ENVIRONMENTAL IMPACTS OF PACKAGING IN FOOD PRODUCT SYSTEMS: REVIEW

By

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ABSTRACT

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Environmental viewpoints focusing on packaging waste made it useful to investigate the contribution of packaging to the food product system. Life Cycle Assessment (LCA) provides comprehensive environmental information about the whole product system. LCA studies of some food product categories, i.e., milk, yogurt, fish, fruits, meat, and grain, that included the packaging were selected and reviewed. A summary of the global warming potential and energy consumption revealed that the contribution of packaging was maximum at 25% and 35%, respectively. Factors influencing the difference of the contribution across different categories were the type of food raw material (plant-based and animal-based), the degree of processing after crop production, and the complexity of the packaging material and the related processes. The limited contribution of packaging implies that improvements that focus on reducing packaging waste would benefit only a minimal portion of whole system.

The concern about the global food loss and waste together with massive environmental contributions from the food related life cycle stages indicates the opportunity of packaging to help improve the environmental performance of the product system by reducing loss and waste. The potential solution includes: 1) packaging design and technology to extend the food product shelf life, 2) packaging that prevents physical damage to the food product, 3) packaging that fits the current demography and lifestyles, and 4) a standardized date labeling system. Knowledge, innovative technology and material, additional cost as well as the collaboration of all stake holders are needed to implement any changes. The marginal environmental efficiency that could be improved was expected to compensate for the change.

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

1 INTRODUCTION

In the food product system, packaging is an essential part that keeps the product in a good condition until it reaches the ultimate consumers. However, the given short life cycle of food products, a large amount of packaging is disposed after consumption. Packaging is often picked out to be one of the major causes of the increasing waste problem that has become a public concern for years. In response to the public, environmental regulations on packaging such as Directive 94/62/EC on Packaging and Packaging waste were introduced to push prevention and re-use of packaging [1], [2]. Food producers, as well as packaging manufacturers, put their efforts to reduce the packaging waste problem by minimizing the packaging material and developing recycling schemes for their packaging. These strategies could alleviate the waste problem that is easily visible to consumers.

With the over-focus on packaging waste, the major environmental impact within the system that is caused by food seems to be overlooked. To produce food requires a major portion of the whole supply chain energy [3] . Packaging provides its beneficial function to protect the food, preventing the waste of resources and energy we invested [3]. The solution that pays attention mainly to packaging waste might be able to reduce just a limited part of the overall environmental burden of the food product system. Considering energy use, packaging accounts for only 11% of the total of the supply chain [4]. The decision of packaging alteration and minimization without consideration of its capability to protect food products could generate more food losses due to packaging damage that consequently results in more severe environmental impacts. Hence, to evaluate the environmental impact of the food product system in order to mitigate the overall impact, it is necessary to consider both food and packaging at the same time.

The purpose of this study is to compare the environmental impact of the packaging system with that of the whole food product system in the context of the Life Cycle Assessment (LCA) approach, in order to determine the factors driving differences between environmental impacts of the packaging portion of the system across different categories of food products. The research also aims to address possible areas to be developed which could contribute to effective improvement in terms of the environmental footprint.

2 LITERATURE REVIEW

2.1 Life Cycle Assessment (LCA)

Life Cycle Assessment (LCA) is a tool used to comprehensively evaluate the environmental impacts of a product and/or system. It has been adopted to explore the environmental performance in many areas. According to the International Organization of Standardization (ISO), the principle of LCA is to consider and address the environmental impacts of a product system throughout its entire life cycle, from the raw material acquisition and manufacturing, to use and final disposal [5]. The impacts are determined based on resources input to the process and emissions along the product or system life cycle stages. An LCA study generally is comprised of four main phases: goal and scope definition, life cycle inventory analysis (LCI), life cycle impact assessment (LCIA), and interpretation [5]. The relationship between each phase can be demonstrated by the framework in *Figure 1*.

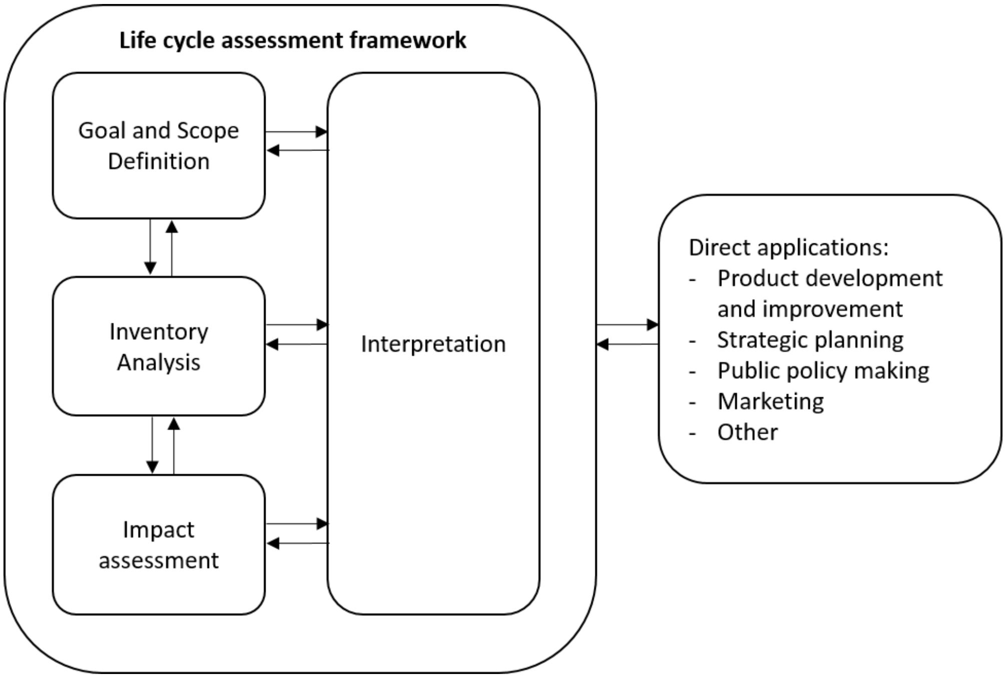

Figure 1: Stages of an LCA (adopted from ISO14040:2006)

Goal and scope definition is the starting phase of an LCA study. The purpose, the reason to carry out the study and the intended audience are specified as a goal of the LCA. In the scope, the product system to study including its function and the functional unit (FU) are defined. The functional unit (FU) is the quantitative term of the product system function. For example, in an LCA comparing choices of public transportation, the functional unit used in the study could be a number of people being transferred a certain distance such as ten people by ten kilometers. A trip of a bus could mean four FU while one trip of a train could mean 10 FU. The impacts such as fuel uses or emissions must be related to the FU of each choice of transportation in order to result in a fair comparison. Other details, e.g., system boundary, impact categories selected, data requirements, assumptions, limitations, are also recommended to be clearly defined in this phase of an LCA study [5].

In the Life Cycle Inventory Analysis or LCI phase, data collecting and modeling take place. Data of inputs, outputs, and emissions of a reference flow of the product system being studied are collected, modeled and calculated to be related to the FU.

In the phase of Life Cycle Impact Assessment (LCIA), the inventory data processed in the LCI phase are evaluated associated with environmental impacts. The impact categories, category indicators, and characterization model are selected in this phase. Mainly two processes are performed in order to translate the inventory data into environmental impacts. The first is classification: items of LCI data were grouped or classified into an impact category, for example, CO_2 and CH_4 emissions are together grouped into the global warming potential category. The second is characterization: a specific input or emission classified into an impact category is characterized based on how much impact it causes compared to other inputs or emissions within the same category. A specific characterization factor of each input or emission is multiplied to the amount of that input or emission. From the previous example, in the global warming potential category, CO_2 has a characterization factor of 1 while CH_4 has a factor of 21 [6]. This means that with the same amount, CH_4 causes 21 times more impact on the global warming potential than CO_2. How the LCI data are classified and characterized is mainly dependent on the characterization model or characterization methodology being used in the LCA study. Since the LCA was established, there are many characterization methodologies that have been developed and used. Some widely used methodologies are CML 2002, Eco-Indicator 99, IMPACT 2002+, and ReCiPe to name a few [7]. The choice of methodologies depends on the goal and scope of the study, and the inputs, emissions and impacts categories that the study intends to focus on. One of the ILCD handbook series, Recommendations for Life Cycle Impact Assessment in the

European Context, provides guidelines on recommended methodologies associated with each specific impact category [8].

In the Life Cycle Interpretation phase, the findings from the LCI and LCIA phases are further processed into understandable, complete and consistent information as the result of the LCA study in accordance with the goal and scope defined. This information is generally intended to be used as information for decision and policy makers.

The process of conducting an LCA study is considered to be iterative. As it goes further to any phases within the framework, the practitioners could be back and forth reviewing and revising the goal and scope in case that some unforeseen situations like lack of inventory data, inconsistency in the nature and quality of data, etc., might have to be faced along the pathway of an LCA study. Iterative work guarantees consistency, completeness, applicability and transparency of an LCA study.

2.2 LCA studies on food products

Since the LCA concept was first developed in the late 1960, many industries have adopted it to investigate the environmental performance of their products, including the food industry. According to the U.S. Department of Commerce, food manufacturing industries are categorized into nine groups: 1) animal food, 2) grain and oilseed, 3) sugar and confectionary products, 4) fruit and vegetables, 5) diary, 6) meat, 7) seafood, 8) bakeries and tortillas, and 9) other food [9]. There are LCA studies conducted in most of these food categories. Since the life cycle of a food product is strongly connected with nature, the system boundaries for the LCA of food products are generally set between the technosphere and nature [10]. ‘Cradle-to-gate’ and ‘cradle-to-grave’ boundaries are both found in the field. The ‘cradle-to-gate’ studies mostly cover from the agricultural phase (e.g., fruit, vegetable, and grain cultivation, animal husbandry, aquaculture, and fishing), and industrial refining processes, until reaching the factory gate, while the ‘cradle-to-grave’ studies further include the consumption and waste handling phases. The consumption and waste handling were often omitted due to their minor environmental impact compared to the production phases [10]. The LCA studies in the food area mainly aimed to identify hot spots, life cycle stages or processes that contribute a high degree of environmental impacts, where improvements could be applied in order to mitigate the product’s environmental burden. Some studies focused on comparing choices of practice: organic and conventional ways of plant cultivation or food and animal husbandry or sizes of industrial facilities, for example.

An identification of a functional unit in a food product LCA is also considered crucial especially in comparison of different systems [10]. Schau and Fet in a summary of LCA studies of food products in 2008, reported that mass, volume, portion or packaging size, energy, economic value, and a more sophisticated functional unit like protein and energy contents are reported to be used [10]. They also proposed the calculation of a quality corrected functional unit (QCFU) where both quantity and quality of a product including fat, protein, and carbohydrate are considered at the same time [10].

2.3 LCA studies on food and beverage packaging

Packaging has been one of the major areas of LCA application since the early stage when the concept was initially developed in response to the public concern about increasing use of plastics in packaging and the related large volume of solid waste generation [11]. Since then with its capability to address comprehensive environmental impacts, and identify environmental critical parts or hot spots in the life cycle, LCA has been used as a decision-making tool in packaging development and investment [11]. Within the food and beverage area, LCAs were widely adopted in comparative studies between choices of packaging material and design [12]–[16].

Generally, functional units used in packaging LCAs are certain amounts of product. The environmental impacts are the result of resources or materials input to and emissions output from the life cycle of the packaging used to contain and deliver the product. Due to the nature of LCA concentrating mainly on inputs and outputs, it brought up concerns of LCA's flaw in failing to account for the true values and functions of packaging [17]. According to Oki and Sasaki [17], LCA could not be perfectly useful without the consideration of the social significance and elevated performance of packaging due to modern technological development. However, the authors also mentioned the complexity that makes it difficult to incorporate these factors into the LCA [17]. They gave an example of combining packaging function to LCA through a comparison of polypropylene monolayer containers and multilayer containers by converting the higher performance to extend the product's shelf life of the multilayer container into the advantage of transportation energy conservation [17]. In order to fill this gap, it requires a very thoughtful process of analyzing and interpreting by the LCA practitioners.

There are some studies that aimed to balance the environmental view of packaging between its negative side of being a waste and its positive benefit of protecting and preventing loss of resources and energy input to produce a product. The publications by the Industry Council for Packaging and the Environment (INCPEN) of the UK communicated this point of view through the energy use and waste generation perspective based on the study of Kooijman in 1995, *Environmental Impact of Packaging Performance in the Food Supply System.* The key findings expressed in the publications are [3], [4]: (1) Across 18 groups of food products, the energy required to produce packaging accounts for 10% of the whole supply chain energy. It is more reasonable to reduce the energy used to grow, pick, farm or fish and prepare food and the energy used to shop and preserve food of consumers than just to focus on reducing packaging waste. (2) In response to demographic and lifestyle changes such as smaller households, increased demand for ready-to-cook prepared meals, and preference of fewer preservatives in food, the food supply system requires an increasing amount of packaging. The policy encouraging the reduction of packaging seems to be unrealistic. (3) Prepared and packaged foods are considered to be environmentally better than fresh foods because that the waste generated in food processing plants is less than the waste from in-home food preparation and the transportation of fresh food needs more secondary packaging for protection.

2.4 Potential capacity of packaging in mitigating overall environmental impact

The attempt to reflect the main purpose of packaging, i.e. to protect the product, into the overall environmental impact of the food packaging system can be seen in the studies of Wikström and Williams in 2010 and 2011. Their studies presented a model calculating the environmental impact of the food packaging system as a function of *eaten food* where food losses in the consumption phase was taken into consideration [18]. Details of their model are briefly described below. Equations (1) and (2) demonstrate the relation between *purchased food*, *eaten food*, and *food losses* defined by the authors.

$$e = B - BL \tag{1}$$

$$B = \frac{e}{1-L} \tag{2}$$

where e is *eaten food*, B is *purchased food*, and L is a fraction of food loss which ranges between 0 (no losses) and 1 (all purchased food is lost). The model of the environmental impact of the system is as shown below.

$$E^i = B\left(F^i + P^i + W_P^i\right) + W^i BL = \frac{\left(F^i + P^i + W_P^i + W^i L\right)}{1-L} \tag{3}$$

E^i is the environmental impact of the whole system that could be global warming potential, energy consumption, etc. Environmental impacts relating to the production and distribution of food and packaging are considered separately as F^i and P^i, respectively. Impacts regarding waste handling of food and packaging are denoted as W^i and W_P^i. Different environmental impact categories were indexed by i.

Assuming a packaging improvement could reduce the environmental impact of the system by decreasing food losses and letting E_1^i and E_2^i be the environmental impact of the system at the initial state and at the improved system, respectively, then

$$E_2^i < E_1^i \tag{4}$$

Substituting E^i with equation (3) and rewrite:

$$\frac{P_2^i}{P_1^i} < \frac{1-L_2}{1-L_1} + \frac{W_{P_1}^i(1-L_2) - W_{P_2}^i(1-L_1) + W^i(L_1-L_2) + F^i(L_1-L_2)}{P_1^i(1-L_1)} \tag{5}$$

The relation of these parameters can be used to demonstrate the potential of packaging development to reduce food losses that consequently reduce the total environmental impact of the system. The model was illustrated using data from LCA studies of food items, i.e. bread, beef, cheese, ketchup, and milk. The opportunity of packaging development is illustrated by the ratio of the packaging impact after the improvement was applied and at the initial state (P_2^i/P_1^i). A higher ratio indicates more impact of packaging that could be allowed to increase due to packaging improvement resulting in food loss reduction. There were four significant conclusions made in the studies including [18], [19]: (1) a food product system with higher initial losses, high L_1, and larger size of food loss reduction, large $(L_1 - L_2)$, allows a higher ratio of P_2^i/P_1^i which indicates more opportunities for packaging development. (2) For food product systems with a high ratio between the impact of food and the impact of packaging (F^i/P_1^i), in other words when the impact of food is relatively high compared to the packaging, more impact of packaging can be allowed to increase in order to reduce food losses (high ratio of P_2^i/P_1^i). (3) Regarding food waste handling, in systems where energy from food waste can be recovered, the opportunities to develop the packaging are lower than in systems where energy needs to be input to organic waste and the waste itself has a substantial environmental impact. For example, a system with landfill and anaerobic digestion of food (W^i is positive) has a higher opportunity for the packaging improvement than a system that incinerates food waste and recovers heat to replace heat generated from oil (W^i is negative). (4) The potential of packaging development is higher in regions with efficient recycling of packaging materials. In regions with efficient handling of food waste and low recycling of packaging, it is more beneficial to accept food waste.

A relation of packaging and food waste was also investigated using a survey method in the work of Williams and Wikström in 2012. Sixty-one Swedish families participated in the study and were asked to measure the amounts and record the reasons for their food waste in a seven-day period [20]. About 20-25% of the households' food waste was reported to be related to packaging [20]. *Too big packages*, *difficulty to empty*, and *passing "best before date"* were dominating packaging causes of food waste [20]. Packaging attributes that help in reducing food waste and influence consumers' behavior during the consumption stage were discussed in the authors' following work in 2014. The attributes include [21]: 1) containing the right quantity, 2) mechanical protection, 3) physical – chemical protection, 4) resealability, 5) easy to: open, grip, dose and empty, 6) food safety/freshness information, and 7) facilitating of sorting of household waste. Two attributes of *"containing right quantity"* and *"easy to dose"* were used to demonstrate when food waste was incorporated in the model evaluating the global warming potential (GWP) impact of food product-packaging system of rice and yogurt [21]. Three packaging types of each product (250 g resealable plastic laminate pouch, 1 kg plastic bag, and 1 kg container with measuring cup of rice and 70 g squeezable and reclosable laminate pouch, 6 pack 175 g connected tubs, and 900 g tub of yogurt) were brought into the evaluation using different simulating levels of food waste of 5%, 12%, and 20% in recycling and incineration systems [21]. The results indicate food waste rates where the packaging formats with *right quantity* and are *easier to dose*, i.e. 1 kg rice container with measuring cup, 70 g laminate yogurt pouch, and 6 pack connected yogurt tubs, are reasonable to use even though the packaging itself has higher impact compared to other options [21]. For example, in the system where packaging is recycled, a rice product system with 1 kg rice container with measuring cup at 5% waste has less GWP compared to a system of 1 kg plastic bag with 12% waste. This indicates that the container with measuring cup is preferable if it could reduce waste to 5% when the plastic bag generates 12% waste even though the container with measuring cup itself has higher impacts compared to the plastic bag [21]. In the case of yogurt, a squeezable, reclosable laminate pouch is motivated only when packaging waste is incinerated and it can reduce the waste to 5% when other alternatives generate 20% waste [21].

Packaging attributes relating to recycling and food waste behavior of the consumer were investigated in the study of Wikström, William and Vankatesh in 2016. Minced meat products with two packaging alternatives, a lightweight polyamide tube and a polyethylene terephthalate (PET) tray, were evaluated using the model they initiated in 2010 [22]. The calculation of greenhouse gas emission, acidification, and ozone depletion impacts revealed that when considering only packaging, a lightweight tube is the better option in all impacts as less material is required to deliver the same amount of minced meat [22]. However, when food waste and recycling behavior are considered, the PET tray is more environmental preferable than the tube as the tray is easier to empty leaving no food waste; also it is easier to clean for recycling resulting in a higher recycling rate [22]. On the other hand, the tube could be a superior option with its better properties of preserving meat. An environmental benefit from avoided food waste due to a longer shelf life is provided if the food waste caused by expiration is higher than the waste during the emptying process by the consumer [22] . The authors suggested that environmental assessments that include these attributes of packaging could contribute more meaningful results than in the case where only material, weight, and end-of-life treatment of the packaging were considered [22].

3 COMPARISON OF ENVIRONMENTAL IMPACT CONTRIBUTION OF PRODUCT AND PACKAGING (FOOD PRODUCT SYSTEM)

A comparison of environmental impact contributions of products and packaging in the food product system was done by summarizing LCA studies of food product systems which reported the contribution of packaging separately from other processes. This information was summarized to show the magnitude of packaging's contribution across different food product categories.

3.1 LCA studies selection

LCA studies were collected based on criteria that the scope of the study covered the life cycle stages involving both the food and the packaging system. The time scope was limited to studies published in 2000 or after. The results of the studies showed impacts associated with packaging separately from other systems.

The food-involving life cycle phases include the agricultural production of raw materials (*e.g.,* crop cultivation, livestock husbandry, and fishery), food processing, distribution, retailing, consumption, and food waste. The term 'packaging' was defined covering consumer packaging and contribution packaging that together bring processed food through the supply chain to ultimate consumers, such as yogurt cups in corrugated boxes. The system boundaries for packaging covered raw material acquisition, material conversion, processes associated with packaging (*e.g.* bottle filling, box erecting, and palletizing), packaging waste management, and packaging transportation. *Figure 2* depicts the general system boundaries of the selected LCA studies which included both "cradle-to-gate" (within the dashed rectangle) and "cradle-to-grave" (within the solid rectangle) boundaries. The detailed system boundaries for each product category are provided in appendix A.

The selected LCA studies covered five categories of food (seventeen studies in total):

1) dairy products (including fluid milk [23]–[25] and yoghurt [26]–[29]),

2) fish products [30]–[32],

3) fruit products [33], [34],

4) meat products [35], [36], and

5) grain products [37]–[39].

A summary of LCA studies included in this review is provided in Table 1.

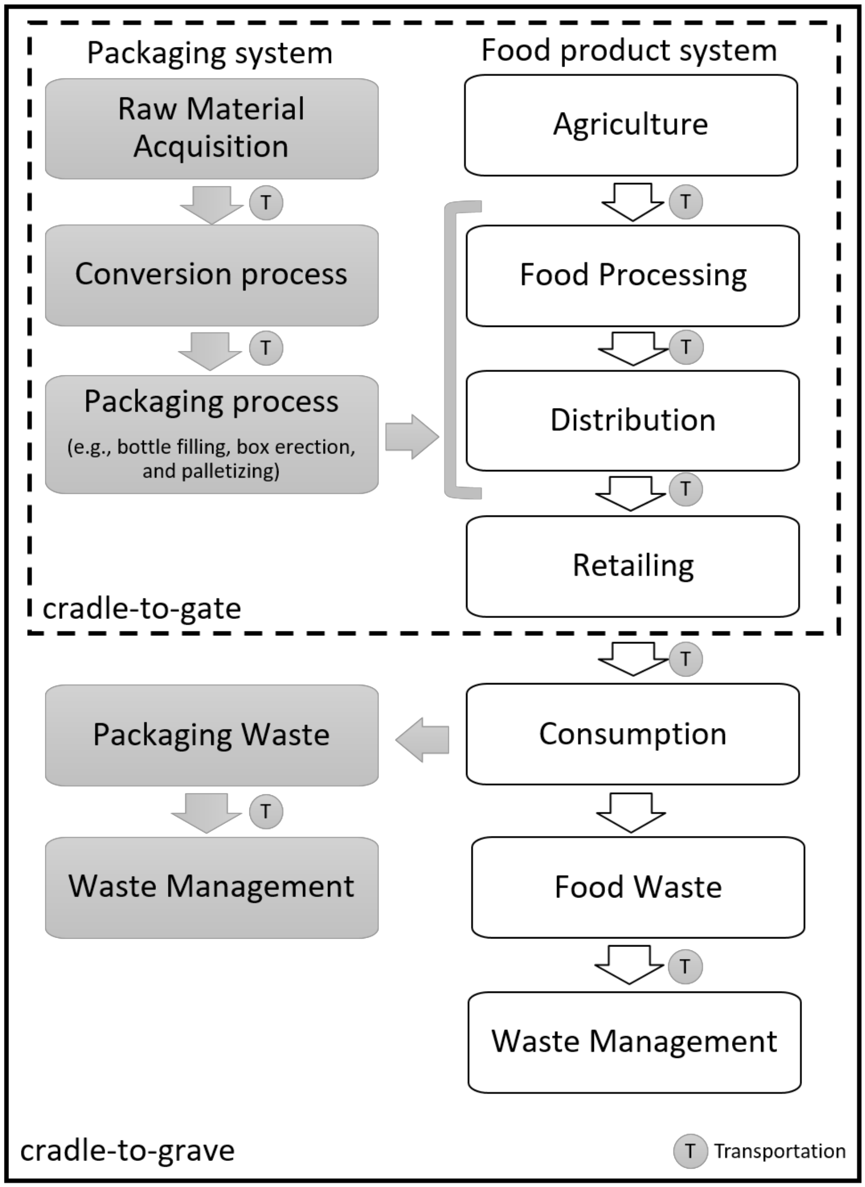

Figure 2: System boundaries of the LCA studies

Gray boxes represent the processes in the packaging system. The white boxes represent the processes in the food product system. Cradle-to-gate and cradle-to-grave are represented by dashed and solid boundaries, respectively.

Table 1: Summary of selected LCA studies		Identifiers: **M**: Fluid milk, **Y**: Yoghurt, **F**: Fish products, **FR**: Fruit products, **ME**: Meat products, **GR**: Grain products
Identifier		M1
Report/Study Title		Using Life Cycle Assessment methodology to assess UHT milk production in Portugal (2013)
System boundary		cradle-to-gate
Geographical scope		Portugal
Functional Unit		1 kg of packaged energy-corrected milk (ECM)
LCIA Method		CML 2001
Software		SimaPro 7.3.2
Database		primary data, literature, and Ecoinvent Database
Packaging	**Primary**	Tetra-Brik
	Secondary	polyethylene film and corrugated box
	Tertiary	pallets
Identifier		M2
Report/Study Title		Life cycle assessment (LCA) of industrial milk production (2002)
System boundary		cradle-to-grave
Geographical scope		Norway
Functional Unit		1,000 l of drinking milk brought to consumers
LCIA Method		CML
Software		not described
Database		primary data, literature, measured data, LCAiT-software database
Packaging	**Primary**	Tetra-Brik
	Secondary	not described
	Tertiary	not described
Identifier		M3
Report/Study Title		Comprehensive Life Cycle Assessment for Fluid Dairy Delivery Systems (2012)
System boundary		cradle-to-gate and cradle-to-grave
Geographical scope		USA
Functional Unit		1,000 kg of milk consumed
LCIA Method		IPCC, ReCiPe, TRACI 2, CED
Software		SimaPro 7.3.3
Database		primary data, literature, US-EI database (V.2.2)
Packaging	**Primary**	18 different packaging types (with or without chilled storage condition)
	Secondary	corrugated box
	Tertiary	pallets, crates

Table 1 (cont'd)		Identifiers: **M**: Fluid milk, **Y**: Yoghurt, **F**: Fish products, **FR**: Fruit products, **ME**: Meat Products, **GR**: Grain products
Identifier		Y1
Report/Study Title		Environmental life cycle assessment of a dairy product: the yogurt (2013)
System boundary		cradle-to-grave
Geographical scope		Portugal
Functional Unit		1,000 kg of yogurt
LCIA Method		CML 2001
Software		SimaPro 7.3.2
Database		Ecoinvent, International Energy Agency (IEA 2009), literature
Packaging	**Primary**	Stirred - PS (120g) Solid - PS (120g) Drinking - HDPE (180 g)
	Secondary	PE tape
	Tertiary	corrugated box with PE film
Identifier		Y2
Report/Study Title		Energy utilization, carbon dioxide emission, and exergy loss in flavored yogurt production process (2012)
System boundary		cradle-to-grave
Geographical scope		Turkey
Functional Unit		1,000 kg of flavored yogurt
LCIA Method		Energy utilization, CExC, CO_2 emission
Software		not described
Database		literature, manufacturer web sites
Packaging	**Primary**	PLA containers (500g)
	Secondary	reusable baskets
	Tertiary	not described
Identifier		Y3
Report/Study Title		LCA of Yogurt Packed in Polystyrene Cup and Aluminum-Based Lidding (Executive Summary) (2009)
System boundary		cradle-to-grave
Geographical scope		Europe (Germany or Swiss)
Functional Unit		1 kg of yogurt
LCIA Method		not described
Software		not described
Database		not described
Packaging	**Primary**	PS cup (150g) with aluminum lid
	Secondary	not described
	Tertiary	not described

Table 1 (cont'd)

Identifiers: **M**: Fluid milk, **Y**: Yoghurt, **F**: Fish products, **FR**: Fruit products, **ME**: Meat Products, **GR**: Grain products

Identifier		Y4
Report/Study Title		Carbon Footprint of Canadian Dairy Products: Calculations and Issues (2013)
System boundary		cradle-to-the exit gate (before distribution)
Geographical scope		Canada
Functional Unit		1 kg of yogurt
LCIA Method		On-farm: ULICEES calculator (Based on IPCC methodology), $(Cafoo)^2$-milk calculator Off-farm: Ecoinvent LCI data base (V2.2, 2010), F4E2 model
Software		SimaPro 7.3.2
Database		Dairyinfo (2011), FPLQ (2007), CIEEDAC (2010), literature
Packaging	**Primary**	PS tubs (4 x 125 g)
	Secondary	not included in the boundary
	Tertiary	not included in the boundary
Identifier		F1
Report/Study Title		Carbon footprint and energy use of Norwegian seafood products (2009)
System boundary		cradle-to-gate
Geographical scope		Norway
Functional Unit		1 kg edible product at wholesaler
LCIA Method		- GHG: IPCC2007 with a 100- year perspective - CED: direct energy used in production chain and energy used to produced supply materials (MJ eq)
Software		not described
Database		official statistics, average data from industry, literatures, single company, unpublished data
Packaging	**Primary**	only transport packaging: corrugated and polystyrene box (consumer packaging is not included)
	Secondary	not described
	Tertiary	not described

Table 1 (cont'd)		Identifiers: **M**: Fluid milk, **Y**: Yoghurt, **F**: Fish products, **FR**: Fruit products, **ME**: Meat Products, **GR**: Grain products
Identifier		F2
Report/Study Title		Life Cycle Assessment of frozen tilapia fillets from Indonesian lake-based and pond-based intensive aquaculture system (2010)
System boundary		cradle-to-gate
Geographical scope		Indonesia
Functional Unit		1 ton of frozen packaged product
LCIA Method		CML 2 Baseline 2000 Cumulative Energy Demand version 1.03
Software		SimaPro 7.1
Database		primary data and literature
Packaging	**Primary**	plastic
	Secondary	corrugated box
	Tertiary	not described
Identifier		F3
Report/Study Title		Life Cycle Assessment of fresh and canned mussel processing and consumption in Galicia (NW Spain) (2010)
System boundary		farm gate-to-grave
Geographical scope		Galicia, Spain
Functional Unit		- 1 kg of commercial fresh mussels for consumption - 1 kg of commercial canned mussel flesh for consumption
LCIA Method		CML 2000
Software		SimaPro 7
Database		primary data, Ecoinvent Database, and literature
Packaging	**Primary**	fresh mussels: HDPE meshes and labels canned mussels: tinplate can
	Secondary	fresh mussels: not described canned mussels: carton
	Tertiary	LDPE bags

Table 1 (cont'd)		Identifiers: **M**: Fluid milk, **Y**: Yoghurt, **F**: Fish products, **FR**: Fruit products, **ME**: Meat Products, **GR**: Grain products
Identifier		FR1
Report/Study Title		A life cycle assessment of non-renewable energy use and greenhouse gas emission associated with blueberry and raspberry production in northern Italy (2013)
System boundary		cradle-to-grave
Geographical scope		Italy
Functional Unit		125 g of fruit
LCIA Method		GWP-IPCC 100a, Non-renewable energy (MJ primary)
Software		SimaPro 7.3
Database		primary data, Ecoinvent 2.2, LCA Food DK
Packaging	**Primary**	PE tray and PE wrap
	Secondary	not described
	Tertiary	not described
Identifier		FR2
Report/Study Title		Life cycle assessment of fresh pineapple from Costa Rica (2012)
System boundary		cradle-to-gate
Geographical scope		Costa Rica and USA
Functional Unit		1 serving of fruit
LCIA Method		TRACI (models customized for Costa Rican Conditions) and USEtox
Software		OpenLCA software
Database		primary data, inventory data were matched with Ecoinvent 2.2 database, converted into EcoSpold XML format for validation using the Ecospold Access plugin for Microsoft Excel
Packaging	**Primary**	corrugated box estimated empty weight 0.689 kg (average 11.5 kg of pineapple or 6.6 pineapples per box)
	Secondary	pallet (not considered in an analysis)
	Tertiary	not described

Table 1 (cont'd)		Identifiers: **M**: Fluid milk, **Y**: Yoghurt, **F**: Fish products, **FR**: Fruit products, **ME**: Meat Products, **GR**: Grain products
Identifier		ME1
Report/Study Title		Carbon Footprint for Australian Agricultural Products and Downstream Food Products in the Supermarket (2011)
System boundary		cradle to supermarket shelf
Geographical scope		Australia
Functional Unit		1 kg of food product
LCIA Method		PAS2050
Software		SimaPro (Pre Consultants 2007)
Database		Industry publication and the literature, LCI library, Australasian Unit Process LCI, Ecoinvent 2.0, LCA Food DK Library
Packaging	**Primary**	not described
	Secondary	not described
	Tertiary	not described
Identifier		ME2
Report/Study Title		Gender as a factor in an environmental assessment of the consumption of animal and plant-based foods in Germany (2012)
System boundary		cradle-to-store
Geographical scope		Germany
Functional Unit		1 kg of consumed product
LCIA Method		IPCC
Software		Federal Statistical Office 2010
Database		Danish LCA Food database and GEMIS 4.6
Packaging	**Primary**	not described
	Secondary	not described
	Tertiary	not described

Table 1 (cont'd)		Identifiers: **M**: Fluid milk, **Y**: Yoghurt, **F**: Fish products, **FR**: Fruit products, **ME**: Meat Products, **GR**: Grain products
Identifier		GR1
Report/Study Title		Environmental life cycle assessment of cereal and bread production in Norway (2012)
System boundary		cradle-to-gate
Geographical scope		Norway
Functional Unit		- cradle to farm gate: 1kg grain delivered at the farm gate - cradle to consumer: 1kg bread
LCIA Method		ReCiPe (USES-LCA model for pesticides)
Software		Matlab (R2009b)
Database		Actual industry data, Ecoinvent database
Packaging	**Primary**	Bread: 80% unbleached paper and 20% polylactide
	Secondary	not described
	Tertiary	not described
Identifier		GR2
Report/Study Title		The carbon footprint of bread (2011)
System boundary		cradle-to-grave
Geographical scope		UK
Functional Unit		One loaf of sliced bread (800g) consumed at home
LCIA Method		PAS 2050 methodology from UK bread supply chain comparing Ecoinvent (2007)
Software		PAS 2050
Database		Primary data, literature, Ecoinvent (2007)
Packaging	**Primary**	polyethylene bag, wax coated paper bag
	Secondary	not described
	Tertiary	not described
Identifier		GR3
Report/Study Title		The life cycle of rice: LCA of alternative agri-food chain management systems in Vercelli (Italy) (2009)
System boundary		cradle-to-gate (Supermarket)
Geographical scope		Italy
Functional Unit		1 kg of refined rice packed and delivered to the supermarket
LCIA Method		IPCC 2001, SEMC 2000, GER (Gross Energy Requirement), NRER (Non-Renewable Energy Requirement)
Software		SimaPro 7 (2006)
Database		Ecoinvent 1.3 (2004)
Packaging	**Primary**	internal: LDPE bag (10g/kg) external: carton box (50g/kg)
	Secondary	plastic film around the pallet (0.36g/kg)
	Tertiary	not described

3.2 Selection of impact categories and determination of packaging contribution

Global warming potential (GWP) and energy consumption (EC) were the main impact categories used for quantitatively demonstrating the contribution of packaging compared to the whole food product-package system since they are available in all selected studies. Other impact categories including acidification potential (AP), eutrophication potential (EP), and ozone layer depletion potential (ODP) are qualitatively discussed. The impact categories included in the selected studies are listed in table B-1 in appendix B.

To determine the packaging contribution within the whole product-package system, the selected studies either gave a direct number or demonstrated the environmental impact value in the form of a stacked bar chart. Where the environmental impact values were provided in a stacked bar chart, additional information such as the total impact was provided in the study that allowed the calculation of the value associated with the packaging impact. The method to obtain the packaging impact from a stacked bar chart was adopted from Kang [40]. The length of the packaging impact stack was measured, then calculated compared to the length of the total impact stack in order to determine the packaging contribution [40].

3.3 Functional unit conversion

In order to compare environmental impacts of packaging between different food product categories, the impacts of the whole product-package system and of packaging in each selected study need to be converted to be related to the same functional unit instead of the functional unit presented in the original study. In this study, the functional units using to compare different food categories are ‘1 kg of finished product’ for the cradle-to-gate system boundaries and ‘1 kg of product consumed by consumers’ for the cradle-to-grave boundaries. These functional units are denoted as “a comparing functional unit” or a “comparing FU” in the following content of this study.

The functional unit conversion used the context provided in the original studies to interpret an “impact conversion factor” that was used to multiply the impact related to the original functional unit to give the impact per the comparing FU. For example, the study M1 presented the original functional unit of ‘1 kg of packaged energy-corrected milk’ which is explained to be equivalent to 1.319 kg of UHT milk, so the impact conversion factor used to multiply the original impact is 1/1.319 = 0.758. The impact conversion factors for each selected study are provided in table C-1 in appendix C.

3.4 Overview and product systems

The seventeen selected LCA studies include thirteen peer-reviewed journal articles and four full reports from research centers published between 2002 and 2013. Each study describes LCA of one or several food products in the context of either food production or food consumption.

The category of dairy products includes fluid milk and yogurt. The selected LCA studies within the category mainly aim to evaluate the environmental performance of production at specific geographical scopes and to identify hotspots to propose improvement options. The system considered in these selected studies starts from agricultural activities related to animal feed and raw milk production which normally occur on a dairy farm. Raw milk produced from the farm is then transported to dairy processing plants. After being received, raw milk is stored under cold conditions before going through further processes, such as standardization, pre-warming, homogenization, pasteurization, and so on. In the yogurt production system, the additional process of milk incubation with a selected microorganism starter culture is included. The final product of fluid milk or yogurt is then packaged in various forms of packaging. The life cycle stages involving packaging, i.e., material acquisition, conversion, and manufacturing, are included at this point. After packaging, the finished products are ready to be transported to distribution centers. The cradle-to-gate boundary ends at the point of the finished product at the factory gate, or at the wholesaler or retailer, while the cradle-to-grave boundary also includes consumption and end-of-life stages where the product waste and packaging waste are disposed or recycled by consumers.

In the fish product category, studies concerning fish and mussel products are included. Life cycles of these products briefly consist of 1) capture fisheries or aquaculture, 2) processing, and 3) consumption. In the case of aquaculture, the production of feed is also covered within the system boundaries. Fish are processed into fresh, frozen, round, gutted, or fillet products while cultured mussels are purified for fresh consumption, or processed into a canned product.

LCA studies of blueberries, raspberries, and pineapples were selected in the fruit product category. The life cycle stems from the cultivation, harvesting, packing, and distribution to the retailer for the cradle-to-gate boundary. The cradle-to-grave additionally includes the disposal of packaging materials. Since the selected products are all for fresh consumption, they require fewer processes after harvesting compared to processed fruits, such as canned fruits and frozen fruits.

The studies included in the meat product category presented the environmental performance of meat products, which are fresh beef, lamb, and pork, in the consumption context. The study ME1 used LCA as a tool to examine global warming potential of consumer choice of products. The study ME2 reported the environmental impact of food products in the consumption pattern of men compared to women. Within these study scopes, meat products are included as one of the main choices of consumption. A detail about the packaging used for meat products in both studies were not described but the impacts of packaging were given to demonstrate the contribution of processes in meat product life cycles.

In the grain product category, barley, oats, wheat, rice, and bread were included in the three selected studies. In the study GR1, the life cycle stages of barley, oat, and wheat belong within the cradle-to-farm gate boundaries, while the life cycle of bread is considered as a cradle-to-point of sale where the end-of-life stages are excluded. The system boundaries of the study GR2 is cradle-to-grave covering the life cycle stages from the cultivation of wheat to the disposal of bread and packaging. The life cycle of rice in the study GR3 is within the cradle-to-gate boundary. It ends where the packaged rice is delivered to the supermarket.

3.5 Life cycle impact assessment (LCIA)

Impact categories that were included in the assessment are not consistent across selected studies. An impact category was included into each study due to its relevance to a product life cycle and also mainly based on the LCIA method used in the study. Different LCIA methods include different impact categories. Similar impact categories are sometimes called by different names depending on the LCIA method. For example, while the acidification potential is called terrestrial acidification in the study GR1 which used the ReCiPe LCIA method, the other studies using the CML method included the impact as acidification potential. The following is a discussion of the impact contribution from the selected studies starting with global warming potential (GWP) and energy consumption (EC) which are included in every selected study, followed by other impact categories included in most of the studies.

3.5.1 Global Warming Potential (GWP)

Global warming potential (GWP) considers the impact of greenhouse gas (GHG) emissions including carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), and so on. A greenhouse gas is defined as a “substance with the ability to absorb infrared radiation from the earth (radiative forcing)” [8]. A summary of the GWP of the selected studies of all food product categories is provided in *Table 2* for the cradle-to-gate boundaries and *Table 3* for the cradle-to-grave boundaries. In the tables, an impact value belonging to a selected study that reported an impact of one product is shown as a single value without a standard deviation. Detailed descriptive statistics of the impact can be found in Appendix D: *Table 8* to *Table 9*. *Figure 3* and *4* show the contribution of packaging compared to the whole product system in the form of a percentage. The percentage of packaging in the charts is the average value where there was more than one selected study within a product category. The charts demonstrate the trend of the packaging contribution across different product categories.

Table 2: Global warming potential (GWP) of packaging compared to the whole product-package system of 'cradle-to-gate' boundaries

			GWP (kg CO_2 eq per kg of finished product)			
Product Categories	**Study ID**	**Products**	**Overall**	**Packaging**	**Processes other than packaging**	**% of Packaging**
Milk	M1	fluid milk	1.32	0.06	1.25	4.93
	M3	fluid milk	1.85±0.32	0.19±0.15	1.67±0.19	9.23±5.56
Yogurt	Y4	yogurt	1.75	0.18	1.57	10.10
Fish	F1	frozen fish	3.24±2.55	0.12±0.05	3.12±2.54	4.61±2.84
	F2	frozen tilapia	2.04	0.06	1.98	3.00
Fruit	FR2	whole pineapple	0.54	0.13	0.41	24.57
Meat	ME1	beef, lamb, pork	16.97±9.68	0.05±0.01	16.92±9.68	0.40±0.35
	ME2	beef, lamb, pork	14.40±5.55	0.45±0.06	13.95±5.55	3.45±1.90
Grain	GR1	bread	0.94	0.02	0.91	2.42
	GR3	rice	2.88	0.14	2.74	4.70

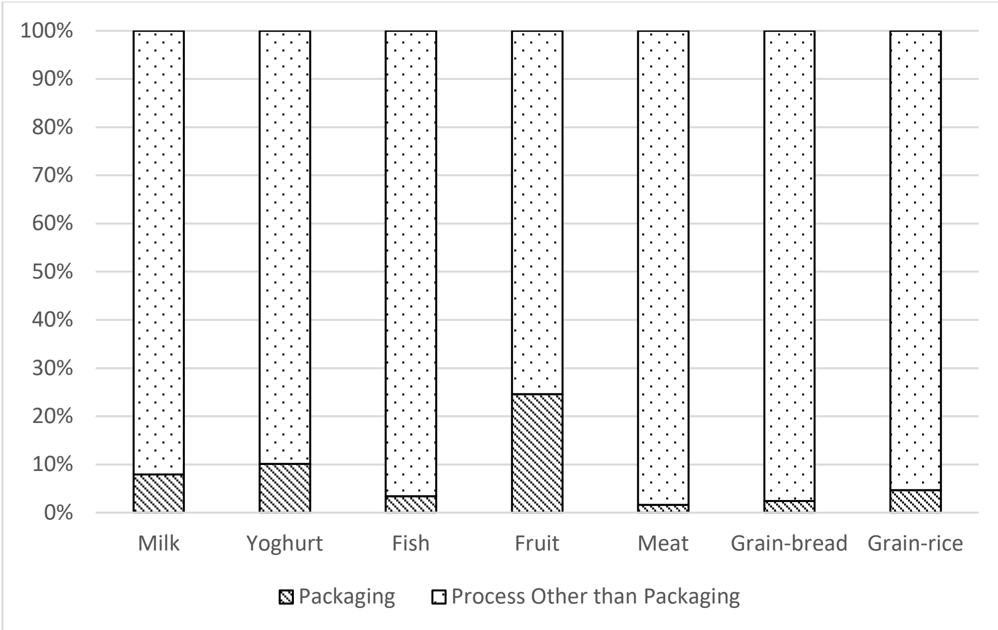

Figure 3: The relative GWP of packaging compared to the whole product-package system of 'cradle-to-gate' boundaries

Table 3: Global warming potential (GWP) of packaging compared to the whole product-package system of 'cradle-to-grave' boundaries

			GWP (kg CO_2 eq per kg of finished product)			
Product Categories	**Study ID**	**Products**	**Overall**	**Packaging**	**Processes other than packaging**	**% of Packaging**
Milk	M2	fluid milk	0.54±0.05	0.02±0.00	0.53±0.04	2.72±0.23
	M3	fluid milk	2.23±0.29	0.24±0.17	1.98±0.14	10.33±5.74
Yogurt	Y1	yogurt	1.78	0.16	1.61	9.30
	Y2	flavored yogurt	2.27	0.30	1.97	13.40
	Y3	yogurt	2.00	0.25	1.75	12.60
Fruit	FR1	blueberry, raspberry	0.43±0.01	0.10±0.01	0.34±0.00	22.31±1.77
Grain	GR2	bread	1.35±0.09	0.05±0.03	1.31±0.10	3.51±1.97

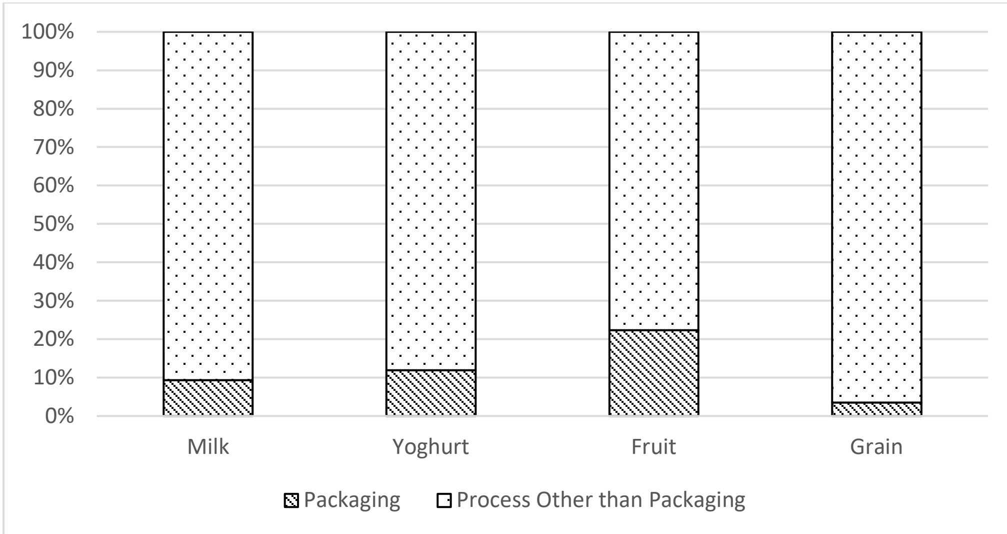

Figure 4: The relative GWP of packaging compared to the whole product-package system of 'cradle-to-grave' boundaries

As shown in the summary, the contribution of packaging ranged from 2% to 25% with the lowest contribution for meat packaging and the highest for fruit packaging. The packaging in animal-based food categories such as dairy, fish and meat products tended to have relatively lower contributions compared to plant-based food, i.e., fruit and grain, since the GWP of the food involved phases were typically large. The agricultural phases of dairy and meat products produced a large amount of methane (CH_4) from enteric fermentation and manure management. In fish products, the main contribution of GWP came from the feed production in culture fisheries and the combustion of fossil fuel in capture fisheries.

Regarding fruit and grain products which are considered as plant-based, during the cultivation phases, plants remove carbon dioxide from the atmosphere. This resulted in the GWP to be less intense compared to the animal-based products. Within the group of plant-based products, the fruit products included in the study, which are blueberries, raspberries, and pineapples for fresh consumption, require only minimal processing. The contribution from the fruits is considered to be less intense compared to grain products which have a higher degree of processing after harvesting. Therefore, the contribution of the fruit packaging was driven to be comparatively large in the whole product system.

Considering animal-based products, the packaging of milk and yoghurt contributed to the whole product system more than the packaging of fish and meat products. This could be because of the more complex packaging and packaging related process for the dairy products. Another factor that is important to consider is the allocation of the impact to multiple products of the whole system. For example, in the case of milk and beef, which we can consider within the same life cycle, the allocation could influence the intensity of the impact associated with each product. In the system that draws more burden to beef, this could result in less intense impacts associated with milk that also drives the portion of packaging to be higher compared to the packaging of the beef system.

3.5.2 Energy Consumption (EC)

Energy consumption (EC) considered in this summary covered both renewable and non-renewable energy since the selected studies defined the energy consumption in different ways. *Table 4* and *Table 5* show the summary of EC of different product categories for cradle-to-gate and cradle-to-grave, respectively. A single value of impact without a standard deviation is reported in the case that the selected study focused in one product. Values belonged to a study with multiple items of product in consideration are reported with the standard deviation. Detailed descriptive statistics of the impact can be found in Appendix D: *Table 10* to *Table 11*. *Figure 5* and *6* demonstrate the contribution of packaging toward the whole product system. In the product category with more than one selected study, the percentage presented in the charts

(*Figure 5* and *Figure 6*) are average values, which aimed to roughly demonstrate the trend of the packaging contribution across different product categories.

Table 4: Energy consumption (EC) of packaging compared to the whole product-package system of 'cradle-to-gate' boundaries

			EC (MJ per kg of finished product)			
Product Categories	**Study ID**	**Products**	**Overall**	**Packaging**	**Processes other than packaging**	**% of Packaging**
Milk	M1	fluid milk	9.14	1.10	8.04	12.08
	M3	fluid milk	10.50±4.09	3.60±3.31	6.90±0.94	29.52±13.80
Fish	F2	frozen tilapia	26.40	1.85	24.55	7.00
Fruit	FR2	whole pineapple	6.06	2.01	4.05	33.19
Grain	GR3	rice	16.64	3.77	12.90	22.50

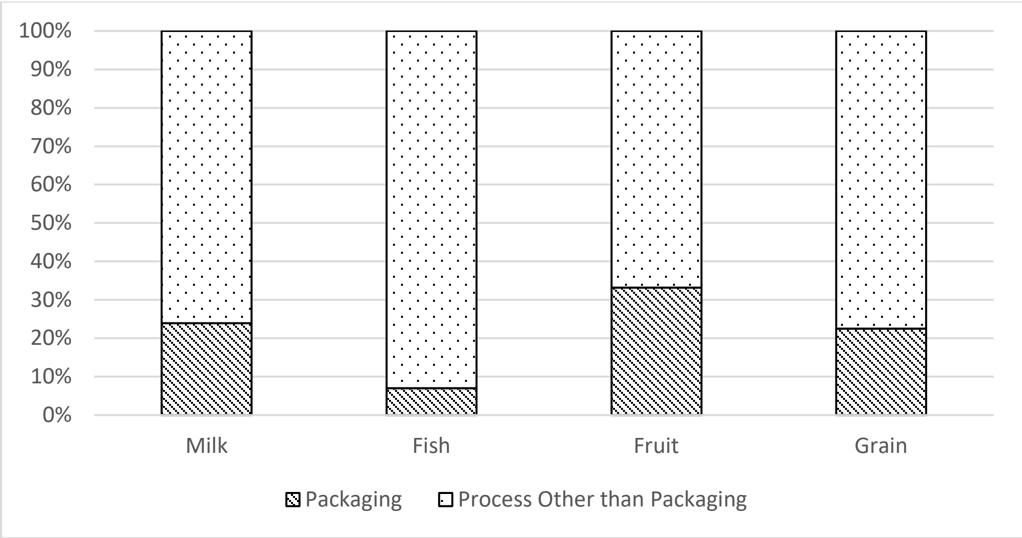

Figure 5: The relative EC of packaging compared to the whole product-package system of 'cradle-to-gate' boundaries

Table 5: Energy consumption (EC) of packaging compared to the whole product-package system of 'cradle-to-grave' boundaries						
			EC (MJ per kg of finished product)			
Product Categories	**Study ID**	**Products**	**Overall**	**Packaging**	**Processes other than packaging**	**% of Packaging**
Milk	M2	fluid milk	4.45±1.43	0.68±0.02	3.78±1.41	16.04±4.11
	M3	fluid milk	13.91±3.66	3.59±3.38	10.32±0.39	22.52±13.66
Yogurt	Y1	yogurt	17.18	4.77	12.41	27.79
	Y2	yogurt	31.69	2.18	29.51	6.86
Fruit	FR1	blueberry, raspberry	8.97±0.02	2.71±0.23	6.26±0.21	30.25±2.47

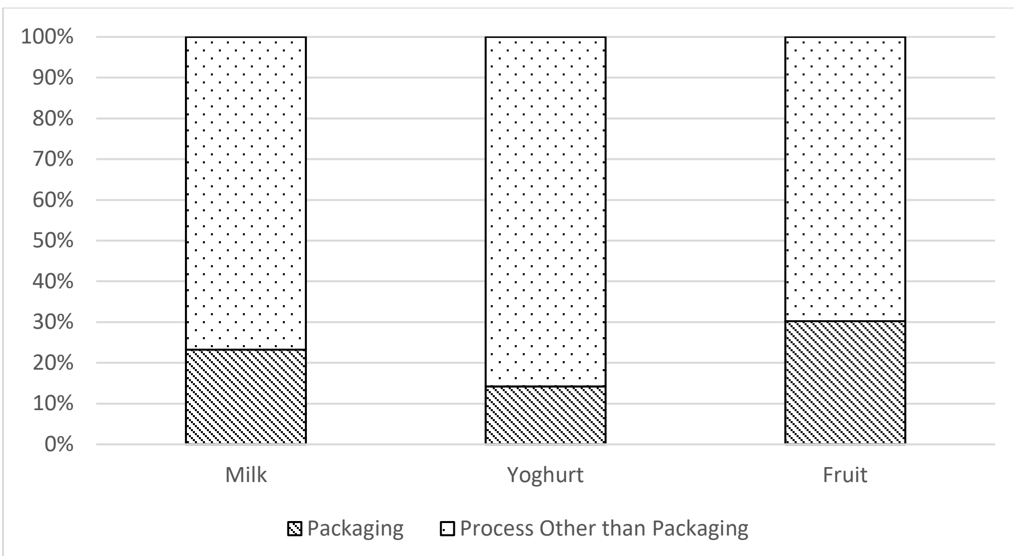

Figure 6: The relative EC of packaging compared to the whole product-package system of 'cradle-to-grave' boundaries

The summary revealed that across different food product categories, the contribution of packaging to the energy consumption (EC) of the whole product system was between 5% and 35%. The trend of the packaging contribution across the product categories was quite similar to the trend of GWP impact. The least packaging contribution belonged to the fish product, while the packaging in the fruit product category had the highest contribution.

The complexity of the food involved process tended to be more influential in the EC than GWP. The products that require more complex processes had a higher portion of the contribution associated with food products. For example, comparing milk and yogurt, yogurt requires more processes in the dairy factory than milk. The portion of energy attributed to the food is higher in the case of yogurt, resulting in less contribution of packaging compared to milk. Within the plant-based products, grain and fruit, the selected products in the fruit category, require fewer post-harvesting processes than rice. The contribution of packaging in the fruit category appeared to be high compared to the grain products, which could be explained by the above reasons.

On the contrary, regarding the animal-based products, milk requires more complex processes after the agricultural phase than fish but the contribution associated with the food turned out to be less intense, resulting in a high contribution of packaging. This might be explained as the result of the greater complexity of the packaging materials and the packaging related process of milk products than of the fish products. Long distance distribution of fish products required a lot of energy. This drove the impact associated with food to be high and the contribution of packaging to be obviously low.

3.5.3 Other impact categories

Besides global warming potential (GWP) and energy consumption (EC), the impact categories covered by many of the selected studies are eutrophication potential (EP), acidification potential (AP), and ozone layer depletion potential (ODP).

The impact category of EP was included in ten out of seventeen selected studies (M1, M2, M3, Y1, Y3, F2, F3, FR2, GR1, GR3) covering the product of milk, yogurt, frozen tilapia, mussel, pineapple, bread, and rice. In plant-based products (pineapple, bread, and rice), agriculture phases contributed up to more than 90% of the impact of the overall product system due to emissions of nitrogen and phosphorus from fertilizer application during farm related activities. The leakage of nutrients in waste water is one of the main contributors in both dairy-based and fishery products. According to the study M2, during the raw milk production phases at the farm level, milk is emitted to waste water from the equipment cleaning process and the disposal of milk that does not meet the quality standard. In the same way, water containing nutrients discharged to the ocean was a dominant contributor in fishery products. During dairy farm activities, the ammonia losses from manure also have a significant contribution to the EP. The fertilizers used in the cultivation of crops used directly as animal feed and as inputs for the production of animal feed are the main sources of nitrogen and phosphorus significantly contributing to the EP of dairy-based products and culture fisheries products.

While the EP contribution of the agriculture phases of milk and fishery products ranged from 70% and up to 95%, yogurt products, according to the study Y1, had less intensive contribution from dairy farm phases of 55%. Intensive EP contribution due to the production of other milk-based ingredients, i.e. powdered milk and concentrated milk, input to the yogurt production process drove the contribution of the dairy factory to be high, up to 41%.

In terms of AP, the studies that included the impact into their assessment are M1, M2, Y1, Y3, F2, F3, GR1, and GR3. Across various products of fluid milk, yogurt, frozen tilapia, canned and fresh mussels, bread, and rice, the agriculture life cycle stages of these products were reported to be the main contributors to the impacts. The contribution was between 50% to 80%

varying by product. The ammonia (NH_3) loss from manure was the greatest contributor in the farm phases of dairy products followed by the emissions of mono-nitrogen oxides (NO_x) and sulfur dioxide (SO_2) during diesel combustion of the agricultural machinery. Energy and electricity production are also considered as significant contributors to the impact. According to the study F2, energy intensive processes of crop-derived input production, i.e. corn-gluten meal, and the transportation of soy lecithin were both major contributors in cultured tilapia. Likewise, the electricity production for mussel purification was the main contributor to the AP in fresh mussels [32]. The AP of pineapples for fresh consumption was also mainly from farm phases with additional potential from the production of nitrogen (N) and sulfur (S) containing fertilizers, and the refrigeration during transport and while in storage [34].

Regarding the ODP, among all selected studies, the studies of milk, yogurt, mussels, pineapples, and rice (M1, M2, Y1, Y3, F3, FR2, and GR3) included the impact into their assessments. Fossil fuel production and electricity production were identified as main contributors to the impact [32]. The degree of contribution of activities within a product life cycle tended to relate to the diesel and fossil fuel consumption level of each process. Compared to other impacts (EP and AP), the contribution of agricultural phases toward the ODP was less intensive, ranging between 30% and 65%. The factory processing phases as well as distribution and retailing of the food products became more prominent in the ODP impact since the related activities consume a significant amount of energy that drives the contribution of these processes to be high. The processes consuming more fossil fuel compared to the others within the life cycle, e.g., diesel combustion of farming machinery, heating boilers in dairy processing factories, raw material delivery, finished product distribution, and electricity required for the production or the refrigeration at selling points, were likely to be dominant contributors to the ODP impact across various products [23], [28], [32]. The emission of cooling medias belonging to the hydrochlorofluorocarbon family (HCFCs) from a refrigeration systems in on-farm cooling tanks, distribution lorries, and retailers, was also mentioned in the study M2 to be a significant ODP contributor [24]. Nevertheless, the study M1 did not include this factor into its assessment due to the complexity and incomplete understanding about the substances [23].

The contribution of packaging toward EP, AP, and ODP, according to the selected studies, is generally limited within the portion of the product life cycle after the agriculture phase. The factory processing phase together with the distribution and consumption of the products in the selected studies contributed to the EP, AP, and ODP at most 30%, 50% and 70%, respectively. The contribution of the packaging toward the EP was mostly less than 5% of the overall product system except the bread product of the study GR1 in which packaging contributed about 7% to marine eutrophication. In terms of the AP, packaging of fluid milk (M1) and frozen tilapia (F2) had the lowest contribution at 1%. The packaging of pineapple had the highest contribution toward the AP and ODP at 15% and 30%, respectively. The lower energy intensity of the process after the agriculture phases of the pineapple product life cycle drove the contribution of packaging to be comparatively high. The contribution of the packaging of other products on the ODP ranged between 2% and 10%.

The contribution of different packaging systems was discussed in the study M3, where eighteen packaging systems of fluid milk based on four main packaging materials of high density polyethylene (HDPE), paperboard, low density polyethylene (LDPE), and polyethylene terephthalate (PET) were assessed. The EP was included as two impacts, marine eutrophication and fresh water eutrophication. The different contribution of various packaging systems toward both impacts were driven by the electricity consumption which traced back to the background coal mining [25]. The fresh water eutrophication of the packaging life cycle stage was predominantly contributed by the disposal of spoil from coal mining in surface landfills [25].

3.6 Conclusions

Across selected LCA studies covering the food product categories of milk, yogurt, fish, fruit, meat, and grain, the contributions of packaging toward the whole product-package system on the global warming potential (GWP) and the energy consumption (EC) were maximum at 25% and 35%, respectively. Factors influencing the magnitude of the packaging contribution according to the summary of the selected LCA studies are discussed as follows.

1) The type of raw material of the food products (plant-based and animal-based products) had a tendency to govern the proportion of the packaging contribution within the product system on the GWP. The packaging of animal-based products tended to have comparatively less contribution towards the whole product system than the packaging of plant-based products. Agricultural activities related to the animal-based raw material tended to be more intense on GWP than the plant-related activities. This caused the impact associated with food from animal-based systems to be large and drove the contribution associated with packaging to be proportionally small.
2) The degree of processing of the food after the agriculture phase drove the difference of the packaging contribution in both GWP and EC. A product that requires more processes had higher impact involving food than a product with less processes. In the system where the impact associated with food was high, the portion of packaging impact was driven to be small. For example, within the plant-based products group, grain products such as bread and rice require more processing than fruits for fresh consumption; more intense

contribution of food drove the contribution of the grain packaging to be smaller than fruit packaging.

3) The greater complexity of the packaging material and the packaging related process drove both GWP and EC associated with packaging to be high.

Regarding other impact categories (EP, AP, and ODP), the impacts were contributed mainly by the processes associated with food including both the agricultural phase and the factory phase. The contribution of the packaging toward EP, AP, and ODP were maximum at 7%, 15%, and 30%, respectively.

4 OPPORTUNITY OF PACKAGING TO REDUCE OVERALL ENVIRONMENTAL IMPACT OF FOOD SYSTEMS

As we learned from the previous chapter, the environment impact of the food product system is mainly contributed by the food related phases which include agricultural and industrial processing. Food loss and waste not only means wasting of resources and energy invested to produce food but also the impacts caused by emissions from the series of processes along its life cycle. By definition, food loss is food that was originally intended for human consumption but leaves the supply chain before it gets to the consumer for reasons such as not meeting the quality standard, being destroyed by natural disasters, insects, and diseases, etc. In contrast, food waste is food that satisfies the human consumption standard but does not get consumed, for instance, food left on a plate, and food stored until passing the best by date and geting thrown away by the consumer, and the food that is never purchased before it expires and is discarded by the retail store. There are some interesting key points about global food loss and food waste reported in the working paper "Creating a Sustainable Food Future" of the World Resources Institute and the United Nations Environmental Programme (UNEP) and the Food and Agriculture Organization (FAO)'s report including [41], [42]:

1) Food loss typically occurs during production, storage, processing, and distribution due to the shortage of appropriate handling technologies, packaging, and marketing.
2) More than half of the loss from these stages of the supply chain occurs in the developing countries including South and Southeast Asia, Sub-Saharan Africa, North Africa, West and Central Asia, and Latin America.

3) Food waste, on the other side, happens at the distribution and the consumption stage due to the negligence and conscious decisions of players in the supply chain, which are the retailer and the consumer.
4) Food loss and waste at consumption can be seen more in developed countries, i.e. Industrialized Asia (China, Japan, and South Korea), North America and Oceania, and Europe.

The attempt to reduce food loss and waste has been promoted as an important mission at the global level since it could alleviate not only adverse environmental impacts, but also social and economic problems including poverty, gender inequity, food security, etc [41], [43]. Sets of solutions to reduce food loss and waste were proposed and applied at the points of loss and waste, e.g. improvement and development of harvesting techniques and storage facilities in developing countries where food loss often occurs, and campaigns to increase consumer's awareness in developed countries where food waste is more visible [41], [42].

Packaging as a part of the food supply chain is also considered as a potential area where some solutions can be applied. Packaging, in the food product life cycle, has environmental impacts associated with its processes of raw material extraction, production, transportation to the food manufacturing site as well as processes of food packing such as bottle filling, bag sealing, and box erecting. The large number of packages left after the consumption of food caught attention and raised the concern of the environmentally aware public. This led to the initiation of the strategies focusing on minimizing packaging material and packaging waste. However, after taking a closer look at the whole system, packaging causes relatively small environmental impacts compared to the entire food supply chain. Such attempts to reduce packaging might result in only limited improvement in the total product system environmental performance.

Targeting packaging development for the reduction of food loss and food waste is potentially more environmentally efficient by directly alleviating the overall environmental impact. Following is a discussion of the opportunities for packaging to reduce the overall environmental impact of the food product system by improving its capability to prevent food loss and waste.

4.1 Packaging design and technology to extend shelf life

Multiple packaging technologies aim to maintain nutritional quality and sensory characteristics at the same time ensuring the safety of the food to be able to store for consumption longer. One major area of the extended shelf life technology is Active Packaging. Various active packaging techniques were described by Vermeiren et al. [44] including; oxygen (O_2) scavengers, carbon dioxide (CO_2) scavengers and emitters, ethylene (C_2H_4) scavengers and emitters, moisture regulators, ethanol emitters, antimicrobial release, antioxidant release, flavor releasing film, and flavor absorption. These methods prevent or retard the food from getting rancid, off flavor, ripening, and spoilage causing by microbes, depending on the type of food and its sensitive condition triggering the quality degradation and deterioration. Other techniques, for example, multi-layer barrier packaging, modified atmosphere packaging (MAP), edible coatings, and aseptic packaging, are among the technologies of primary packaging used to extend the products' shelf life [45]. Extended shelf life products also provide opportunities for businesses to reach more customers in distant markets.

Considering the life cycle perspective, extended shelf life food packaging can reduce the need to produce a particular product. If the demand is constant, and the product lasts longer, then less amount of product is required to meet the market demand. When less product needs to be produced, the resources, energy, and water needed as inputs to the production and processing can be reduced. The longer time the food can maintain its quality and safety for consumption compensates for the cost and energy required for product transportation as well as the impacts caused by both production and transportation.

Obviously, to change from a conventional to an innovative extended shelf life technology requires the product owners to put more effort in research and development and could increase the cost associated with the packaging per unit package. Regarding the cost-benefit consideration, the economies of scale, an ability to decrease the total cost due to large scale production, allow active packaging devices, i.e., scavengers, absorbers, and emitters to continually grow and apply in the industrial and mass commercial scale [46]. While the product manufacturers draw the benefit from an increased profit margin, consumers perceive their advantages of better quality products for the money they pay [46] .

4.2 Packaging that prevents food product physical damage

The physical damage that occurs in two areas of the food supply chain, post-harvest transportation (farm to processing) and product distribution (farm to retail store and post-processing to retail store) can be prevented by a proper packaging and handling system. According to FAO [42], one important point of food loss is improper post-harvest handling and storage which includes the transportation between the farm and the processing, especially in developing countries where associated facilities such as a cold chain are not well designed and constructed. A sturdy and well-designed container and proper arrangements are required for safe transportation of the food raw materials including fresh produce, fish, meat, etc. to the processing facility. The other characteristics, for instance, temperature and humidity control, and air circulation, are also important to consider depending on the type of food. Protective packaging, transportation, and storage systems assure the amount of raw material that meets the quality standard and is able to get into the processing is maximized.

At the point where the food products are transported to the retail store, shock and vibration from truck transportation could damage the food products. Whole fruits for fresh consumption, fresh-cut fruits and vegetables, and whole vegetables are sensitive to physical damage. The damage to the fresh produce could be considered as a critical and potential cause of food waste at the retail store. Damage such as bruises and cuts not only increase the spoilage caused by microorganisms and other contaminants, but also tends to cause the consumer to refuse to buy the products because of the defective appearance. The rejected products are further discarded by the store and wasted. Studies of the transportation damage to some fruits such as apples, grapes, strawberries, and watermelons, examined the condition causing the damage and suggested solutions to the problem including packaging related changes [47]–[49]. Verghese et al. [45] described how a banana injury problem was resolved by changing the secondary package from an ordinary two-piece carton to a stronger box. Better process monitoring and a better understanding of the nature of the product also helped in addressing issues such as poor product handling and inadequate packaging material.

4.3 Food packaging that fits current demography and lifestyle

With the current demography of smaller households, it has been recommended that packaged food be sold in smaller portions to fit the size of the household to prevent excess food being thrown away and wasted [4]. Some additional functions such as a reclosable package, or a bulk package with small divided portions could be options to limit food waste due to left-over food.

Pre-packed and processed food, such as fresh cut produce or frozen meal, became popular due to its short preparation and cooking time [45]. Pre-packed and processed food is more environmentally efficient than in-house prepared food since less organic waste from the food manufacturer ends up in the landfill compared to the waste from the household [45]. More packaging material needed to be input to the system to produce smaller package sizes, and more innovative materials and techniques are required to produce extended shelf life pre-packed and processed food. The environmental impact due to the change is expected to be traded off by the food loss and waste it could prevent.

4.4 Standardized date labelling system

Date labeling systems have been visible on food products for a long time, comprising two systems, i.e., open dating, and closed dating. In the US, open date, a date code that contains month, date, and year that consumers can understand, was initially put on food packages in the 1970s to fulfill consumers' demand for the information concerning the freshness of food. Closed date, symbols, and numerical codes the consumer is unable to understand, had been used to communicate between manufacturers and retailers for the purpose of stock rotation for a long time before.

In recent years, the concern about food waste due to misinterpretation of date labeling (*e.g.,* sell by date, use by date or best before) on the package has been highlighted [50]. It was estimated that up to 20% of food waste during the consumption stage in England is caused by confused interpretation of these dates [51]. Retailers and consumers make the decision to throw away food based on the date labeled on the package without any recognition that the date does not relate to a food safety issue. This causes edible food to be wasted. In the US, the confusion of consumers about the date labels on food product packages involves a long, complicated story. The report in partnership between the Harvard Food Law and Policy Clinic and the National Resources Defense Council (NRDC) concerning the confusion about the food date labels that leads to food waste, revealed interesting key points about the issues including [50];

1) Lack of standardized federal level regulation on food product date labeling left a void in how to put the date to provide consumers the information they increasingly demanded regarding food freshness. Different state level laws and manufacturers' decisions led to various inconsistent date coding practices that caused considerable confusion among consumers.
2) Date labeling terms such as use by date and best if used by date, are based on a quality aspect of the product. The standpoints of the manufacturers mainly aimed to preserve their product's reputation.
3) Infant formula is the only product regulated by the government about date labeling to assure the required nutrients are maintained as declared.
4) Overreliance on date codes not only contributes to the waste of edible food but also leads to ignorance of other factors that affect food safety risks such as time and temperature control.

Aiming to encourage collaboration to solve the issue, the report provided the following recommendations [50]:

1) The "sell by" dates that are mainly used for stock control should be omitted and made invisible to the consumer since these dates often generate confusion that could lead to the discard of edible food passing these dates.

2) A reliable and uniform open dating system involving the following practices need to be established:

    a. The language should be clear for both quality-based and safety-based date labels.
    b. The term “freeze by” date is helpful to be promoted as it raises the consumer’s awareness of the benefit of freezing that could extend the shelf life of many products.
    c. The quality-based dates on non-perishable and shelf-stable products should be removed or replaced by other useful date terms such as “Best within XX days of opening” and “Maximum quality XX months/years after pack date.”
    d. Date labels on the package should be easily located by the consumer.
    e. Best practices of methods for manufacturers and retailers on determining date coding for the product should be transparently established and accessible by interested consumers.

3) Safe handling instructions and “smart labels,” for example, QR codes and time-temperature indicators, should be encouraged to be used together with date labels.
4) Collaboration of the involved key players is needed to solve the problem. Food manufacturers should initiate the change to the less confusing, uniform, and more helpful practice. Government authorities should move forward to issue a standardized date labeling regulation for both industry and consumers to rely on. Education for consumers to increase understanding should be provided from both manufacturers and government. Meanwhile, the consumers’ self-education and information seeking are not only beneficial in reducing food waste but also enhance their food safety knowledge and practice.

The improvement of packaging date labeling could be a powerful way to decrease food waste at the retailer and consumer levels. However, establishing a uniform system will face difficulties including the consumer perception, established industrial practices, balancing between business benefits and the public interest, and moreover regulatory issues. The collaboration of the stakeholders is the most important factor in making progress on this issue. Public awareness and concern are the best encouragement to government and industry to take action.

4.5 Conclusions

The environmental impact of the food product system is predominantly contributed to by the food related processes. Food loss and waste is one of the top global concerns as it connects with environmental, social, and economic problems. Packaging as an inseparable component of the food product system, has opportunities to reduce food loss and waste. Packaging has a limited environmental contribution compared to the whole food product environmental performance. Packaging improvements to reduce food loss and waste potentially can reduce the overall environmental burden of the whole system, even though the improvement increases the portion of the impact belonging to the packaging. Possible improvements include packaging design and technology that extends the shelf life, packaging that prevents physical damage to the food product, food packaging that fits the current demography and lifestyle, and a standardized date labelling system. Food that lasts longer for consumption reduces the total production over time, so less resources and environmental impact associated with the input, production, and transportation can be expected. Less physical damage increases the amount of raw material that meets the standards for processing and final products that fit the quality perception and get bought by the consumer. This reduces the waste of resources, energy, and water input to produce the food products. The size of packaged food that fits the size of the household reduces purchase of excess food that will be wasted. These solutions assure the resources invested to produce food are ultimately utilized at the consumer level and the fulfillment of human hunger compensates for the burden of emissions along the food product life cycle. The clarification and standardization of date labelling systems reduces the consumer's confusion that leads to discards of edible food as well as increases the food safety involved awareness and handling practices without overreliance on date labels. However, to implement a uniform date labelling system requires collaboration between government, industry, and consumers.

5 CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE RESEARCH

5.1 Conclusions

To understand the contribution of packaging to the whole food product system in terms of environmental impacts, life cycle assessment (LCA) studies of some food product categories, i.e. milk, yogurt, fish, fruit, and grain products, were reviewed. By focusing on the impact categories of global warming potential (GWP) and energy consumption (EC), it was seen that the contribution of packaging was maximum at 25% and 35%, respectively. In other impact categories; eutrophication potential (EP), acidification potential (AP), and ozone depletion potential (ODP), packaging contributed a maximum of 30%. The factors influencing the difference of the contribution across different food product categories were the type of food product raw material (plant-based and animal-based products), the degree of processing after the agricultural stage, and the complexity of the packaging material and the packaging related processes.

The limited contribution to the whole product system provides room for packaging improvement to enhance the environmental performance of the food product system. Massive impacts concerning the food involved life cycle stages together with the severe situation of the global food loss and waste imply the opportunity of packaging to improve the environmental efficiency of the system by aiming to reduce such loss and waste. Possible packaging solutions include: 1) packaging design and technology to extend the food product shelf life, 2) packaging that prevents physical damage to the food product, 3) packaging that fits the current demography and lifestyles, and 4) a standardized date labeling system. Knowledge, resources, cost, as well as the collaboration of all players in the supply chain are required to implement the changes into the system. The better environmental performance of the whole system is expected to compensate for the change.

5.2 Recommendations for future research

Recommendations for future research include:

- To better identify the factors influencing the magnitude of the packaging contribution across different food product categories; more selected LCA studies in each category would allow proper statistical analysis that could address correlations between factors and degree of dependence of the contribution on each factor.
- A meta-analysis, a technique belonging to the group of systematic reviews using statistical methods to integrate results of multiple studies [52], is interesting to be used to analyze results of LCA studies in order to determine factors influencing the contribution of packaging in different food categories, and also to use in other areas of packaging LCA study. For example, in the study of Kang [40], meta analysis was used in the review of LCA studies of the PET beverage bottle system to evaluate the variation of the environmental impacts belonging to each life cycle stage of the system and identify the main source of the impacts.
- Using different comparing functional units such as nutritional energy would result in different comparison outcomes because a certain unit weight of different types of food gives different amounts of energy.
- To broaden the assessment to other impact categories would help in identifying the hot spots in different life cycle stages since each impact category relates to

different emissions. The environmental improvement could be applied to a specific area or in balancing of the whole life cycle performance.

- In depth LCA studies on the food product system after applying the recommended packaging changes would result in useful knowledge to be used as supporting information for policy makers, industry, and consumers.
- A consequential LCA approach could be used to address the marginal outcome related to the changes in packaging.
- Perception and opinion studies as well as a cost-benefit analysis of the standardized date labeling system could contribute useful information for stake-holders in the food supply chain.

APPENDICES

APPENDIX A: System boundaries of the food products by product categories

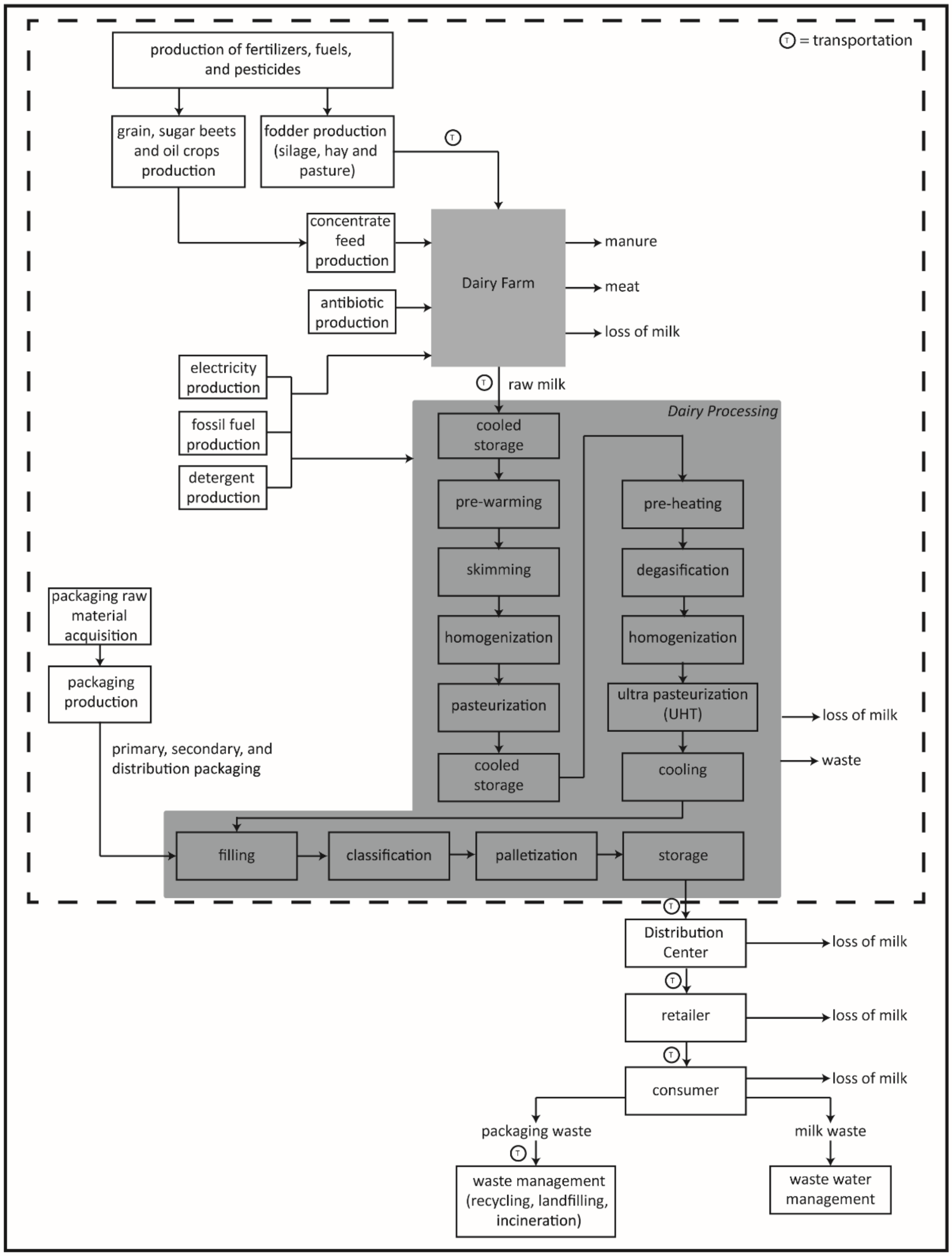

Figure 7: System boundaries and processes of the life cycle of fluid milk products

The dash line represents the cradle-to-gate boundary and the solid line represents the cradle-to-grave boundary. Adapted from González-García et al. [23] and Eide [24].

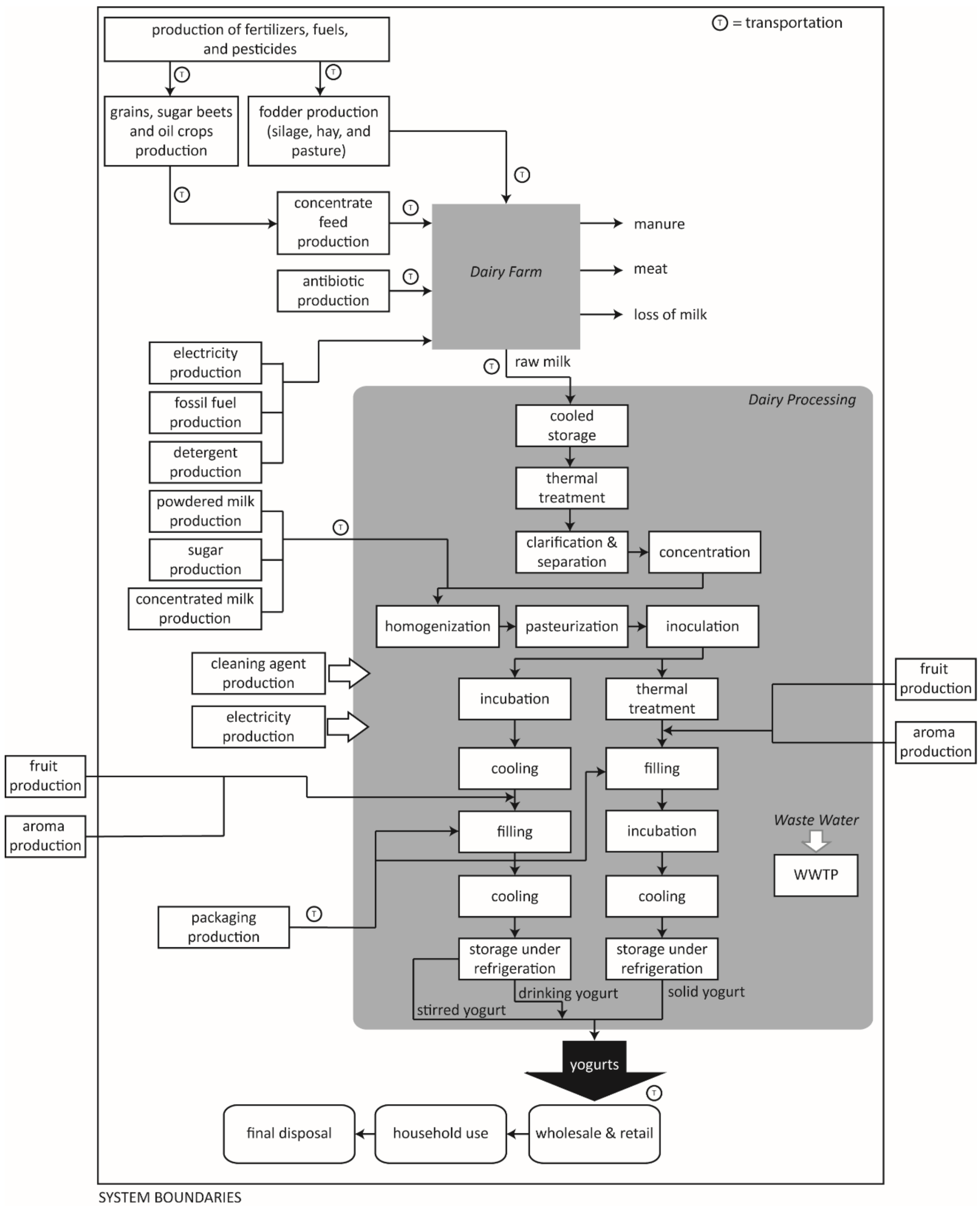

Figure 8: System boundaries and processes of the life cycle of yogurt products

Adapted from González-García et al. [26].

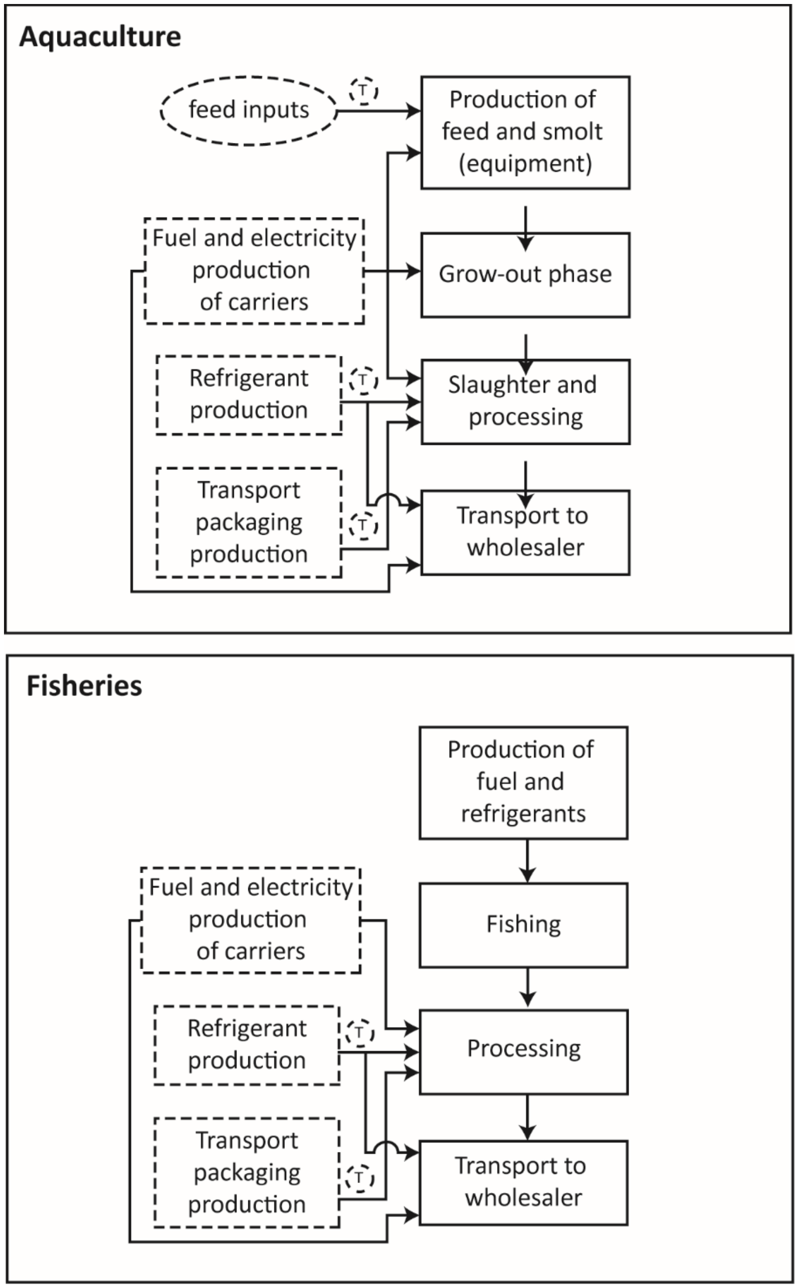

Figure 9: System boundaries and processes of fish products (aquaculture and fisheries)

Solid boxes are foreground processes and dashed boxes are background processes. Adapted from Winther et al. [30] and Pelletier and Tyedmers [31].

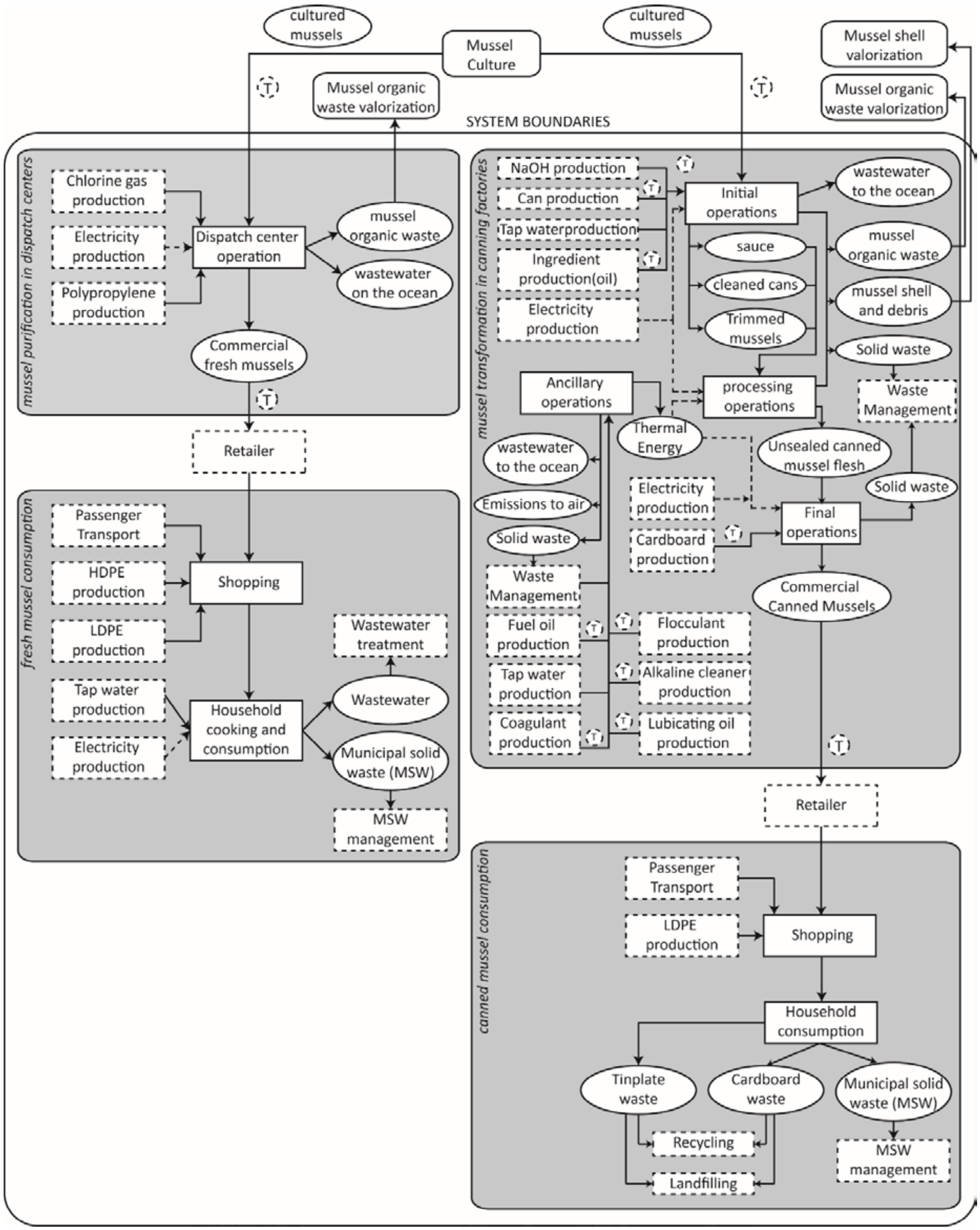

Figure 10: System boundaries and processes of fresh and canned mussel products

Solid boxes are foreground processes and dashed boxes are background processes. Adapted from Iribarren et al. [32].

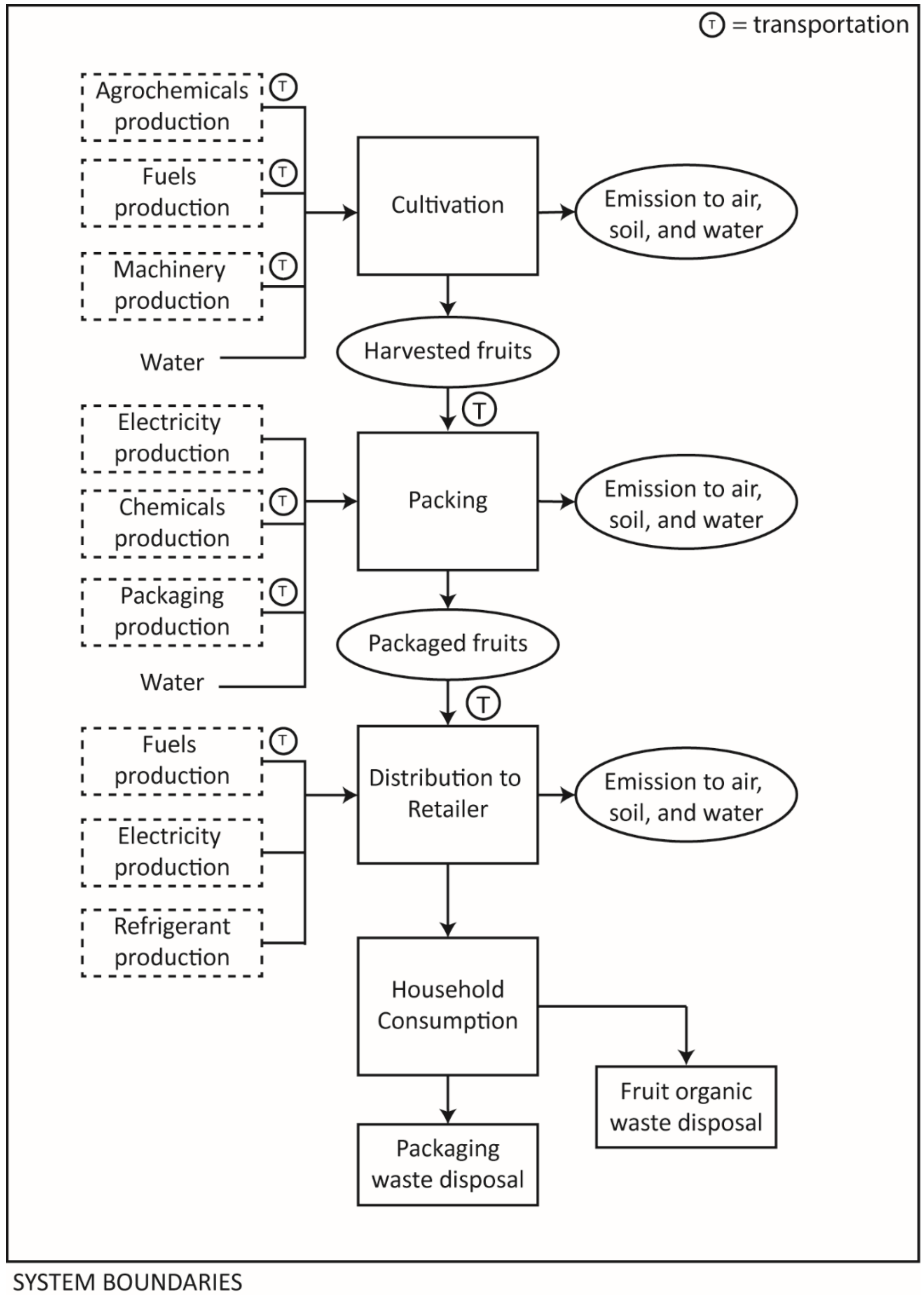

Figure 11: System boundaries and processes of fruits for fresh consumption

Adapted from Girgenti et al. [33] and Ingwersen [34].

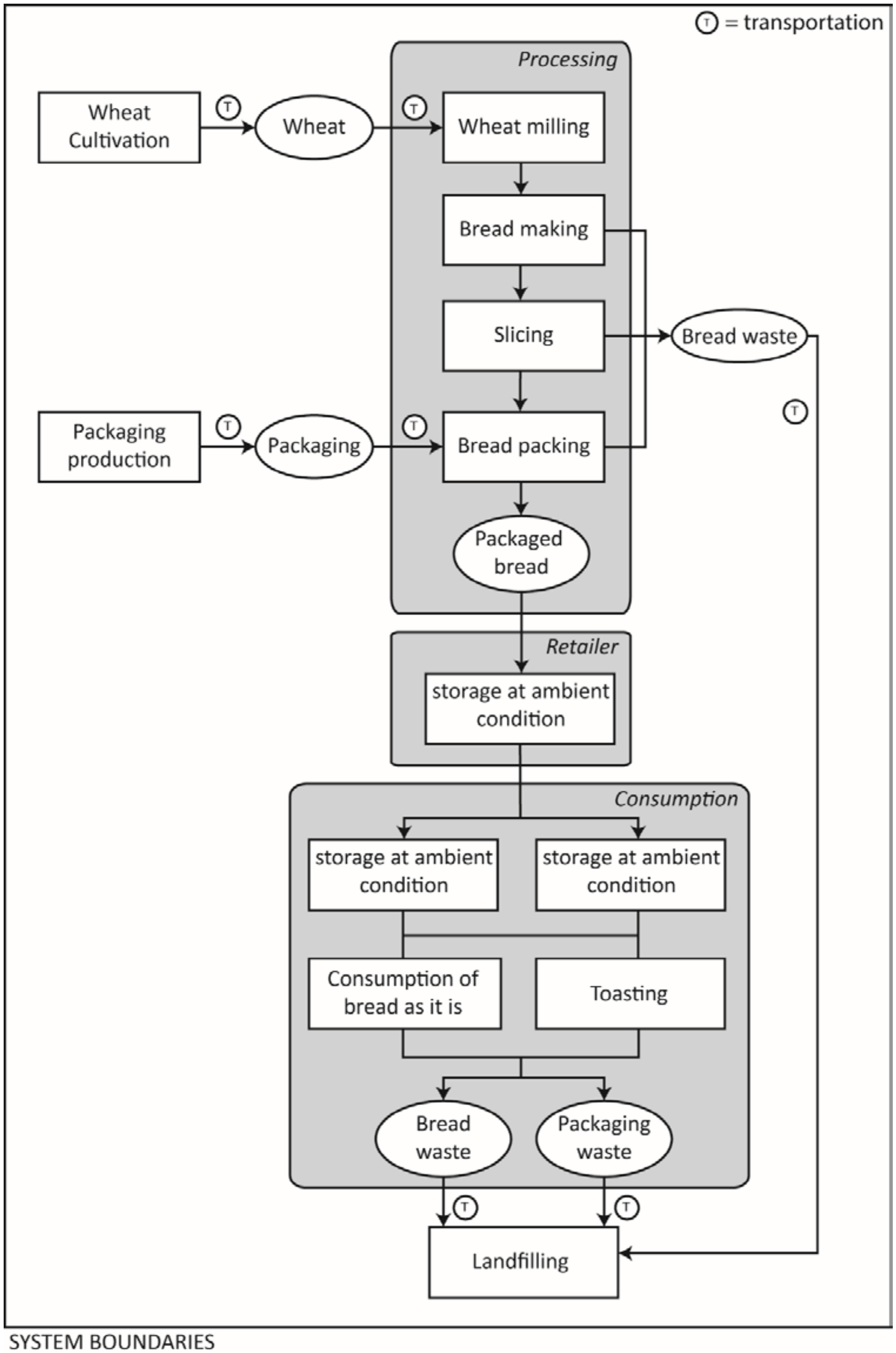

Figure 12: System boundaries and processes of bread

Adapted from Korsaeth et al. [37] and Espinoza-Orias et al. [38].

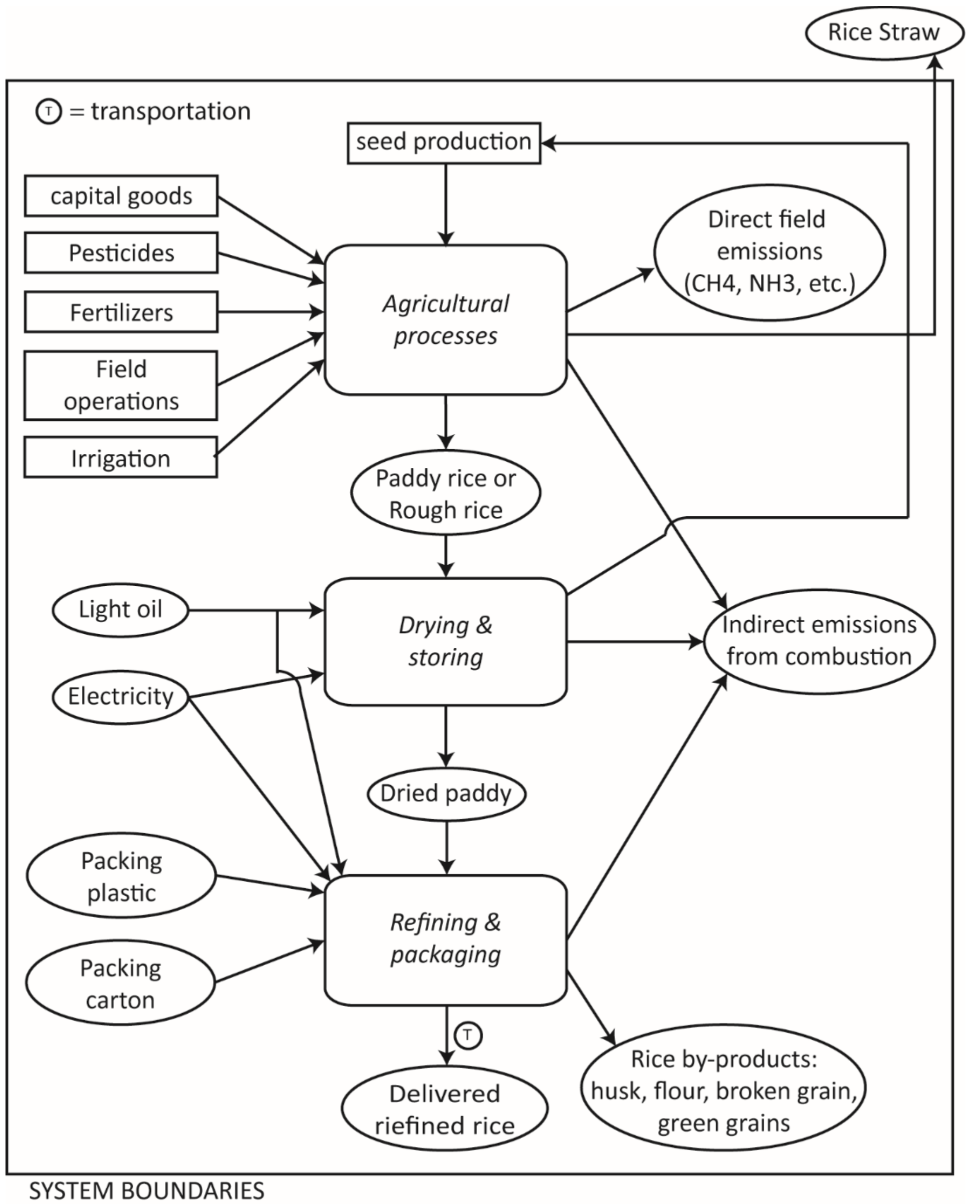

Figure 13: System boundaries and processes of rice product

Adapted from Blengini and Busto [39].

APPENDIX B: Impact categories included in the selected LCA studies

Table 6: Impact categories included in the selected LCA studies

Impact Category	***M1***	***M2***	***M3***	***Y1***	***Y2***	***Y3***	***Y4***	***F1***	***F2***	***F3***	***FR 1***	***FR 2***	***ME 1***	***ME 2***	***GR 1***	***GR 2***	***GR 3***
Abiotic depletion potential	x			x								x					
Acidification potential	x	x		x		x			x	x							x
Terrestrial acidification															x		
Eutrophication potential	x	x		x		x			x			x					x
Marine eutrophication potential			x												x		
Fresh water eutrophication potential			x												x		
Global warming potential	x	x	x	x		x			x		x	x		x	x	x	x
Greenhouse gas emission							x	x					x				
Ozone layer depletion potential	x	x		x		x				x		x					x
Photochemical oxidants formation potential	x	x	x	x						x							
Photochemical ozone creation potential																	x
Ecosystems: Damage to ecosystem diversity			x														
Land competition				x													
Soil erosion												x					
Emergy												x					

Table 6 (cont'd)

Impact Category	***M1***	***M2***	***M3***	***Y1***	***Y2***	***Y3***	***Y4***	***F1***	***F2***	***F3***	***FR 1***	***FR 2***	***ME 1***	***ME 2***	***GR 1***	***GR 2***	***GR 3***
Smog formation												x					
Human toxicity potential	x		x							x		x			x		
Fresh water aquatic ecotoxicity	x									x		x			x		
Marine aquatic ecotoxicity	x									x					x		
Terrestrial ecotoxicity	x									x					x		
Ecotoxicity potential		x	x														
Pesticides		x													x		
Antibiotics		x															
Water depletion potential		x	x									x		x			x
Total Energy		x						x									x
Cumulative non-renewable energy demand	x		x	x		x			x		x	x					x
Cumulative degree of perfection					x												
Cumulative energy consumption					x												
Cumulative exergy consumption					x												
Cumulative carbon dioxide emission					x												
Biotic resource use									x								

Table 6 (cont'd)

Impact Category	***M1***	***M2***	***M3***	***Y1***	***Y2***	***Y3***	***Y4***	***F1***	***F2***	***F3***	***FR 1***	***FR 2***	***ME 1***	***ME 2***	***GR 1***	***GR 2***	***GR 3***
Land use														x	x		
Fossil fuel depletion															x		

APPENDIX C: Impact conversion factors

Table 7: Impact conversion factors of the selected LCA studies

Study ID	Original Functional Unit	Impact conversion factor	Explanation
M1	1 kg of packaged energy-corrected milk (ECM)	1/1.319 = 0.758	1 kg of packaged ECM is equivalent to 1.319 kg of UHT milk
M2	1000 liters of drinking milk brought to the consumers	$1/1033 = 9.681\times10^{-3}$	1000 liters of drinking milk is equivalent to 1033 kg of drinking milk
M3	1000 kg of milk consumed	$1/1000 = 1.000\times10^{-3}$	
Y1	1000 kg of yoghurt	$1/1000 = 1.000\times10^{-3}$	
Y2	1000 kg of flavored yoghurt	$1/1000 = 1.000\times10^{-3}$	
Y3	1 kg of yoghurt	1	
Y4	1 kg of yoghurt	1	
F1	1 kg edible product at wholesale	1	
F2	1 ton of frozen packaged product	$1/1000 = 1.000\times10^{-3}$	
F3	1 kg of commercial product for consumption	1	
FR1	125 g of fruit	1000/125=8	
FR2	1 serving of fruit	6.06	49% of pineapple is non-edible, 0.51 fraction edible. 3.09 servings/kg fresh pineapple at retailer is equivalent to 3.09 servings/0.51 kg of edible fruit. Therefore, 1 kg of edible fruit is equivalent to $(1/0.51)\times3.09$ = 6.06 servings.
ME1	1 kg of food product	1	
ME2	1 kg of consumed product	1	
GR1	1 kg of bread	1	
GR2	800 g loaf of sliced bread	1000/800 = 1.25	
GR3	1 kg of refined rice	1	

APPENDIX D: Descriptive statistics of the impacts in the selected studies

Table 8: Global Warming Potential (GWP) of cradle-to-gate boundaries

Product	Study ID	N		Total Impact	Packaging	Process other than Packaging	% Packaging
Milk	M1	1	Value	1.3192	0.0650	1.2542	4.9275
	M3	18	Mean	1.8524	0.1860	1.6665	9.2320
			Std Dev	0.3203	0.1506	0.1884	5.5621
			Std Err	0.0755	0.0355	0.0444	1.3110
			Minimum	1.5664	0.0427	1.5212	2.7260
			Maximum	2.5606	0.5660	1.9946	22.1042
Yogurt	Y4	1	Value	1.7500	0.1768	1.5733	10.1000
Fish	F1	22	Mean	3.2377	0.1200	3.1177	4.6138
			Std Dev	2.5539	0.0535	2.5385	2.8388
			Std Err	0.5445	0.0114	0.5412	0.6052
			Minimum	0.9800	0.0300	0.8600	1.0101
			Maximum	13.8600	0.2100	13.7200	12.2449
	F2	1	Value	2.0400	0.0612	1.9788	3.0000
Fruit	FR2	1	Value	0.5454	0.1340	0.4114	24.5690
Meat	ME1	3	Mean	16.9667	0.0465	16.9201	0.4000
			Std Dev	9.6821	0.00670	9.6836	0.3464
			Std Err	5.5900	0.00387	5.5908	0.2000
			Minimum	6.3000	0.0388	6.2496	0.2000
			Maximum	25.2000	0.0504	25.1496	0.8000
	ME2	3	Mean	14.4000	0.4499	13.9501	3.4487
			Std Dev	5.5507	0.0777	5.5520	1.2903
			Std Err	3.2047	0.0449	3.2055	0.7449
			Minimum	8.9000	0.4045	8.4955	2.0270
			Maximum	20.0000	0.5396	19.5946	4.5455
Bread	GR1	1	Value	0.9370	0.0226	0.9144	2.4168
Rice	GR3	1	Value	2.8800	0.1354	2.7446	4.7000

Table 9: Global Warming Potential (GWP) of cradle-to-grave boundaries							
Product	**Study ID**	**N**		**Total Impact**	**Packaging**	**Process other than Packaging**	**% Packaging**
Milk	M2	3	Mean	0.5439	0.0149	0.5290	2.7193
			Std Dev	0.0465	0.00257	0.0440	0.2313
			Std Err	0.0269	0.00149	0.0254	0.1335
			Minimum	0.5127	0.0134	0.4993	2.5641
			Maximum	0.5974	0.0178	0.5796	2.9851
	M3	18	Mean	2.2297	0.2446	1.9851	10.3293
			Std Dev	0.2913	0.1691	0.1401	5.7348
			Std Err	0.0687	0.0399	0.0330	1.3517
			Minimum	1.9280	0.0476	1.8500	2.4234
			Maximum	2.8840	0.6405	2.2435	22.2087
Yogurt	Y1	1	Value	1.7760	0.1651	1.6109	9.2982
	Y2	1	Value	2.2733	0.3046	1.9687	13.3990
	Y3	1	Value	2.0000	0.2520	1.7480	12.6000
Fruit	FR1	2	Mean	0.4320	0.0965	0.3355	22.3100
			Std Dev	0.0113	0.0102	0.0012	1.7678
			Std Err	0.0080	0.0072	0.0008	1.2500
			Minimum	0.4240	0.0893	0.3347	21.0600
			Maximum	0.4400	0.1037	0.3363	23.5600
Bread	GR2	16	Mean	1.3537	0.0469	1.3068	3.5131
			Std Dev	0.0906	0.0258	0.1018	1.9712
			Std Err	0.0227	0.0065	0.0255	0.4928
			Minimum	1.2214	0.0186	1.1814	1.2397
			Maximum	1.5553	0.0786	1.5306	6.2222

Table 10: Energy Consumption (EC) of cradle-to-gate boundaries							
Product	**Study ID**	**N**		**Total Impact**	**Packaging**	**Process other than Packaging**	**% Packaging**
Milk	M1	1	Value	9.1433	1.1049	8.0384	12.0837
	M3	18	Mean	10.4967	3.5973	6.8993	29.5195
			Std Dev	4.0909	3.3057	0.9425	13.8018
			Std Err	0.9642	0.7792	0.2222	3.2531
			Minimum	6.8991	0.7560	6.1161	10.9579
			Maximum	19.9820	11.1630	8.9430	56.6876
Fish	F2	1	Value	26.4000	1.8480	24.5520	7.0000
Fruit	FR2	1	Value	6.0600	2.0113	4.0487	33.1897
Rice	GR3	1	Value	16.6400	3.7440	12.8960	22.5000

Table 11: Energy Consumption (EC) of cradle-to-grave boundaries							
Product	**Study ID**	**N**		**Total Impact**	**Packaging**	**Process other than Packaging**	**% Packaging**
Milk	M2	3	Mean	4.4530	0.6754	3.7777	16.0387
			Std Dev	1.4326	0.0225	1.4144	4.1142
			Std Err	0.8271	0.0130	0.8166	2.3753
			Minimum	3.4850	0.6529	2.8096	11.4433
			Maximum	6.0987	0.6979	5.4008	19.3798
	M3	18	Mean	13.9094	3.5925	10.3170	22.5203
			Std Dev	3.6621	3.3787	0.3864	13.6559
			Std Err	0.8632	0.7964	0.0911	3.2187
			Minimum	11.0130	0.7409	10.0288	6.7271
			Maximum	22.4420	11.1810	11.3860	50.0448
Yogurt	Y1	1	Value	17.1800	4.7742	12.4058	27.7895
	Y2	1	Value	31.6855	2.1754	29.5101	6.8656
Fruit	FR1	2	Mean	8.9680	2.7131	6.2549	30.2500
			Std Dev	0.0226	0.2288	0.2062	2.4749
			Std Err	0.0160	0.1618	0.1458	1.7500
			Minimum	8.9520	2.5513	6.1091	28.5000
			Maximum	8.9840	2.8749	6.4007	32.0000

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