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Calculating the energy and water use in food processing and assessing the resulting impacts

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Abstract

Purpose The food processing industry is a major consumer of energy and water, the consumption of which has environmental impacts. This work develops a method to determine process-specific water use and utilizes an existing energy use toolbox to calculate the energy and water required for each step of food processing. A life cycle assessment (LCA) is conducted to determine how much processing contributes to a particular product's cradle to gate impacts for two impact categories.

Methods A method to determine water use at each unit process was developed, and in conjunction with an already developed energy use unit process toolbox, the methods were tested using two case studies. Processing data such as flow rates, operation temperatures, and food losses were used from two Swiss food production facilities. Calculation results were compared to measured facility data such as yearly energy and water use. Results were then used to develop LCAs for a total of seven food products, including five types of juice and two types of potato products.

Results and discussion The toolboxes were able to calculate the water use of both facilities within 25%, the thermal energy use within 9%, and electricity use within 24%. Impacts from processing were particularly important for the potato products, particularly potato flakes, due to impacts stemming from thermal energy use. For juices, impacts due to raw material growth dominate the LCA, and impacts due to processing are much less significant. A unit process analysis may not be necessary when there is little variation in the unit processes between the different products. In this case, a simple allocation of measured facility energy and water data may be sufficient for calculating the impacts associated with processing. However, products with largely varying unit processes may have very different impacts. Impacts are sensitive to the type of energy required (thermal or electrical) and the sources of electricity and water.

Conclusions These water and energy toolboxes can improve transparency in processing and identify the most water- and energy-intensive steps; however, in facilities with similar products, such an extensive analysis may not be necessary. Results from these calculations are useful in developing food product LCAs.

Keywords Energy demand · Food processing · Juice processing · Potato processing · Water consumption

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1 Introduction

Processing of foods is done in order to extend storage life, offer increased consumer convenience, develop new food products, and improve the taste and texture of unprocessed materials (Singh 1987; Pardo and Zufía 2012; Fellows 2009). Processed food requires inputs in the form of raw material, transport, processing energy (thermal and electrical), and clean water. Though much research has been done on agricultural impacts associated with growing food, the considerable use of energy and water in food processing (Canning et al. 2010; Masanet et al. 2008; Carlsson-Kanyama and Faist 2000), and its contribution to environmental impacts (in terms of climate change, respiratory effects from particulate emissions, acidification, toxicity, water stress, etc.), is less studied (Sanjuán et al. 2014; Roy et al. 2009).

Notarnicola et al. (2015) has conducted a literature review of various life cycle assessments (LCA) and case studies associated with food production and processing and summarized the results, best practices, and methodologies in several food sectors (olive oil, wine, cereals and derived products, livestock, and fruit). While this review offers impacts for crops or products under many growing conditions, with different functional units, and for many impact categories, detailed information on processing is lacking. Recently, several food inventory databases were published, such as the World Food Database (Nemecek et al. 2014) and the AGRIBALYSE v1.2 database (www.ademe.fr), which include some manufactured food products and include processing data; however, in both the literature review and databases, there is little information that includes in-depth manufacturing data that can be applied to other food products. Several other papers on LCA of some processed food items have been published, such as energy in the olive oil production chain (Cappelletti et al. 2014), the environmental impacts of breakfast cereals and snacks (Jeswani et al. 2015), or as summarized by Roy et al. (2009).

The relevance of food processing in the food chain depends on many factors such as the impact being considered or the system boundaries set in the life cycle assessment. In the case of olive oil (Cappelletti et al. 2014), it was determined that the majority of the required energy is used to grow the olives, particularly in the production of fertilizers, and little energy is associated with the oil extraction (however, other unit processes and packaging are not considered). While this study provides energy embedded in each liter of olive oil, it stops short of assessing the environmental impacts associated with either the energy or water use, which would be highly dependent on the water scarcity of the region and type of electricity used in production. The results of Jeswani et al. (2015) found that the major contributors to the product's climate change impacts were both ingredients and energy use in processing. The water footprint of the cereal products was largely driven by crop irrigation requirements and less by processing water demands. However, the majority of processing facilities were located in countries with little water scarcity, which can lessen the severity of the water footprint impacts.

Current processor's data often do not include energy or water use at the unit process level, but instead include energy and water consumption for the factory as a whole (Cooke 2008). Because processors generally produce a variety of products, one cannot easily separate the energy and water use (and associated environmental impacts) of one particular product from the total energy and water use of the facility (International Dairy Federation 2010), as was seen in Jeswani et al. (2015), where all produced products were analyzed as one. Typically, product-specific information can then be interpreted through an LCA, as has been summarized by Roy et al. (2009). Food product-related LCAs have typically measured climate change impacts (Heller et al. 2013); however, current research shows the importance of including water stress and availability in a food impact assessment (Stoessel et al. 2012; Ridoutt and Pfister 2013).

This paper develops on the energy toolbox proposed by Sanjuán et al. (2014) by offering methods for calculating the water required to produce the final food product based on the unit processes required for manufacturing. This allows for the following: (a) transparency and reproducibility in determining energy/water use per type of product produced instead of the typical "black box" energy/water use widely used in food processing (Sanjuán et al. 2014), (b) data that allows for evaluation of the most energy/water intensive unit operations and therefore chances to evaluate process optimization, and (c) product-specific energy and water use. Both Sanjuán et al.'s (2014) energy toolbox and the water demand calculation methods developed here, based on the proposal of Sanjuán et al. (2014), are tested through two case studies. Results are then interpreted through LCAs using two impact categories (climate change and water stress) to determine the contribution of processing to the products' LCA and to compare the differences in impacts between various food products produced by the same facility.

2 Methods

2.1 Unit process calculations

2.1.1 Energy

A toolbox for unit process energy calculations has been developed by Sanjuán et al. (2014). This toolbox requires input information such as food properties (e.g., specific heat), process-specific parameters (e.g., temperature), and equipment motor size. Electricity (for cold processes and motors) and thermal energy (for heating processes such as drying, cooking, frying, pasteurization) (Marcotte and Grabowski 2008) requirements for each unit process can be calculated using this toolbox. Equations regarding calculation information for each unit process are included in the Electronic Supplementary Material.

2.1.2 Water

A similar toolbox to determine water demand per unit process does not exist. This paper develops a method of estimating unit process water demand based on the food products produced, type and size of equipment used, size of the facility, and cleaning practices. A decision diagram isolating the five main steps in determining unit process water demand is shown in Fig. 1. Each step is further described below.

Step 1: Identify processing equipment that requires water

The first step is to identify any processing equipment that requires water and verify the water flow rate required, operation time per year, and product flow rate using either equipment manuals or measured water use rates. The following equations can be used to estimate water use for each unit process:

$$W_{\mathrm{y}} = W_{\mathrm{r}} \times t \quad (1)$$

$$t = \frac{TP}{F} \quad (2)$$

W_{y} represents yearly equipment water use (m^3/year), W_{r} is the equipment water use rate (m^3/h), t is operating time (h/year), TP is total throughput of product through equipment (kg/year or l/year), and F is the product flow through rate (kg/h or l/h). The unit kilogram per year is used in the case of solid foods, while the unit liter per year is used in the case of liquids such as juices.

Common unit processes requiring water include washing, peeling, thawing, milling, blanching, and container washing. Chosen washing methods depend heavily on the end product as well as how dirty the incoming product is. Root vegetables may require pre-washing, drum washing, and then polishing in order to maximize dirt removal (Kader 2002); whereas, more delicate items such as lettuce and berries require a gentler process (i.e., belt-driven spray washer) (Sinha 2012). In order to estimate water use, several variables need to be considered. If the product is being sold raw (i.e., lettuce) and will not undergo further heat processing, wash water requirements will be higher, as water reuse is less possible because of decreasing water quality with repeated reuse (Lehto et al. 2014). If the washing process involves the use of sanitizers and antimicrobials (UV technology, addition of acids, etc.), water reuse becomes a more feasible option and therefore can significantly lower the water requirements (Gil et al. 2009; Center for Food Safety and Applied Nutrition (U.S.) 1998). In some situations, product washing is combined with product transport through the use of a flume (BREF 2006). Often, this flume water is obtained from the wastewater of other processes. If this is the case, water use should only be attributed to the unit process where it was initially used. In the case of sugar beets, flume water can be generated as a byproduct of the water in the produce itself (ILSI Europe Environmental and Health Task Force 2008), which would lead to an input of water into the system rather than the other way around.

In meat and fish processing facilities, often the product comes to the processor frozen and requires thawing prior to further processing. Thawing can be completed without the use of water using a controlled air temperature; however, this is a time-intensive process. Other thawing methods include the use of an intermittent shower or immersion of the product into a water bath, where water can be recirculated (EBMUD 2008; Ölmez 2014). Agitating the water with compressed air can reduce water consumption by approximately 40% (James et al. 2014).

Peeling is the removal of the outer layer of a fruit, vegetable, or grain in order to access the inner tissue (Cleland and Valentas 1997). Peeling methods include wet or dry caustic peeling, steam, abrasion, or knife, the water requirements of which vary. Often, peeling is combined with product or waste transport, as water for knife peeling is required to keep the waste products moving away from the blades.

Processes requiring fine milling or other motor operations can require a water source in order to cool the equipment as it is operating.

Water use required for blanching depends on the type of blancher, the method of product cooling, and whether or not blanching water is reused. Combinations of steam, water, and air can be used to heat and cool the product. Water reuse may be possible in certain situations; however, in the case of many vegetables, sugars and other nutrients are leached during blanching, and continuous reuse of this water will affect the results (Kozempel et al. 1985) (Ozilgen 1998). Water use depends on product residence time; longer residence times require more intensive water use (Kozempel et al. 1985).

At facilities where products are bottle or canned, container washing can be a high water user (ILSI Europe Environmental and Health Task Force 2008), and it is estimated that almost 50% of wastewater produced from the beverage industry comes from the process of bottle washing (Haroon et al. 2013; Camperos et al. 2004). Water consumption due to washing can vary depending on the type of beverage packaging (i.e., returned glass bottles or new cans, kegs) being used (Tokos and Glavič 2007). However, water associated with washing can be collected and reused (in pre-wash cycles or elsewhere) (Camperos et al. 2004). These facilities must also consider belt lubrication for smooth container movement. While dry lubrication is becoming more common, many facilities still require water as a lubricant at the rate of about 0.54 l water/kg product (Colston and Smallwood 1974), or 5% of the facility's water use (ILSI Risk Science and Innovation Application 2013). Typical rates of water consumption for each of these processes are included in the Electronic Supplementary Material (Table S1 and S3) and should be used if facility-specific information is not available.

Step 2: Determine water required in the final product

This step accounts for water demand in the final product, which varies depending on the industry. Dairy and meat

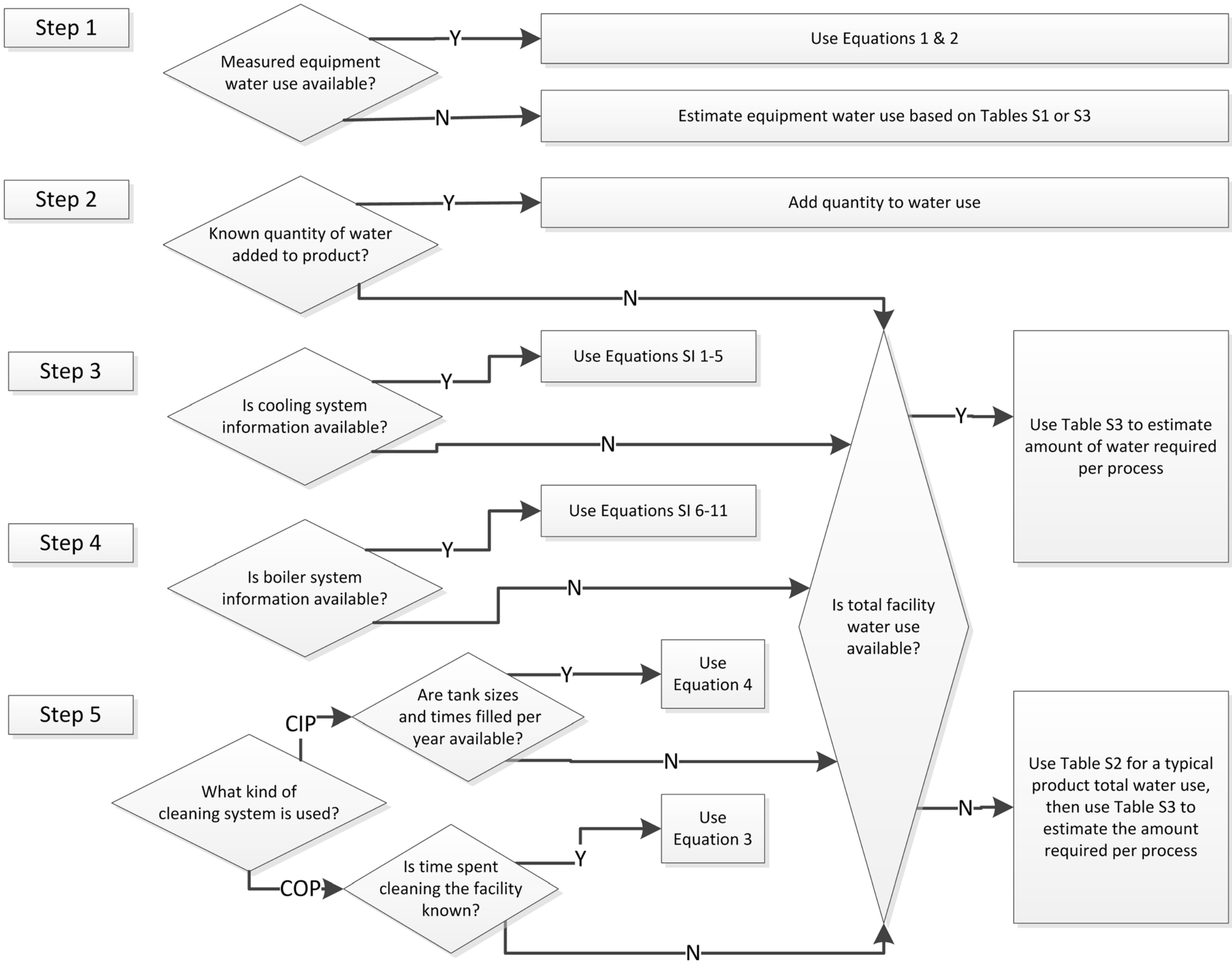

Fig. 1 Flow diagram for determining water demand per unit process. *SI* refers to Electronic Supplementary Material

processors typically do not add water to the final product, whereas water added to the product can be substantial for baked goods, canned goods, and beverages. Food labels on products or recipe data from the processor can be used to estimate the amount of water added to the product, if this information is available. If it is not available, a top-down approach from the processor's yearly water demand can be used based on the product manufactured and typical recipe water demand percentages (Table S3—Electronic Supplementary Material).

Step 3: Evaluate water needs of the cooling system

This step accounts for water demand in the processor's cooling system. Open recirculating evaporative cooling systems use water to remove heat from certain processes (i.e., refrigeration units). In these systems, the heated water moves to the cooling tower, where it is lost as evaporation. Water that does not evaporate becomes concentrated with salts, and this brine is eventually lost through blowdown. Equations for calculating makeup water demand are in the Electronic Supplementary Material or can be estimated using a top-down approach as a percentage of the processor's yearly water use (between 2 and 27% depending on the product, Table S3—Electronic Supplementary Material).

Step 4: Evaluate water needs of the boiler system

This step accounts for water demand in the boiler system at the processor. Boilers at processing facilities provide the thermal heat (plant steam) required for processing. Steam used by food processors can fall into two categories—culinary and plant steam. Culinary steam is used for direct injection into the product or to clean/sterilize product contact surfaces, and therefore, all steam is lost in the product or through evaporation. Plant steam is used as indirect heating; the water can be recovered as condensate or unused steam and returned directly to the boiler for reuse. In this case, certain system water losses (blowdown, steam losses) must be considered. Details for calculating boiler makeup water, based on cycles of concentration, are in the Electronic Supplementary Material. If information about the boiler is unknown, the water demand for water losses can be estimated to be between 1 and 3% (but up to 15% in some cases) of the total steam output of the boiler system (Wang 2008) or can be estimated as a percentage of facility water use (between 1 and 11% depending on product, Table S3—Electronic Supplementary Material).

Step 5: Determine the processor's cleaning methods

Cleaning of the processing equipment and facility can be a major contributor to the processor's water demand. Strategies for equipment cleaning may be classified in two groups: cleaning out of place (COP) and cleaning in place (CIP). In COP operation, the equipment is disassembled as much as needed to expose all possibly soiled surfaces (Berk 2009). The parts are rinsed, cleaned, sanitized, and reassembled. Facility cleaning, which includes surfaces such as floors, walls, and ceilings, is usually done manually with the aid of hoses, pressurized water, and/or sprays and can also be calculated using Eq. (3).

$$W_T = t_{\text{day}} \times S \times n \tag{3}$$

COP water demand estimates (W_T [m^3/year]) can be based on the amount of time spent cleaning the facility (t_{day} [hours/day]), the flow rate from the water source (S [m^3/h]), and number of days spent cleaning (n [days of facility operation per year]) (Eq. (3)).

CIP is an automatically performed method of cleaning, applied to remove residues from complete items of plant equipment and pipeline circuits without dismantling or opening the equipment. The system works by circulating chemical (detergent and disinfectant) solutions and rinsing water through food production equipment (tanks and piping) that remain assembled in its production configuration and by jetting or spraying the product contact surfaces under conditions of increased turbulence and flow velocity (Moerman et al. 2014). CIP systems are commonly found in dairy, beverage, and brewery plants. The installation of these systems allow for CIP cleaning solution to either be used once (single use CIP) and then disposed, or for cleaning solution reuse (reuse CIP). Water use can change significantly with reuse (SPX White Paper 2013), as these systems can reduce water and chemical consumption up to 50% (Ölmez 2014) when compared to single use systems. Typical CIP systems consist of a pre-rinse with water, a caustic cleaning, intermediate rinse, acid cleaning step, and a final rinse (Sanjuán et al. 2011); however, one-stage CIP (which eliminates the acidic cleaning agent and the subsequent rinse) can reduce water use by 40% when compared to a conventional system (Sanjuán et al. 2011). In facilities where there is little change between products, cleaning is not required as frequently as a facility where different products use the same processing line.

$$W_T = \Sigma\, V_i \times t_{i\text{year}} \tag{4}$$

Yearly water use estimates for cleaning with CIPs (W_T [m^3/year] per CIP tank) can be based on the sum of the facility's CIP tank sizes (V_i [m^3]) and the number of times each of these CIP tanks are refilled with new water/cleaning solution ($t_{i\text{year}}$ [times tank is filled per year]), as shown in Eq. (4). If information about the cleaning method or size of CIP tanks is unknown, the water demand for cleaning can be estimated as a percentage of the facility water use depending on the product type (Table S3—Electronic Supplementary Material).

2.2 Case study

The water and energy unit process calculation methods were tested through two case studies from Swiss-based food processors. One case study involved the processing of several non-concentrate juices and one case study involved the processing of various potato-based products. These processors were chosen not only because of data availability but also because of the wide range of unit processes that the two facilities cover.

The goals of the LCA were twofold. First, the LCA determined the contribution of processing on a food product's impacts. Second, it compares the differences in impacts between various food products produced by the same factory. System boundaries of the LCA (Fig. S1—Electronic Supplementary Material) included inputs for growth of the raw material, transportation of the raw material to the processor and the final product up to the point of distribution, and energy and water use associated with processing.

The functional unit was defined as 100 kcal as provided by the finished product. The motivation for this choice of functional unit was that, although food has many purposes, its primary function is to provide energy, and this unit links the different products analyzed, while disregarding weight or volume changes due to processing effects. All results were also calculated for the reference flows of 1 kg for potato products and 1 l for juices.

The food processors provided detailed information about their equipment operating temperatures and flows, raw material input and product output weights or volumes, and facility-wide annual water use, electricity use, and thermal energy use based on factory records and utility bills. Using this information, energy and water use per unit process and per product were calculated using the methods described above.

Process flow diagrams (Fig. S1—Electronic Supplementary Material) were developed based on a tour of the facilities and interviews with factory managers. To calculate the energy use per unit process, the toolbox developed by Sanjuán et al. (2014) was utilized. Uncertainties in the energy calculations were based on variations in unit process flow rates, operation temperatures, food properties, heat losses, and equipment efficiencies (Electronic Supplementary Material, Tables S4 to S15). Steps 1 through 5 were followed to calculate the water demand per unit process, with the details and assumptions shown in Table 1. Uncertainties in the water demand calculations were captured through the use of minimum and maximum water demand values per unit process as determined by either water use of similar facilities or by water use of similar unit process equipment (Table 1). Where measured unit process energy or water use was provided by the facility, no uncertainties were included.

In order to determine the calculated facility-wide energy or water use to compare against the utility bills, a weighted sum of the product-specific calculated values, based on final production percentages (Tables 2 and 3), was determined and compared to the measured facility-wide values (Table 4). Measured values were determined by taking the total measured facility energy or water use (as provided by utility bills or facility records) and dividing by the total kilograms of product produced by the facility. This measured value cannot differentiate between products, as measured energy or water use is only available for the entire facility.

In processing calculations, for each unit process, energy or water use was calculated per kilogram of the product at that point in the processing. In order to determine the total energy or water required for the production of one reference flow, the energy or water use per unit process needs to be adjusted by the reference flow correction number shown in Tables 2 and 3. For example, in Table 2, potato transport/washing requires 6.5 l of water per kilogram of raw potato; however, 2 kg of raw potatoes are washed for every 1 kg of french fries produced due to losses through sorting, peeling, and cutting. These reference flow correction numbers were determined based on mass flow diagrams developed from the manufacturers' data on estimated losses at each unit process. To determine the calculated energy or water use for the end product (e.g., 1 kg of french fries), the energy or water use at each unit process is summed after correcting for the final reference flow (i.e., for 1 kg of french fries, transport/washing water demand use was 6.5 l/kg raw potato × 2.0). The final energy or water use values per reference unit are referred to as the "calculated values" in Tables 2 and 3 and are used as input into the LCA calculations.

Transport is based on distance, type of truck/tractor/ship utilized, and refrigeration requirements (Wild 2008) (Table S16, Electronic Supplementary Material). Regionalized electricity, thermal energy, and water impacts are based on the Ecoinvent 3.2 database (Ecoinvent Life Cycle Inventory Database 2014). Details of the life cycle inventory are in Table S17 (Electronic Supplementary Material). Production of packaging material, other ingredients, and chemicals used in processing were not included based on limited available data; however, the impact of new glass bottles for juice packaging can be a large part of the total juice impact (Accorsi et al. 2015).

Inventory inputs for raw material and initial transport (origin and transportation distances shown in Table S16—Electronic Supplementary Material) are adjusted to account for losses during processing (Table S17—Electronic Supplementary Material), and are calculated based on facility data. Inventory inputs for processing energy are taken from the calculated values in Tables 2 and 3. Inventory inputs for water were taken from the calculated values in Tables 2 and 3 and adjusted to include only consumptive water.

For the juice processor, some juice is fully processed at the facility (arriving as whole fruits/vegetables), while other juices are pre-processed (up to and including pasteurization) at an off-site processor. When pre-processed juices arrive at the Swiss facility, they are pumped into aseptic storage tanks before entering the bottling process. Approximately 5% of the imported juices are re-pasteurized. When completing the LCA, energy and water demands for pre-processed juices are accounted for as "off-site." Inventory inputs for energy and water use for off-site processors are based on the Swiss facility's energy and water use (up to and including pasteurization). Impacts, however, are based on the country in which the processing took place.

Two impact assessment methods (IPCC 2013 GWP 100a Version 1.0 (IPCC 2006) and Water Scarcity V1.02 (Pfister et al. 2009)) were utilized. The IPCC Global warming potentials (GWP) were used as characterization factors for assessing impacts due to climate change, using the software SimaPro 8.0.5.13 developed by Pré Consultants, which does not consider impacts due to biogenic carbon dioxide. Impacts for the water scarcity (WS) method are calculated only for consumptive water (Ridoutt and Pfister 2013). For the juice facility, typical industry-specific evaporative losses were used (25% of total water demand) (Vionnet et al. 2012). For the potato facility, consumptive water demand was determined by comparing the yearly facility water demand to the measured discharge water flow,

Table 1 Analysis of the five water demand steps as conducted for the case studies

Step 1: Identify unit process equipment and determine individual water use			
		Minimum	Maximum
Juice	Washer/destoner	1.5 m^3/h (equipment manual, provided by facility)	
	Fine miller	10 m^3/h (equipment manual, provided by facility)	
	Bottle rinser	2 m^3/h (equipment manual, provided by facility)	
	Line lubrication (wet)	6.5% of facility water use[a,b]	5.40E-4 m^3/l juice[b]
Potato	Washing/transporting (flume)	0.005 m^3/kg potato[c]	0.008 m^3/kg potato[c]
	Steam peeling (batch, 16 bar)	0.001 m^3/kg potato[c]	0.002 m^3/kg potato[c]
	Water blancher (no water reuse)	0.00025 m^3/kg cut potato (provided by facility)	
Step 2: Recipe water required. No recipe water required for both facilities			
Step 3: Cooling system information			
	Minimum	Maximum	
Juice	1.3% of facility water use for similar facility[a,b]	5.5% of facility water use for similar facility[a,b]	
Potato	5% of facility water use for similar facility[b]	24% of facility water use for similar facility[b]	
Step 4: Boiler system information			
Juice	2.5% of total facility water use for similar beverage facilities[a,b]	15% of total facility water use for similar beverage facilities[a,b]	
Potato	1% of boiler steam output (Wang 2008)	Up to 15% of boiler steam output (Wang 2008)	
Step 5: Cleaning system			
Juice	63% total facility water use for similar facilities utilizing COP as a cleaning method[a,b]	74% total facility water use for similar facilities utilizing COP as a cleaning method[a,b]	
Potato	12% of facility water use (provided by facility)		

[a] Facility water use percentages were adjusted for no recipe water use condition

[b] Table S3, Electronic Supplementary Material

[c] Table S1, Electronic Supplementary Material

which indicated that 21% was lost through evaporation during processing.

3 Results

3.1 Unit process energy and water demand of food processing stage

Calculated unit process energy and water use for products produced at both the potato and juice facilities are shown in Tables 2 and 3, respectively. Based on the calculated results for the potato facility, the most intensive thermal energy user is the drum dryer in the flake production line, the largest electrical energy draw is the freezing operation for the french fry line, and the potato washing/transport has the largest water demand. Potato flakes require more thermal energy per kilogram of product than french fries (7.23 vs. 3.51 MJ per kilogram of product, respectively), driven by the need for the drum dryer, and french fries require more electricity per kilogram of product than potato flakes (1.41 vs. 0.08 MJ per kilogram of product), driven by the need for freezing. Water use per kilogram of product was similar for potato flakes and french fries, as the major water demand is for washing/transport, a unit process that is utilized by both products.

In the potato analysis, energy use uncertainties are the largest for the steam peeling unit process. Energy use for this process is based on a published range of typical energy requirements from a similar batch steam peeler, as information regarding the facility's batch steam peeler was not available. However, because steam peeling requires so little thermal energy when compared to other processes (i.e., dehydration or frying), this higher uncertainty has little effect on the calculated facility-wide energy uncertainties. Energy use uncertainties for other unit processes such as blanching, dehydration, drying, and freezing (all calculated based on facility operation details) were considerably lower. Water demand uncertainties are the largest for boiler makeup, which are based on typical boiler makeup ranges as a percentage of steam output (Table 1). Even though boiler water use had high uncertainties, its contribution to facility-wide water demand uncertainties is low because this process requires so little water in comparison to other unit processes, such as washing/transport or cleaning water.

Juices with the lowest import rates (i.e., carrot at 28%, potato at 40%, and beetroot at 72%) required higher energy and water demands per liter produced, while juices that were imported at 100% (i.e., pineapple, tomato, orange, and apple),

Table 2 Unit process energy and water demand for the potato facility (per kilogram)

Potato unit processes	Reference flow correction		Energy use (MJ/kg input at unit process)		Water use (l/kg input at unit process)
	French fries	Potato flakes	Thermal	Electrical	
Raw material storage, washing, transport	2.0	1.80		0.0005[a]	6.5 ± 1.5[e]
Sorting and calibration	2.0	1.80		3E-3 ± 4E-5[c]	
Steam peeling	1.77	1.80	0.29 ± 0.14[a]		0.15 ± 0.05[e]
French fry cutter	1.37	0.0		0.001 ± 1.5E-4[c]	
French fry sorting	1.37	0.0		3E-3 ± 4E-5[c]	
Blancher	1.33	0.0	0.24 ± 0.033[b]	0.003 ± 0.0004[b]	0.25[e]
Frying	1.13	0.0	2.07 ± 0.32[b]	0.06[d]	
Cooling/freezing	1.0	0.0		1.1 ± 0.13[b]	
Flake line cutting	0.0	1.72		0.014 ± 0.002[b]	
Flake production cooker	0.0	1.72	1.05[a]		
Flake line drum drying	0.0	1.72	2.68 ± 0.38[b]		
Refrigeration	1.0	1.0		0.029[d]	
Cleaning water	1.0	1.0			2.15 ± 0.755[e]
Boiler makeup	1.0	1.0			0.121 ± 0.106[e]
Cooler makeup	1.0	1.0			0.772 ± 0.070[e]
Building functions	1.0	1.0	0.34[g]	0.12[g]	0.0[f]
Final production percentages	91.75%	8.25%			
Calculated thermal (MJ/kg product)	3.52 ± 0.65	7.26 ± 0.90			
Calculated electricity (MJ/kg product)	1.32 ± 0.13	0.056 ± 0.002			
Calculated water (l/kg product)	16.8 ± 5.75	15.0 ± 3.69			

[a] Estimate from similar equipment types/processes (Boema 2016) (Masanet et al. 2008; Buchli 2013)

[b] Calculation details in Electronic Supplementary Material Tables S4 through S14

[c] Calculation details in Electronic Supplementary Material Table S15

[d] Value provided by the facility

[e] Averages from min/max in Table 1

[f] Domestic water separate from processing water

[g] 8% of total energy consumption (Okos et al. 1998)

required much lower energy and water demands from the facility, as expected. A hypothetical scenario in which all juices were fully processed at the facility was run. In this scenario, electricity and processing water use for each juice were the same, at 0.71 MJ per liter and 0.6 l of water per liter of juice, respectively; however, thermal energy use ranges between 1.48 and 1.58 MJ per liter depending on the juice type. The variations in thermal energy are due to differences in processing times and temperatures based on acidity and density. For the juice facility, juice heating and bottle cleaning are the highest consumers of thermal energy, refrigeration is the highest consumer of electricity, and facility cleaning requires the highest water demand.

Energy use uncertainties are calculated based on facility-provided ranges in flow rate and temperature and were the highest for the pre-heater and pasteurization unit processes. Uncertainties were not included in cases where the water demand was available based on equipment manuals. Uncertainties for boiler and cooler makeup water were relatively large because of the wide ranges of demand from similar juice facilities on which the calculation was based (Table 1). However, because the boiler and cooler account for so little of the total water demand, these did not have a large effect on the total uncertainties for the end product.

The comparison between the calculated and measured facility-wide values (Table 4) shows that the calculated thermal energy use of the potato facility was 8.5% lower than the measured value and differences between electricity and water demand were around 20% lower and 23% higher, respectively. When considering the uncertainties of the calculated values, both measured thermal energy and water use fell in the calculated range. The calculated value of the required thermal energy

Table 3 Unit process energy and water demand for the juice facility

Reference Flow Correction								Energy Use (MJ/ kg input at unit process)		Water Use (lit/kg at input unit process)
Juice Unit Processes	Potato	Carrot	Beetroot	Pineapple	Tomato	Apple/ Orange (calculation not shown)	Celery (calculation not shown)	Thermal[a]	Electrical	
Initial Storage	0.1	0.14	0.06	0.0	0.0	0.0	0.11		0.115 ± 0.028[a]	
Washing/Destoning	0.92	1.0	0.38	0.0	0.0	0.0	1.18		4.03E-03 ± 4.03E-04[b]	0.30[d]
Milling	0.92	1.0	0.38	0.0	0.0	0.0	1.18		6.85E-03 ± 6.85E-04[b]	
Mesh/Pre-Heater	0.89	0.97	0.36	0.0	0.0	0.0	1.13	Carrot, Beetroot:0.211 ± 0.010 Potato:0.188 ± 0.035		
Fine Milling	0.89	0.97	0.36	0.0	0.0	0.0	1.13		7.46E-03 ± 7.46E-04[b]	2.0[d]
Decanting Centrifugation	0.89	0.97	0.36	0.0	0.0	0.0	1.13		1.51E-02 ± 1.51E-03[b]	
Pasteurization (Swiss produced)	0.60	0.72	0.28	0.0	0.0	0.0	0.79	Tomato: 0.201 ± 0.025 Pineapple:0.222 ± 0.025		
Pasteurization (Pre-Processed)	0.02	0.01	0.04	0.05	0.05	0.05	0.01	Carrot/Beetroot:0.245 ± 0.024 Potato:0.233 ± 0.023		
Cold Storage in Tanks (imported)	0.40	0.28	0.72	0.04[4]	1.0	1.0	0.21		4.08E-03 ± 5.86E-04[a]	
Cold Storage in Tanks (Swiss Made)	0.60	0.72	0.28	0.0	0.0	0.0	0.79		5.05E-01 ± 3.09E-02[a]	
Juice Heating	1.0	1.0	1.0	1.0	1.0	1.0	1.0	Tomato: 0.359 ± 0.004 Pineapple:0.341 ± 0.004 Carrot/Beetroot:0.346 ± 0.004 Potato:0.320 ± 0.004		
Bottle Cleaning/Rinser	1.0	1.0	1.0	1.0	1.0	1.0	1.0	0.5[c]	2.24E-03 ± 2.24E-04[b]	0.37[d]
Bottle Filling	1.0	1.0	1.0	1.0	1.0	1.0	1.0		1.6E-02[c]	
Bottling Cooling	1.0	1.0	1.0	1.0	1.0	1.0	1.0		1.63E-02[c]	
Boiler Make-up	1.0	1.0	1.0	1.0	1.0	1.0	1.0		3.02E-02[c]	2.9E-04 ± 2.06E-04[e]
Cooler Make-up	1.0	1.0	1.0	1.0	1.0	1.0	1.0			0.118 ± 6.54E-02[e]
Cleaning Water	1.0	1.0	1.0	1.0	1.0	1.0	1.0			2.24 ± 0.27[e]
Bottling Line Lubrication	1.0	1.0	1.0	1.0	1.0	1.0	1.0			0.373 ± 0.17[e]
Building functions	1.0	1.0	1.0	1.0	1.0	1.0	1.0	0.04[f]	0.0[d]	0.16[f]

Table 3 (continued)

Reference Flow Correction								Energy Use (MJ/ kg input at unit process)		Water Use (lit/kg at input unit process)
Juice Unit Processes	Potato	Carrot	Beetroot	Pineapple	Tomato	Apple/ Orange (calculation not shown)	Celery (calculation not shown)	Thermal[a]	Electrical	
Final Production Percentages	2%	24%	24%	2%	7%	39%	2%			
CALCULATED Thermal Energy (MJ/liter)	1.21 ± 0.07	1.28 ± 0.04	1.04 ± 0.03	0.90 ± 0.01	0.91 ± 0.01	0.90 ± 0.01	1.40 ± 0.08			
CALCULATED Electricity (MJ/liter)	0.41 ± 2.5E-2	0.48 ± 3.0E-2	0.23 ± 3.8E-3	0.073 ± 2.5E-4	0.065 ± 2.2E-4	0.069 ± 3.5E-2	0.52 ± 3.2E-2			
CALCULATED Water demand (liter/liter)	5.33 ± 0.5	5.50±0.5	4.11 ± 0.5	3.27 ± 0.5	3.27 ± 0.5	3.27 ± 0.5	5.89 ± 0.5			

[a] Calculation details in Electronic Supplementary Material Tables S4 through S14

[b] Calculation details in Electronic Supplementary Material Table S15

[c] Estimate from similar equipment types/processes (Masanet et al. 2008)

[d] Values provided by the facility

[e] Averages from min/max in Table 1

[f] 8% of total energy use, 10% of water use (Okos et al. 1998)

Table 4 Facility-wide calculated values (based on unit process calculations) compared to measured values (based on facility utility records) for the production of 1 kg or 1 l of product

	1 kg of potato product			1 l of juice		
	Measured	Calculated	Difference (%)	Measured	Calculated	Difference (%)
Thermal (MJ/product)	4.23	3.88 ± 0.67	−8.5	1.10	1.05 ± 0.03	−4.5
Electric (MJ/product)	1.52	1.22 ± 0.12	−19.9	0.29	0.22 ± 0.03	−23.7
Water (l/product)	13.52	16.7 ± 5.6	+23.3	3.3	4.1 ± 0.5	+25.2

for the juice facility was 4.5% lower than the measured value, the calculated electricity demand was about 24% lower, and the calculated water demand is about 25% higher.

3.2 LCA

The results of the LCAs for each product are shown in Figs. 2 and 3 (potato products and juices, respectively). For potato products, processing energy contributes the most to climate change impacts, with raw material growth making up a smaller percentage of the impacts. There are differences between potato flakes' and french fries' impacts largely due to the type of energy required for production. Production of 1 MJ of Swiss electricity has an impact of 0.0322 kg CO_2-eq, whereas production of 1 MJ of thermal energy has an impact of 0.104 kg CO_2-eq; therefore, potato flakes, which have a higher thermal energy requirement than french fries, have a larger climate change impact. Frying oil production added a small additional impact to french fries due to raw material growth and oil processing. The results of the WS assessment are the opposite of the climate change impact results, with raw material growth dominating the impacts and the high water impacts due to Swiss electricity production driving the WS impacts for french fry production at the processing level. Impacts due to consumptive water use in processing are minimal when compared to raw material growth.

For the juice (Fig. 3), raw material growth tends to dominate the impacts in both climate change and the WS assessment. Climate change impacts from raw material growth for tomatoes are significantly larger than those for the other fruits and vegetables. Raw material growth in locations where irrigation is required (i.e., tomatoes from Italy and pineapples from India) has particularly high WS impacts. In the climate change assessment, transport and thermal energy (off-site and on-site) are also major contributors to the impacts, with the electricity requirements (both on-site and off-site) minimally contributing to the total impacts. For all juices, off-site processing water demands were the same (demand of 4.29 l/l of juice); however, the impacts, as measured through WS, vary heavily depending on the water stress index of the country in which the off-site processing takes place (potato, carrot, and beetroot are processed in Germany, pineapple in India, and tomato in Italy). There were similar patterns of impacts due to transport across both assessments, with pineapple juice exhibiting a larger impact due to the large transport distance required between raw material growth and the Swiss processing facility (Table S16, Electronic Supplementary Material). All other raw materials and/or pre-processed juices were sourced from locations in Europe (Switzerland, Germany, or Italy) and therefore had smaller impacts associated with transportation.

Adjusting the impacts to incorporate the functional unit of 100 kcal yields the results shown in Table 5. Climate change impacts for juice show that an analysis using product energy content instead of weight does not change the ranking of the juice impacts. However, in the case of the WS assessment, impacts from pineapple juice were considerably lower when analyzed on a kilocalorie basis. The impacts of the potato products change under an energy-based functional unit; potato flakes' climate change impacts by weight are initially higher than those of french fries; however, when compared on an energy basis, potato flakes' are actually lower than french fry impacts per kilocalorie. Concerning the potato product WS assessment, the ranking of impacts stays the same regardless of the functional unit.

4 Discussion

With regard to the unit processes, there were high water demand uncertainties in recreating the boiler and cooler system makeup water requirements, particularly due to limited data availability about the facilities' units. If information such as cycles of concentrations is available, more accurate calculations using the described methods may limit the uncertainty. In most cases, however, the contribution of makeup water demand for the facility is relatively small, and high uncertainty in this particular unit process does not largely affect the results.

When unit processes are aggregated into facility-wide energy and water demand values per product, thermal energy demands in both facilities are fairly accurately reproduced (within 10% of the measured values). There were larger differences (up to 25%) when reproducing the facility-wide

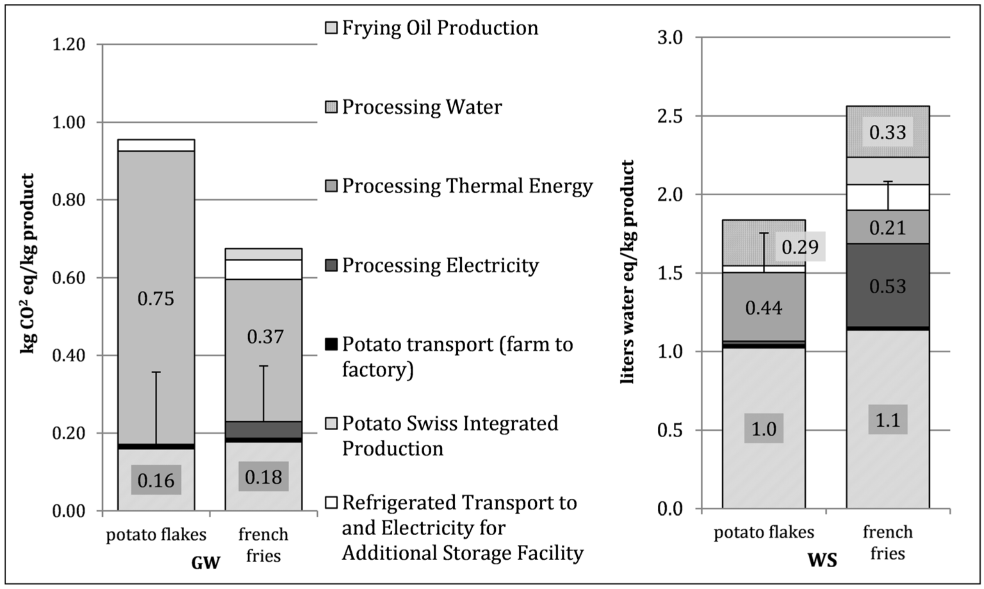

Fig. 2 LCA results of potato products. The *left graph* shows the results as kilograms of carbon dioxide equivalent and the *right graph* shows the results as liters equivalent. *Error bars* indicate the possible range of LCA results due to the uncertainties in product-specific calculated values for thermal energy, electricity, and water

electricity and water demands (Table 4). This may be due to the fact that in the case studies analyzed, there were less processes requiring thermal energy than processes requiring electricity and water, thereby decreasing the chances of error. Along these lines, there may be several smaller pieces of equipment that require electricity that are simply not accounted for, leading to lower calculated values. Processes requiring thermal energy generally need to be connected into the boiler system, whereas smaller electrical processing equipment may simply be plugged into an already existing electricity supply system. Similarly, water use tends to be unregulated, and it is difficult to account for water that is not used specifically for a particular piece of equipment or for a regulated activity, such as daily or monthly cleaning, without metering the flow. Future work should account for the possibilities of small pieces of additional electrical equipment and unscheduled water requirements.

The most accurate estimates require facility operating data such as total energy and water use, production weights and volumes, equipment types and manuals, cleaning methods and schedules (COP/CIP), product flow rates, and equipment operating temperatures. Clear goals in data collection (i.e., knowing what processes are most important and focus on collecting information with regards to these processes) can help with efficient and accurate data collection. If facility-specific data is not available, generic unit process flow diagrams can be developed from unit processes typically associated with production of a specific product, and energy and water use values per unit process can be estimated based on published data from other production facilities or equipment

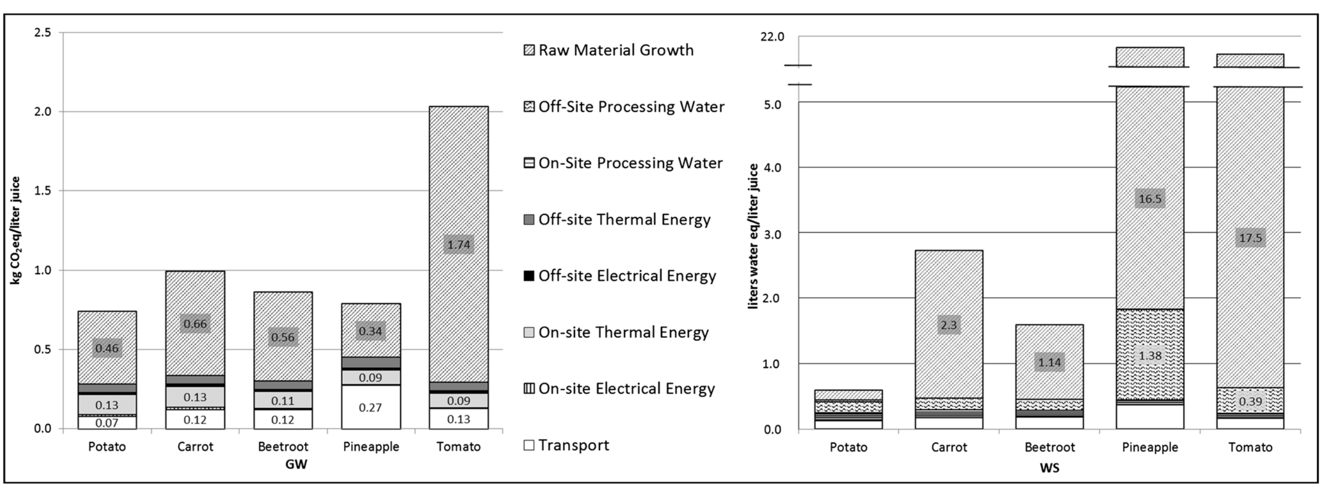

Fig. 3 LCA results of juices. The *left graph* shows the results as kilograms of carbon dioxide equivalent and the *right graph* shows the results as liters equivalent. Uncertainties in calculated on-site processing energy and water use were so small compared to the magnitude of other impacts they were not shown

Table 5 Impacts per product based on the functional unit (100 kcal) and reference flows (weight or volume)

Product	kcal per	Climate change impacts (kg CO_2-eq) per		WS (liter eq) per	
	Liter product	Liter product	100 kcal	Liter product	100 kcal
Potato	700	0.75	0.11	0.45	0.06
Carrot	280	1.01	0.36	2.73	0.97
Beet	440	0.87	0.20	1.60	0.36
Pineapple	580	0.79	0.14	18.33	3.16
Tomato	150	2.04	1.36	18.13	12.08
	kg product (USDA)	kg product	100 kcal	kg product	100 kcal
French fries	1,500	0.68	0.05	2.59	0.17
Potato flakes	3,540	0.95	0.03	1.84	0.05

manufacturers, some of which is summarized in the Electronic Supplementary Material (Tables S1, S2, and S3).

The results of this case study also show that an energy and water analysis may not be necessary when there is little variation in the unit processes between the products. In the case of juices, each type of juice underwent very similar processing, and the results show no difference in electricity or water use, and small differences in thermal energy use. In this particular case, a simple allocation of facility-wide energy and water use for each liter of juice produced, without differentiation between types, may be sufficient for the purposes of determining energy and water use per liter of juice. This, however, does not allow for increasing processing transparency and identifying high demand unit processes. For potato products, however, there were definite differences between required unit processes (and therefore energy or water requirements per product). In this case, simply assigning impacts based on measured facility-wide data without breaking down for specific products would not provide an accurate product-specific impact assessment.

The LCA results show that, in some cases, impacts due to food processing can, but not always, heavily contribute to total impacts and therefore processing should be included in food LCAs. In cases where processing is a large factor, accuracy with regard to product-specific energy and water use demand is important. This becomes clear in the case study when comparing potato products to juice products. Thermal energy demand becomes a large contributor to the climate change impact assessment of potato products, and a large uncertainty in this calculation can significantly alter results. In this case, accuracy with regard to electricity per product is less important; however, this is very location dependent and can only be applied to the scenario in which Swiss electricity is used because of its low climate change impacts (due to high amounts of hydro and nuclear electricity sources). Analyses of the juice products show very little climate change impacts due to processing; meaning, accuracy in the energy calculations does not heavily affect the results of the LCA.

In the case of WS for potato products, consumptive water use, thermal energy, and electricity demand all contribute to the product's impacts, especially those for french fries, which require higher amounts of water-dependent Swiss electricity. In this case, accuracy in each calculated processing demand (thermal energy, electricity, and water) is important for an accurate LCA. Juice WS impacts indicate that water demand due to energy production does not largely affect the LCA results; however, consumptive process water, while not a large contributor to processing impacts in Germany and Switzerland, is a large contributor to the overall impacts in regions with a high water stress index.

The impacts of each product were adjusted to a functional unit of 100 kcal. For potato products, the difference between potato products in climate change impacts and WS becomes much less pronounced, for reasons described subsequently. In climate change impacts, juices maintain their order of impact levels (i.e., potato continued to have the lowest impact and tomato the highest); however, as the kilocalories per liter of juice varied between 150 and 700, there were large changes in the impacts from one juice to the next. This was also true for WS impacts, where pineapple juice impacts changed drastically under the functional unit of 100 kcal.

In this case, other functional units should be considered. The choice of functional unit depends on the purpose of the food—is its primary purpose to be for pleasure or for nutrition? In this study, impacts due to a weight- or volume-based reference unit were adjusted to a functional unit of nutritional energy (measured as kcal) provided by each food after processing. If the primary purpose of food consumption is the supply of minerals or vitamins, the incorporation of other nutrient-based functional units (such as the nutrient-rich food index) should be considered. In the case of potato products, kilocalorie is an appropriate functional unit choice to compare the two products, as the removal of water weight from potato flakes concentrates their energy into a smaller mass when compared to french fries, and because both require potatoes as the raw material, end products will have similar mineral and vitamin contents. For comparing juices, however, a functional unit incorporating both nutrient availability and kilocalorie may function better in terms of comparing products with not only different energy contents for the same volumes but also different nutrient concentrations for the different raw materials. For example, carrot juice provides a high source of vitamin A, but no protein, whereas potato juice provides potassium and protein, but no vitamin A, and all juices had widely varying kilocalorie contents (from 150 to 700 kcal per liter). The use of a functional unit that incorporates nutrients is particularly important in cases where certain nutrient concentrations are susceptible to reduction during processing. For instance, concentrations of fat-soluble vitamins such as vitamin A and other carotenoids tend to decrease during thermal processing (Reddy and Love 1999). Retention of water-soluble vitamins depends on the food's exposure to water, which can cause leaching of the vitamins (Reddy and Love 1999). In the case of juice processing, plant fiber lost during centrifuging (between milling and pasteurizing) affects the dietary fiber content of the product, a nutritional aspect often considered in measuring a food's nutritional value (Fulgoni et al. 2009).

The end choice of the functional unit should be chosen based on the goal of the LCA—if impacts are desired to simply know impacts associated with, for example, 1 l of pineapple juice, a functional unit as a volume of the product may be sufficient. If impacts are desired to minimize an individual's impact and optimize their energy and nutrient intake for their diet, the chosen functional unit may be better as one that incorporates nutrition and energy content of a particular food.

5 Conclusions

While the case studies focus on food processing in Switzerland, the method can be applied to other regions. Particularly in developing countries, the agro-industry is a vital part of the economy, and the application of this method may thus be especially relevant there. However, although this method can be applied directly to most food processing facilities, care must be taken in applying empirical water or energy use values or estimated equipment efficiencies in facilities operating under conditions that could potentially largely differ from the more modern facilities and equipment on which this method was based.

Application of this method can highlight unit processes or products that are particularly high users of a certain resource (raw material, electricity, water, or thermal energy). This can lead to not only more efficient use of resources but can also lead to reduced production costs and higher product output, among other things. In addition, this method can identify which resource is driving the majority of the impacts. Impacts from food processing in one region to another can be compared and, from these synergies between the regions, can be investigated. For example, processing of products with high processing water demands might be moved to areas with more abundant water sources, or products with high electricity demands might be moved to areas utilizing low-impact energy sources.

Despite the uncertainties, the procedures presented here for calculating unit process water demand and those developed by Sanjuán et al. (2014) for unit process energy can be used to achieve the initial goals of improving transparency in processing, identifying the most energy-/water-intensive steps with relative accuracy, and developing product-specific LCAs. In some cases, however, such a data-intensive and in-depth analysis may not provide enough benefits to outweigh a simple energy and water allocation per product from the facility's measured energy and water use if the goal is to have an end value for energy and water use per product. For a product-specific LCA, impacts due to processing can make up a large part of the product's impact when compared to other inputs such as raw material growth; however, there is sensitivity to location of electricity generation, the country from which the water is sourced, the impact category used to evaluate the product, and the functional unit chosen for the analysis.

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