses of fresh potatoes with those of French fries. With the aid of a Life Cycle Assessment, we assessed the impact categories "demand for nonrenewable energy resources", "global warming potential", "human toxicity", "terrestrial ecotoxicity" and "aquatic ecotoxicity". Our results show that 1 kg of potatoes consumed as French fries causes 3–5 times more environmental impacts than the same quantity of fresh potatoes, but also that the proportion of impacts relating to losses is considerably lower for French fries (5%–10% vs. 23%–39%). The great majority of processing potato losses occur before the resource-intensive, emission-rich frying processes and therefore the environmental "backpack" carried by each lost potato is still relatively small. Nonetheless, appropriate loss treatment can substantially reduce the environmental impact of potato losses. In the case of French fries, the frying processes and frying oil are the main "hot spots" of environmental impacts, accounting for a considerably higher proportion of damage than potato losses; it is therefore also useful to look at these processes.

Keywords: French fries; potato supply chain; food loss; Life Cycle Assessment (LCA); environmental impacts

1. Introduction

Common food production, processing and consumption patterns are increasingly viewed as unsustainable because they stress the environment dramatically [1]. To improve the sustainability of food supply chains and to ensure food security, the entire supply chain needs to be assessed and improved [2]. Food losses in particular are critical from both an environmental and a social viewpoint [3]. Minimizing food losses along the entire supply chain makes it possible to avoid major environmental impacts related to the production, processing and disposal of these food losses at a time when around 800 million people on earth are chronically undernourished [4]. By reducing losses in the food industry, fewer inputs (e.g., energy, natural resources, human labor) would be necessary [3,5,6] and external effects could consequently be minimized [7]. In addition, food losses do not just strain resources but also result in the needless production of various environmentally relevant emissions [8].

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However, even if loss treatments may substantially improve the environmental performance of food losses [9], the food itself and the related resources for its production, transportation and disposal are used in an inefficient manner [10]. Losses can be treated, e.g., used as animal feed or in biogas plants, thus avoiding the need to produce animal feed or energy elsewhere.

One of the commodities with the highest loss rates along the entire supply chain in Switzerland is the potato [11,12]. Scholz et al. [8] emphasized the importance of not only considering loss quantities while trying to define food loss reduction goals, but also keeping in mind their environmental impacts. Thus, Willersinn et al. [13] used the ISO-standardized Life Cycle Assessment (LCA) method [14] to estimate the environmental impacts of Swiss fresh potatoes and potato losses on five environmental impact categories (i.e., demand for nonrenewable energy resources, global warming potential (GWP), human toxicity, terrestrial and aquatic ecotoxicity). They found that all fresh potato losses together (53% of the initial potato production is lost instead of consumed) cause 23%–39% of the observed environmental impacts when excluding potential loss treatments [13]. As the name suggests, fresh potatoes are not processed intensively. We can therefore assume that their total environmental impacts and strained resources are smaller throughout the entire life cycle than for a highly processed potato product such as French fries. Throughout the processes in the processing industry, additional inputs are required and additional outputs arise. At this supply chain stage, inevitable losses occur despite adopting waste minimization strategies [15].

The aim of the present study is to assess the environmental impacts and losses from the field to the consumer of a highly processed potato product (i.e., French fries). Furthermore, the study estimates the potential to reduce the environmental impacts of the entire Swiss French fry supply chain through (i) loss reduction; (ii) loss treatment (e.g., loss use for feed or energy production); and (iii) process modifications.

The methods applied, as well as the goal and scope of this study, are described in detail in Section 2. In Section 3, the results of the environmental impact assessment and a contribution analysis identifying hot spots of impacts along the supply chain are presented. In Section 4, our results are discussed—notably by comparing French fries with previous studies of fresh potatoes. Finally, conclusions and recommendations for improving the environmental performance of the French fry supply chain are presented in Section 5.

2. Materials and Methods

2.1. Goal and Scope Definition

Life Cycle Assessment (LCA) is a widely approved method for assessing environmental impacts throughout the life cycle of a product (e.g., [16–18]) and is frequently used for environmentally related decision making [19]. The scope of this study is determined by all processes occurring at any stage of the Swiss French fry supply chain, from the potato field to the frying process and meal preparation in private households. In particular, the influence of food losses and potential loss treatments, including substitution effects, have been respected. Furthermore, we assume that all produced processing potatoes are traded by wholesalers, processed in the processing industry, then sold by retailers and finally consumed within private households. French fry consumption occurring outside private households is not included because, according to Betz et al. [20] and Willersinn et al. [12], potato and potato product losses in the out-of-home sector in Switzerland seem to be similar to losses at the retailer and private household stages combined. The goals of the study are to:

- Assess the environmental impacts of each stage of the Swiss French fry supply chain and to identify environmental hot spots;
- Demonstrate the impact on the environment of losses, loss reduction and loss treatment at each stage of the French fry supply chain;
- Evaluate how the total environmental impacts of the entire Swiss French fry supply chain might be reduced beyond loss reduction or loss treatments.

2.2. Mass Flow of the Current Supply Chain, System Boundary and Data Sources

This study is based on the potato loss quantification results of Willersinn et al. [12]. In that study, the authors assessed all losses occurring throughout the entire French fry supply chain in Switzerland. Figure 1 displays the most common French fry supply chain configuration. For our analyses, we divided the entire French fry life cycle into five modules (agricultural production, wholesaler, processing industry, retailer and private household) according to the typical supply chain stages of this product. As the functional unit, we chose 1 kg of potatoes consumed as French fries, ready to eat in Swiss private households. Thus, our functional unit consists of 1 kg raw potatoes but also considers the frying processes at the processing industry and private households. While frying the potatoes, water evaporates and frying oil is absorbed which leads to a change in mass. The extent of this mass change depends on the duration of the frying process and the size of the French fries. The selected functional unit (1 kg potatoes consumed as French fries) allows us to compare the LCA results with those of 1 kg fresh potatoes that will be consumed just boiled. Before the respective potato quantity is ultimately consumed, losses occur at several supply chain stages. We investigated both mass flows: the loss stream and the product stream of French fries until consumption. Between each supply chain stage, potatoes or French fries respectively need to be transported. For the LCA we assumed that transportation to a specific supply chain actor was part of the respective stage. Furthermore, for the accuracy of the LCA results, the phase within a module at which losses occur was crucial. The module "processing industry" was therefore subdivided into two phases: (1) the delivery, quality rating, washing, peeling, cutting and sorting phase; and (2) the blanching, frying, cooling, freezing and packaging phase. At all other modules, losses mostly occur at the end; we thus related all environmental impact to the entire amount of potatoes or French fries respectively delivered at the relevant supply chain stage.

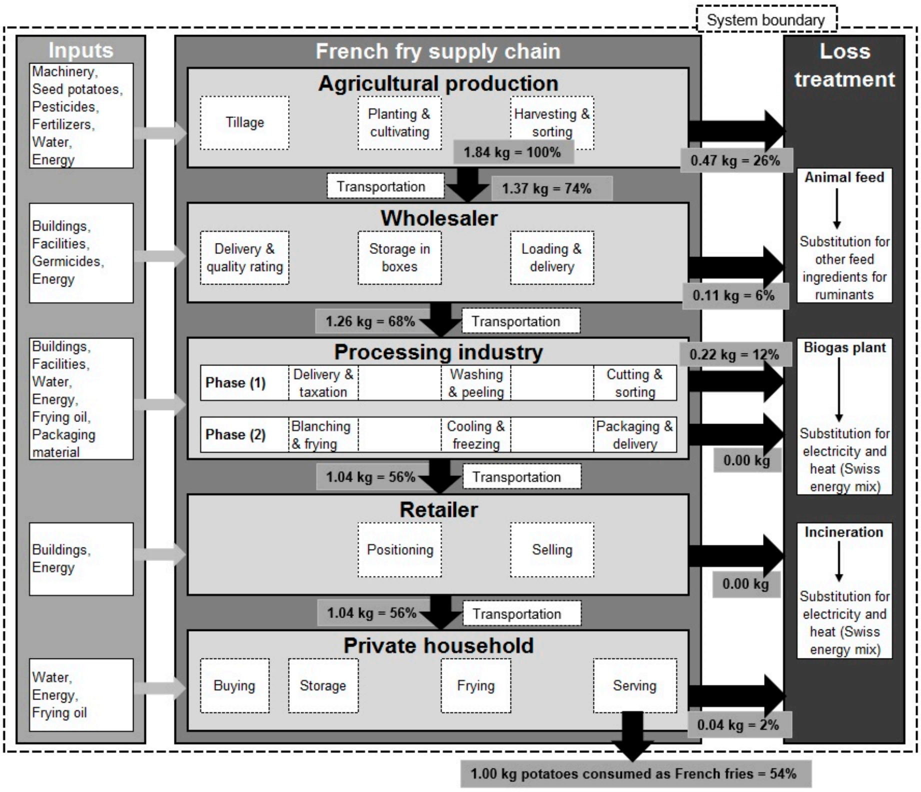

Figure 1. System boundary of the investigated system including the mass flow of processing potatoes and potato losses until final consumption of 1 kg potatoes consumed as French fries in the current situation.

To facilitate comparability with LCA results for the Swiss fresh potato supply chain [13], the same inputs and outputs were considered. We assumed that losses which occur directly at the site of agricultural production are not transported because farmers use them as animal feed directly on their farms. At each subsequent stage, we considered all inputs and outputs associated with all relevant processes including the transportation of potato or French fry losses respectively to the loss treatment spot. The mass flow of processing potatoes until final consumption of 1 kg of potatoes consumed as French fries and all associated losses at each stage of the current Swiss French fry supply chain are shown in Figure 1. Furthermore, Figure 1 presents the system boundary and the relevant inputs which have been considered, as well as the loss treatments.

The data for our analyses were mostly collected through structured face-to-face interviews with supply chain participants in 2014/2015 [12]. Furthermore, we supplemented this dataset with specifications provided within the literature or publicly available databases. These additional data mostly refer to Switzerland or at least to other European countries.

2.3. *Life Cycle Assessment*

In the first step, we collected all relevant input and output streams at each particular stage of the French fry supply chain which build the basis for the life cycle inventories according to ISO 14040 [14]. We excluded all inputs and outputs which represent less than 1% of the mass flows or energy consumption from the analysis. The life cycle inventories are presented in Appendix A.

2.3.1. Modeling Structure

The modules were modeled with the aid of the Swiss Agricultural Life Cycle Assessment (SALCA) method in combination with a specific calculation tool for agricultural production [21]. Therefore, direct field emissions are based on emission parameters (e.g., soil type, precipitation, slope) representing Swiss conditions for arable areas. The LCA software SimaPro (v7.3.3, PRé Sustainability, Amersfoort, The Netherlands) was used to conduct the LCA. After modeling, it was possible to connect each module and thus to assess the entire supply chain [22]. Where necessary for our analysis, Ecoinvent database v2.2 (ecoinvent, Zurich, Switzerland) [23] was used to gain secondary data [24].

2.3.2. Agricultural Production Input Data

According to the data provided by Keiser et al. [25], we assumed an average processing potato yield of 48,759 kg/ha. Therefore, 3238 kg seed potatoes had been planted on average per hectare [25]. The production data provided by Keiser et al. [25] were collected between 2001 and 2003. Several pesticides applied during that time are now prohibited. We therefore excluded all parcels from our LCA where such pesticides had been applied. Furthermore, we respected specific mineral fertilizers within the SALCA calculations according to Bystricky et al. [26]. A typical Swiss crop rotation sequence including potatoes was provided by Keiser et al. [25]. We estimated the amount of irrigation water based on specifications provided by the Federal Statistical Office [27] and Keiser et al. [25].

2.3.3. Wholesaler Input Data

At the wholesaler stage, processing potato losses basically occur during size calibration and sorting. Secondary data from the Ecoinvent database were used to model the storage facilities. We assumed a service life duration of the necessary buildings of 50 years [28] and a construction duration of two years [29]. All processes require electricity (0.032 kWh/kg; source: Uhlmann et al. [30]) and germicides are applied during the storage phase (0.018 g/kg; Omya AG [31]).

2.3.4. Processing Industry Input Data

As mentioned above, the processes at the processing industry were divided into two phases. In phase (1), the major inputs were electricity (0.002 kWh/kg; Uhlmann et al. [30] and Eima [32]), heat for the steam peeler (0.25 MJ/kg; own calculations based on personal communication with an engineer for potato processing machines) and water for the washing process (18 kg/kg; personal communication with an engineer for potato processing machines). Concerning the machinery used, only the weight of the machines and the required stainless steel were considered [13]. In phase (2), the major inputs were heat for blanching (4.75 MJ/kg; Foster et al. [33]), electricity (0.32 kWh/kg; Ponsioen and Blonk [34]), packaging material (0.0041 kg/kg polyethylene bag; 0.03 kg/kg paperboard; personal communication with a processor) and the rapeseed oil used for frying (0.05 kg/kg; personal communication with a processor). The machinery used were considered in the same way as in phase (1). Furthermore, the buildings were modeled in the same way and we assumed the same utilization and construction period as we did at wholesaler stage with the aid of Ecoinvent data.

2.3.5. Retailer Input Data

At the retailer stage, the demand for electricity for cooling and lighting and the demand for heat are the most important inputs and were estimated based on the Danish LCA food database [35]. For our purposes, we calculated the arithmetic mean between the specifications of a small-sized and a large-sized supermarket according to the Danish LCA food database. In addition, the Swiss Federal Office of Energy [36] provided data on the proportions of natural gas and mineral oil used to produce the heat.

2.3.6. Private Household Input Data

In private households, some assumptions were necessary, e.g., about storage duration and frying habits (see Section 2.6). The main inputs are electricity for the freezer and deep-fryer (1.8 kWh/kg; Franke and Strijowski [37] and Sonesson et al. [38]), and the sunflower oil used for frying (0.4 kg/kg; Franke and Strijowski [37] and DGF [39]). In addition, to model the transportation process of 1 kg of French fries from retailer to household, we assume an average transportation distance of 4.7 km (round trip) [40]; 10 kg of groceries per shopping trip [22,41]; and 55% of all purchases being made by car [41].

2.3.7. Process Modification

Hypothetically, production processes could be modified—compared to the current situation—at any stage of the supply chain. For example, there are different oils available in Switzerland suitable for frying French fries (e.g., rapeseed oil, sunflower oil, palm oil). In order to compare different options of process modifications with the current situation, we apply the LCA modeling rules as described in the guidelines of the World Food LCA Database [42]. These guidelines ensure a best practice of comparability, especially when comparing inputs used in the supply chain from different countries.

2.4. Allocation

To estimate the environmental impacts related to the marketable share of potatoes (product) and potato losses (co-product), the environmental impacts resulting from the LCA need to be assigned to each of these product lines [43]. Therefore, we calculated allocation factors (Af) based on the prices and quantities of the product and co-product. The allocation factors were calculated according to Equation (1):

$$\mathrm{Af} = \frac{\mathrm{Mass}_{\mathrm{Product}} \times Price_{Product}}{\left(\mathrm{Mass}_{\mathrm{Product}} \times Price_{Product}\right) + \left(\mathrm{Mass}_{\mathrm{Co-product}} \times Price_{Co-product}\right)} \quad (1)$$

Table 1 contains the resulting allocation factors for marketable potatoes and potato losses as well as the assumed prices (based on Agridea [44] and Coop [45]) and quantities (based on Willersinn et al. [12]). From phase (2) at the processing industry stage until the final consumer stage, we assume that all French fries or the related raw potatoes have the same initial quality (defective items had been sorted out at previous stages). Consequently, all potatoes or French fries have the same price irrespective of their further journey.

Table 1. Allocation factors at each stage of the investigated French fry supply chain (current situation). Prices derive from Agridea [44] and Coop [45], quantities from Willersinn et al. (2015).

Module		**Product (Marketable Potatoes)**		**Co-Product (Potato Losses)**		**Allocation Factor**	
		Mass (kg)	**Price (CHF/kg)**	**Mass (kg)**	**Price (CHF/kg)**	**Marketable Potatoes**	**POTATO LOSSES**
Agricultural production		1.37	0.47	0.47	0.06	0.955	0.045
Wholesaler		1.26	1.63	0.11	0.06	0.997	0.003
Processing industry	Phase (1)	1.04	1.63	0.22	0.06	0.992	0.008
	Phase (2)	1.04	4.00	0.00	4.00	1.000	0.000
Retailer		1.04	4.00	0.00	4.00	1.000	0.000
Private household		1.00	4.00	0.04	4.00	0.962	0.038

2.5. Substitution

In Switzerland, all potato losses are reused or recycled as animal feed or to produce energy [12]. Thus, depending on the specific loss treatment, several goods can be substituted, which might lead to environmental benefits (for details, e.g., which feed ingredients are substituted by potato losses, see Willersinn et al. [13]). Willersinn et al. [13] calculated the environmental impacts of 1 kg of fresh potato losses in Switzerland in three different loss treatments: (a) animal feed; (b) biogas plant; and (c) incineration. To estimate the substitution effects within the present study, we used the same specifications as in [13], even though this study is based on fresh potatoes.

Table 2 contains the environmental impact of 1 kg of potatoes for three different loss treatments as well as the impacts of loss transportation [13]. All losses at agricultural production are used as animal feed directly on the farms (no transportation necessary); at the wholesaler stage, 91% of potato losses are fed to animals, whereas 9% are used in a biogas plant; at the processing industry stage, 83% are used as animal feed and 17% in a biogas plant; at retailers, no French fry losses occur; and in private households, all losses were assigned to incineration [12]. Transportation of losses is considered at all further stages of the supply chain.

Table 2. Impacts of three loss treatments for 1 kg of potato loss according to Willersinn et al. [13].

Impact Category	**Impact of Loss Treatment**			**Impact of Loss Transportation from … to Farms/Biogas Plant ***	
	Animal Feed	**Biogas**	**Incineration**	**Wholesaler**	**Processing Industry**
Demand for nonrenewable energy resources (MJ eq.)	−0.8621	−4.8032	−3.4448	0.1465	0.3079
Global warming potential (kg CO_2 eq.)	−0.1198	−0.1265	−0.1622	0.0093	0.0190
Human toxicity (kg 1.4-DB eq.)	−0.0500	−0.0340	0.0013	0.0116	0.0131
Terrestrial ecotoxicity (kg 1.4-DB eq.)	-1.34×10^{-3}	-1.44×10^{-5}	9.62×10^{-6}	0.0000	0.0000
Aquatic ecotoxicity (kg 1.4-DB eq.)	−0.0424	−0.0248	0.0575	0.0024	0.0031

* Impacts of loss transportation (1 kg) are relevant only to the wholesaler and retailer stages as these losses need to be transported to farms or a biogas plant. Losses at the private household stage are disposed of via residual waste and thus transported to an incineration plant. The impacts of these transports are already included in the value of incineration.

2.6. Further Assumptions

Due to time and cost restrictions, it is virtually impossible to consider all potential configurations of the Swiss French fry supply chain. Thus, some assumptions and simplifications were necessary to conduct this LCA. All of these assumptions can be found in Appendix B.

2.7. Impact Assessment

For comparability of our French fry LCA results with the environmental impacts of fresh potatoes and fresh potato losses, we selected the same impact categories as in [13]. Therefore, the demand for nonrenewable energy resources (CED method [46]) was selected as an indicator for the resource use related to food losses; global warming potential (GWP) (IPCC method [47]), terrestrial and aquatic ecotoxicity (CML 2001 method [48]) were chosen to demonstrate the effect of food losses on environmental quality and, finally, human toxicity (CML 2001 method [46]) was selected to show how losses affect human health [13].

2.8. Sensitivity Analyses

Sensitivity analyses were conducted for those model assumptions which showed significant impacts on the total LCA results according to the contribution analysis. Therefore, the assumed input amounts of the identified parameters were varied by ±25. In all cases, just one of these meaningful model assumptions was varied. The others were left constant. Furthermore, we tested how the assessment results would change if French fries were not fried but baked in the oven.

3. Results

3.1. Environmental Impact Profile of the Current Supply Chain

The environmental profile of the current situation in Switzerland is visualized in Figure 2 with the bars labeled as "losses are treated" (i.e., use of defective potatoes for animal feed or energy production). The profile of the supply chain is dominated by the impact contribution of the household, with nonrenewable energy resources, GWP, human toxicity, terrestrial ecotoxicity and aquatic ecotoxicity accounting for 60%, 61%, 64%, 66% and 67%, respectively. The household stage includes the activities of buying, storing, frying and serving prepared French fries. The second important contributor is the processing industry (phase 2, i.e., blanching, frying, cooling, packaging), especially for GWP (25%), nonrenewable energy resources (24%), and human toxicity (14%). For the two impact categories, terrestrial and aquatic ecotoxicity, the activities of agricultural potato production are of similar importance to the processing industry (phase 2). Very little influence on environmental impacts is caused by wholesalers, processing industry (phase 1) or retailers.

3.2. Potential to Reduce Impacts by Loss Treatment and Loss Reduction

Theoretically, we can expect loss treatment to result in lower impacts compared to the situation if losses were not treated, which is a hypothetical situation in the case of Switzerland. Similarly, the hypothetical outcome of assuming that no losses occur at any stage of the supply chain results in lower impacts compared to the current situation. As can be inferred from Figure 2, neither loss treatments nor avoiding losses would significantly reduce the total amount of environmental impacts over the entire chain. Only for terrestrial ecotoxicity and aquatic ecotoxicity does the total impact reduction through loss treatment reach 14% and 10%, respectively. For all other impact categories, the reduction is less than 5%. This seems to be a main characteristic of the French fry supply chain. This might appear surprising but it can be explained by the fact that the chain stages with the highest proportion of total losses (i.e., agricultural production, processing industry phase 1, and wholesaler, accounting for 56%, 26% and 13% of losses, respectively) have the lowest shares of environmental impact. Conversely, the stages with the highest proportion of impacts (i.e., household and processing industry phase 2) make only minor contributions to total food losses (i.e., 5% and 0% respectively). Thus, neither loss reduction nor loss treatment (avoided environmental burdens) are meaningful approaches to optimize the French fry supply chain, at least in the case of Switzerland.

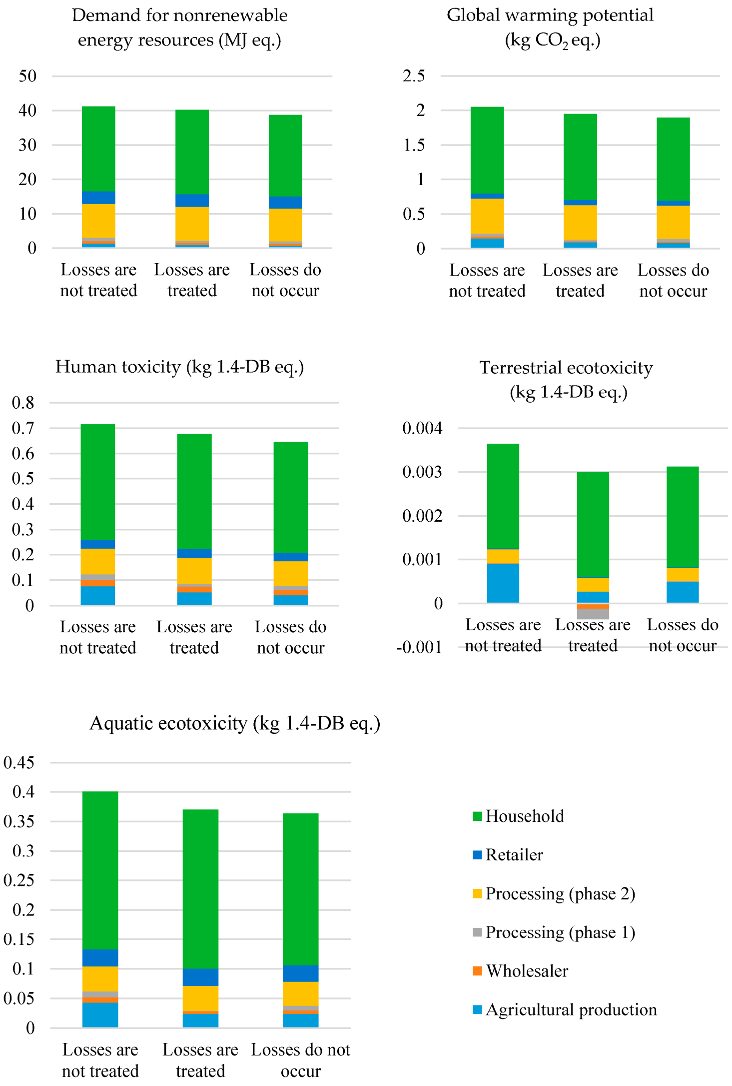

Figure 2. Contribution of the supply chain stages to environmental impact categories per kg potatoes consumed as French fries for the current situation without and with consideration of loss treatments.

3.3. Hot Spots for Process Modifications

Activities along the supply chain that are major contributors to environmental impacts are described as "hot spots". Such activities have the potential to significantly improve the environmental performance of the chain if a modification of the process is feasible.

Figure 3 shows that, for agricultural production, fertilizer use is a hot spot for improving terrestrial and aquatic ecotoxicity, whereas machinery (production, maintenance and diesel consumption) is crucial for nonrenewable energy resources and human toxicity. At wholesalers, transportation of the potatoes from the farm and the electricity used to run the cooling units in storage facilities are hot spots (Figure 3). In the processing industry (phase 1), wastewater treatment from washing potatoes and natural gas for producing the steam to be used in the peeling machine are hot spots (Figure 3). During phase 2 of the processing industry (finishing activities), the use of natural gas and electricity for heating, the frying oil, as well as the use of frying oil itself cause major environmental impacts

(Figure 3). At the retailer stage, the electricity for cooling units and lighting is the clear hot spot (Figure 3). Finally, at the stage of the household, the use of frying oil and electricity for heating the oil are by far the most important contributors. The production of frying oil dominates the impact categories GWP, human toxicity and terrestrial ecotoxicity. The production of electricity dominates the demand for nonrenewable energy resources and aquatic ecotoxicity. Thus, the frying activity at household and processing industry stages (phase 2) are the main hot spots where the highest effects can be expected in terms of improving the environmental performance of the whole chain. A comparison of different frying oils and their origins is presented in the next section.

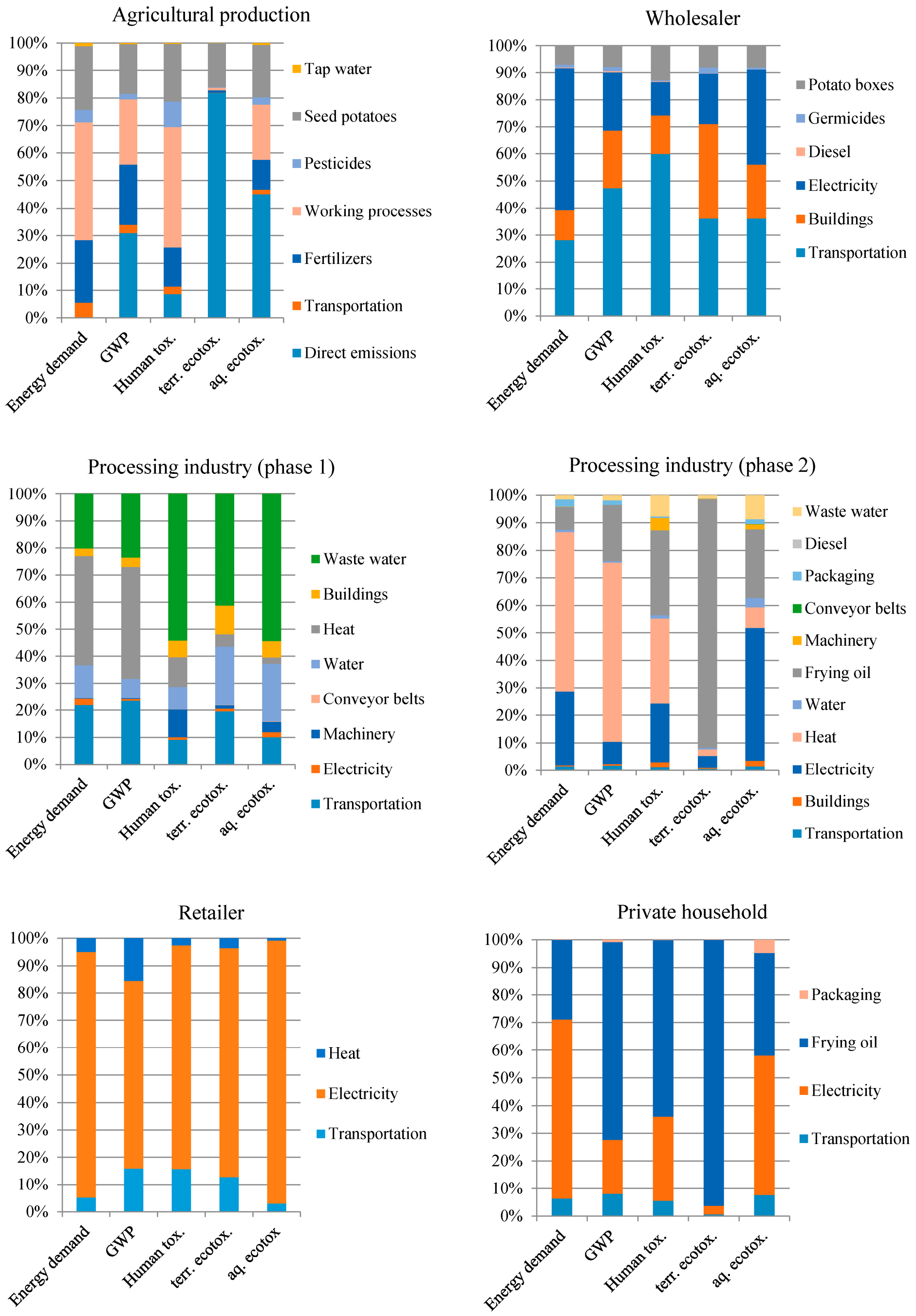

Figure 3. Contributions of the various stages of the Swiss French fry supply chain to the selected impact categories per kg potatoes consumed as French fries. Losses are not treated. GWP = Global Warming Potential; tox. = toxicity; terr. ecotox. = terrestrial ecotoxicity; aq. ecotox. = aquatic ecotoxicity.

3.4. Optimization Potential of Choosing Frying Oils

For the current situation, we assumed that rapeseed oil produced in Switzerland was used in industrial processing (phase 2) for pre-frying the potatoes, whereas in households, sunflower oil produced in Switzerland was used for finishing the French fries before serving. As options, rapeseed oil, sunflower oil and palm oil from main exporting countries were analyzed. Figure 4 shows the environmental impact profile of rapeseed oil produced in Switzerland compared to available options from major exporting countries for oils from rapeseed, sunflower and palm. Rapeseed oil from Switzerland has the lowest impact among the options. Rapeseed global, a mixture of oils originating from the most important export countries worldwide (global export share of rapeseed oil: Canada 44%, France 9%, United States 2%, Germany 2%), has a similar or slightly higher impact compared to Swiss rapeseed. Among the rapeseed exporting countries, Canada and Germany have the lowest impacts compared to the environmental profile of rapeseed from Switzerland.

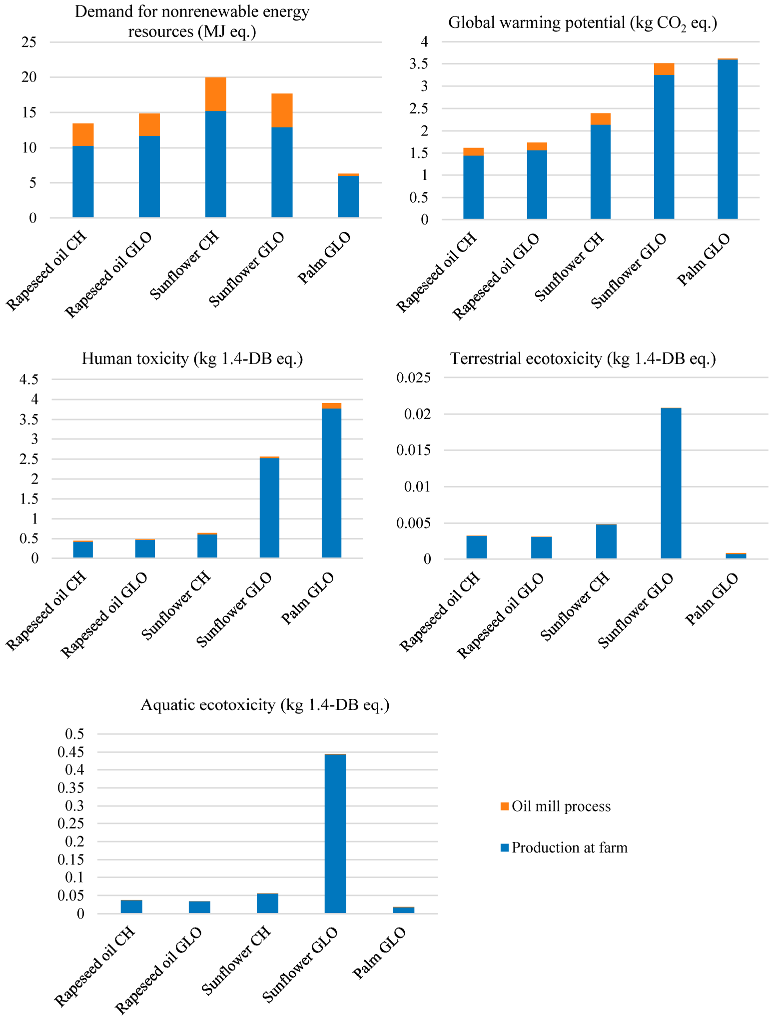

Figure 4. Comparing environmental impacts of different oil types and origins of conventional production per kilogram of oil at oil mill; no transport to the marketplace is considered, CH = seed production and oil mill processes representative of Switzerland; GLO = Global, i.e., a mixture of main producing counties according to their global export share. Rapeseed oil (GLO): Canada 44%, France 9%, United States 2%, Germany 2%. Sunflower oil (GLO): Hungary (18%), France (11%), Ukraine (8%), Russia (3%). Palm oil (GLO): Indonesia (46.7%) and Malaysia (42.2%). Export shares are averages of the years 2008–2010 [49].

Sunflower oil produced in Switzerland (rapeseed oil CH) shows the closest environmental profile to the reference but has disadvantages in terms of nonrenewable energy resources and global warming potential. This disadvantage is mainly caused by the fact that to produce 1 kg of oil takes 3.3 kg of sunflower seeds but only 2.2 kg of rapeseed seeds. Sunflower oil (global mix) with a global export share—Hungary (18%), France (11%), Ukraine (8%), Russia (3%)—shows substantial disadvantages especially for terrestrial and aquatic ecotoxicity as well as for human toxicity. The reason for the greater ecotoxicity in the case of global export countries for sunflower oil is due to higher pesticide use compared to Switzerland, where only herbicides are allowed, as fungicides or insecticides are prohibited in sunflower production. Human toxicity is very high, especially in Ukraine, because of high impact from land use change.

Palm oil (global mix) with a global export share of Indonesia (46.7%) and Malaysia (42.2%) has a similar environmental profile to sunflower oil (global mix). But caution must be exercised with palm oil produced in Indonesia, where burning of primary forest and water drainage are practiced, causing a very high global warming potential (5.8 kg CO_2 eq.) about three times higher than in the case of Malaysia (2.0 kg CO_2 eq.).

3.5. Sensitivity Analyses

The processing industry and the private households were identified as the main contributors of environmental impacts (Figure 2). During processing, heat, electricity, transportation and the frying oil are crucial concerning the LCA results (Figure 3). As the model assumptions which were made on these three parameters might significantly impact total assessment results, we varied the respective input amounts of these three parameters by ±25%. Figure 5 shows the results of this sensitivity analysis. The total supply chain impacts per functional unit vary less than 5% by increasing or decreasing these model assumptions by 25%.

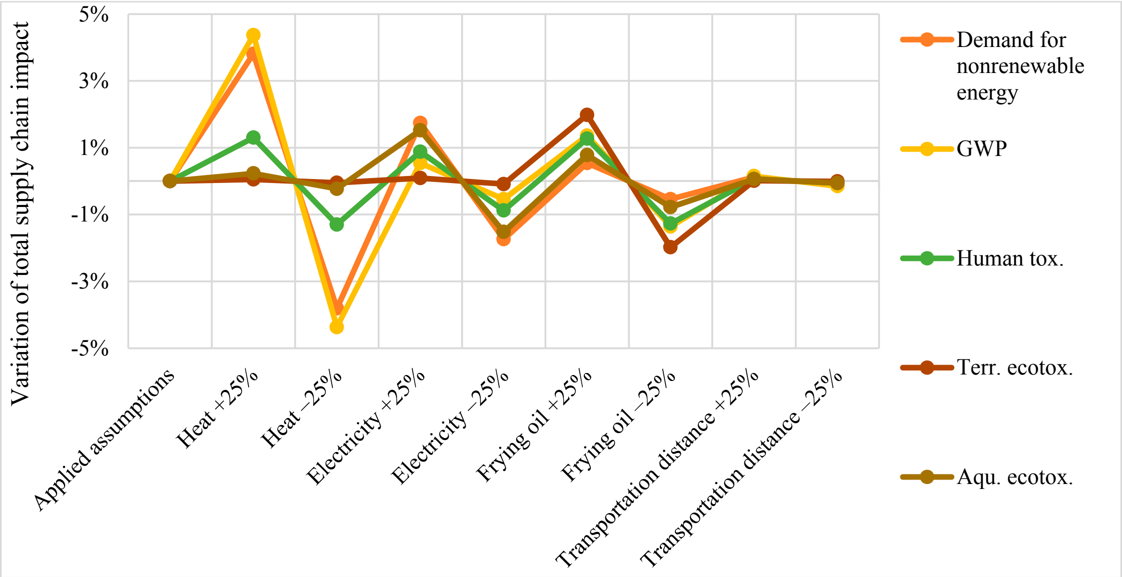

Figure 5. Sensitivity analysis of total supply chain impacts per kg potatoes consumed as French fries by varying the most impactful model assumptions at processing stage.

In private households, electricity and the frying oil significantly impact the LCA results at this particular stage (Figure 3). Thus, on Figure 6, we varied the model assumptions concerning the amount of electricity and frying oil by ±25%. By varying the amount of electricity, the total supply chain impacts per functional unit do not exceed 10%. The impact of the frying oil is bigger. An increase or decrease of the amount of oil by 25% would lead to a total impact variation up to 16%. These results emphasize again the importance of the frying oil concerning French fries. Alternatively, French fries could also be baked in the oven without using any frying oil. This would significantly impact the total assessment results and reduce the total impacts per functional unit by 17%–63%.

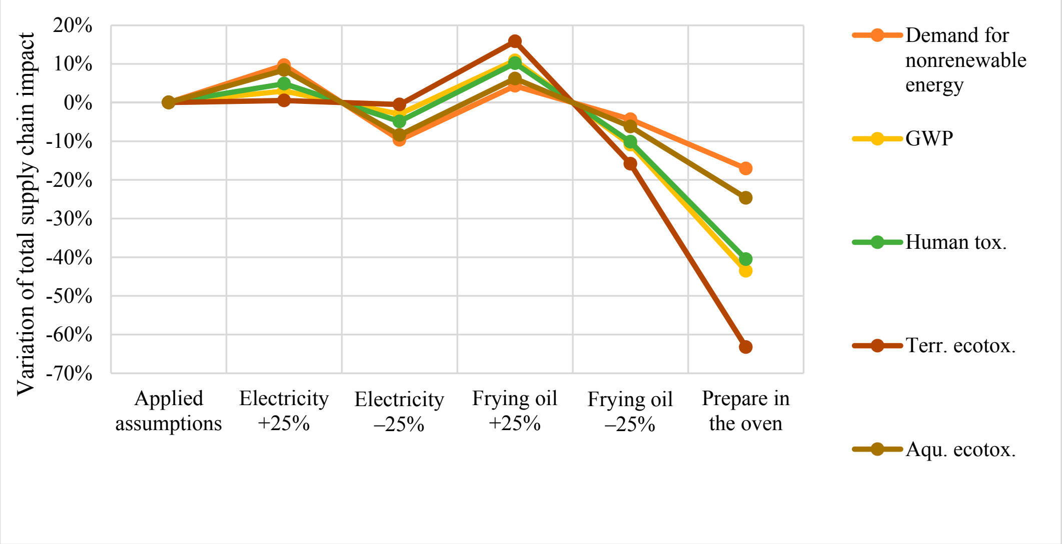

Figure 6. Sensitivity analysis of total supply chain impacts per kg potatoes consumed as French fries by varying the most impactful model assumptions in private households.

4. Discussion

4.1. Environmental Benefits from Loss Reduction

The shares of environmental impacts per kilogram of potatoes consumed as French fries which have been assigned to losses are rather small while the total loss quantity across the entire supply chain is significantly high. According to Willersinn et al. [12], 46% of all harvested processing potatoes (to be used for French fry production) are lost somewhere on the way from the field to the consumer's plate. Our study revealed that these relatively large losses are responsible for 10% of all environmental impacts related to terrestrial ecotoxicity, 7% of human toxicity and aquatic ecotoxicity, 6% of GWP and 5% of the demand for nonrenewable energy resources. Compared with the shares of environmental impacts assigned to fresh potato losses according to Willersinn et al. [13], these shares are rather low. Within the fresh potato supply chain, 39% of terrestrial ecotoxicity, 31% of human toxicity and GWP, 28% of aquatic ecotoxicity and 23% of demand for nonrenewable energy resources refer to potato losses [13]. Thus, the environmental impact reduction potential seems to be higher for fresh potatoes than for processing potatoes. The reason is that processing potato losses occur mostly at the first three stages (i.e., agricultural production, wholesaler and processing industry) of the French fry supply chain, in contrast to the fresh potato supply chain, where considerable losses occur at the last two stages, i.e., retailers and private households [12]. However, this is just one side of the coin. In absolute values, the environmental impacts of French fries are much higher than those of fresh potatoes. It has been estimated that 1 kg of potatoes consumed as French fries on the consumer's plate takes five times more nonrenewable energy resources (41.16 MJ eq. vs. 8.16 MJ eq.) than 1 kg of fresh potatoes at the same stage. Furthermore, its GWP (2.05 kg CO_2 eq. vs. 0.48 kg CO_2 eq.) and terrestrial ecotoxicity (0.0036 kg 1.4-DB eq. vs. 0.0010 kg 1.4-DB eq.) are around four times greater, while human toxicity (0.71 kg 1.4-DB eq. vs. 0.22 kg 1.4-DB eq.) and aquatic ecotoxicity (0.40 kg 1.4-DB eq. vs. 0.13 kg 1.4-DB eq.) are three times greater than for the same amount of fresh potatoes. If we compare the absolute values of the environmental impacts assigned to losses for fresh and processing potatoes, the demand for nonrenewable energy resources related to fresh potatoes is even smaller than for processing potatoes

(–10%). The absolute environmental loss impacts of fresh potatoes compared to processing potatoes for the other observed impact categories are: GWP +21%; human toxicity +28%; terrestrial ecotoxicity +1% and aquatic ecotoxicity +23%. Thus, even though the potential for minimizing environmental impact through loss reduction appears relatively small at first glance, it could be even greater (demand for nonrenewable energy resources) or similar (terrestrial ecotoxicity) than for fresh potato losses if we look at the absolute environmental impacts caused by losses along the entire supply chain. Scholz et al. [8] therefore emphasized the importance of looking not just at loss quantities but also at the environmental impacts of such losses.

4.2. Environmental Benefits from Loss Treatment

If losses occur, loss treatment is very effective to reduce environmental impacts of a supply chain according to [13]. If potato losses are used as animal feed, the effects are most significant on terrestrial ecotoxicity (−150%). For aquatic ecotoxicity, GWP and human toxicity, the reduction potential is 30% to 40%. Using losses for feed is most likely for losses occurring at the agricultural production or wholesaler stages. In the case of Switzerland, a high proportion of potato producers also keep livestock [50] and therefore use the losses on their own farm. In areas with specialized potato farms, which is usual in the main potato-producing countries such as the United States, UK, India or China, additional logistics would be needed to transport the potato losses to feed buyers.

If potato losses are used for energy production in biogas plants, effects are mainly on reducing energy demand (−65%) and GWP (−30%). In Switzerland, biogas plants are usually used for loss treatment at the processing industry, where large volumes of food losses occur.

In the case of incineration with energy-producing technology, similar effects on reducing energy demand and GWP occur as for biogas plants. Incineration as loss treatment is most likely for losses at the private household stage. Despite these positive environmental effects through loss treatment, loss prevention shows a higher environmental impact reduction potential according to the food waste hierarchy [51]. Thus, Bernstad Saraiva Schott and Andersson [52] recommended focusing on loss minimization rather than on the collection and treatment of losses. In addition, Gentil et al. [53] highlighted the advantages of loss prevention compared with loss treatment concerning emission reduction and climate change mitigation.

4.3. Optimization Frontiers

To our knowledge, only one study has assessed the entire French fry supply chain [34]. That study did not consider any losses occurring across the entire supply chain and reports a GWP per kilogram French fries of 2.06 kg CO_2 equivalents which is very close to our study with 1.93 kg CO_2 equivalents if losses (hypothetically) do not occur. The other impact categories were of the same magnitude. In addition, Ponsioen and Blonk [34] identified the frying processes and frying oil as environmental hot spots, even though the oil quantity they assumed was just half of ours. They therefore included other inputs in their study, such as the electricity used for cleaning dishes after meals. Compared with that study, the novelty of ours is that we considered losses which occur along the entire supply chain and that we assigned environmental impacts to those losses.

Regarding the French fry supply chain in our study, it is at the stage of agricultural production that most losses occur (26% of total harvested potatoes). These losses are mainly due to quality standards from the processing industry which reflect the quality preferences of consumers who, for example, have low tolerance to dark spots on French fries. About 8% of the losses at agricultural stage are due to overproduction [12]. Overproduction could theoretically be avoided by lowering the average Swiss production by about 8%. In years with unfavorable weather conditions, imports would be necessary. But imports from the world market would very likely increase the environmental impacts compared to Swiss potatoes, even though losses would decrease. The reason is that Swiss potato producers have about the same environmental profile per hectare while yielding about 2.5 times more per hectare than the main potato-exporting countries according to the World Food LCA Database [42]. The main exporting countries are China, India, Russia and Ukraine, which together account for 47% of global exports (average of 2008–2010; [49]). Thus, there is no real potential to decrease losses at the agricultural stage in the case of Switzerland. Also, at the other stages from wholesaler to private household, loss reduction is difficult to achieve. The processing industry has already adopted loss reduction measures such as modern technology to peel and cut French fries, including the successful market introduction of "mini French fries". At the retailer, and surprisingly also at the private household stage, losses are not significantly high [12].

A promising potential way to reduce the environmental impacts of the Swiss French fry supply chain is to reduce the amount of frying oil used in private households as demonstrated within our sensitivity analysis. There might be room for this improvement, since Ponsioen and Blonk [34] report about 50% lower frying oil use compared to our study. If frying oil use in private households could be halved, the environmental performance of the whole supply chain would improve by about 20%–25% for GWP, terrestrial ecotoxicity and human toxicity. If consumers would bake the French fries in the oven instead frying them, the total supply chain impacts per functional unit could be reduced up to 63%. However, we need to consider that the taste is significantly different between fried French fries and those prepared in the oven.

In order to reduce the demand for nonrenewable energy resources, the impact of electricity use for frying in households is crucial. This could theoretically be achieved by new technologies for frying or by improving the electricity mix, such as lowering the proportion of electricity derived from coal or fossil fuels. We estimate that an environmentally friendly electricity mix might lower the demand of nonrenewable energy resources by about 20%–40%.

4.4. Strengths and Limitations

We conducted a single-product study along the entire supply chain, providing environmental impacts per stage related to all activities as well as information on food loss and food treatment. Hot spots are clearly identified and potential for improvement is discussed. The methods applied are comparable to a previous study [13] on the environmental profile of another potato product (fresh potatoes), thus similarities and differences between French fries and fresh potatoes could be discussed. Most primary data used in our study were collected especially for the purposes of this study and represent the current situation in Switzerland. These are the clear strengths of our study.

Our general conclusions are limited by using primary data from one country. In addition, during the life cycle impact assessment, we did not consider the influence of the packaging of the frying oil on the environmental impacts. Accorsi et al. [18] demonstrated that the packaging could have significant impacts on the LCA results of oils. As a part of this study, we compared different types of oil and we assume that the impacts of the packaging might be identical for rapeseed, sunflower or palm oil and, thus, we could neglect these impacts without influencing the rank order of the different oil types.

Furthermore, food losses also need to be considered from an economic viewpoint, but their costs are usually undervalued or hidden [54]. Especially within supply chains with low margins, effective waste management is essential to maintain or ultimately increase their profitability [55]. In the end, food losses have negative impacts on both producers and consumers [56]. Even though Seuring and Müller [57] stated that a complete sustainability assessment is essential to improve the entire supply chain performance, they also assigned a central role to LCA because it identifies hot spots on which all supply chain participants can work. Thus, our study can be seen as a first step towards a supply chain that performs more sustainably than in the current situation.

5. Conclusions

The environmental impacts of the total supply chain from field to consumer for 1 kg of potatoes consumed as French fries in Switzerland account for 2.05 kg of CO_2 equivalents (global warming potential), 41.16 MJ equivalents (demand for nonrenewable energy resources), 0.71 kg 1.4-DB equivalents (human toxicity), 0.004 kg 1.4-DB equivalents (terrestrial ecotoxicity), and 0.40 kg 1.4-DB equivalents (aquatic ecotoxicity). These environmental profiles for 1 kg potatoes consumed as French fries at the consumer stage are rather high, comparable with values for 1 kg of meat, and 3–5 times higher than for fresh potato. About 70%–80% of total supply chain emissions are caused by the frying processes at the industrial and private household stages. Thus, it is most crucial to prevent food losses and minimize the amount of frying oil and electricity used in the private household. The choice of the type and origin of the frying oil is also crucial. Rapeseed oil shows the best environmental profile, whereas sunflower oil shows disadvantages mainly for ecotoxicity and human toxicity. Palm oil from countries where primary forest is burned or drainage of soil is practiced for palm production (e.g., Malaysia) has huge global warming potential, whereas palm oil produced without land use changes shows a profile comparable to sunflower oil (according to the World Food LCA Database).

Losses from harvested potatoes to the private household add up to 46%; i.e., from 1.84 kg of harvested potatoes, only 1 kg will be consumed. Most losses occur during agricultural production due to quality sorting, but agriculture contributes to only 5%–25% of environmental impacts. In general, because most environmental impacts occur at chain stages where only small proportions of losses occur, loss reduction has only a minor effect on improving the environmental profile. Based on this fact, loss treatment (substitute of animal feed, or energy production by biogas plant or incineration) improves the environmental profile only a little (less than 5%). On the other hand, loss treatment in general is very powerful for reducing the actual environmental impact of losses, as with the 40%–60% in the case of demand for nonrenewable energy resources and global warming potential (GWP).

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Appendix A

Table A1. Inventory data for agricultural production.

Input	Amount Per Hectare Processed Potatoes		Source
Seed potatoes	3238	kg	Keiser et al. [25]
Fungicides	8174	g	Keiser et al. [25] and specifications from SALCA database
Herbicides	2776	g	
Insecticides	42.75	g	
Slurry (cattle)	7.05	m^3	Keiser et al. [25]
Slurry (pork)	1.19	m^3	
Feces (poultry)	0.6	m^3	
Cow dung	4.05	t	
Horse dung	0	t	
Poultry dung	0.29	t	
Nitrogen	90.73	kg	Keiser et al. [25] and specifications from SALCA database
Phosphorus as P_2O_5	40.35	kg	
Potassium as K_2O	201.5	kg	
Surface water	213	m^3	Keiser et al. [25]; Weber et al. [58]
Underground water	172	m^3	Keiser et al. [25]; BFS [27]
Tap water	75	m^3	

Table A2. Inventory data for storage of 1 kg potatoes at wholesalers.

Inputs	Amount	Unit	Source
Transportation from farm	30	km	Own calculations based on personal communication with a wholesaler and Kellenberger et al. [28]
Building (storage building)	0.000014	m^2	
Demand for land	0.0015	m^2/year	
	0.00006	m^2/year	
Land transformation	0.00003	m^2	
	0.00003	m^2	
Inputs phase			
Electricity for storage	0.032	kWh	Own calculations based on Uhlmann et al. [30]
Germicides	0.018	g	Omya [31]
Loading of boxes with a forklift	1.00×10^{-3}	MJ	Own calculations based on Uhlmann et al. [30]
Potato boxes	0.00025	p	
Outputs phase			
Potatoes	1	kg	
CIPC—Emissions to water	1.80×10^{-2}	g	Bos et al. [59]
CIPC—to air	2.00×10^{-3}	g	Kerstholt et al. [60]

Table A3. Inventory data for processing of 1 kg French fries at processing industry.

Inputs	Amount	Unit	Source
Transportation from wholesaler	50	km	Own calculations based on Verbund et al. [61] and Kellenberger et al. [28]
Building (processing building)	0.00001	m^2	
Demand for land	0.0016	m^2/year	
	0.00007	m^2/year	
Land transformation	0.00003	m^2	
	0.00003	m^2	
Inputs phase (1)			
Electricity	0.002	kWh	Own calculations based on Boema S.p.A. [62], Eima [32] and Uhlmann et al. [30]
Heat	0.25	MJ	Own calculations based on personal communication with a project engineer
Water	18	kg	Personal communication with a potato processor
Machinery	0.00002	kg	Own calculations based on personal communication with a project engineer
Conveyor belts	6.91×10^{-9}	m	
Outputs phase (1)			
Raw potato strips	1	kg	
Wastewater	0.018	m^3	Own assumption
Inputs phase (1I)			
Electricity	0.32	kWh	Ponsioen and Blonk [34]
Heat	4.75	MJ	Calculations based on Foster et al. [33] and personal communications
Frying oil	0.05	kg	Personal communication with a potato processor
Packaging material (PET bag, film)	0.0041	kg	
Packaging material (paperboard)	0.03	kg	
Machinery	4.53×10^{-5}	kg	Calculations based on personal communication with a project engineer
Conveyor belts	6.91×10^{-9}	m	
Loading of boxes with a forklift	0.001	MJ	Calculations based on Uhlmann et al. [30]
Outputs phase (1I)			
French fries	1	kg	

Table A4. Inventory data for 1 kg processed potatoes at retailers.

Inputs	Amount	Unit	Source
Transportation from wholesaler	50	km	Personal communication
Electricity	0.37	kWh	Nielsen et al. [35]
Heat from natural gas Heat from mineral oil	0.05 0.08	MJ MJ	Nielsen et al. [35]; Bachmann et al. [63]
	Outputs		
French fries	1	kg	

Table A5. Inventory data for 1 kg processed potatoes in private households.

Inputs	Amount	Unit	Source
Transportation from retailer	4.7	km	BFS [40]
Electricity	1.8	kWh	Own calculations based Franke et al. [37] and manufacturer's specifications; Sonesson, et al. [38]
Frying oil	0.4	kg	Own calculations based on Franke et al. [37], DGF [39] and manufacturer's specifications
	Outputs		
French fries	1	kg	

Appendix B

The following assumptions were made:

- Tractors with two-tire trailers transport potatoes from farm to wholesaler. Average transportation distance from farm to wholesaler was calculated (weighted average) based on information from two Swiss potato wholesalers (30 km).
- Storage occurs in wooden boxes; filling weight: 1 ton; weight of each box: 55 kg; useful life: 10 years [30].
- Average storage duration (under cool conditions): 125 days; packing density: 338 kg/m^3; energy consumption: 10.8 kWh/m^3/year [26].
- Used germicide: Gro-Stop HN (active ingredient: 23.4% CIPC; contains 50%–70% dichloromethane; maximum application rate: 60 mL/ton; mass density of CIPC: 1.28 g/mL). Emissions to air: 11% of the CIPC [59]; emissions to washing water: 10% of the CIPC [60].
- Trucks (20–28 tons effective load) transport potatoes from wholesaler to processing industry; transportation distance: 50 km (personal communication with a potato processor).
- Trucks (20–28 tons effective load; cooling system integrated based on data of Tassou et al. [64]) transport potatoes from processing industry to retailers (average transportation distance according to four retailers: 50 km).
- Water input for potato washing and processing equals water output.
- Machines consist of 100% stainless steel.
- In private households, French fries are stored in a freezer: average energy consumption: 0.27 kWh (calculated on models according to Sonesson, Janestad and Raaholt [38]; model assumptions: large freezer: 270 L; small freezer: 120 L; average storage time: 15 days; storage density of French fries: 420 kg/m^3 [65]; volume of all products comprises 80% of freezer's volume).
- In private households, French fries are fried in a deep-fryer: oil volume: 22 L; heating power: 1.82 kW (average calculated according to Franke and Strijowski [37]).
- Heating period and frying time: 18 min [66].

- Oil consumption for frying: 0.4 L/kg French fries (calculated on following assumptions: fat uptake of French fries: 9%; ratio of food to frying oil 1:10 [39]; changing fat after seven frying cycles [67].

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