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Improving environmental performance of post-harvest supply chains of fruits and vegetables in Europe: Potential contribution from ultrasonic humidification

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Keywords
Humidification; life cycle assessment; food supply; food loss; food waste; ultrasonic

Supporting information

Expected changes introduced by implementation of humidifiers; sensitivity scenarios; life cycle impact assessment methods and normalization factors; parameters and data underlying the LCA model; uncertainty factors and squared geometric standard deviations; LCI results; and additional LCIA results

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Declaration of interest

The authors declare that they have no conflict of interest.

1. Introduction

Addressing the challenges of achieving sustainable supply chain management (SSCM) has stimulated extensive discussions in the literature and among industries (Seuring and Müller, 2008; Govindan et al., 2016; Sarkis, 2003). One of the major challenges for SSCM is the increasing complexity of globalized food supply chains, with longer cold chains and more intermediaries, resulting in higher risk of food losses. The Food and Agriculture Organization of the United Nations (FAO) estimates that approximately one-third of all food produced for human consumption, including fruits and vegetables, is lost (i.e. discarded during production and post-harvest due to microbial and chemical spoilage) or wasted (i.e. discarded due to retailers' or consumers' behavior) each year globally (FAO, 2013).

Effective management of food supply chains is one of the key strategies for the reduction of post-harvest food losses and for increasing the overall sustainability of supply chains (Priefer et al., 2016). Humidification is one of the technologies that can reduce food losses in the post-harvest of fruits and vegetables, thereby contributing to increase the environmental sustainability of food supply chains. Humidification has mainly been applied in retail cabinet displays (Barth et al., 1992), however, it has also been tested in cooling rooms for application in other post-harvest stages, like storage at distribution centers and wholesalers (Delele et al., 2009). To realize the full potential of the humidification technology, it could be applied in all post-harvest stages of fruits and vegetables, i.e. during storage in cooling rooms (i.e. at the farm, processing center, distribution center and wholesaler), road transport and retailing (in cabinet displays or cooling room). The feasibility of implementing this approach has already been tested in demonstration case studies conducted in Europe (Fresh-Demo, 2015).

The application of ultrasonic humidifiers to the entire post-harvest supply chain of European fruits and vegetables (from farm to retail) can potentially minimize food losses, but virtually nothing is known about environmental performance of the technology considering all processes in the underlying life cycle, like the need for manufacturing of humidifiers and operation of the whole humidification systems. Expected consequences from implementation of humidification systems on environmental performance of the new supply chain system are summarized in Table S1, Supporting Information (SI). These consequences can be quantified using life cycle assessment (LCA), where resource consumption and emissions of pollutants stemming from processes in the life cycle are translated into impact indicator scores using substance-specific characterization factors for various life cycle impact categories, like climate change, resource depletion or water use.

To date, environmental performance of ultrasonic humidification technology has not been assessed using LCA.

The aim of this study was to assess environmental performance of humidification technology as a potential technology to reduce post-harvest losses of fruits and vegetables in Europe. For this purpose, process-based LCA was carried out to: (i) quantify the tradeoffs between potential benefits and burdens when humidifiers are employed in storage, transport and retailing; and (ii) compare the environmental performance of humidification-based supply chains with that of conventional supply chains. Implications of implementing the technology in the post-harvest food sector, in the light of the current challenges that global supply chains face in achieving sustainability, were discussed. Four different fruits and vegetables in Europe, namely strawberries, peaches, table grapes and asparagus, were studied. These products are farmed in different countries and their supply chains vary both in terms of transport distances, number of intermediate storage periods and destination country for retailing.

2. Methods

2.1. Ultrasonic humidification

Different types of humidification systems are commercially available (Morton, 2015); in this study ultrasonic humidification is assessed. An ultrasonic humidifier uses ultrasonic waves to generate an aerosol of water droplets of ca. 1-2 µm (dry mist), which increases the relative humidity of the air surrounding the fresh produce, thereby preventing drying out of the product (Brown et al., 2007). By reducing weight losses from water evaporation (by up to 50%) and preventing microbial growth, produce shelf life can be extended and its appearance improved (Dieckmann et al., 1993; Tirawat et al., 2017, Hung et al., 2011, Ngcobo et al., 2013, Brown et al., 2004; Mohd-Som et al., 1995). When applied in these post-harvest stages, the technology works in combination with conventional vapor compression or adsorption cooling refrigerators, which provide basic cooling at a level of about 10 – 15°C. Humidifiers are expected to further lower the temperature down to around 5°C, as a consequence of the adiabatic cooling effect from evaporation of the water droplets.

The humidifiers used in this study are either existing units already offered in the market, or prototypes specifically designed for demonstration by the Dutch manufacturer Contronics Engineering B.V. (Fresh-Demo, 2015). They are modelled in our LCA based on primary data obtained from the manufacturer. Humidifiers used for storage at the farm or processing center are combined with sanitation using natural flavonoid sanitizer extracted from *citrus aurantium amara* (bitter orange), applied in a water and citric acid solution. This formula is not yet used in current supply chains, but it has been tested in demonstration case studies as potential alternative to common inorganic sanitizers (chloride). We thus assumed in our LCA that this sanitizer is used. An overview of the post-harvest supply chains and the humidifiers employed is given in Table 1.

2.2. Overview of post-harvest supply chains and demonstration case studies

The post-harvest supply chains are based on demonstration case studies (using strawberries, peaches, table grapes, and asparagus) carried out between 2015 and 2016 within the context of the Fresh-Demo European project, with the aim to demonstrate the performance of the technology (Fresh-Demo, 2015). Table 1 shows details of the geographic location of the supply chains. The number of storage and transportation stages varies depending on the location of the market. These post-harvest supply chains represent typical supply chains in Europe in terms of transportation distances and direction of the supply (with the general trend from the South of Europe to other European countries). To demonstrate the potential of the technology when applied at full scale, as part of sensitivity check, we made comparisons with scenarios where supply chains are based on European market statistics for each of the considered products. This leads to differences in modelling agricultural production, transportation distances, energy consumption and biowaste disposal.

Table 1. Geographic location of the post-harvest supply chains in the demonstration case studies that are the starting point for the LCA (baseline scenario for each fruit and vegetable) and characteristics of ultrasonic humidifiers.

Parameter		**Production and processing**	**Storage at distribution center 1**	**Storage at distribution center 2**	**Retailing**		**Transportation (from - to)**
					Cooling room	**Display**	
Geographic location	**Strawberries**	Huelva Region (Spain)	Kehl (Germany)	Westerstede (Germany)	Bremerhaven (Germany)		Spain - Germany
	Peaches	Emilia Romagna (Italy)	Trevenzuolo (Italy)	No storage	Roosendaal (Netherlands)		Italy - Netherlands
	Table grapes	Apulia (Italy)	Trevenzuolo (Italy)	No storage	Roosendaal (Netherlands)		Italy - Netherlands

	Asparagus	Kirchdorf (Germany)	No storage	No storage	Bremerhaven (Germany)		Germany - Germany
Humidification equipment characteristics	**Humidifier type**	Prototype 1	HT-254	HT-254	HT-45	HT-85	Prototype 2
	Osmosis unit type	LP-10	LP-20BPWS	LP-20BPWS	LP-10	LP-10BP	LP-10
	Weight[1] (kg)	78.8	112.2	112.2	38	101.4	115.6
	Total power rating[1] (kW)	0.51	1.56	1.56	0.51	0.71	0.38
	Total power consumption (kWh/kg/day)[1,2]	1.71E-03	2.81E-03	2.81E-03	1.71E-03	2.00E-02	1.26E-03[3]
	Water consumption (kg/h)	6	18	18	3	6	0.8
	Power supply	Electrical grid	Electrical grid	Electrical grid	Electrical grid	Electrical grid	Car battery
	Water supply	Water tank	Water supply	Water supply	Water supply	Water tank	Water tank

[1] Sum of all humidifier components (humidification, osmosis, control and sensor units)

[2] Data on energy turnover for the humidification-based supply chains is found in Table S12, SI

[3] Average, depending on transport distances

2.3. Life cycle assessment

The environmental life cycle assessment (LCA) methodology is applied in accordance with the requirements of the ILCD Handbook (JRC, 2010) and the ISO standard (ISO 14044).

2.3.1. Functional unit

The functional unit is defined as “1 kg of fresh produce sold at the retailer, with fresh and turgid appearance and no signs of deterioration and microbial contamination”. As we do not expect that the quality of the four fruits and vegetables in terms of their nutritional value changes as a result of humidification, and as the demonstration case studies did not show this, the functional unit based on mass unit is deemed to be sufficient (Heller et al., 2013).

2.3.2. System boundaries

Fig. 1 shows the system boundaries considered for the study. They include all life cycle stages constituting a supply chain for the studied fruits and vegetables: (i) agricultural production; (ii) regular transport from the field to a processing center located at the farm; (iii) processing (i.e.

washing, pre-cooling and packaging) at the processing center; (iv) storage at the processing center (v) transport from processing to distribution center(s); (vi) storage at the distribution center(s); (vii) transport from distribution center(s) to retailer (viii) storage and retailing at the retailer (supermarket). For the conventional supply chain without humidification, to which the humidification-based post-harvest supply chains are compared, cold chain is maintained until the point of retail, with the use of refrigeration systems (typically vapor compression systems) in cooling rooms, truck trailers and supermarket displays. When humidification is applied, production, use and disposal of the technology are considered and conventional sanitation is replaced by humidifiers' sanitation with the flavonoid-based sanitizer. Total amounts of produce flowing through the life cycle stages and total amounts of produce losses will also change when humidifiers are used.

Agricultural production includes the use of fertilizers and pesticides on the field, irrigation, machinery use for all agricultural activities (planting, fertilization, pesticide application, tillage and harvesting), production of fertilizers and pesticides, extraction of raw materials and their transport to the location of use (e.g. crude oil is extracted and transported to the farm). Processing includes washing with water and a sanitizer, pre-cooling, packing in open cardboard boxes (with additional plastic packaging materials depending on the product) and refrigerated storage in a cooling room. Disposal of the packaging at the destination countries is also included. Road transport from the field to the processing center at the farm occurs in regular non-refrigerated trucks (regular transport); the remaining transportation stages occur in conventionally refrigerated trucks. At the distribution center(s), the produce is refrigerated in cooling rooms. Similarly, at the retailer, after a storage period in cooling room, the product is kept refrigerated in open displays. Finally, any losses of the product (e.g. due to spoilage) are disposed of according to the waste management system in the country of disposal.

The ultrasonic humidification technology is applied during all refrigerated storage and transport processes, from storage at the processing center to the refrigerated displays at the retailer (Fig. 1). The energy, water and natural sanitizer consumption of the humidifiers are accounted for, together with the energy savings in conventional refrigeration. The production of humidifiers considers extraction of raw materials and production process of the single components (e.g. steel for the case, mainboard, control unit), without accounting for the energy requirements of the assembling process. Finally, disposal of the technology is included according to the waste management system in the EU.

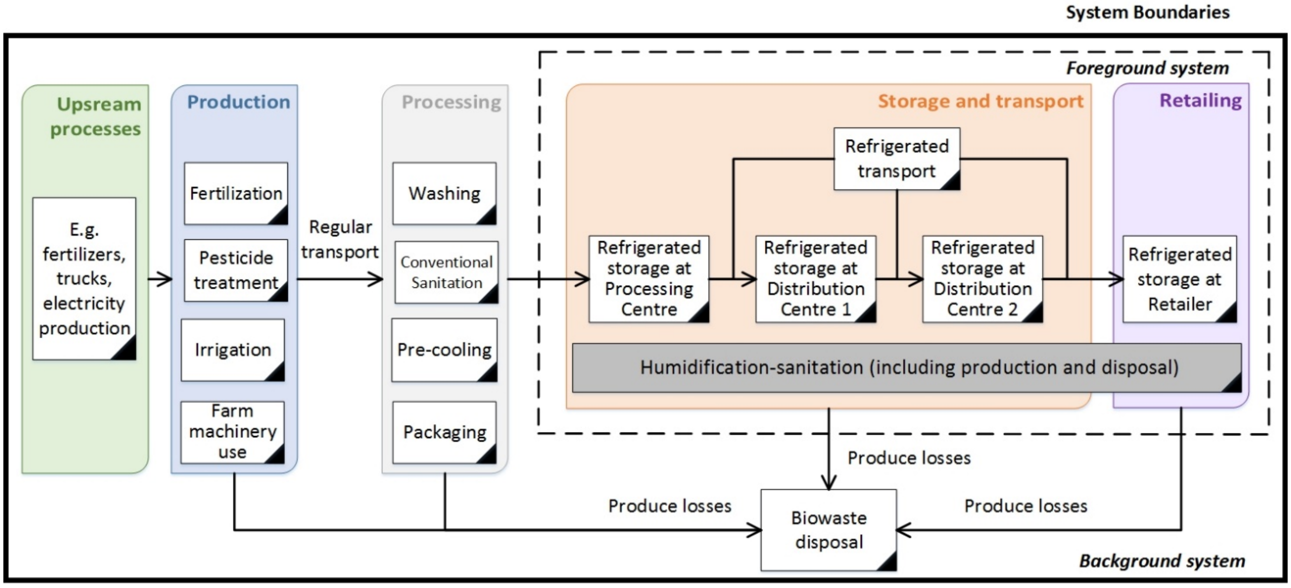

Fig.1. System boundaries for the studied fruits and vegetables supply chains. The dark gray box indicates the changes introduced when humidifiers are applied: production, use and disposal of the humidifiers and production of the natural sanitizer are considered.

2.3.3. Sensitivity scenarios

Sensitivity scenarios were constructed to consider factors that are uncertain, variable or can potentially influence the performance of the humidifiers. First, the efficiency of the humidifiers in reducing produce losses is not defined precisely, although the manufacturing company suggests that there is potential for up to 50% reduction in each stage of application of the technology. Thus, this figure (considered as high efficiency) is used for the baseline scenarios and other possible efficiencies are tested in separate scenarios. Second, produce losses along supply chains may vary depending, for example, on complexity of the supply chain. To illustrate these potential influences, different inherent food loss scenarios are tested besides baseline scenarios (where average inherent losses per fruit and vegetable are considered). Finally, the geographical location of the supply chains in Europe also varies and to illustrate the applicability of our findings beyond case study locations, alternative locations are compared.

Table 2: Overview of compared scenarios for the studied fruits and vegetables supply chains. Please refer to Table 3 for precise information on average, lowest and highest produce losses and Table S2, SI for more details on baseline and sensitivity scenario locations (Location 1/Location 2).

	No.	Humidifier efficiency (% losses reduction in each stage of application)[1]	Inherent produce losses	Geographic location[2]
Conventional supply chain	1-4 Baseline scenarios	-	Average	Baseline
	5-12	-	Lowest/highest	Baseline
	13-20	-	Average	Location 1/Location 2
Humidification-based supply chain	21-24 Baseline scenarios	High (50%)	Average	Baseline
	25-32	High (50%)	Average	Location 1/Location 2
	33-40	High (50%)	Lowest/highest	Baseline
	41-44	Medium (30%)	Average	Baseline
	45-52	Medium (30%)	Average	Location 1/Location 2
	53-60	Medium (30%)	Lowest/highest	Baseline
	61-64	Low (20%)	Average	Baseline
	65-72	Low (20%)	Average	Location 1/Location 2
	73-80	Low (20%)	Lowest/highest	Baseline
	81-84	Zero (0%)	Average	Baseline
	85-92	Zero (0%)	Average	Location 1/Location 2
	93-100	Zero (0%)	Lowest/highest	Baseline

[1] Reductions were applied only to refrigerated storage and transport processes (i.e. where humidification technology is applied), whereas losses during agricultural production and processing remain the same per compared conventional and humidification system, (as these stages are not influenced by the technology).
[2] e.g. for strawberries, Baseline, Location 1 and Location 2 have total transport distances of about 3000, 1800 and 280 km respectively.

To summarize, sensitivity scenarios were made to consider differences in (i) humidifiers efficiency in reducing produce losses, accounting for zero, low and medium efficiency of the technology (respectively 0, 20 and 30% losses reduction in the stage of application); (ii) percentage of inherent produce losses, by accounting for supply chains with the lowest and highest possible inherent losses for each specific product and (iii) geographic location, by considering two alternative supply chain locations based on major import/export trends of the considered product in the European market, retrieved from Trade Map 2015 (see Table 2 and SI, Table S2). The scenario for zero efficiency of the humidifiers is not realistic, but was made to better understand the consequences of introducing the technology in terms of materials, water and energy inputs. It was assumed that only half of the food losses in each stage is due to poor storage system, thus the scenario for high efficiency (50% losses reduction), corresponds to the maximum possible reduction achievable with an improved storage system. The remaining losses are caused by other factors and are therefore not affected (see Section 4.1, SI). In our assessment, different food losses influence the initial quantities to be produced and disposed, whereas geographical location determines differences mainly in (i) transport distances, (ii) number of storage and transport processes, (iii) use of land and water resources for agricultural production, (iv) energy mixes for power supply and crediting of avoided production and (v) type of biowaste management system (as determined by the location of disposal of the food waste).

2.3.4. Modelling framework

The ILCD guidelines provide methodological guidance according to different decision situations and, in this context, the current study is considered a micro-level decision support (type-A) situation. Due to the relative immaturity of the technology and its consequent limited application at this point, the changes derived from using it in food supply chains are not expected to have consequences on the other systems (like the need for installation of new water supply plants for the water supply). It follows that an attributional LCA approach is applied, where average country-specific data and energy mixes are used, as well as modelling of average technology, e.g. refrigerated transport. For globally produced and traded commodities, such as raw materials and humidifier components, global production is modelled. Refrigerated transport processes are also modelled according to global conditions as no regionalized inventories are available. Packaging and produce waste disposal methods and water supply technology for agriculture and humidifiers operation reflect European conditions. Average country-specific electricity mixes are used during every stage of refrigerated storage and waste disposal process. In cases of processes with more than one functionality (i.e. delivering one or more by-products), system expansion is performed. This is the case of waste incineration, where recovered heat and electricity are credited for internal plant energy redistribution and recycling processes, where recycled steel, paper and plastic substitute the production of virgin material. In organic waste composting, credits are given to avoided primary production of fertilizers and the use of biogas (from anaerobic digestion) in heat and power cogeneration plants is credited with the respective avoided energy production. Note, that we apply system expansion (through crediting) using average processes in this attributional approach, consistently with both ILCD and the ISO hierarchy to solving multifunctionality, although system expansion using marginal processes has traditionally, particularly before the ILCD recommendations were made, been considered for the consequential approach to inventory modelling (allocation has traditionally been used for the attributional approach).

2.3.5. Life cycle impact assessment

Modelling was performed with the software SimaPro, version 8.2.3 (PRé Consultants, the Netherlands). Environmental impact scores were calculated using characterization factors according to ILCD's recommended methods at midpoint (ILCD 2011 Midpoint+, version 1.08), as implemented in SimaPro (EC-JRC, 2011). Normalization references are based on national inventories calculations for the EU 27, version 4.0, in the reference year 2010 (Benini et al., 2014). LCIA methods and normalization factors are presented in SI, Section S3.

2.3.6. Data and model parameters

Unit processes for the foreground system are modelled using model parameters based on primary data from the manufacturer Contronics Engineering B.V. combined with data from the literature. Unit processes for the background system, like agricultural production or biowaste disposal, are based on data from ecoinvent, version 3.2 (ecoinvent, 2015; Moreno Ruiz et al., 2015). Model parameters and unit processes are synthesized in SI, Section S4, and references given.

2.3.6.1. Fruits and vegetables' post-harvest losses

Data on produce losses vary depending on the type of product and are mainly based on European product-specific sources or on average data among fruits and vegetables in Europe. When information for lowest and highest losses was not available, average figures were assumed as described in Table 3.

Table 3: Average, lowest and highest losses of produce at each life cycle stage. Assumed values were calculated by subtracting (a) or adding (c) 5 point % to the baseline figure (for baseline figures above 10%) or by halving (b) or doubling (d) the baseline figure (for baseline figures below 10%). This was done assuming that figures above 10% have greater variability than lower figures. Additional information about selection of data and assumptions is found in SI, Section S4.1.

	Stage	Average (%)	Source	Lowest (%)	Source	Highest (%)	Source
Strawberries	**Agricultural production**	2.5	Terry et al., 2011	2	Terry et al., 2011	20	Gustavsson et al., 2011
	Processing	3.5	Terry et al., 2011	2	Gustavsson et al., 2011	10.5	Terry et al., 2011
	Storage/ Distribution	9.5	Terry et al., 2011 (storage) Gustavsson et al., 2011 (transport)	0.5	Terry et al., 2011	13.5	Prusky, 2011
	Retail	6.1	Terry et al., 2011; Prusky, 2011	2	Terry et al., 2011	10	Gustavsson et al., 2011

Peaches	**Agricultural production**	20	Gustavsson et al., 2011	15	a	25	c
	Processing	2	Gustavsson et al., 2011	1	b	4	d
	Storage/ Distribution	5	Gustavsson et al., 2011	2.5	b	10	d
	Retail	11.9	Prusky, 2011	6.9	a	16.9	c
Grapes	**Agricultural production**	20	Gustavsson et al., 2011	15	a	25	c
	Processing	2	Gustavsson et al., 2011	1	b	4	d
	Storage/ Distribution	5	Gustavsson et al., 2011	2.5	b	10	d
	Retail	4.95	Prusky, 2011; Eriksson et al., 2012	2.3	Eriksson et al., 2012	10	Gustavsson et al., 2011
Asparagus	**Agricultural production**	20	Gustavsson et al., 2011	15	a	25	c
	Processing	2	Gustavsson et al., 2011	1	b	4	d
	Storage/ Distribution	5	Gustavsson et al., 2011	2.5	b	10	d
	Retail	10	Gustavsson et al., 2011	5	a	15	c

2.3.6.2. Agricultural production

Unit processes and model parameters regarding agricultural production of all analyzed products are taken from Stoessel et al., 2012, who provide a consistent life cycle inventory on agricultural production of a large range of fruits and vegetables in different countries (as implemented in ecoinvent 3.2 database). The only available datasets for strawberries, asparagus and grapes were used and these are representative for production in Switzerland (strawberries and asparagus) and Spain (grapes). Data on peaches is retrieved from the dataset of apple production in Switzerland assuming that farming of peaches and apples are similar, since no inventory for peaches was available. Asparagus and peaches production schemes were modelled based on integrated production methods, while conventional production methods were used for strawberries and grapes, according to availability in ecoinvent. For strawberries produced in Spain and peaches produced in Italy, country-specific information about land and water use for irrigation was available. This information was used based on (Lozano et al., 2016), who provide information about water use for strawberries produced in the south-west of Spain, and based on data on land use from governmental authorities for agriculture and agro-food policies of Andalusia (Spain) and Emilia Romagna (Italy).

2.3.6.3. Processing, refrigeration and transport

Extensive research is made on search engines (*ISI Web of Knowledge*, *Google Scholar*) to gather information on fruits and vegetables processing and energy consumption during refrigerated storage at European level. When representative data for Europe was not available this was complemented with U.S. sources. For instance, amounts of washing water and conventional chlorinated sanitizer during processing reflect Swiss and U.S. common practices, respectively (Stoessel et al., 2012)

(Suslow, 2000). Energy consumption of pre-cooling is calculated using the method presented in Sanjuán et al., 2014, who provide estimation tools for energy demand of various pre-cooling methods. Energy consumption at retailer displays is calculated considering the consumption of a specific refrigerated display size and using the data in (Fricke and Becker, 2010), which provides the electricity consumption per meter (meters of display length) of typical displays in U.S. supermarkets. Note that assuming cooling at display for the selected products is a realistic option that may vary from country to country. In cases when produce-specific information was not found, data on the closest product category (e.g. bulk packed density) or the most recent and accurate data were used. This applies to energy consumption during cooling room storage, which is retrieved from Stoessel et al., 2012 (refrigerated storage of apples in Germany at 1°C in cooling room) and is used for all produce. Transport distances between the production site and retail were taken from Google maps and data on additional fuel consumption for power supply to the refrigeration unit are based on the generic process available in ecoinvent, version 3.2.

2.3.6.4. Humidification systems

Data on ultrasonic humidification equipment (i.e. energy and water consumption, bill and type of materials, type of installation per life cycle stage, composition of the natural sanitizer, energy savings in conventional refrigeration) is provided by the manufacturer (see Table 1 and SI, Table S5). Data for the reverse osmosis unit are retrieved from literature (DOW, 2013).

2.3.6.5. Waste disposal

Data regarding shares of biowaste treatment method per country are based on mixed food waste (animal and vegetal) Eurostat statistics, reference year 2012 (see SI, Table S9). As the share of waste for composting and anaerobic digestion treatment was not available, a figure of 50% each was assumed. Metal emissions from produce landfilling and incineration are adjusted to reflect average content of the analyzed fruit or vegetable, which was very low (see SI, Table S10). Data on humidifiers disposal are based on generic process for electronic equipment disposal available in ecoinvent 3.2 and steel disposal rates refer to average European figures from Eurostat.

2.4. Uncertainty analysis

Uncertainty of parameters in the foreground system was estimated using the Pedigree matrix approach (Ciroth et al., 2013). First, each uncertain input and output data was assigned a numerical uncertainty factor by assessing data quality on the basis of five criteria, i.e. reliability, completeness, temporal correlation, geographical correlation and further technological correlation. Next, a basic uncertainty factor was given to each data point based on the type of data (e.g. natural resource, emission, waste treatment service) and square geometric standard deviations calculated, assuming that the data follow a log-normal distribution. Uncertainty factors and geometric standard deviations are presented in SI, Section S5.

Uncertainties in the background processes were based on geometric standard deviations already assigned to flows in the ecoinvent processes. Monte Carlo simulations were performed to compare the sensitivity scenarios and establish an uncertainty range in the calculated results. Differences in impact scores between compared scenarios were considered significant in the cases in which the 95% confidence intervals of the impact scores, retrieved from 1000 iterations, did not overlap.

3. Results and discussion

In the following sections, we first address representativeness of life cycle inventories and present an overview of LCIA results for the conventional system without humidification, as starting point for the comparison and as illustration of potential benefits from introducing humidification in the post-harvest. Next, we present results for the systems with humidification, including comparison between selected scenarios for three selected impact categories. Finally, we interpret our results and highlight the major implications of these in the food sector.

3.1 Life cycle inventories

Documentation of unit processes used to model life cycle inventories of both conventional and humidification-based supply chains is presented in the SI, Section S6. The inventories are representative for the studied supply chains of strawberries, peaches (with some assumptions), grapes and asparagus in Europe and for the ultrasonic humidification systems developed by Contronics Engineering B.V.

3.2 Overview of life cycle impact assessment results for conventional systems

Characterized life cycle impact assessment (LCIA) results for conventional supply chains (baseline scenarios) are presented in Fig. 2, for three selected impact categories. They represent typical trends in supply chain performance observed for all 15 ILCD’s impact categories (impact scores for all 15 categories are found in SI, Section S7). Peaches show the best performance in 10 impact categories (although with significant differences in only 5 impact categories), followed by grapes with the lowest impact scores in 3 categories. On the other hand, asparagus shows the worst performance in 11 categories out of 15 (including climate change and mineral, fossil and renewable resource depletion) compared to the other fruits, followed by strawberries, being the worst in 4 categories (including water depletion). Statistically significant differences in impact scores between asparagus and the other products are found in 10 impact categories (SI, Table S20). The results for climate change impacts are below 2 kg CO_2 eq per kg of produce sold, which is within the variability range reported in other studies for similar supply chains (i.e. Europe as geographical scope, distribution by truck, system boundaries including post-harvest stages) of strawberries and asparagus (Soode et al., 2015; Stoessel et al., 2012; Michalský and Hooda, 2015), but higher compared to studies on similar fruits (Cerutti et al., 2011). For peaches and grapes, the results are approximately 4 to 8 times higher compared to studies assessing only the production stage (Vinyes et al., 2015; Villanueva-Rey et al., 2014), highlighting the need for considering impacts stemming from post-harvest stages of supply chains.

Normalized results show that the highest scores are seen in six impact categories (freshwater ecotoxicity, water depletion, resource depletion, marine eutrophication, human toxicity cancer and non-cancer effects), with figures up to 0.01% of the annual impact of an average European for at least one of the products (see SI, Section S7, Fig. S5). For the remaining categories, impact scores are lower, down to 0.001% of annual average European impact. Assuming equal weighting across impact categories, the 6 categories with highest scores are the most relevant to consider, particularly water and resources depletion for the possible impacts derived from water and materials needs of humidifiers (see SI, Table S1).

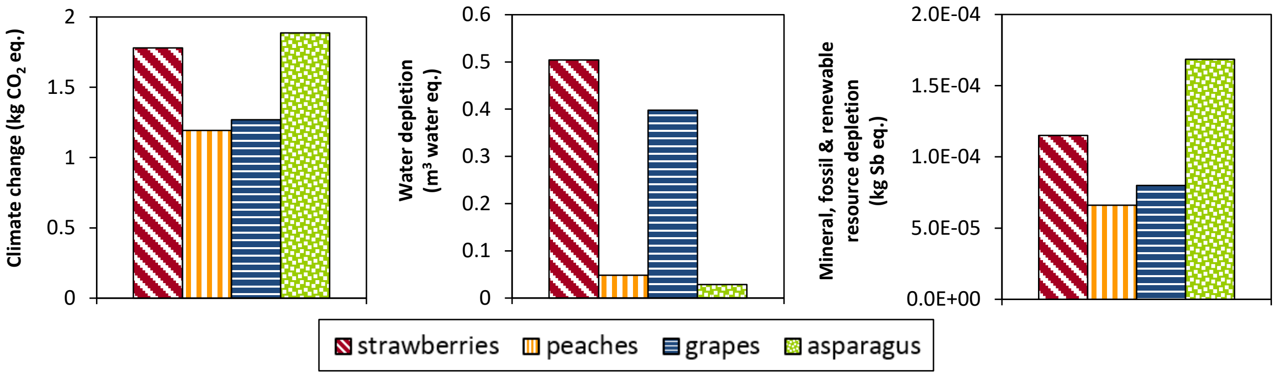

Fig. 2: Characterized impact scores for three impact categories for conventional supply chains of each type of produce (baseline scenarios). Monte Carlo iterations showed statistically significant differences in impact scores in the majority of the cases, when comparing fruits and vegetables between each other (SI, Table S20).

3.3 Process contribution for the conventional and humidification systems

Process contribution analysis was carried out to identify drivers of the impacts in the conventional supply chain and elucidate potential implications from introducing humidification (Fig. 3). The drivers vary depending on the impact category and the type of produce, however some common trends are observed. First, for strawberries, peaches and grapes the majority of the impacts are caused by the transportation processes (in particular from the related CO_2, NO_x, hydrocarbons and metals emissions to air) and the agricultural activities. Second, the contribution of biowaste treatment is generally below 15% of total impact score, except for climate change and eutrophication impacts, where important contributions up to 51% are observed for peaches and grapes. Finally, some negative contributions up to 37% (mainly avoided particulate matter and land use impacts) are primarily related to avoided virgin material production from plastic and cardboard packaging recycling (classified to the processing stage).

Transport activities contribute on average around 52, 44 and 52%, whereas agriculture about 33, 37 and 33%, for strawberries, peaches and grapes respectively. This predominant contribution of transport processes is in contrast to what is found in other LCA studies on fruits and vegetables, where farming is found to be major driver of impacts (Canals et al., 2008; Cellura et al., 2012; Soode et al., 2015). However, other authors report significant contributions of transport to different impact categories (Hospido et al., 2009; Sim et al., 2007; Payen et al., 2014). The role of transport in this study is explained by: (i) relatively longer transport distances, and (ii) differences in the modelled farming methods (e.g. greenhouse farming not considered in this study), leading to lower environmental impacts from the production stage in our study. Contribution analysis for asparagus supports these explanations. For asparagus, agricultural production is the dominant contributor to all impacts (average 87%), with only marginal contributions from transport processes. This is a consequence of the shorter transport distances and the larger environmental impacts of asparagus production compared to the other fruits (i.e. greater land occupation, higher pesticide emissions, higher fertilizer and field machinery use). The latter also explains the slightly higher LCIA results observed for asparagus (Table S19).

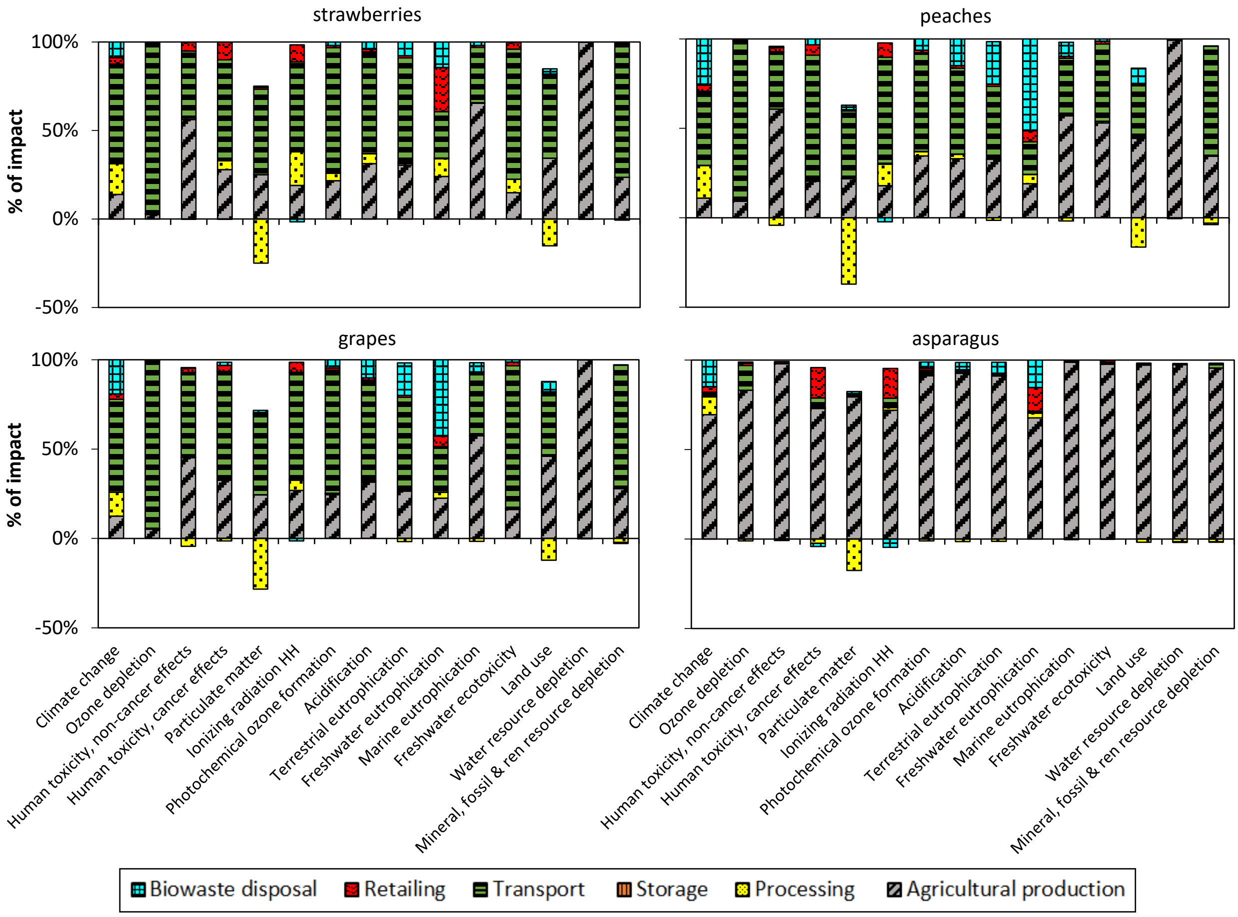

Fig. 3: Contribution of life cycle stages to total impact scores (scaled to 100%) for the conventional supply chains of four fruits and vegetables. Each stage includes processes as illustrated in Fig. 1.

Humidification systems show similar process contribution results regarding the importance of agriculture and transport (Fig. S7, SI). The contribution of humidifiers production, operation and disposal in the whole supply chain is around 2% on average for most categories, with the exception of ozone depletion impacts where emissions of ozone depleting substances (CFC-113) during production of humidifiers components (reverse otsmosis unit) are the driving factors (up to 87% contribution). This has relevant implications only in the case this substance is still used in the industry, which is not likely since major ozone depleting substances have been phased out (UNEP, 1989). Electricity consumption of humidifiers plays a major role compared to their production and disposal for almost all remaining categories (above 60%), whereas the contribution to mineral resources depletion derives mainly from the consumption of tantalum and nickel in the manufacturing of electronic components (electrolyte tantalum capacitors contained in printed wiring boards) and stainless steel respectively.

Overall, our findings about the conventional and humidification systems indicate that: (i) the performance of the humidification technology depends mainly on how much agriculture and transport processes can be reduced, i.e. how much humidifiers can reduce food losses; (ii) for the majority of the impact categories, a reduction in the amount of produce to be disposed will bring only marginal improvements, (iii) changes in energy consumption during storage are not expected to be an important factor in the overall performance and (iv) choosing other types of electrolyte capacitors other than tantalum-based ones, e.g. aluminum capacitors, could improve the performance of humidifiers, as the latter show lower mineral depletion impacts.

3.4 Does humidification bring environmental benefits?

Fig. 4 shows the comparison in environmental performance between baseline humidification-based supply chains and the corresponding conventional supply chains for the four fruits and vegetables. The comparison is done both among different humidifier efficiencies and different inherent food losses scenarios. Three main trends are observed for all four products: (i) applying humidifiers in the post-harvest improves the environmental performance of the system, (ii) this performance improves with increasing efficiency of the humidifiers and (iii) the higher the inherent food losses the greater is the improvement. In scenarios where humidifiers reduce food losses, most of the environmental impacts are also reduced by 0.2 to 23%, depending on the product, efficiency of humidifiers and inherent food losses of the supply chain. This suggests that there is potential for humidification to improve the environmental performance of produce supply chains. Results for strawberries, peaches and grapes are characterized by high uncertainty, since no statistically significant differences between any of the systems were found (except for water depletion impacts at highest efficiency of humidifiers). For asparagus instead, differences were found to be statistically significant in most of the cases when efficiency is high (Table S25, SI). As Monte Carlo simulations take into account the correlation between uncertainties of the compared systems, this high uncertainty must originate from foreground processes which are not shared between conventional and humidification-based systems, i.e. related to humidifiers. The uncertainty analysis also revealed that the differences in impact scores between scenarios with various performances of the humidifiers are statistically significant. (Table S26, SI).

The potential benefits from using humidifiers are due to the provided reduction in produce losses. Considering that transport processes and agricultural production are the main contributors to environmental impacts (Section 3.3), the benefits stem principally from lower needs for these two processes, resulting in: (i) lower greenhouse gasses emissions (e.g. CO_2, N_2O, hydrocarbons) from transport exhausts and from nitrogen fertilizers application and production; (ii) reduced use of water for irrigation during farming and (iii) reduced metal depletion (e.g. Zn, Pb) from machinery and fertilizers production. Only for freshwater eutrophication impacts for peaches and grapes the benefits are mainly due to reduced food waste disposal, i.e. reduced nutrient emissions to water (nitrate and phosphate) from treatment of anaerobic digestion digester sludge. The importance of reducing food losses is further demonstrated by the fact that, in the scenarios with zero efficiency of humidifiers (i.e. when losses are not reduced), humidification slightly increases environmental burdens. This is due to (i) greenhouse gasses emissions from additional needs for transport (e.g. additional diesel and lorry production) and from reverse osmosis membrane production, (ii) water consumption from increased diesel production (for transport) and from humidifiers use, and (iii) minerals, metals and fossil resources depletion from additional transport (e.g. diesel, lorry and refrigeration machine’s refrigerant production) and from humidifiers’ components production (e.g. steel and motherboard). Nevertheless, the higher the reduction in losses the better is the environmental performance of the system. An improvement is already observed when humidifiers work at low efficiency, i.e. when losses are cut by 20% during each stage of application.

The performance of the humidification systems is also influenced by the inherent food losses of the supply chain. When inherent losses are below 24%, the benefits from humidification are the lowest observed and in some cases (climate change and resource depletion impacts for strawberries and grapes) there are no significant benefits even at the highest efficiency of the humidifiers. This suggests that in supply chains with already low inherent losses, the additional reduction of losses is not a factor that can significantly influence the environmental performance (as would be for example the farming method), thus in this case humidifiers are not particularly beneficial. As opposite, it is more convenient to apply humidification in supply chains characterized by substantial post-harvest produce losses, i.e. above 24% of the produced amount.

The reduced environmental impacts upon implementation of humidifiers show that the burdens associated to the new technology are outweighed by the benefits of reducing produce losses. No burden shifting occurs when considering the additional need for materials, energy and water of humidifiers, provided that the humidifiers allow reducing food losses in the post-harvest.

Even increased demand for transport and the possible increase in diesel consumption for power supply (Table S12) do not undermine the overall performance. Reductions of impacts from agriculture and transport processes are the main reasons for the improved environmental performance, whereas reduced biowaste treatment does not bring significant improvements for most of the categories.

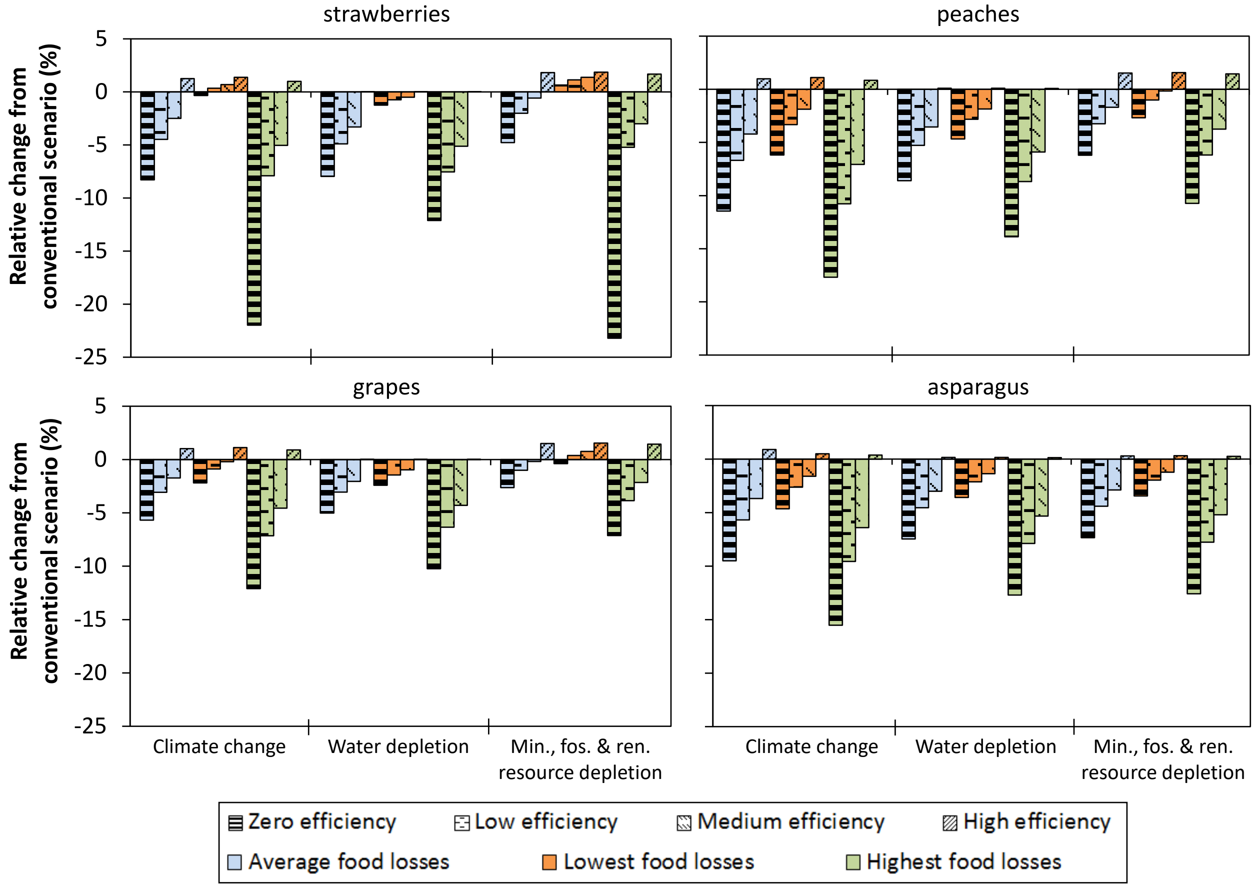

Fig. 4: Percentage of relative difference in impact scores between baseline humidification-based (scenarios no. 21 – 24) and conventional supply chains (scenarios no. 1 – 4), for three selected impact categories and all produce types. Comparisons between different humidification system efficiencies (scenarios no. 41 – 44, 61 – 64, 81 – 84 are compared to scenarios 1 – 4) and between different inherent produce losses (scenarios no. 33 – 40, 53 – 60, 73 – 80, 93 – 100 are compared to scenarios 5 – 12) are also shown (see Table 2 for description of scenarios). Please refer to Tables S21 – S24 (SI, Section S6) for results on all 15 ILCD's impact categories and Table S25 for results of uncertainty analysis. Zero, low, medium and high efficiency: 0, 20, 30 and 50% losses reduction

respectively. Average, lowest and highest food losses: 20 – 33%, 4 – 24% and 42 – 67% total inherent losses respectively.

3.5 Influence of geographic location and transportation distance

The scenarios with alternative supply chain locations show some similar trends to those found for the baseline locations, i.e. better environmental performance with humidifiers already at low efficiency and major benefits with increasing efficiency (Fig. S7, SI). However, since the extent of impact reductions is found to be almost the same in all scenarios for all produces, changing the geographic location does not have a significant effect on the systems' environmental performance. This suggests that the performance of humidifiers is not influenced by the geographic location of the supply chain. Similar benefits are observed in systems where the difference in transport distances is up to 2800 km and where the number of storage processes varies from three to one (e.g. for strawberries baseline location and location 2 in Fig. S7). Also in this case, uncertainties are high as statistically significant differences with the conventional system are found mainly only for asparagus (Table S27, SI).

No significant differences in performance are found when varying those parameters that are determined by the location of the supply chain, such as use of land and water resources for agricultural production, energy production mixes and biowaste management system. Probably the variation of these parameters among the studied locations is not sufficiently large to undermine the benefits from applying humidifiers in different geographic contexts, making the use of the technology environmentally convenient irrespective of the supply chain location. Despite the use of scenario-specific transport distances, we do not expect to obtain different results if considering average transport distances. Indeed, while the main contributors to environmental impacts may change depending on the length of the supply chain (which can either be agriculture or transport as observed in the contribution analysis), the performance of humidifiers will not be significantly affected. Note that, transport distances and number of storage processes do not influence humidifiers' performance because it was implicitly assumed that inherent produce losses during storage and transport stages (and thus losses reduction induced by humidifiers) remain the same regardless of the number of sub-processes. This assumption might not always hold, as losses can be lower in short supply chains. However, considering that the utilized inherent losses are average European figures that cover also differences in number of stages and distances, the conclusion that these two factors do not influence the performance is still considered valid as long as remaining in the European context.

4. Implications for management, policy and research

We showed that applying humidification technology in the post-harvest stages of fruits and vegetables can improve the environmental performance of the supply chains. For such a more sustainable supply chain management to be realized in real life, however, the technology should be implemented along the whole post-harvest supply chain. All the different actors in the supply chain must engage to install, properly operate the technology and ensure that no breaks occur in the cold chain. This can be a challenge as it requires a significant level of collaboration, communication and knowledge sharing along the chain. Such interactions are indeed recognized as key factors but also major barriers for achieving sustainable management in supply chains (Boström et al., 2015; Van Hoof and Thiell, 2014; Silvestre, 2015). Another barrier for implementation of the technology is the increase in costs, in this case, related to the introduction of new equipment and training of employees (e.g. truck drivers, warehouse and supermarket workers), which can jeopardize implementation of the technology, at least initially. However, stimulating cooperation and innovation to achieve full implementation in the chain can be effectively led by retailers, who have the power to influence upstream actors by creating “economic selection pressure throughout the chain” (Mylan et al., 2015). This implies that humidification systems should be first introduced at retailers, which can then exploit their buying power to stimulate full implementation upstream the chain. Initiatives such as best practice sharing, workshops, demonstration projects, guidance documents are useful tools for i) retailer engagement, ii) engagement of other actors in the chain, iii) training and development of technical skills for employees.

Our findings have important implications for policy. Namely, we recommend the use of humidifiers in supply chains where poor temperature and storage management causes the loss of more than 24% of what was produced. This is more likely to occur as length and complexity of the supply chain increases. This number is below the total average losses for fruits and vegetables traded in Europe from production to retailing (Gustavsson et al., 2011), demonstrating that there is room for improvement and potential for applying the technology to fruits and vegetables which have higher losses. Humidification could thus play a role in the EU Action Plan for Circular Economy which proposes to ‘halve per capita global food waste at the retail and consumer levels and reduce food losses along production and supply chains, including post-harvest losses’ by 2030 in support of the Sustainable Development Goals of the United Nations (EC, 2015; UN, 2015). In addition, humidification can contribute to lower European carbon emissions by reducing environmental impacts stemming from agriculture and transport. An average of 0.1 kg CO_2 eq can be avoided per 1 kg of product sold, which would equal roughly 22 million tons CO_2 eq considering implementation of humidification to the whole quantity of fruits and vegetables produced in Europe and then distributed throughout the continent (approximately 190 million tons, according to FAOSTAT, 2014). This represents approximately 0.9 % of the total emission reduction target set by 2030 (EEA, 2016; EC, 2013). We stress, however, that the interpretation of this results is constrained by the decision context of the study, and our results are not directly applicable to decisions which may have large structural consequences on the market. For example, in a hypothetical situation where ultrasonic humidification becomes a dominant technology for reducing losses in post-harvest, consideration of consequences that its implementation will have on the market would have to be made, like the need for additional capacity for provision of clean water for running of humidifiers. This would require an additional, consequential LCA study. The benefits found by introducing humidification systems in European supply chains, demonstrate the great potential of this technology for application in longer, global chains, in particular when produce is outsourced to developing countries, where post-harvest losses of fruits and vegetables are significantly higher compared to developed countries (Gustavsson et al., 2011).

Although demonstration case studies were promising, more research is needed to determine the efficiency of the technology in reducing food losses when fully implemented along supply chains. Finally, more research is needed to determine the influence of humidification on of food losses at consumer level, which was not considered here.

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