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Abstract

Berries are highly perishable fruits and require both low storage temperature and suitable packaging throughout the supply chain to preserve their organoleptic qualities. However, the energy consumption of refrigerated equipment and the use of packaging materials, plastic in particular, might generate important environmental impacts. Besides, there is a strong commitment to reduce the use of plastic in the food industry.

The aims of the current work are first to assess the energy consumption of refrigerated equipment and second to analyze the environmental performance of the strawberry supply chain. Various stages of the supply chain from transport from growers to retail storage were modeled using data from field measurement and interviews with professional stakeholders. Life Cycle Assessment (LCA) was performed for the strawberry supply chain. Different packaging materials, plastic (PET, RPET) and alternatives (molded pulp, recycled paper, cardboard), were used. The processes that generated the most important environmental burden were the packaging production and the long-distance refrigerated transport. To limit the impact related to packaging production, it is necessary to consider not only the type of packaging material but also the processes and energy consumption used in their manufacturing.

Keywords: cold chain, packaging, strawberry, energy consumption, LCA

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Abbreviation

COP	Coefficient of performance of refrigerated machine
EMAP	Equilibrium modified atmosphere packaging
GHG	Greenhouse gases
LCA	Life Cycle Assessment
MPP	Macro perforated packaging
PE	Polyethylene
PET	Polyethylene terephthalate
RPET	Recycled polyethylene terephthalate

1. Introduction

Strawberry consumption is continuously increasing worldwide. In France, it is one of the favorite fruits with an annual consumption of 110 000 tonnes (Rolland, 2022). However, strawberry is a highly perishable fruit with a relatively short shelf life and requires intensive use of energy for low-temperature storage and distribution (Kelly et al., 2019). A recent report (FAO, 2019) has estimated that around 14 % of food produced was lost during distribution from the post-harvest stage up to the retail store. This figure did not include the lost in the retail stage. In the same report, the carbon footprint of food loss and waste corresponded to 3.3 gigatonnes of CO2 equivalent: about 7 % of global GHG emissions. The refrigeration sector consumes 20% of the overall energy used worldwide and accounts for about 8 % of global GHG emissions (IIR, 2019). Therefore, two sources generating environmental impacts in the strawberry supply chain are product loss and use of refrigeration equipment.

Packaging made of non-biodegradable materials (polyethylene PE, polyethylene terephthalate PET, etc.) represents 39% of the consumption of petrochemical plastic materials in France (Labouze and Le Guern, 2007). The European Union (EU, 1994) established three types of packaging for the strawberry industry. Primary packaging which are sale units used for retail and consumers (i.e., punnet of strawberries), secondary packaging which groups several units (i.e., crate) and tertiary packaging conceived to facilitate handling and transport of crates (i.e., pallet).

Recently, several studies have focused on environmental burden of the strawberry supply chain and packaging using Life Cycle Assessment (LCA). Matar et al. (2021) compared the environmental impacts related to the use of two primary packages: equilibrium modified atmosphere packaging (EMAP) and conventional macro perforated packaging (MPP) both made of PET. For short household storage, well optimized EMAP could replace MPP. Sasaki et al. (2022) proposed an optimal package for strawberry transportation considering both losses due to vibration during the transport and environmental loads due to packaging production. The materials considered in the study were PE and PET for primary packaging and cardboard for secondary packaging. As the use of plastics has generated substantial environmental impacts both due to its production and disposal phases (Cabernard et al., 2022), other materials for packaging have been more and more considered (Semple et al., 2022).

To our knowledge, the comparison of environmental performance between different materials for strawberry packaging has not yet been studied. The aim of this work was to evaluate energy and environmental performance of the strawberry supply chain while considering various types of primary packaging: plastic (PET and RPET – recycled PET), cardboard, recycled paper and molded pulp. As one of the greatest challenges in performing assessment of food supply chains is the lack of data from industrial operational conditions, data from field measurement and interviews were used. It should be emphasized that field tests are rare in this domain (Chaomuang et al., 2022; Lu et al., 2022) because they need to be well planned and coordinated between researchers and industry collaborators.

2. Materials and methods

2.1 Description of the scope of the study

The scope of the study was presented in Fig. 1. A real-time strawberry supply chain was studied. The focus was on stages involving professional stakeholders of the supply chain, in particular when refrigerated equipment was used. The studied segment began with the transport (T1) from the grower to the packing station and ended with the storage (S3) in a cold room at retailer. The segment was composed of multiple transport (T) and storage (S) stages.

- T1: Transport from the grower to the packing station at a distance of 15 km

- S1: Refrigerated storage at the packing station at Lacropte, in Dordogne.

- T2: Transport in a refrigerated truck to a distribution platform located at Tigery, in Ile-de-France at a distance of 600 km

- S2: Refrigerated storage and allotment at the distribution platform

- T3: Transport in a refrigerated truck to a retailer at Reims in Grand-Est at a distance of 150 km

- S3: Refrigerated storage in a cold room at retailer

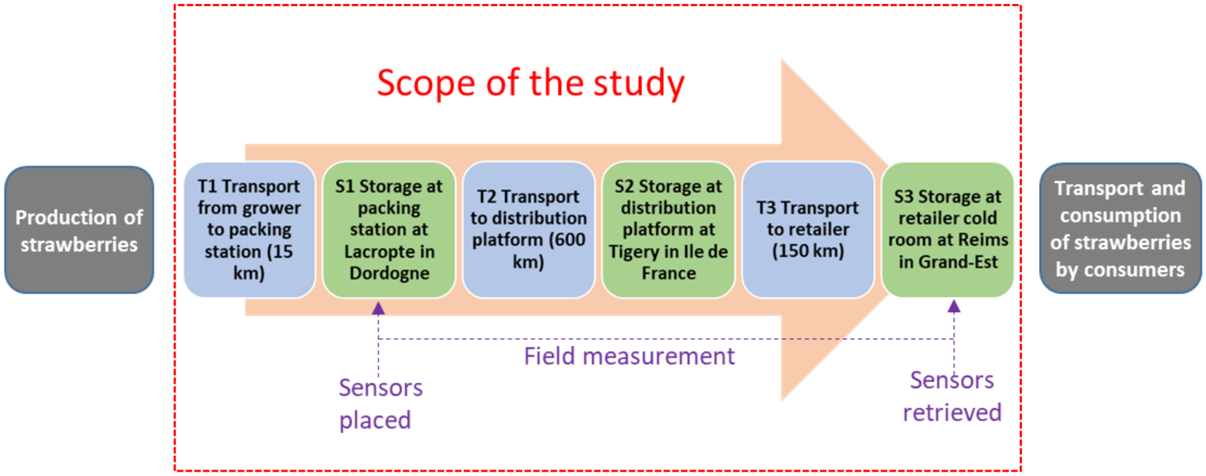


Figure 1: Scope of the study

2.2 Field measurement, packaging and instrumentation

The field measurement, illustrated in Fig.1, began at the packing station (S1) which was assured by thirty growers within a radius of 15 km from the packing station. This choice was made to ensure the availability of strawberries on the day of the measurement: growers might not deliver to the packing station on the same day, as this depended on their actual production. The field measurement began on May 18th 2021. The instrumentation was performed at the packing station on the afternoon of the 18th and collected from the retailer by mid-day on the 20th.

The strawberries (cultivar Gariguette) were harvested commercially in greenhouses. The strawberries were put directly into punnets and not precooled. Then, the punnets were sent to the packing station at Lacropte, Dordogne. Here the punnets were packed (flow-pack) in the ambient air at 14°C. The field measurement by the research team began after this packing.

For the field measurement, the primary packaging was an RPET punnet with a macro-perforated polypropylene film around the punnet (Fig. 2a). More packaging materials (PET, recycled paper, cardboard, molded pulp) were taken into account in the LCA (section 2.5). Secondary packaging (grouping 10 punnets, Fig. 2b) was a plastic crate (IFCO 60 cm x 40 cm x 11.7 cm). A pallet (tertiary packaging) consisting of 48 IFCO crates arranged on 12 levels was presented in Fig. 2d.

In order to detect temperature heterogeneity within the refrigerated equipment, two pallets were instrumented. As shown in Fig. 2e, for each pallet, thermo-hygrometers (Testo 174H, manufactured by Testo) were placed at the top and half-height to measure the relative humidity and temperature of the air around the pallet. Temperature loggers were placed in three crates (two at top and one at haft- height of the pallet, Fig. 2e) to measure air and product temperatures. For each crate, two punnets were instrumented, one next to the center of the pallet and one at the outer side of the pallet. One instrumented punnet had one small penetration probes (type TESTO 171, calibrated, uncertainty ± 0.2 °C, manufactured by Testo) introduced inside one strawberry (Fig. 2c) and one small sensor (type Ibutton, calibrated, uncertainty ± 0.3 °C, supplied by Proges Plus) glued on the cover film of the punnet to measure the air temperature (Fig. 2a). The sensors were calibrated in our laboratory using a thermostatic bath at 5 temperature levels between -10 and 30 °C; small sensors (Ibutton) were inserted in a glove finger to avoid liquid infiltration.

2.3 Interviews of professional stakeholders

Twelve interviews were conducted with various stakeholders at different stages of the strawberry supply chain: two growers, three packing stations, one transporter, three distribution platforms and three retailers. A customized survey was prepared for each stakeholder to collect information on:

- Refrigerated transport: vehicle type, distance, duration, temperature level
- Condition of storage: temperature level and duration
- Packaging material
- Loss percentage, problems related to product quality

The interviewees were quality and/or logistics managers or department managers. They were aware of the information or requested it from the persons concerned when necessary.

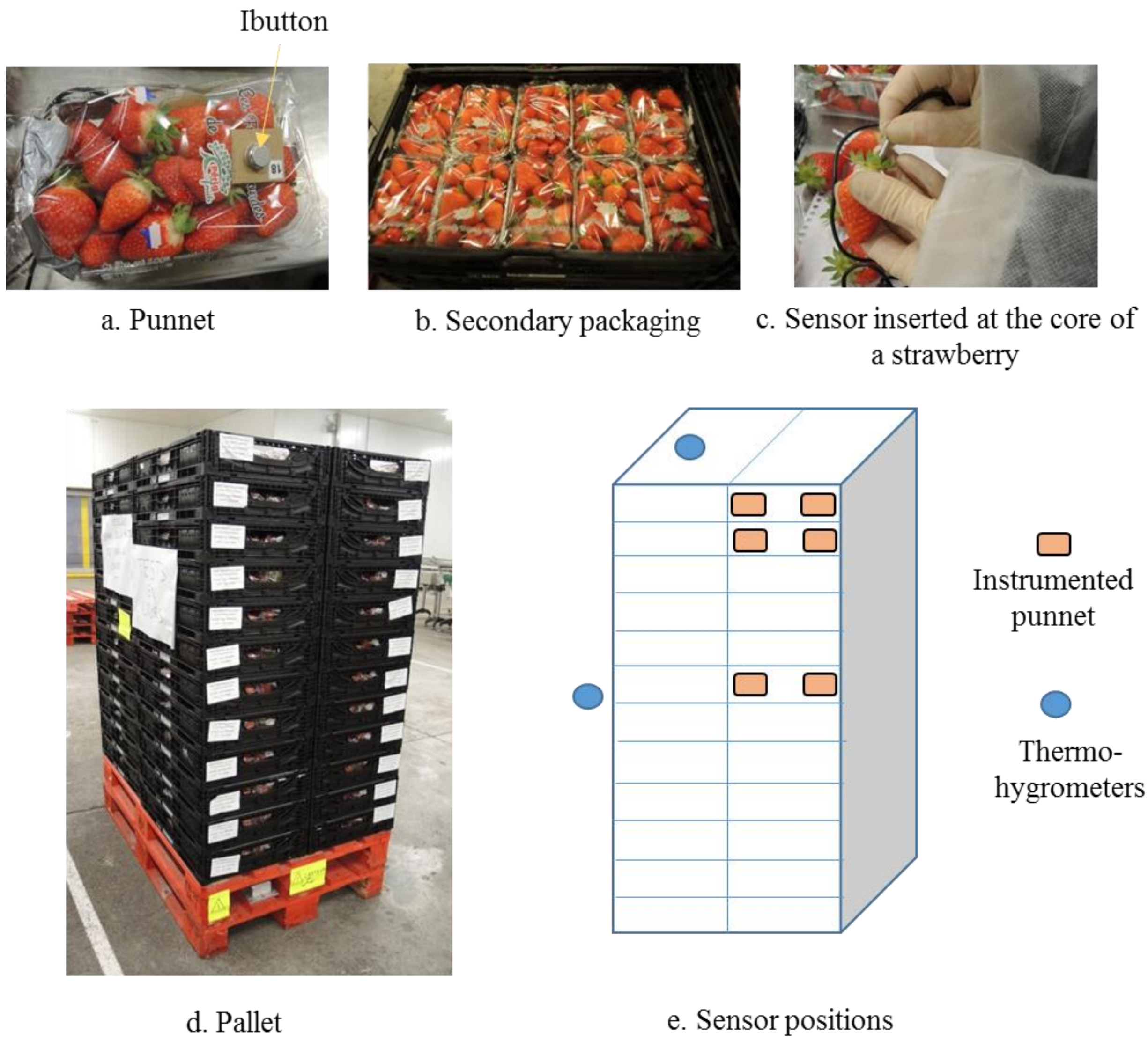


Figure 2: Packaging and instrumentation

2.4 Energy consumption assessment of storage stages

The energy consumption related to the cooling and temperature maintenance of one strawberry punnet (primary packaging) was evaluated for three cold storage stages (S1 packing station, S2 distribution platform, S3 retail cold room) using the method developed in our previous work (Duret et al., 2020) and data from the field study. For each stage (Si), the energy consumption was calculated as follows:

$$E_{punnet,Si} = \frac{Q_{f,Si}}{\eta_{Si} \times COP_{Si}} \quad [J] \qquad (1)$$

Where $E_{punnet,Si}$(J) the energy (electrical) consumption of one punnet in stage Si; $Q_{f,Si}$(J) the cooling demand for one punnet; η_{Si} the global performance coefficient of the cooling unit; COP_{Si} the Carnot Coefficient Of Performance of the refrigeration unit.

The cooling demand was calculated using Eq. (2):

$$Q_{f,Si} = Q_w + Q_c \quad [J] \quad (2)$$

Where Q_w (J) the cooling demand related to the heat loss through the wall and Q_c (J) the cooling demand for cooling the product to the equipment's setpoint temperature in case when the product is hotter than the setpoint temperature at the beginning of the stage Si. The cooling demand was evaluated for one punnet using Eq. (3) and (4).

$$Q_w = \frac{m_{punnet}}{M_{total}} K_w A_w (T_{ext} - T_{th}) dt_{Si} \quad [J] \quad (3)$$

Where m_{punnet} (kg) mass of one punnet; M_{total} (kg) total mass of stored products in stage Si; A_w(m^2) total area of the storage zone in contact with external air; K_w ($Wm^{-2}K^{-1}$) global heat transfer coefficient of the walls of the room; T_{ext} (°C) external temperature; T_{th} (°C) setpoint temperature; dt_{Si} (s) product residence time in stage Si.

$$Q_c = m_{punnet} c_p (T_i - T_f) \quad [J] \quad (4)$$

Where T_i (°C) the initial temperature of product at the beginning of stage Si; T_f (°C) the final temperature of product at the end of stage Si; c_p ($Jkg^{-1}K^{-1}$) the heat capacity of the strawberry.

The different mass of packaging was not taken into account in Eq.3 and 4 as the differences in packaging (thermal) mass was considered to have negligible effect on the energy required to cool the product.

2.5 Environmental assessment of the strawberry supply chain by LCA

LCA is a standardized methodology (Hoang et al., 2016; ISO_14044, 2006) used to evaluate the environmental burden associated with a product, technology or activity during its life cycle, based on the compilation of an inventory of inputs and outputs of different natures (material, energy, process, waste, etc.).

In a LCA study, the functional unit is a measure of the function of the system studied and provides a reference to which the inputs and outputs can be related and enables objective comparisons across different products that serve the same final function. The chosen functional unit for this study was

1 kg of strawberries at the end of the retail stage. The product loss in different stages (% of loss was a global estimate by professional stakeholders, Table 3) was taken into account in this mass. It was assumed that the product loss becomes biowaste (Frenchgovernment, 2022) that is treated by both anaerobic digestion (50 % of the waste) and composting (other 50 %).

2.5.1 Life cycle inventory – data collection

This section presents the collected data for LCA on packaging and refrigerated transport. The modelling of the supply chain was performed with information and data from the field measurement and interviews (section 3.1) and the energy assessment result (section 3.2).

It is acknowledged that the packaging materials may affect the quality of the strawberry and hence the loss rate of the strawberry fruits due to the cushioning or other functional protection performance. However, this information was not available in the present study and hence was not considered.

2.5.1.1 Packaging

Five types of packaging materials: cardboard, molded pulp, recycles paper, PET and RPET (Fig. 3) were selected for the environmental assessment. These packaging materials were representative of the primary packaging of strawberry, according to the interviews. Data on the manufacture of punnets were presented in Table 1. These data were calculated for a 250 g punnet of strawberries (about 15 medium-sized strawberries). The dimensions of the punnets were (length x width x height): 13.5 ± 0.5 cm x 9.0 ± 0.5 cm x 5.5 ± 0.5 cm. Although the type of primary packaging (punnets) may be different, the field study showed that the macro-perforated polypropylene films covering the trays, secondary and tertiary packaging were of the same type and did not depend on the primary packaging. The cover film, the secondary and the tertiary packaging were not taken into account in this work as a first approach. The data in Table 1 referred to one type of punnets from one manufacturer. The variability of these data as a function of the punnet mass was investigated in the sensitivity analysis (section 2.5.3).

Figure 3: Different types of primary packaging

Table 1: Material, energy and water inputs related to the production of a punnet containing 250 g of strawberries

	Molded pulp	Cardboard	Recycled paper	PET	RPET
Input of raw materials	sawdust 20.16 g	kraft paper 12.28 g	waste paperboard 12.6 g sawdust 1.4 g	PET granulate 14.2 g	Recycled PET granulate 14.2 g
Energy consumption (kWh)	0.0334	-	0.042	Process “thermoforming“	
Water consumption (kg)	0.0223	-	0.101		
Adhesive		adhesive 0.115 g			

For molded pulp, cardboard and recycled paper, these data were obtained by exchanges with manufacturers. The production of a cardboard punnet uses only kraft paper and adhesion. However, energy and water are needed for the production of kraft paper and adhesion. The production of PET and RPET punnets are done by thermoforming process, a stretching technique of manufacture of three-dimensional mouldings from flat plastic preforms such as films or sheets, under the influence of heat and pressure or vacuum. The data for different processes (kraft paper, adhesive, sawdust, PET and RPET granulate, thermoforming, energy and water consumption) are from EcoInvent database(ecoinvent, 2022).

The transport of the packaging could impact on the present analysis. For instance, if the punnets were produced far away from strawberry fields, it would increase the environmental impact of the packaging itself. However, as the data related to the packaging transport were not available, it was assumed that the distance of packaging transport was the same (500 km) for all options of packaging materials, so that this element would not affect the comparisons between options.

2.5.1.2 Refrigerated transport

Generic data and inventories on refrigerated transport were presented in Table 2. Distances and vehicle types were obtained from the field study: small truck (<7.5 ton) was used for the first transport T1 from the grower to the packing station, while larger refrigerated lorries were used for second and third transports T2 and T3. The refrigerated transport processes in ecoinvent database was used (ecoinvent, 2022). These data considered both the transport fuel and the refrigeration unit operation for the transportation of refrigerated goods. The vehicle operates with diesel and uses R134a as refrigerant. The lorry has a life span of 15 years and its emission standard is classified as EURO3.

Table 2. Refrigerated transport

Transport stage	Distance (km)	Process (from Ecoinvent)
T1	15	'transport, freight, lorry with refrigeration machine, 3.5-7.5 ton, EURO3, R134a refrigerant, cooling'
T2	600	'transport, freight, lorry with refrigeration machine, 7.5-16 ton, EURO3, R134a refrigerant, cooling'
T3	150	'transport, freight, lorry with refrigeration machine, 7.5-16 ton, EURO3, R134a refrigerant, cooling'

2.5.1.3 Energy generation mix

The environmental impacts of the energy generation system (the electricity mix in this study) can be obtained by combining of the impacts from different parts of the system: the generation plants of different energy sources, the transmission networks and the distribution lines. Each part can have environmental impacts at different stages of their life cycle: construction, use, decommissioning and disposal. In this study, the environmental impacts of the energy generation system were obtained from the electricity consumption (kWh) using the ecoinvent database (ecoinvent, 2022). The data in this database were collected mainly from national statistics and the International Energy Agency (IEA).

2.5.2 Impact assessment method

The environmental impacts were assessed by Simapro software (v9.3) using the IMPACT 2002+ method (EU, 2010). Two levels of assessment were proposed: midpoint and endpoint categories.

2.5.2.1 Midpoint categories

As first analysis, the results were presented in 15 intermediate categories (midpoint), the following scores were used:

Sa(i, m): absolute score of the impact i related to the material m

Sr(i, m): relative score of the impact i related to the material m

$$Sr(i,m) = \frac{100 \times Sa(i,m)}{\sum_{m=1}^{5} Sa(i,m)} \quad (5)$$

Where:

- index i from 1 to 15 for midpoint categories: human toxicity carcinogenic effect; human toxicity non-carcinogenic effects; respiratory effects (caused by inorganics); ionizing radiation; ozone layer depletion; respiratory effects (caused by organics); aquatic ecotoxicity; terrestrial ecotoxicity; terrestrial acidification and nitrification; land occupation; aquatic acidification; aquatic eutrophication; global warming; non-renewable energy consumption and mineral extraction;

- index m from 1 to 5 for packaging material type: molded pulp, cardboard, recycled paper, PET and RPET

2.5.2.2 Endpoint categories and single score

The midpoint categories were aggregated into 4 categories of damage (endpoint) using this score:

Sd(d, m): score of damage d related to the material m

With index d from 1 to 4 for endpoint categories: human health, quality of ecosystems, climate change and resources. The links between midpoint and endpoint categories can be found in Humbert et al. (2012).

A single score Ss(m) could be obtained to characterize the global impact score of a strawberry punnet using the material m:

$$Ss(m) = \sum_{d=1}^{4} Sd(d,m) \quad (6)$$

2.5.3 Sensitivity analysis

2.5.3.1 Mass of the punnet

Two case studies on the mass variation of the strawberry punnets, + 10 % and -10 %, were conducted and compared to the reference case (Table 1). It was assumed that the energy and water consumption associated with punnet production was proportional to the mass of the punnet. Thus, for each case study, the energy and water consumption was recalculated using the data from the reference case and a coefficient of variation (1.1 or 0.9 respectively for the + 10 % mass or -10 % mass).

2.5.3.2 Distance of refrigerated transport

A sensitivity analysis on the longest transport distance T2 was conducted. In addition to the reference case in which the distance of T2 was 600 km, LCA simulations were carried out for: 50 km, 300 km, 900 km and 1200 km. The other parameters were those of the reference case.

3. Results and discussion

3.1 Field study

3.1.1 Field measurement

Fig. 4 presented the evolution of product and air temperatures along the supply chain: the temperatures of two strawberries (one at the center of the pallet and one at the external side of the pallet) and nearby ambient air could be observed. The strawberries were packed in RPET punnets. Leaving the packing station at a temperature of about 13.5 °C, the strawberries were cooled down during the refrigerated transport T2. At the end of the T2 stage, a difference of 3 °C was observed between strawberries which was mainly due to the uneven distribution of air flow and temperature inside the pallet and the vehicle (Hoang et al., 2012; Moureh et al., 2009). The strawberry at the center of the pallet was hotter while the one at the external side had a temperature closer to the ambient temperature. During the distribution platform S2 and the refrigerated transport T3, the strawberries were slightly heated. The temperature increase at the beginning of the retail S3 stage corresponded to the unloading of the refrigerated vehicle at the retail site. Then the strawberries were placed inside the retail cool room where they were cooled down.

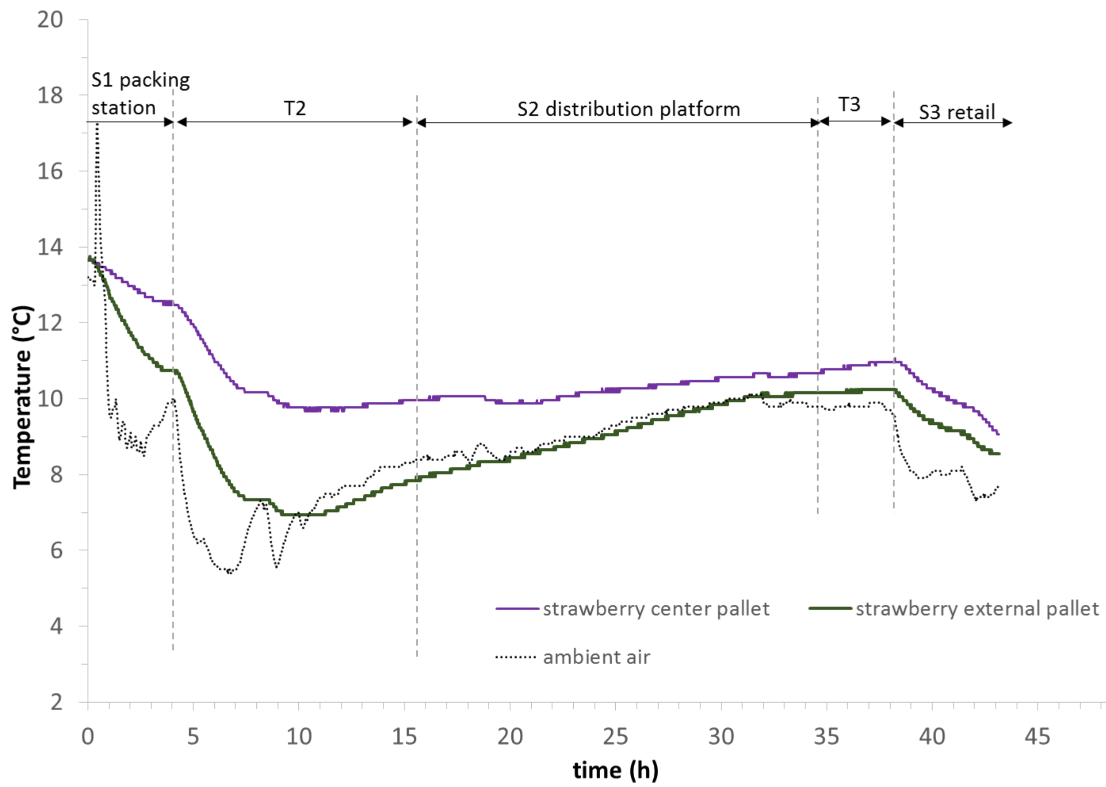


Figure 4: Example of product and air temperatures obtained during field measurement

3.1.2 Interviews on the strawberry cold chain

The data on air temperature and duration of the different stages of the supply chain obtained from the interviews are presented in Table 3. Three values are reported: minimal, mode and maximal. The air temperature was considered as 7 °C along the commercial supply chain. An important variation was observed in the duration of different stages. The longest stages were: refrigerated transport T2 and storage stages S1, S2 and S3. The percentages of loss (product that did not meet quality limits) were shown for packing station, distribution platform and retail. Highest loss (7 %) occurred at retail.

Table 3: Data from interviews with professional stakeholders of the supply chain

Cold chain stages	Air temperature (°C)	Duration (h)			Loss (%)
	mode	min	mode	max	
T1 Refrigerated transport	na	0.08	0.5	2.5	na
S1 Packing station	6	1	10	72	4
T2 Refrigerated transport	7	0.5	7	12	na
S2 Distribution platform	na	1.5	8.5	48	1.5
T3 Refrigerated transport	7	0.17	3	10	na
S3 Retail	7	0	7	48	7

na = unavailable data ; mode: most frequently encountered value

3.2 Assessment of the energy consumption of a strawberry punnet in the storage stages

Table 3 shows the results of the energy consumption assessment (section 2.2) of a strawberry punnet in the storage stages S1, S2 and S3. The evaluation was performed using data from the field measurement and interviews (Table 3). Although data from the interviews may be subjective and inaccurate, the data used in this assessment were most frequently encountered values (mode columns in Table 3) and can be considered representative of the commercial supply chain. The assessment was carried out for one strawberry punnet so that it could be used as input data for LCA. Two ambient temperatures (T_{ext}) of 20 and 40 °C were considered to represent moderate and high temperatures. The energy consumption for one punnet (250 g) in stage Si ($E_{punnet,Si}$) was calculated from Eq. 1 which takes into account the cooling demand both to cool the product to the equipment's setpoint temperature Q_c and to compensate for heat loss through the wall Q_w. The initial product temperature T_i was taken from the field measurement data while the final product temperature T_f was assumed to be the air temperature from interviews (Table 3). For the distribution platform, as the data on the air temperature was not available, a temperature difference T_i - T_f of 2 °C was used. As observed in the field study, T_f could be higher so that Q_c could be overestimated by this method. The results from Table 4 showed that the energy consumption for cooling the product to the equipment's setpoint temperature (Q_c) was higher than that related to heat loss through the wall (Q_w). Moreover, the packing station stage S1 was more energy consuming than the other two stages S2 and S3 and represented about two thirds of the total consumption of the three storage stages because S1 duration was longer and the product was subjected to the highest temperature drop (from 16 °C to 6°C). Q_c (Eq. 4) was not directly dependent on T_{ext} while Q_w (Eq. 3) increased and the coefficient of performance of the refrigeration equipment COP_{si} decreased significantly when T_{ext} increased. As a consequence, $E_{punnet,Si}$ increased nearly 2 times when T_{ext} increased from 20 °C to 40 °C.

Table 4: Energy consumption of one strawberry tray (250 g) in storage stages

						T_{ext}=20°C			T_{ext}=40°C	
	T_i (°C)	T_f (°C)	Duration (h)	Q_c (J)	COP_{Si}	Q_w (J)	$E_{punnet,Si}$ (J)	COP_{Si}	Q_w (J)	$E_{punnet,Si}$ (J)
S1 Packing station	16	6	10	10122	3.96	325	2639	2.49	790	4379
S2 Distribution platform	T_i - T_f = 2		8.5	2024	4.55	93	465	2.73	279	843
S3 Retail cold room	10	7	7	3037	4.09	352	828	2.55	894	1542
Total							3932			6764

Where T_i (°C) the initial temperature of product at the beginning of stage Si; T_f (°C) the final temperature of product at the end of stage Si, COP_{Si} the Carnot Coefficient Of Performance of the refrigeration unit, Q_w (J) the cooling demand related to the heat loss through the wall, Q_c (J) the cooling demand for cooling the product to the equipment's setpoint temperature, $E_{punnet,Si}$(J) the energy consumption of one punnet in stage Si

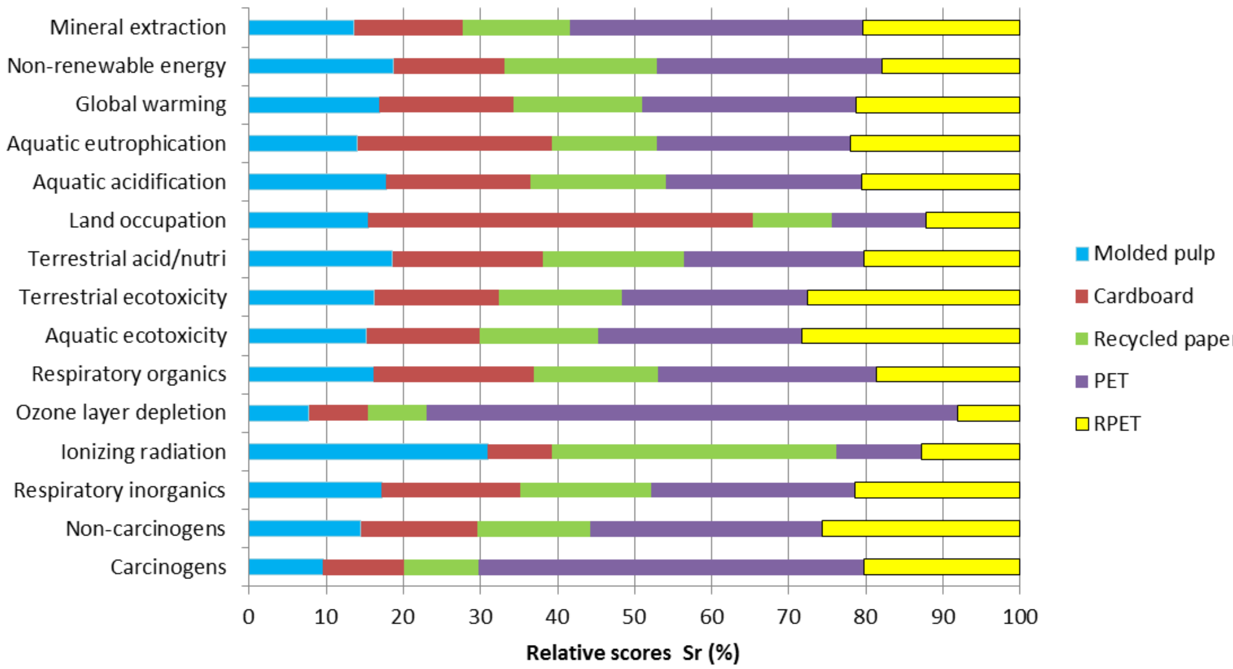
The total electrical consumptions of the storage stages for one 250 g strawberry punnet were 3932 J (T_{ext} = 20 °C) and 6764 J (T_{ext} = 40 °C) which corresponded to the use of a light bulb of 60 W for 65 s and 112 s respectively. It should be noted that these results corresponded to the consumption of one strawberry punnet during its passage through the supply chain; the energy consumption of the cold equipment is important and different methods need to be used for its evaluation.

3.3 Environmental assessment of strawberry supply chain

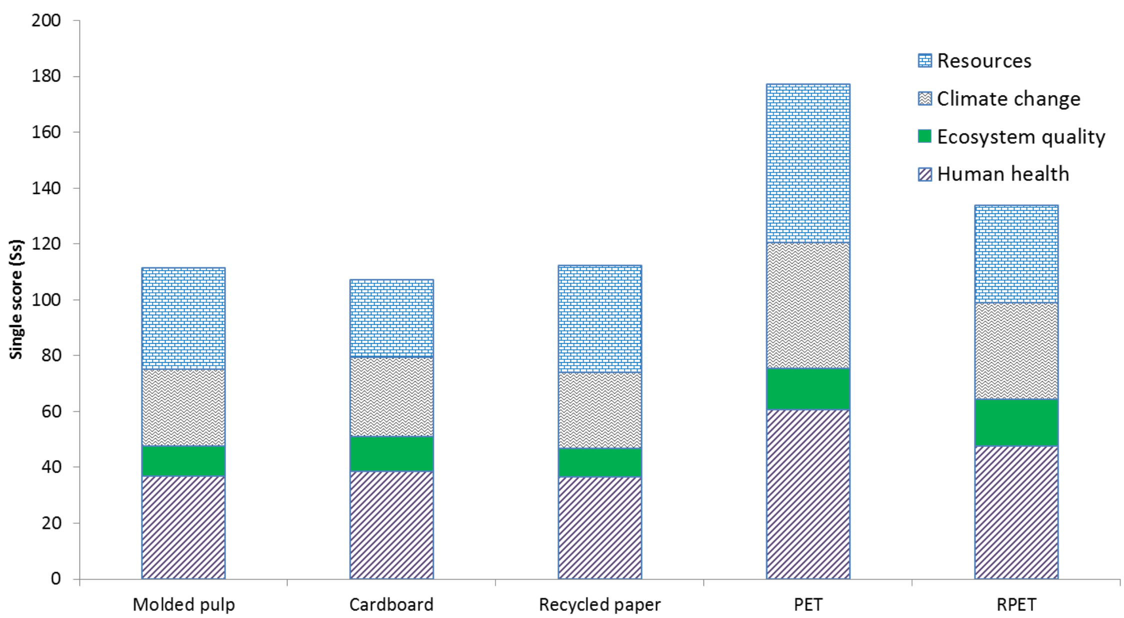
3.3.1 Comparison of different types of packaging materials

Fig.5 presented the environmental performance of the strawberry chain obtained by LCA. The use of 5 types of primary packaging: molded pulp, cardboard, recycled paper, PET and RPET was compared. Fig. 5a showed the relative scores (Sr, Eq. 5) on 15 midpoint categories. For most categories, the relative scores showed the same trends with higher values for PET and RPET. The use of these packaging materials generated higher impacts. The production of raw materials for packaging was the main source of the high scores of PET, in particular for mineral extraction, ozone layer depletion and carcinogens categories. High score of cardboard in land occupation was also due to the production of raw material.

The single scores representing the global impact of the studied packaging are presented in Fig. 5b. For each packaging type, a single score was obtained by summing up the score of four endpoint categories: human health, quality of ecosystems, climate change and resources (Ss, Eq. 6). In this analysis, the use of molded pulp, cardboard and recycled paper, generated significantly less impact than PET and RPET and their scores were almost the same. The packaging material that brought the most significant impact is PET, mostly because of its petrochemical origin. The RPET, as a recycled material, had better environmental performance than PET. In the present analysis, the smallest single score was obtained for cardboard. A closer look at the endpoint categories showed that the results obtained for molded pulp and recycled paper were quite similar while cardboard showed a higher impact on ecosystem and lower impact on resources.



a)



b)

Figure 5: LCA results on environmental impacts of strawberry supply chain using different packaging materials: a) Relative scores Sr (%) and b) Single score Ss

3.3.2 Process impact – role of different stages in the supply chain

In order to assess the role of the different stages of the strawberry supply chain, the LCA process was applied to two extreme configurations: the use of primary packaging with the most and least impact, i.e. PET (Fig.6) and cardboard (Fig.7). Different processes were shown as rectangles and their participation (%) in the single score (i.e. total impact, Eq. 6) are indicated at the bottom left corner of each rectangle. The score of a higher process was the combination of the scores of the lower level processes. For example, in Fig.6, the score of the strawberry punnet at the packing station S1 (49.9 %) was the combination of the scores of refrigerated transport T1 (2.37 %), packaging production (47 %), energy consumption in S1 (0.158 %), biowaste treatments (for the product loss in S1) by anaerobic digestion (0.174 %) and by composting (0.242 %). In the case of PET, the process that had the most significant impact was the packaging production 47 %, followed by the refrigerated transport T2 (39.4 %). For cardboard (Fig.7), the process that had the most significant environmental impact is the refrigerated transport T2 (64.6 %). The environmental impact due to the electricity consumption in storage stages S1, S2 and S3 was not significant. The product loss at S1, S2 and S3 was also considered in this analysis. These biowaste treatments (from 3 storage stages) represented less than 2 % of the single score for both configurations.

In Fig.8a, the scores related to processes of the same nature (refrigerated transport and production of packaging) were regrouped. Compared to Fig.5b, the single score (total impact, Eq.6) for each of the five configurations was the same. The results were similar for configurations using cardboard, molded pulp and recycled paper. For these configurations, the most significant process was the refrigerated transport representing the aggregation of the impacts of T1, T2 and T3. For configurations using PET and RPET, other than the refrigerated transport, the production of punnets played a significant role.

The same analysis could be performed for one category of damage. Fig. 8b presented the results obtained for the global warming which was characterized by the kg of CO_2 equivalent generated by different processes. The comparison between process impact on the single score (Fig. 8a) and on the global warming (Fig. 8b) showed that the general behaviors were quite similar: the plastic packaging (PET and RPET) generated more CO_2 than molded pulp, cardboard and recycled paper. However, small differences could be observed. For example, the configuration using cardboard produced higher global warming effect than configuration using molded pulp and recycled paper. Indeed, the production of the punnets using molded pulp and recycled paper generated less CO_2 than the production of punnet using cardboard.

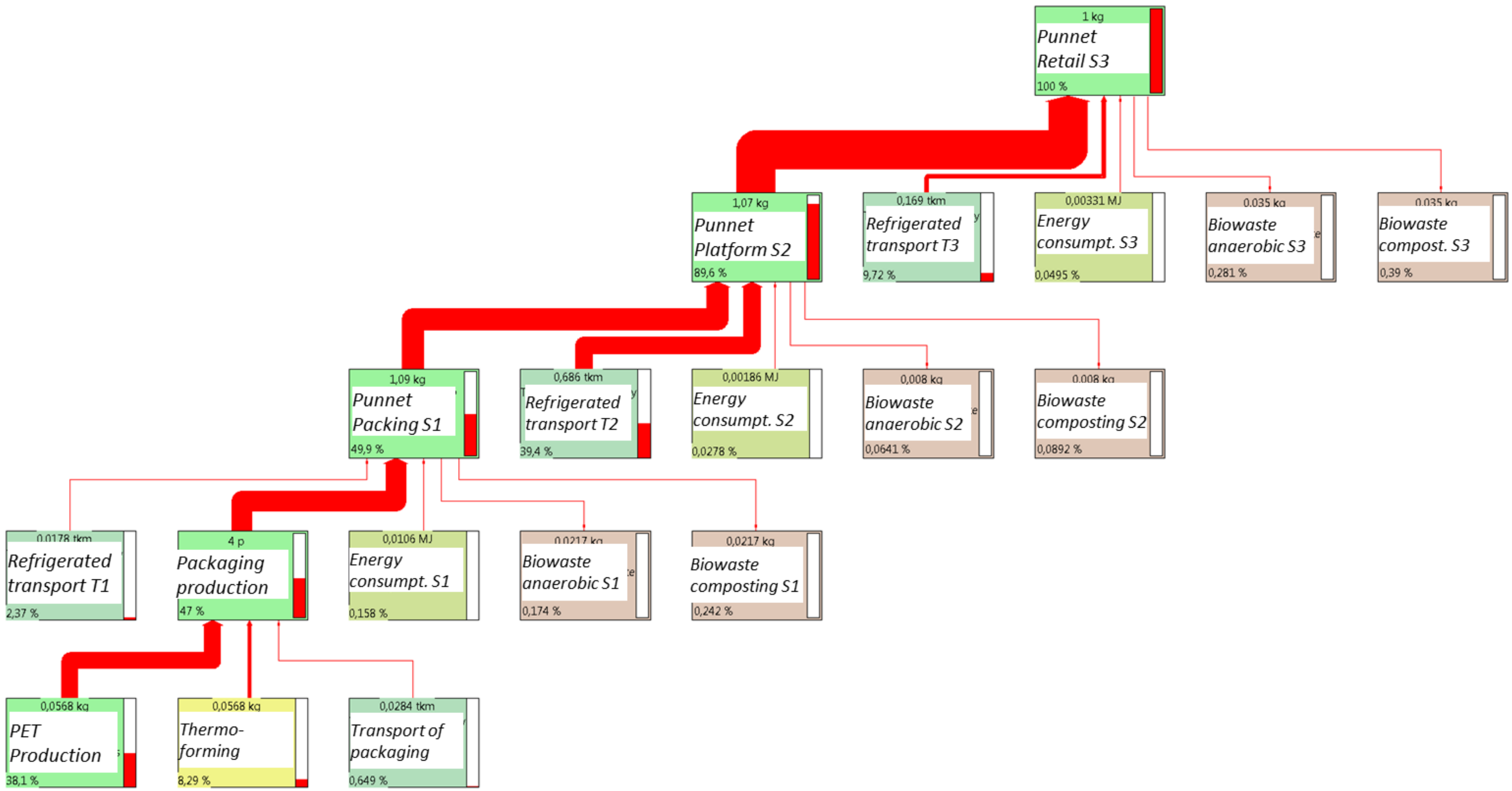


Figure 6: LCA process network of strawberry supply chain using PET as primary packaging

4 p means 4 packs as 4 packs of 250 g were used to obtain 1 kg of strawberries (functional unit).

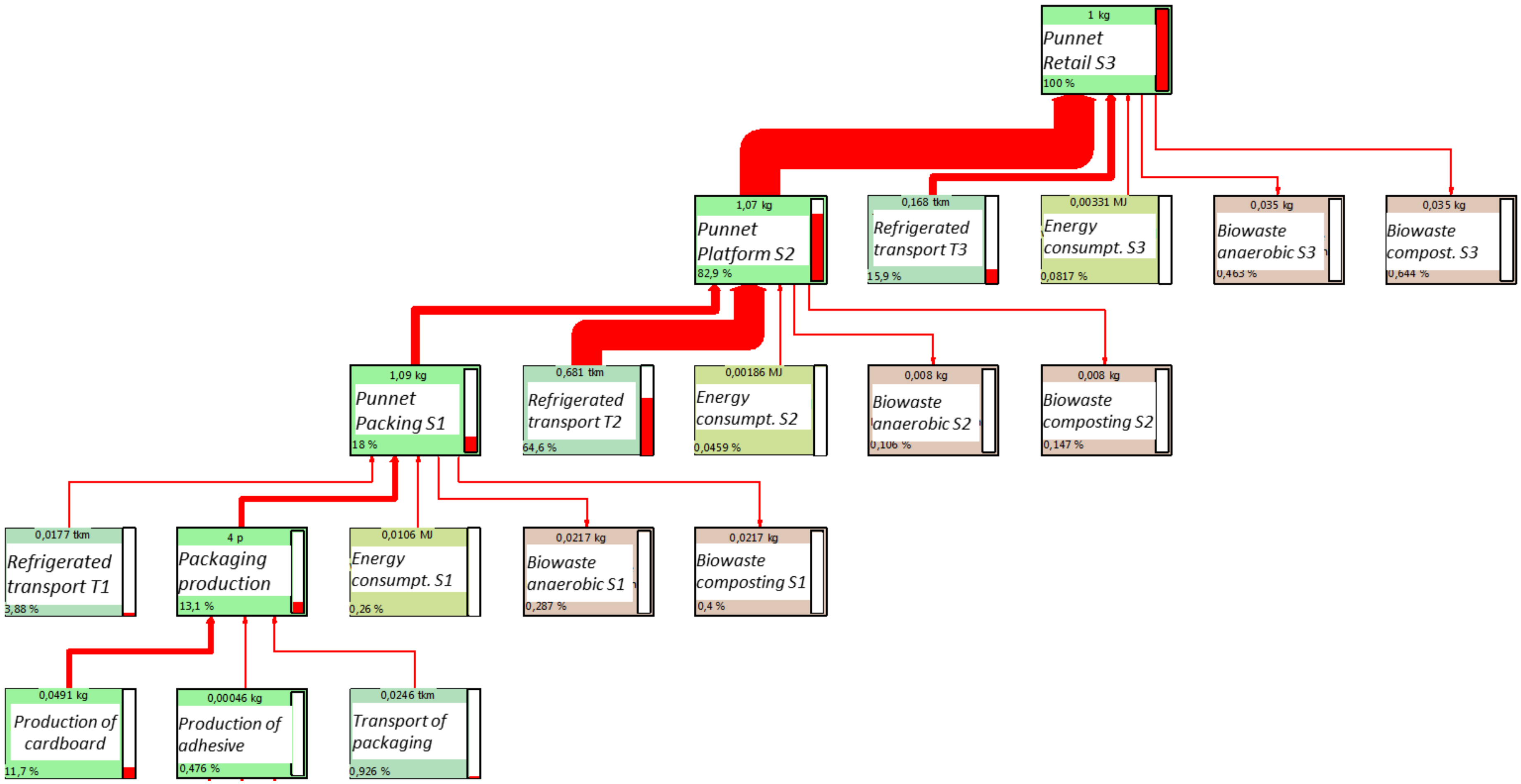
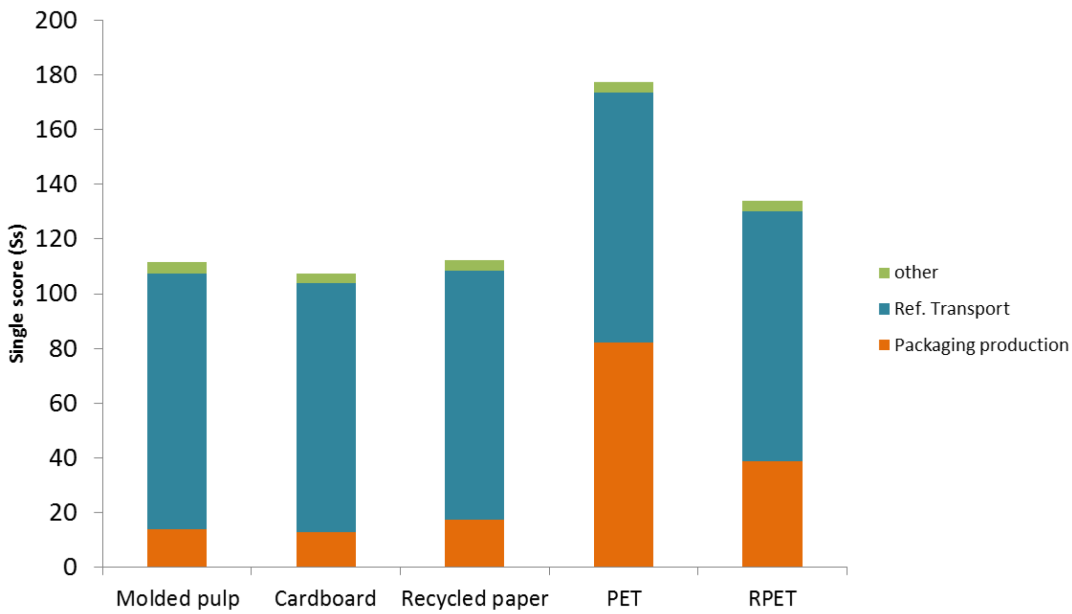
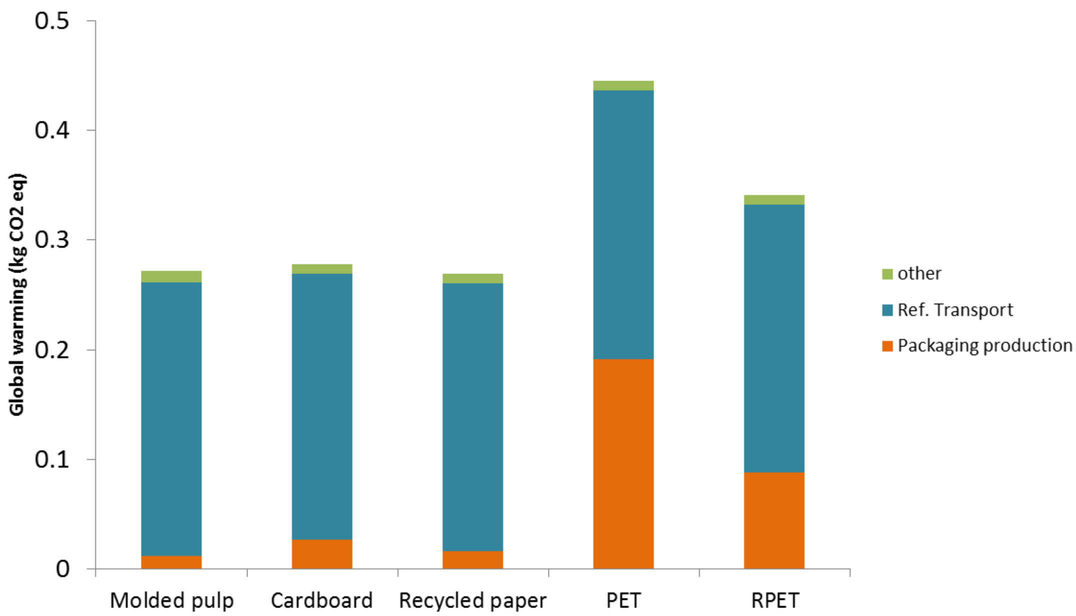


Figure 7: LCA process network of strawberry supply chain using cardboard as primary packaging

4 p means 4 packs as 4 packs of 250 g were used to obtain 1 kg of strawberries (functional unit).



a)



b)

Figure 8: Process impact analysis: a) Process impact on global note (single score) and b) Process impact on global warming. Strawberry production, packaging material disposal and fruit losses after purchase were not considered.

3.3.3 Sensitivity analysis

3.3.3.1 Mass of the punnet

An analysis of the impact of the mass of the punnet on the single score was carried out and illustrated in Fig.9. The variation in mass had a greater effect on the single score for the PET than for other materials. For example, increasing the mass of PET and non-plastic punnets by 10% led to an increase in the single score of 5% and 1.5 % respectively.

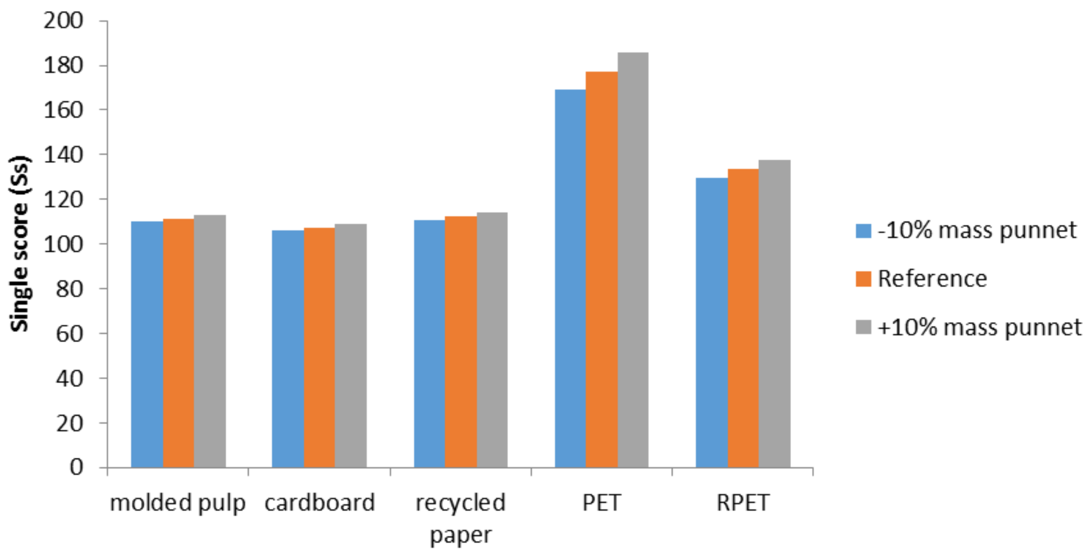


Figure 9: Sensitivity analysis on the mass of the punnet

3.3.3.2 Distance of refrigerated transport

An analysis of the impact of the transport distance on the single score was conducted and illustrated in Fig.10. A linear evolution of the single score of packaging as a function of distance was observed. It can be concluded the same score can be obtained with a PET punnet over a short distance (< 500 km) or with a non-plastic punnet over a long distance (> 1000 km). For example, a score of 142 can be achieved with PET at 300 km and non-plastic punnets (recycled paper, cardboard, molded pulp) at 900 km, while a score of 177 can be obtained with PET at 600 km and non-plastic punnets at 1200 km. Finally, due to the linear trend, replacing PET with a non-plastic punnet was equivalent to reducing the distance by 600 km.

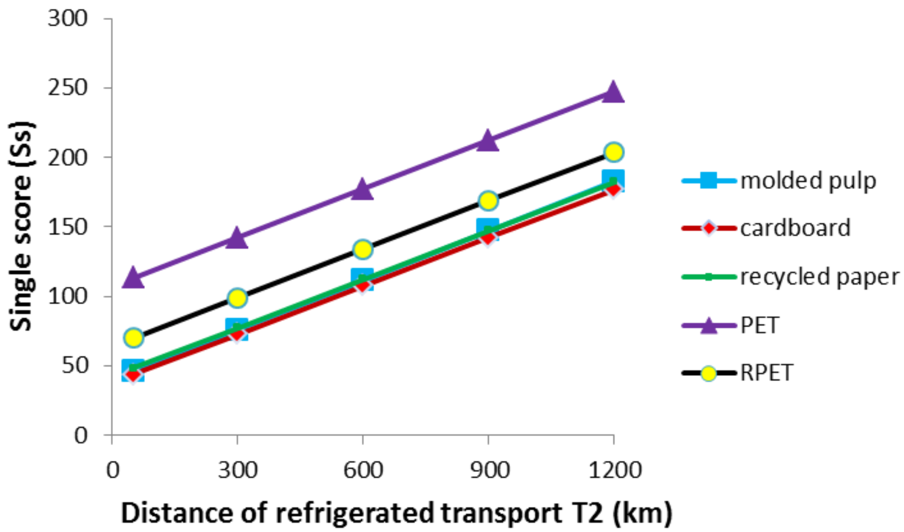


Figure 10: Sensitivity analysis on the distance of refrigerated transport

3.3.4 Discussion

Due to the lack of relevant data, the scope of the present study did not take into account some specific processes, in particular the strawberry production and the disposal of the packages. In this section, the framework and hypothesis of the present results are discussed while considering the impacts of those processes.

Various studied have shown that strawberry production generates high impacts on environment. However, those impacts depend on many factors such as the production mode (open field or greenhouses, heated or not) and the use of fertilizers or machines during cultivation and harvesting. Yildizhan (2018) reported about 0.2 kg CO_2 emission for 1 kg of strawberry produced in open field and 0.5 kg CO_2 emission for 1 kg of strawberry produced in greenhouses in Iran. Higher figures, around 1 kg and 3.5 kg CO_2 emission for 1 kg of strawberry produced in open field and greenhouses respectively, were obtained by Soode-Schimonsky et al. (2017) in Germany and Estonia conditions. Fig. 8b shows that from 0.27 to 0.45 kg CO_2 emission was estimated for the strawberry supply chain for different configurations of packaging material. The impact of the production stage, which could be greater than that of the supply chain, could be added to these figures.

The disposal of the packaging is a complex subject since various treatments could be done for each material and the situation is different among regions and countries. Moreover, the recycling rate of plastics is highly variable. For example, the recycling rate of PET is 41 %, 91 % and 11 % in

Austria, Germany and Serbia, respectively (Schmidt et al., 2020). Non-recycled plastics are incinerated or landfilled and are responsible for important impacts on the environment and human health (Loy et al., 2023). Molded pulp, recycled paper and cardboard are recyclable and biodegradable materials. They also benefit from a higher recycling rate at the end of their life. For instance, in France, the recycling rate was 94 % for paper and cardboard and nearly 30 % for plastics (CNE, 2019). At the moment, as the data related to the impact of different modes of disposal are not available, they were not considered in this study. Meanwhile, it could be considered that the disposal of paper, cardboard and molded pulp, as biodegradable materials with higher recycling rate, would have lower impacts than the disposal of plastic (PET and RPET) packages. More information on disposal treatments can be found in (Chawla et al., 2022).

The use of different packaging materials could have different impacts on the fruit quality. In the case of strawberries, water loss from fruit and humidity from the ambient environment could be absorbed by packages made of molded pulp, paper and cardboard, while this is not the case for plastic packages. Water absorption might lead to lower humidity inside molded pulp, paper and cardboard punnets compared with plastic punnets, thus increasing weight loss of fruits (Merendet, 2023; Mireur, 2022). Moreover, the water absorption could reduce the amount of condensation in the punnet due to temperature fluctuations (Jalali et al., 2019), thus limiting mold development. However, in the case where water absorption is too important, the mechanical resistance of the punnet might be impacted. As data related to the strawberry quality evolution with different packaging materials are not available, the same percentages of losses were used for different configurations of packaging materials in the present study. The variation of the percentage of losses might change the mass of the punnet in different stages: the higher the losses, the more strawberries need to be transported to reach the same quantity to be sold at the supermarket. The percentage of losses could also change the impact of the biowaste treatment.

Other parts of the packaging system (cover films, secondary and tertiary packaging) were not considered in the present work as they did not change between the packaging options, as it was observed in the field study. Moreover, as the secondary (IFCO crates) and the tertiary packaging (pallets) are reused as is (more than five times), their impact was not considered significant. The mass of the film covering the punnet may represent a small component of the punnet mass. Finally, in certain cases of commercial circuits, there is no use of cover films.

4. Conclusion

A strawberry supply chain (transport from growers to retail) was investigated. First, a field study was carried out to explore the organization of the strawberries logistic circuit. Field measurements were performed in order to study the evolution of product and air temperatures through various stages of the circuit. Significant product temperature heterogeneity was observed. A difference of 3 °C between the coldest and warmest products in the second refrigerated transport was measured. Interviews with stakeholders at different stages of the strawberry supply chain were also conducted to gather information on the conditions of transport and storage of the strawberries. The information from the field measurement and interviews constituted an essential database for energy and environmental assessment. For one strawberry punnet, the energy consumption in storage stages (packing station, platform and retail) was not significant. According to the LCA results of the strawberry supply chain, the two processes with the highest environmental impacts were the production of packaging and the refrigerated transport over long distance. The use of non-plastic packaging such as molded pulp, cardboard and recycled paper generated significantly less impact than the use of plastic materials. The impact of packaging was not only due to the origin of the material but also to the use of the manufacturing process, other materials (such as adhesive) and the electricity consumption for their production. In further studies, the effects of the packaging materials on the quality change of the strawberries should be taken into account. Other important processes such as strawberry production in the field, packaging end-of-life treatment and recycling should be considered as well as integration of other performances of the supply chain such as product quality and logistic cost.

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