

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

Fabbri, Serena; Olsen, Stig Irving; Owsianiak, Mikołaj

Published in: Journal of Cleaner Production

Link to article, DOI: 10.1016/j.jclepro.2018.01.157

Publication date: 2018

Document Version Peer reviewed version

Link back to DTU Orbit

Citation (APA):

Fabbri, S., Olsen, S. I., & Owsianiak, M. (2018). Improving environmental performance of post-harvest supply chains of fruits and vegetables in Europe: Potential contribution from ultrasonic humidification. *Journal of Cleaner Production*, *182*, 16-26. https://doi.org/10.1016/j.jclepro.2018.01.157

General rights

Copyright and moral rights for the publications made accessible in the public portal are retained by the authors and/or other copyright owners and it is a condition of accessing publications that users recognise and abide by the legal requirements associated with these rights.

• Users may download and print one copy of any publication from the public portal for the purpose of private study or research.

- · You may not further distribute the material or use it for any profit-making activity or commercial gain
- You may freely distribute the URL identifying the publication in the public portal

If you believe that this document breaches copyright please contact us providing details, and we will remove access to the work immediately and investigate your claim.

1	Improving environmental performance of post-harvest supply chains
2	of fruits and vegetables in Europe: Potential contribution from
3	ultrasonic humidification
4	
5	Serena Fabbri*, Stig Irving Olsen, Mikołaj Owsianiak
6	
7	Division for Quantitative Sustainability Assessment, Department of Management Engineering,
8	Technical University of Denmark, Produktionstorvet, Building 424, DK-2800 Kgs. Lyngby,
9	Denmark
10	
11	* corresponding author
12	<u>serf@dtu.dk</u>
13	
14	Keywords
15	Humidification; life cycle assessment; food supply; food loss; food waste; ultrasonic
16	
17	Supporting information
18	Expected changes introduced by implementation of humidifiers; sensitivity scenarios; life cycle
19	impact assessment methods and normalization factors; parameters and data underlying the LCA
20	model; uncertainty factors and squared geometric standard deviations; LCI results; and additional
21	LCIA results
22	
23	Acknowledgements
24	This research was funded by the European Commission under Horizon 2020; SFS-2014-2: FRESH-
25	DEMO, grant agreement 634699.
26	
27	Declaration of interest
28	The authors declare that they have no conflict of interest.
29	

30 **1. Introduction**

31 Addressing the challenges of achieving sustainable supply chain management (SSCM) has

32 stimulated extensive discussions in the literature and among industries (Seuring and Müller, 2008;

33 Govindan et al., 2016; Sarkis, 2003). One of the major challenges for SSCM is the increasing

34 complexity of globalized food supply chains, with longer cold chains and more intermediaries,

35 resulting in higher risk of food losses. The Food and Agriculture Organization of the United

36 Nations (FAO) estimates that approximately one-third of all food produced for human consumption,

37 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).

40 Effective management of food supply chains is one of the key strategies for the reduction of 41 post-harvest food losses and for increasing the overall sustainability of supply chains (Priefer et al., 42 2016). Humidification is one of the technologies that can reduce food losses in the post-harvest of 43 fruits and vegetables, thereby contributing to increase the environmental sustainability of food 44 supply chains. Humidification has mainly been applied in retail cabinet displays (Barth et al., 1992), 45 however, it has also been tested in cooling rooms for application in other post-harvest stages, like 46 storage at distribution centers and wholesalers (Delele et al., 2009). To realize the full potential of 47 the humidification technology, it could be applied in all post-harvest stages of fruits and vegetables, 48 i.e. during storage in cooling rooms (i.e. at the farm, processing center, distribution center and 49 wholesaler), road transport and retailing (in cabinet displays or cooling room). The feasibility of 50 implementing this approach has already been tested in demonstration case studies conducted in 51 Europe (Fresh-Demo, 2015).

52 The application of ultrasonic humidifiers to the entire post-harvest supply chain of European 53 fruits and vegetables (from farm to retail) can potentially minimize food losses, but virtually 54 nothing is known about environmental performance of the technology considering all processes in 55 the underlying life cycle, like the need for manufacturing of humidifiers and operation of the whole 56 humidification systems. Expected consequences from implementation of humidification systems on 57 environmental performance of the new supply chain system are summarized in Table S1, 58 Supporting Information (SI). These consequences can be quantified using life cycle assessment 59 (LCA), where resource consumption and emissions of pollutants stemming from processes in the 60 life cycle are translated into impact indicator scores using substance-specific characterization 61 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 assessedusing LCA.

64 The aim of this study was to assess environmental performance of humidification 65 technology as a potential technology to reduce post-harvest losses of fruits and vegetables in 66 Europe. For this purpose, process-based LCA was carried out to: (i) quantify the tradeoffs between 67 potential benefits and burdens when humidifiers are employed in storage, transport and retailing; 68 and (ii) compare the environmental performance of humidification-based supply chains with that of 69 conventional supply chains. Implications of implementing the technology in the post-harvest food 70 sector, in the light of the current challenges that global supply chains face in achieving 71 sustainability, were discussed. Four different fruits and vegetables in Europe, namely strawberries, 72 peaches, table grapes and asparagus, were studied. These products are farmed in different countries 73 and their supply chains vary both in terms of transport distances, number of intermediate storage 74 periods and destination country for retailing.

75

76 **2. Methods**

77 2.1. Ultrasonic humidification

78 Different types of humidification systems are commercially available (Morton, 2015); in this study 79 ultrasonic humidification is assessed. An ultrasonic humidifier uses ultrasonic waves to generate an 80 aerosol of water droplets of ca. 1-2 µm (dry mist), which increases the relative humidity of the air 81 surrounding the fresh produce, thereby preventing drying out of the product (Brown et al., 2007). 82 By reducing weight losses from water evaporation (by up to 50%) and preventing microbial growth, 83 produce shelf life can be extended and its appearance improved (Dieckmann et al., 1993; Tirawat et 84 al., 2017, Hung et al., 2011, Ngcobo et al., 2013, Brown et al., 2004; Mohd-Som et al., 1995). 85 When applied in these post-harvest stages, the technology works in combination with conventional 86 vapor compression or adsorption cooling refrigerators, which provide basic cooling at a level of 87 about $10 - 15^{\circ}$ C. Humidifiers are expected to further lower the temperature down to around 5°C, as 88 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

92 obtained from the manufacturer. Humidifiers used for storage at the farm or processing center are

93 combined with sanitation using natural flavonoid sanitizer extracted from *citrus aurantium amara*

94 (bitter orange), applied in a water and citric acid solution. This formula is not yet used in current
95 supply chains, but it has been tested in demonstration case studies as potential alternative to
96 common inorganic sanitizers (chloride). We thus assumed in our LCA that this sanitizer is used. An
97 overview of the post-harvest supply chains and the humidifiers employed is given in Table 1.

98

99 2.2. Overview of post-harvest supply chains and demonstration case studies

100 The post-harvest supply chains are based on demonstration case studies (using strawberries, 101 peaches, table grapes, and asparagus) carried out between 2015 and 2016 within the context of the 102 Fresh-Demo European project, with the aim to demonstrate the performance of the technology 103 (Fresh-Demo, 2015). Table 1 shows details of the geographic location of the supply chains. The 104 number of storage and transportation stages varies depending on the location of the market. These 105 post-harvest supply chains represent typical supply chains in Europe in terms of transportation 106 distances and direction of the supply (with the general trend from the South of Europe to other 107 European countries). To demonstrate the potential of the technology when applied at full scale, as 108 part of sensitivity check, we made comparisons with scenarios where supply chains are based on 109 European market statistics for each of the considered products. This leads to differences in 110 modelling agricultural production, transportation distances, energy consumption and biowaste 111 disposal.

112

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.

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

	Asparagus	Kirchdorf (Germany)	No storage	No storage	Bremerhaven (Germany)		Germany - Germany
	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
Humidification equipment characteristics	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

¹¹¹⁸² Data on energy turnover for the humidificat ³ Average, depending on transport distances

120

121 **2.3. Life cycle assessment**

122 The environmental life cycle assessment (LCA) methodology is applied in accordance with the

123 requirements of the ILCD Handbook (JRC, 2010) and the ISO standard (ISO 14044).

124

125 **2.3.1. Functional unit**

126 The functional unit is defined as "1 kg of fresh produce sold at the retailer, with fresh and turgid

127 appearance and no signs of deterioration and microbial contamination". As we do not expect that

128 the quality of the four fruits and vegetables in terms of their nutritional value changes as a result of

129 humidification, and as the demonstration case studies did not show this, the functional unit based on

- 130 mass unit is deemed to be sufficient (Heller et al., 2013).
- 131

132 2.3.2. System boundaries

133 Fig. 1 shows the system boundaries considered for the study. They include all life cycle stages

134 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.

136 washing, pre-cooling and packaging) at the processing center; (iv) storage at the processing center 137 (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 138 139 (supermarket). For the conventional supply chain without humidification, to which the 140 humidification-based post-harvest supply chains are compared, cold chain is maintained until the 141 point of retail, with the use of refrigeration systems (typically vapor compression systems) in 142 cooling rooms, truck trailers and supermarket displays. When humidification is applied, production, 143 use and disposal of the technology are considered and conventional sanitation is replaced by 144 humidifiers' sanitation with the flavonoid-based sanitizer. Total amounts of produce flowing 145 through the life cycle stages and total amounts of produce losses will also change when humidifiers 146 are used.

147 Agricultural production includes the use of fertilizers and pesticides on the field, irrigation, 148 machinery use for all agricultural activities (planting, fertilization, pesticide application, tillage and 149 harvesting), production of fertilizers and pesticides, extraction of raw materials and their transport 150 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 151 152 plastic packaging materials depending on the product) and refrigerated storage in a cooling room. 153 Disposal of the packaging at the destination countries is also included. Road transport from the field 154 to the processing center at the farm occurs in regular non-refrigerated trucks (regular transport); the 155 remaining transportation stages occur in conventionally refrigerated trucks. At the distribution 156 center(s), the produce is refrigerated in cooling rooms. Similarly, at the retailer, after a storage 157 period in cooling room, the product is kept refrigerated in open displays. Finally, any losses of the 158 product (e.g. due to spoilage) are disposed of according to the waste management system in the 159 country of disposal.

160 The ultrasonic humidification technology is applied during all refrigerated storage and 161 transport processes, from storage at the processing center to the refrigerated displays at the retailer 162 (Fig. 1). The energy, water and natural sanitizer consumption of the humidifiers are accounted for, 163 together with the energy savings in conventional refrigeration. The production of humidifiers 164 considers extraction of raw materials and production process of the single components (e.g. steel for 165 the case, mainboard, control unit), without accounting for the energy requirements of the 166 assembling process. Finally, disposal of the technology is included according to the waste 167 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.

172

173 2.3.3. Sensitivity scenarios

Sensitivity scenarios were constructed to consider factors that are uncertain, variable or can 174 175 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 176 177 there is potential for up to 50% reduction in each stage of application of the technology. Thus, this 178 figure (considered as high efficiency) is used for the baseline scenarios and other possible 179 efficiencies are tested in separate scenarios. Second, produce losses along supply chains may vary 180 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 181 182 losses per fruit and vegetable are considered). Finally, the geographical location of the supply 183 chains in Europe also varies and to illustrate the applicability of our findings beyond case study 184 locations, alternative locations are compared. 185

Table 2: Overview of compared scenarios for the studied fruits and vegetables supply chains.

- 187 Please refer to Table 3 for precise information on average, lowest and highest produce losses and
- 188 Table S2, SI for more details on baseline and sensitivity scenario locations (Location 1/Location 2).
- 189

	No.	Humidifier efficiency	Inherent produce	Geographic location ²
		(% losses reduction in	losses	
		each stage of application) ¹		
Conventional supply	1-4	-	Average	Baseline
chain	Baseline scenarios			
	5-12	-	Lowest/highest	Baseline
	13-20	-	Average	Location 1/Location 2
Humidification-based	21-24	High (50%)	Average	Baseline
supply chain	Baseline scenarios			
	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.

196 To summarize, sensitivity scenarios were made to consider differences in (i) humidifiers 197 efficiency in reducing produce losses, accounting for zero, low and medium efficiency of the 198 technology (respectively 0, 20 and 30% losses reduction in the stage of application); (ii) percentage 199 of inherent produce losses, by accounting for supply chains with the lowest and highest possible 200 inherent losses for each specific product and (iii) geographic location, by considering two 201 alternative supply chain locations based on major import/export trends of the considered product in 202 the European market, retrieved from Trade Map 2015 (see Table 2 and SI, Table S2). The scenario 203 for zero efficiency of the humidifiers is not realistic, but was made to better understand the 204 consequences of introducing the technology in terms of materials, water and energy inputs. It was 205 assumed that only half of the food losses in each stage is due to poor storage system, thus the 206 scenario for high efficiency (50% losses reduction), corresponds to the maximum possible reduction 207 achievable with an improved storage system. The remaining losses are caused by other factors and 208 are therefore not affected (see Section 4.1, SI). In our assessment, different food losses influence the 209 initial quantities to be produced and disposed, whereas geographical location determines differences

- 210 mainly in (i) transport distances, (ii) number of storage and transport processes, (iii) use of land and
- 211 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
- 213 disposal of the food waste).
- 214

215 2.3.4. Modelling framework

216 The ILCD guidelines provide methodological guidance according to different decision situations 217 and, in this context, the current study is considered a micro-level decision support (type-A) 218 situation. Due to the relative immaturity of the technology and its consequent limited application at 219 this point, the changes derived from using it in food supply chains are not expected to have 220 consequences on the other systems (like the need for installation of new water supply plants for the 221 water supply). It follows that an attributional LCA approach is applied, where average country-222 specific data and energy mixes are used, as well as modelling of average technology, e.g. 223 refrigerated transport. For globally produced and traded commodities, such as raw materials and 224 humidifier components, global production is modelled. Refrigerated transport processes are also 225 modelled according to global conditions as no regionalized inventories are available. Packaging and 226 produce waste disposal methods and water supply technology for agriculture and humidifiers 227 operation reflect European conditions. Average country-specific electricity mixes are used during 228 every stage of refrigerated storage and waste disposal process. In cases of processes with more than 229 one functionality (i.e. delivering one or more by-products), system expansion is performed. This is 230 the case of waste incineration, where recovered heat and electricity are credited for internal plant 231 energy redistribution and recycling processes, where recycled steel, paper and plastic substitute the 232 production of virgin material. In organic waste composting, credits are given to avoided primary 233 production of fertilizers and the use of biogas (from anaerobic digestion) in heat and power 234 cogeneration plants is credited with the respective avoided energy production. Note, that we apply 235 system expansion (through crediting) using average processes in this attributional approach, 236 consistently with both ILCD and the ISO hierarchy to solving multifunctionality, although system 237 expansion using marginal processes has traditionally, particularly before the ILCD 238 recommendations were made, been considered for the consequential approach to inventory 239 modelling (allocation has traditionally been used for the attributional approach). 240

241 2.3.5. Life cycle impact assessment

- 242 Modelling was performed with the software SimaPro, version 8.2.3 (PRé Consultants, the
- 243 Netherlands). Environmental impact scores were calculated using characterization factors according
- to ILCD's recommended methods at midpoint (ILCD 2011 Midpoint+, version 1.08), as
- 245 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).
- 247 LCIA methods and normalization factors are presented in SI, Section S3.
- 248

249 **2.3.6. Data and model parameters**

250 Unit processes for the foreground system are modelled using model parameters based on primary

- 251 data from the manufacturer Contronics Engineering B.V. combined with data from the literature.
- 252 Unit processes for the background system, like agricultural production or biowaste disposal, are
- 253 based on data from ecoinvent, version 3.2 (ecoinvent, 2015; Moreno Ruiz et al., 2015). Model
- 254 parameters and unit processes are synthesized in SI, Section S4, and references given.
- 255

256 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.

261

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	с
	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	а	16.9	с
Grapes	Agricultural production	20	Gustavsson et al., 2011	15	а	25	с
	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	а	25	с
	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	С

269 **2.3.6.2.** Agricultural production

270 Unit processes and model parameters regarding agricultural production of all analyzed products are 271 taken from Stoessel et al., 2012, who provide a consistent life cycle inventory on agricultural 272 production of a large range of fruits and vegetables in different countries (as implemented in 273 ecoinvent 3.2 database). The only available datasets for strawberries, asparagus and grapes were 274 used and these are representative for production in Switzerland (strawberries and asparagus) and 275 Spain (grapes). Data on peaches is retrieved from the dataset of apple production in Switzerland 276 assuming that farming of peaches and apples are similar, since no inventory for peaches was 277 available. Asparagus and peaches production schemes were modelled based on integrated 278 production methods, while conventional production methods were used for strawberries and grapes, 279 according to availability in econvent. For strawberries produced in Spain and peaches produced in 280 Italy, country-specific information about land and water use for irrigation was available. This 281 information was used based on (Lozano et al., 2016), who provide information about water use for 282 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). 283

284

285 **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)

291 (Suslow, 2000). Energy consumption of pre-cooling is calculated using the method presented in 292 Sanjuán et al., 2014, who provide estimation tools for energy demand of various pre-cooling 293 methods. Energy consumption at retailer displays is calculated considering the consumption of a 294 specific refrigerated display size and using the data in (Fricke and Becker, 2010), which provides 295 the electricity consumption per meter (meters of display length) of typical displays in U.S. 296 supermarkets. Note that assuming cooling at display for the selected products is a realistic option 297 that may vary from country to country. In cases when produce-specific information was not found, 298 data on the closest product category (e.g. bulk packed density) or the most recent and accurate data 299 were used. This applies to energy consumption during cooling room storage, which is retrieved 300 from Stoessel et al., 2012 (refrigerated storage of apples in Germany at 1°C in cooling room) and is 301 used for all produce. Transport distances between the production site and retail were taken from 302 Google maps and data on additional fuel consumption for power supply to the refrigeration unit are 303 based on the generic process available in ecoinvent, version 3.2.

304

305 **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).

310

311 **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.

319

320 **2.4. Uncertainty analysis**

321 Uncertainty of parameters in the foreground system was estimated using the Pedigree matrix

322 approach (Ciroth et al., 2013). First, each uncertain input and output data was assigned a numerical

323 uncertainty factor by assessing data quality on the basis of five criteria, i.e. reliability,

324 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

326 resource, emission, waste treatment service) and square geometric standard deviations calculated,

- 327 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.

335

336 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 postharvest. 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.

343

344 **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),

- 348 grapes and asparagus in Europe and for the ultrasonic humidification systems developed by
- 349 Contronics Engineering B.V.

350

351 **3.2** Overview of life cycle impact assessment results for conventional systems

352 Characterized life cycle impact assessment (LCIA) results for conventional supply chains (baseline

- 353 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

355 categories are found in SI, Section S7). Peaches show the best performance in 10 impact categories 356 (although with significant differences in only 5 impact categories), followed by grapes with the 357 lowest impact scores in 3 categories. On the other hand, asparagus shows the worst performance in 358 11 categories out of 15 (including climate change and mineral, fossil and renewable resource 359 depletion) compared to the other fruits, followed by strawberries, being the worst in 4 categories 360 (including water depletion). Statistically significant differences in impact scores between asparagus 361 and the other products are found in 10 impact categories (SI, Table S20). The results for climate 362 change impacts are below 2 kg CO₂ eq per kg of produce sold, which is within the variability range 363 reported in other studies for similar supply chains (i.e. Europe as geographical scope, distribution 364 by truck, system boundaries including post-harvest stages) of strawberries and asparagus (Soode et 365 al., 2015; Stoessel et al., 2012; Michalský and Hooda, 2015), but higher compared to studies on 366 similar fruits (Cerutti et al., 2011). For peaches and grapes, the results are approximately 4 to 8 367 times higher compared to studies assessing only the production stage (Vinyes et al., 2015; 368 Villanueva-Rey et al., 2014), highlighting the need for considering impacts stemming from post-369 harvest stages of supply chains.

370 Normalized results show that the highest scores are seen in six impact categories (freshwater 371 ecotoxicity, water depletion, resource depletion, marine eutrophication, human toxicity cancer and 372 non-cancer effects), with figures up to 0.01% of the annual impact of an average European for at 373 least one of the products (see SI, Section S7, Fig. S5). For the remaining categories, impact scores 374 are lower, down to 0.001% of annual average European impact. Assuming equal weighting across 375 impact categories, the 6 categories with highest scores are the most relevant to consider, particularly 376 water and resources depletion for the possible impacts derived from water and materials needs of 377 humidifiers (see SI, Table S1).

378



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).

384

385 3.3 Process contribution for the conventional and humidification systems

386 Process contribution analysis was carried out to identify drivers of the impacts in the conventional 387 supply chain and elucidate potential implications from introducing humidification (Fig. 3). The 388 drivers vary depending on the impact category and the type of produce, however some common 389 trends are observed. First, for strawberries, peaches and grapes the majority of the impacts are 390 caused by the transportation processes (in particular from the related CO₂, NO_x, hydrocarbons and 391 metals emissions to air) and the agricultural activities. Second, the contribution of biowaste 392 treatment is generally below 15% of total impact score, except for climate change and 393 eutrophication impacts, where important contributions up to 51% are observed for peaches and 394 grapes. Finally, some negative contributions up to 37% (mainly avoided particulate matter and land 395 use impacts) are primarily related to avoided virgin material production from plastic and cardboard 396 packaging recycling (classified to the processing stage).

397 Transport activities contribute on average around 52, 44 and 52%, whereas agriculture about 398 33, 37 and 33%, for strawberries, peaches and grapes respectively. This predominant contribution 399 of transport processes is in contrast to what is found in other LCA studies on fruits and vegetables, 400 where farming is found to be major driver of impacts (Canals et al., 2008; Cellura et al., 2012; 401 Soode et al., 2015). However, other authors report significant contributions of transport to different 402 impact categories (Hospido et al., 2009; Sim et al., 2007; Payen et al., 2014). The role of transport 403 in this study is explained by: (i) relatively longer transport distances, and (ii) differences in the 404 modelled farming methods (e.g. greenhouse farming not considered in this study), leading to lower 405 environmental impacts from the production stage in our study. Contribution analysis for asparagus 406 supports these explanations. For asparagus, agricultural production is the dominant contributor to all 407 impacts (average 87%), with only marginal contributions from transport processes. This is a 408 consequence of the shorter transport distances and the larger environmental impacts of asparagus 409 production compared to the other fruits (i.e. greater land occupation, higher pesticide emissions, 410 higher fertilizer and field machinery use). The latter also explains the slightly higher LCIA results 411 observed for asparagus (Table S19).



412

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.

416 Humidification systems show similar process contribution results regarding the importance 417 of agriculture and transport (Fig. S7, SI). The contribution of humidifiers production, operation and 418 disposal in the whole supply chain is around 2% on average for most categories, with the exception 419 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% 420 421 contribution). This has relevant implications only in the case this substance is still used in the 422 industry, which is not likely since major ozone depleting substances have been phased out (UNEP, 423 1989). Electricity consumption of humidifiers plays a major role compared to their production and 424 disposal for almost all remaining categories (above 60%), whereas the contribution to mineral 425 resources depletion derives mainly from the consumption of tantalum and nickel in the

426 manufacturing of electronic components (electrolyte tantalum capacitors contained in printed wiring
427 boards) and stainless steel respectively.

428 Overall, our findings about the conventional and humidification systems indicate that: (i) the 429 performance of the humidification technology depends mainly on how much agriculture and 430 transport processes can be reduced, i.e. how much humidifiers can reduce food losses; (ii) for the 431 majority of the impact categories, a reduction in the amount of produce to be disposed will bring 432 only marginal improvements, (iii) changes in energy consumption during storage are not expected 433 to be an important factor in the overall performance and (iv) choosing other types of electrolyte 434 capacitors other than tantalum-based ones, e.g. aluminum capacitors, could improve the 435 performance of humidifiers, as the latter show lower mineral depletion impacts.

436

437 **3.4 Does humidification bring environmental benefits?**

438 Fig. 4 shows the comparison in environmental performance between baseline humidification-based 439 supply chains and the corresponding conventional supply chains for the four fruits and vegetables. 440 The comparison is done both among different humidifier efficiencies and different inherent food 441 losses scenarios. Three main trends are observed for all four products: (i) applying humidifiers in 442 the post-harvest improves the environmental performance of the system, (ii) this performance 443 improves with increasing efficiency of the humidifiers and (iii) the higher the inherent food losses 444 the greater is the improvement. In scenarios where humidifiers reduce food losses, most of the 445 environmental impacts are also reduced by 0.2 to 23%, depending on the product, efficiency of 446 humidifiers and inherent food losses of the supply chain. This suggests that there is potential for 447 humidification to improve the environmental performance of produce supply chains. Results for 448 strawberries, peaches and grapes are characterized by high uncertainty, since no statistically 449 significant differences between any of the systems were found (except for water depletion impacts 450 at highest efficiency of humidifiers). For asparagus instead, differences were found to be 451 statistically significant in most of the cases when efficiency is high (Table S25, SI). As Monte Carlo 452 simulations take into account the correlation between uncertainties of the compared systems, this 453 high uncertainty must originate from foreground processes which are not shared between 454 conventional and humidification-based systems, i.e. related to humidifiers. The uncertainty analysis 455 also revealed that the differences in impact scores between scenarios with various performances of 456 the humidifiers are statistically significant. (Table S26, SI).

457 The potential benefits from using humidifiers are due to the provided reduction in produce 458 losses. Considering that transport processes and agricultural production are the main contributors to 459 environmental impacts (Section 3.3), the benefits stem principally from lower needs for these two 460 processes, resulting in: (i) lower greenhouse gasses emissions (e.g. CO₂, N₂O, hydrocarbons) from 461 transport exhausts and from nitrogen fertilizers application and production; (ii) reduced use of water 462 for irrigation during farming and (iii) reduced metal depletion (e.g. Zn, Pb) from machinery and 463 fertilizers production. Only for freshwater eutrophication impacts for peaches and grapes the 464 benefits are mainly due to reduced food waste disposal, i.e. reduced nutrient emissions to water 465 (nitrate and phosphate) from treatment of anaerobic digestion digester sludge. The importance of 466 reducing food losses is further demonstrated by the fact that, in the scenarios with zero efficiency of 467 humidifiers (i.e. when losses are not reduced), humidification slightly increases environmental 468 burdens. This is due to (i) greenhouse gasses emissions from additional needs for transport (e.g. 469 additional diesel and lorry production) and from reverse osmosis membrane production, (ii) water 470 consumption from increased diesel production (for transport) and from humidifiers use, and (iii) 471 minerals, metals and fossil resources depletion from additional transport (e.g. diesel, lorry and 472 refrigeration machine's refrigerant production) and from humidifiers' components production (e.g. 473 steel and motherboard). Nevertheless, the higher the reduction in losses the better is the 474 environmental performance of the system. An improvement is already observed when humidifiers 475 work at low efficiency, i.e. when losses are cut by 20% during each stage of application.

476 The performance of the humidification systems is also influenced by the inherent food 477 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 478 479 strawberries and grapes) there are no significant benefits even at the highest efficiency of the 480 humidifiers. This suggests that in supply chains with already low inherent losses, the additional 481 reduction of losses is not a factor that can significantly influence the environmental performance (as 482 would be for example the farming method), thus in this case humidifiers are not particularly 483 beneficial. As opposite, it is more convenient to apply humidification in supply chains characterized 484 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. 489 Even increased demand for transport and the possible increase in diesel consumption for power

- 490 supply (Table S12) do not undermine the overall performance. Reductions of impacts from
- 491 agriculture and transport processes are the main reasons for the improved environmental
- 492 performance, whereas reduced biowaste treatment does not bring significant improvements for most
- 493 of the categories.



495 Fig. 4: Percentage of relative difference in impact scores between baseline humidification-based 496 (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 497 498 efficiencies (scenarios no. 41 - 44, 61 - 64, 81 - 84 are compared to scenarios 1 - 4) and between 499 different inherent produce losses (scenarios no. 33 – 40, 53 – 60, 73 – 80, 93 – 100 are compared to 500 scenarios 5 - 12) are also shown (see Table 2 for description of scenarios). Please refer to Tables 501 S21 – S24 (SI, Section S6) for results on all 15 ILCD's impact categories and Table S25 for results 502 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.

505

506 **3.5 Influence of geographic location and transportation distance**

507 The scenarios with alternative supply chain locations show some similar trends to those found for 508 the baseline locations, i.e. better environmental performance with humidifiers already at low 509 efficiency and major benefits with increasing efficiency (Fig. S7, SI). However, since the extent of 510 impact reductions is found to be almost the same in all scenarios for all produces, changing the 511 geographic location does not have a significant effect on the systems' environmental performance. 512 This suggests that the performance of humidifiers is not influenced by the geographic location of 513 the supply chain. Similar benefits are observed in systems where the difference in transport 514 distances is up to 2800 km and where the number of storage processes varies from three to one (e.g. 515 for strawberries baseline location and location 2 in Fig. S7). Also in this case, uncertainties are high 516 as statistically significant differences with the conventional system are found mainly only for 517 asparagus (Table S27, SI).

518 No significant differences in performance are found when varying those parameters that are 519 determined by the location of the supply chain, such as use of land and water resources for 520 agricultural production, energy production mixes and biowaste management system. Probably the 521 variation of these parameters among the studied locations is not sufficiently large to undermine the 522 benefits from applying humidifiers in different geographic contexts, making the use of the 523 technology environmentally convenient irrespective of the supply chain location. Despite the use of 524 scenario-specific transport distances, we do not expect to obtain different results if considering 525 average transport distances. Indeed, while the main contributors to environmental impacts may 526 change depending on the length of the supply chain (which can either be agriculture or transport as 527 observed in the contribution analysis), the performance of humidifiers will not be significantly 528 affected. Note that, transport distances and number of storage processes do not influence 529 humidifiers' performance because it was implicitly assumed that inherent produce losses during 530 storage and transport stages (and thus losses reduction induced by humidifiers) remain the same 531 regardless of the number of sub-processes. This assumption might not always hold, as losses can be 532 lower in short supply chains. However, considering that the utilized inherent losses are average 533 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 inthe European context.

536

537 4. Implications for management, policy and research

We showed that applying humidification technology in the post-harvest stages of fruits and 538 539 vegetables can improve the environmental performance of the supply chains. For such a more 540 sustainable supply chain management to be realized in real life, however, the technology should be 541 implemented along the whole post-harvest supply chain. All the different actors in the supply chain 542 must engage to install, properly operate the technology and ensure that no breaks occur in the cold 543 chain. This can be a challenge as it requires a significant level of collaboration, communication and 544 knowledge sharing along the chain. Such interactions are indeed recognized as key factors but also 545 major barriers for achieving sustainable management in supply chains (Boström et al., 2015; Van 546 Hoof and Thiell, 2014; Silvestre, 2015). Another barrier for implementation of the technology is the 547 increase in costs, in this case, related to the introduction of new equipment and training of 548 employees (e.g. truck drivers, warehouse and supermarket workers), which can jeopardize 549 implementation of the technology, at least initially. However, stimulating cooperation and 550 innovation to achieve full implementation in the chain can be effectively led by retailers, who have 551 the power to influence upstream actors by creating "economic selection pressure throughout the 552 chain" (Mylan et al., 2015). This implies that humidification systems should be first introduced at 553 retailers, which can then exploit their buying power to stimulate full implementation upstream the 554 chain. Initiatives such as best practice sharing, workshops, demonstration projects, guidance 555 documents are useful tools for i) retailer engagement, ii) engagement of other actors in the chain, 556 iii) training and development of technical skills for employees.

557 Our findings have important implications for policy. Namely, we recommend the use of 558 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 559 560 supply chain increases. This number is below the total average losses for fruits and vegetables 561 traded in Europe from production to retailing (Gustavsson et al., 2011), demonstrating that there is 562 room for improvement and potential for applying the technology to fruits and vegetables which 563 have higher losses. Humidification could thus play a role in the EU Action Plan for Circular 564 Economy which proposes to 'halve per capita global food waste at the retail and consumer levels 565 and reduce food losses along production and supply chains, including post-harvest losses' by 2030

566 in support of the Sustainable Development Goals of the United Nations (EC, 2015; UN, 2015). In 567 addition, humidification can contribute to lower European carbon emissions by reducing environmental impacts stemming from agriculture and transport. An average of 0.1 kg CO₂ eq can 568 569 be avoided per 1 kg of product sold, which would equal roughly 22 million tons CO_2 eq considering 570 implementation of humidification to the whole quantity of fruits and vegetables produced in Europe 571 and then distributed throughout the continent (approximately 190 million tons, according to 572 FAOSTAT, 2014). This represents approximately 0.9 % of the total emission reduction target set by 573 2030 (EEA, 2016; EC, 2013). We stress, however, that the interpretation of this results is 574 constrained by the decision context of the study, and our results are not directly applicable to 575 decisions which may have large structural consequences on the market. For example, in a 576 hypothetical situation where ultrasonic humidification becomes a dominant technology for reducing 577 losses in post-harvest, consideration of consequences that its implementation will have on the 578 market would have to be made, like the need for additional capacity for provision of clean water for 579 running of humidifiers. This would require an additional, consequential LCA study. The benefits 580 found by introducing humidification systems in European supply chains, demonstrate the great 581 potential of this technology for application in longer, global chains, in particular when produce is 582 outsourced to developing countries, where post-harvest losses of fruits and vegetables are 583 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.

588

590 **References**

- Barth, M.M., Perry, A.K., Schmidt, S.J., Klein, B.P., 1992. Misting affects market quality and
 enzyme activity of broccoli during retail storage. J Food Sci 57, 954–957. doi:10.1111/j.13652621.1992.tb14332.x
- Benini, L., Mancini, L., Sala, S., Schau, E., Manfredi, S., Pant, R., 2014. Normalisation method and
 data for Environmental Footprints. Report EUR 26842 EN. Ispra. doi:10.2788/16415
- Boström, M., Jönsson, A.M., Lockie, S., Mol, A.P.J., Oosterveer, P., 2015. Sustainable and
 responsible supply chain governance: Challenges and opportunities. J. Clean. Prod. 107, 1–7.
 doi:10.1016/j.jclepro.2014.11.050
- Brown, T., Corry, J.E.L., Evans, J. a., 2007. Humidification of unwrapped chilled meat on retail
 display using an ultrasonic fogging system. Meat Sci. 77, 670–677.
- 601 doi:10.1016/j.meatsci.2007.05.021
- Brown, T., Corry, J.E.L., James, S.J., 2004. Humidification of chilled fruit and vegetables on retail
 display using an ultrasonic fogging system with water/air ozonation. Int. J. Refrig. 27, 862–
 868. doi:10.1016/j.ijrefrig.2004.04.009
- Canals, L.M.I., Muñoz, I., Hospido, A., Plassmann, K., McLaren, S., 2008. Life Cycle Assessment
 (LCA) of domestic vs. imported vegetables. Case studies on broccoli, salad crops and green
 beans, Rural Economy and Land Use (RELU) programme.
- 608 Cellura, M., Longo, S., Mistretta, M., 2012. Life Cycle Assessment (LCA) of protected crops: An
 609 Italian case study. J. Clean. Prod. 28, 56–62. doi:10.1016/j.jclepro.2011.10.021
- 610 Cerutti, A.K., Galizia, D., Bruun, S., Mellano, G.M., Beccaro, G.L., 2011. Assessing Environmental
 611 Sustainability of Different Apple Supply Chains in Northern Italy. In: Finkbeiner M. (eds)
- Towards Life Cycle Sustainability Management. Springer, Dordrecht 618. doi:10.1007/97894-007-1899-9_33
- 614 Ciroth, A., Muller, S., Weidema, B.P., Lesage, P., 2013. Refining the pedigree matrix approach in
 615 ecoinvent : Towards empirical uncertainty factors, in: LCA Discussion Forum. p. 31.
- 616 Delele, M.A., Schenk, A., Ramon, H., Nicolaï, B.M., Verboven, P., 2009. Evaluation of a chicory
- 617 root cold store humidification system using computational fluid dynamics. J. Food Eng. 94,
- 618 110–121. doi:10.1016/j.jfoodeng.2009.03.004

- Dieckmann, A., List, D., Zache, U., 1993. Cold water mist humidification to preserve quality of
 fresh vegetables during retail sale. LWT Food Sci. Technol. 26, 340–346.
- 621 DOW, 2013. FILMTEC membranes product information [WWW Document]. URL
- http://www.dowwaterandprocess.com/en/products/reverse_osmosis_and_nanofiltration/sea_wa
 ter_elements (accessed 6.15.15).
- 624 EC, 2015. An EU action plan for the circular economy, European Commission. Brussels.
- EC, 2013. Green Paper A 2030 framework for climate and energy policies, European
 Commission, Brussels.
- 627 EC-JRC, 2011. International Reference Life Cycle Data System (ILCD) Handbook-
- Recommendations for Life Cycle Impact Assessment in the European context., Publications
 office of the European Union, EUR 24571 EN. Luxembourg.
- 630 ecoinvent, 2015. The ecoinvent database, v3.2; Zürich.
- EEA, 2016. Greenhouse gas emissions by source sector [WWW Document]. URL
- http://ec.europa.eu/eurostat/statistics-explained/index.php/Greenhouse_gas_emission_statistics
 (accessed 4.18.17).
- Eriksson, M., Strid, I., Hansson, P.A., 2012. Food losses in six Swedish retail stores: Wastage of
 fruit and vegetables in relation to quantities delivered. Resour. Conserv. Recycl. 68, 14–20.
 doi:10.1016/j.resconrec.2012.08.001
- 637 FAO, 2013. Food wastage footprint. Impacts on natural resources. Summary Report.
- FAOSTAT, 2014. Food and Agriculture Organization of the United Nations. FAOSTAT Database.
 Rome. [WWW Document]. URL http://www.fao.org/faostat/en/#data/QC (accessed 4.18.17).
- 640 Fresh-Demo, 2015. Waste reduction and quality improvement of fruits and vegetables via an
- 641 innovative and energy-efficient humidification/disinfection technology [WWW Document].
- 642 URL http://www.fresh-demo.eu/ (accessed 11.1.16).
- Fricke, B., Becker, B., 2010. Energy Use of Doored and Open Vertical Refrigerated Display Cases,
 in: International Refrigeration And Air Conditioning Conference. Purdue University.
- 645 Govindan, K., Seuring, S., Zhu, Q., Azevedo, S.G., 2016. Accelerating the transition towards
- sustainability dynamics into supply chain relationship management and governance structures.
- 647 J. Clean. Prod. 112, 1813–1823. doi:10.1016/j.jclepro.2015.11.084

- Gustavsson, J., Cederberg, C., Sonesson, U., van Otterdijk, R., Meybeck, A., 2011. Global food
 losses and food waste Extent, causes and prevention. Rome: Food and Agricolture
 Organization of the United Nations.
- Heller, M.C., Keoleian, G.A., Willett, W.C., 2013. Toward a life cycle-based, diet-level framework
 for food environmental impact and nutritional quality assessment: A critical review. Environ.
 Sci. Technol. 47, 12632–12647. doi:10.1021/es4025113
- Hospido, A., Milà I Canals, L., McLaren, S., Truninger, M., Edwards-Jones, G., Clift, R., 2009. The
 role of seasonality in lettuce consumption: A case study of environmental and social aspects.
 Int. J. Life Cycle Assess. 14, 381–391. doi:10.1007/s11367-009-0091-7
- Hung, D. Van, Tong, S., Tanaka, F., Yasunaga, E., Hamanaka, D., Hiruma, N., Uchino, T., 2011.
 Controlling the weight loss of fresh produce during postharvest storage under a nano-size mist
 environment. J. Food Eng. 106, 325–330. doi:10.1016/j.jfoodeng.2011.05.027
- JRC, 2010. International Reference Life Cycle Data System (ILCD) Handbook -- General guide for
 Life Cycle Assessment -- Detailed guidance. Ispra. doi:10.2788/38479
- Lozano, D., Ruiz, N., Gavilán, P., 2016. Consumptive water use and irrigation performance of
 strawberries. Agric. Water Manag. 169, 44–51. doi:10.1016/j.agwat.2016.02.011
- Michalský, M., Hooda, P.S., 2015. Greenhouse gas emissions of imported and locally produced
 fruit and vegetable commodities: A quantitative assessment. Environ. Sci. Policy 48, 32–43.
 doi:10.1016/j.envsci.2014.12.018
- Mohd-Som, F., Spomer, L.A., Martin, S.E., Schmidt, S.J., 1995. Microflora changes in misted and
 nonmisted broccoli at refrigerated storage temperatures. J. Food Qual. 18, 279–293.
- Moreno Ruiz, E., Lévová, T., Bourgault, G., Wernet, G., 2015. Documentation of changes
 implemented in ecoinvent Data 3.1, Ecoinvent Centre, Zürich, Switzerland.
- 671 Morton, B.W., 2015. DriSteem Humidification handbook.
- Mylan, J., Geels, F.W., Gee, S., McMeekin, A., Foster, C., 2015. Eco-innovation and retailers in
 milk, beef and bread chains: Enriching environmental supply chain management with insights
 from innovation studies. J. Clean. Prod. 107, 20–30. doi:10.1016/j.jclepro.2014.09.065
- Ngcobo, M.E.K., Delele, M.A., Chen, L., Opara, U.L., 2013. Investigating the potential of a
 humidification system to control moisture loss and quality of "Crimson Seedless" table grapes
- 677 during cold storage. Postharvest Biol. Technol. 86, 201–211.

doi:10.1016/j.postharvbio.2013.06.037

- Payen, S., Basset-Mens, C., Perret, S., 2014. LCA of local and imported tomato: an energy and
 water trade-off. J. Clean. Prod. 87, 139–148. doi:10.1016/j.jclepro.2014.10.007
- Priefer, C., Jörissen, J., Bräutigam, K.R., 2016. Food waste prevention in Europe A cause-driven
 approach to identify the most relevant leverage points for action. Resour. Conserv. Recycl.
- 683 109, 155–165. doi:10.1016/j.resconrec.2016.03.004
- Prusky, D., 2011. Reduction of the incidence of postharvest quality losses, and future prospects.
 Food Secur. 3, 463–474. doi:10.1007/s12571-011-0147-y
- 686 Sanjuán, N., Stoessel, F., Hellweg, S., 2014. Closing data gaps for LCA of food products:
- Estimating the energy demand of food processing. Environ. Sci. Technol. 48, 1132–1140.
 doi:10.1021/es4033716
- Sarkis, J., 2003. A strategic decision framework for green supply chain management. J. Clean. Prod.
 11, 397–409. doi:10.1016/S0959-6526(02)00062-8
- Seuring, S., Müller, M., 2008. From a literature review to a conceptual framework for sustainable
 supply chain management. J. Clean. Prod. 16, 1699–1710. doi:10.1016/j.jclepro.2008.04.020
- 693 Silvestre, B.S., 2015. A hard nut to crack! Implementing supply chain sustainability in an emerging
 694 economy. J. Clean. Prod. 96, 171–181. doi:10.1016/j.jclepro.2014.01.009
- Sim, S., Barry, M., Clift, R., Cowell, S.J., 2007. The relative importance of transport in determining
 an appropriate sustainability strategy for food sourcing. Int. J. Life Cycle Assess. 12, 422–431.
 doi:10.1007/s11367-006-0259-3
- 698 Soode, E., Lampert, P., Weber-Blaschke, G., Richter, K., 2015. Carbon footprints of the
- horticultural products strawberries, asparagus, roses and orchids in Germany. J. Clean. Prod.
 87, 168–179. doi:10.1016/j.jclepro.2014.09.035
- Stoessel, F., Juraske, R., Pfister, S., Hellweg, S., 2012. Life cycle inventory and carbon and water
 footprint of fruits and vegetables: application to a Swiss retailer. Environ. Sci. Technol. 46,
 3253–3262.
- Suslow, T., 2000. Chlorination in the production and post-harvest handling of fresh fruits and
 vegetables, in: D. McLaren (Ed.), Fruit and Vegetable Processing. Food Processing Center at
 the University of Nebraska, Linkoln, NE, pp. 2–15.

Terry, L., Mena, C., Williams, A., Jenney, N., Whitehead, P., 2011. Fruit and vegetable resource
maps, Waste and Resources Action Program (WRAP).

709 Tirawat, D., Flick, D., Mérendet, V., Derens, E., Laguerre, O., 2017. Combination of fogging and

refrigeration for white asparagus preservation on vegetable stalls. Pos 124, 8–17.

711 doi:http://dx.doi.org/10.1016/j.postharvbio.2016.09.010

- 712 Trade Map, 2015. List of importing/exporting countries for selected products in 2015 [WWW
- 713 Document]. URL http://www.trademap.org/Index.aspx (accessed 10.19.16).
- UN, 2015. Transforming our world: The 2030 agenda for sustainable development A/RES/70/1.
 doi:10.1007/s13398-014-0173-7.2
- UNEP, 1989. Handbook for the Montreal Protocol on Substances that Deplete the Ozone Layer
 [WWW Document]. URL http://ozone.unep.org/en/handbook-montreal-protocol-substancesdeplete-ozone-layer/25411 (accessed 1.30.17).
- Van Hoof, B., Thiell, M., 2014. Collaboration capacity for sustainable supply chain management:
 Small and medium-sized enterprises in Mexico. J. Clean. Prod. 67, 239–248.
 doi:10.1016/j.jclepro.2013.12.030
- 722 Villanueva-Rey, P., Vázquez-Rowe, I., Moreira, M.T., Feijoo, G., 2014. Comparative life cycle
- assessment in the wine sector: Biodynamic vs. conventional viticulture activities in NW Spain.
 J. Clean. Prod. 65, 330–341. doi:10.1016/j.jclepro.2013.08.026
- Vinyes, E., Gasol, C.M., Asin, L., Alegre, S., Muñoz, P., 2015. Life Cycle Assessment of multiyear
 peach production. J. Clean. Prod. 104, 68–79. doi:10.1016/j.jclepro.2015.05.041