From trash to treasure

Accounting for global unavoidable food loss and waste of vegetables and fruits and exploring valorisation strategies

MSc Industrial Ecology

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by

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Mona H. Delval
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Summary

Food loss and waste (FLW) generation is a global issue that has recently gained an increasing attention. It has previously been estimated that approximately one third of all food globally produced is wasted. Recently, other accounts have been made, for various food products and focusing on various geographical scopes, sometimes disaggregating between various qualities of FLW, but none was found to quantify FLW per quality at the global level. This would be a pertinent addition to the ongoing research, as the type of treatment (or valorisation) possible is dependent on the type of FLW, and this would be of great relevance in the global actions towards the achievement of the Sustainable Development Goal (SDG) 12.3 aiming at the reduction of food loss and food waste globally by halve by 2030. Additionally, recent literature focuses on avoidable FLW or does not separate between avoidable and unavoidable, although it is essential to address unavoidable FLW on its own as by its nature it cannot simply be prevented and its generation should thus be appropriately managed. Therefore, this thesis project aimed at answering how much food is currently being lost and wasted regarding fruits and vegetables at the global level and how it can be valorised. In the first part of the research, a Material Flow Analysis (MFA) was conducted at the global level to quantify unavoidable loss generated at the processing stage and unavoidable waste generated at the retail and consumption stages. The results show that the fruit value chain generates more unavoidable loss and waste than the vegetable value chain and that the retail and consumption stages generate more unavoidable waste than the processing stage of unavoidable loss. Additionally, regional hotspots were identified. In the second part of the research, an assessment of the valorisation pathways is conducted on the category of loss and waste streams identified as the most problematic by the MFA results, which was fruit and vegetable peel. The valorisation assessment was conducted following the concept of the FLW management hierarchy, which ranks the various end-of-life (EoL) treatments by prioritizing the most environmental-friendly and resource-efficient ones. In this study, the potential of fruit and vegetable peel loss and waste for reuse in food and feed, for the production of biobased materials, biofertilizers as well as biofuels was explored and quantified. The results suggest that an optimal FLW management system should be an adequate mix of various valorisation pathways. In regard to the SDG 12.3, efforts should aim on the one hand at preventing FLW that can be avoided and on the other hand at valorising FLW that cannot be avoided.

Keywords: food loss and waste, fruits, vegetables, accounting, valorisation, material flow analysis, waste management hierarchy.

Contents

Nomenclature

Abbreviations

Abbreviation	Definition
EoL	End-of-life
FAO	Food and Agriculture Organization of the United Nations
FLW	Food loss and waste
FVLW	Fruit and vegetable loss and waste
GHG	Greenhouse gas emissions
IC	Income countries
IE	Industrial ecology
K	Potassium
LW	Loss and waste
MFA	Material flow analysis
N	Nitrogen
P	Phosphorus
R&C stages	Retail and consumption stages
sRQ	Sub-research question
TCF	Technical conversion factors
CF	Conversion factors

Symbols

Symbol	Definition
CO_2	Carbon dioxide
CH_4	Methane
N_2O	Nitrous oxide

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Introduction

"Cutting food waste is a delicious way of saving money, helping to feed the world and protecting the planet."
Tristram Stuart, award-winning author, campaigner and expert on food waste.

1.1. Food loss and waste: a global issue

Past and current anthropogenic activities are putting a growing pressure on the Earth systems, resulting in long term and large scale impacts occurring at unprecedented rates (IPCC, 2021). Urgent actions are thus required to mitigate their consequences, globally and in all sectors, notably in the agriculture and food sector. The activities of the agro-food sector contribute to global warming (being responsible for 21%, 53% and 78% of global carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O) emissions respectively in 2019), the massive conversion of land (with 40% of land used for the cultivation of crops or for animal husbandry globally), the reduction of carbon storage in vegetation and soil, the disturbance of nutrient cycles due to the excessive use of fertilisers, the loss of biodiversity, the fragilization of ecosystems, and the generation of food loss and waste (FWL) (EEA, 2010; FAO, 2021; Willett et al., 2019).

The latter, FLW generation, is a global issue that has recently gained an increasing attention. In 2011, the Food and Agriculture Organization of the United Nations (FAO) has estimated global FLW to represent approximately one third of all food globally produced. The magnitude of the waste generated raises both environmental and social problems. Indeed, FLW are difficult to handle due to their important moisture content and biological instability, and an improper disposal leads to issues of surface and groundwater pollution (Nayak & Bhushan, 2019). It also represents a significant level of natural resource consumption, as FLW represents 25% of all water and 23% of all croplands used in agricultural practices (Kummu et al., 2012; Searchinger et al., 2019). Moreover, FLW contributes by 8% to the total global GHG emitted within a year (IPCC, 2022). Additionally, a large portion of food becoming lost or wasted can be avoided (Teigiserova et al., 2020) and could thus rather be consumed. In addition to the significant economic losses it causes (estimated at 1 trillion US dollars at the global level (FAO, 2019b)), this significantly contributes to the problem of nutrition security (Chen et al., 2020; Willett et al., 2019).

With a growing global population coupled with natural resources becoming increasingly restricted, the pressure on food systems will worsen in the coming years, unless profound and sustainable changes are implemented towards more sustainable consumption and production systems (Chen et al., 2020; Teigiserova et al., 2020). In the Sustainable Development Goals (SDGs) structured by the 2030 United Nations Agenda for Sustainable Development in 2015, the SDG 12.3 particularly targets FLW by stating: "by 2030, halve per capita global food waste at the retail and consumer levels and reduce food losses along production and supply chains, including post-harvest losses".

In industrial ecology (IE), the reduction of waste generation is a concern at the core of the field interests (Jelinski et al., 1992), and FLW represents an important outflow of our society that needs to be prevented or if not possible, repurposed. Moreover, the issue of FLW has environmental, social and economic repercussions, which thus require solutions of a multidisciplinary nature. This aligns with the multidisciplinary scope of IE. The goal of this thesis will thus be to contribute to the global effort of finding adapted solutions to the issue of FLW from an IE perspective.

1.2. State-of-the-art

In recent years, research on FLW has rapidly grown, and is articulated around two main aspects; on the one hand, the actual quantification of FLW generation, and on the other hand, the investigation of solutions to reduce FLW, notably via FLW valorisation and optimisation of food systems.

1.2.1. FLW accounting

FLW accounting is an essential first step towards the achievement of SDG 12.3. Indeed, it does not only provide the amount of the global food production becoming waste annually, but it also allows for identifying loss and waste hotspots along the food supply chain. This is important information for designing relevant interventions on the most important identified waste streams. Additionally, it is useful for monitoring the evolution of FLW generation over time and for tracking the progressive achievement of policy targets (Caldeira et al., 2019; Corrado & Sala, 2018).

In recent decades, many studies have been conducted on accounting for FLW; on various food products (Amicarelli, Rana, et al., 2021; Anastasiadis et al., 2020), and notably on fruits and vegetables specifically (De Laurentiis et al., 2018; Ismael, 2023), on all food products (Caldeira et al., 2019), or on losses of nutrients specifically (Chen et al., 2020), from a national scope (Beretta et al., 2013; Blas et al., 2018; Kashyap & Agarwal, 2020), a regional scope, such as Europe (Caldeira et al., 2019; Scherhaufer et al., 2018), or even a global scope (Chen et al., 2020; FAO, 2019b; Mayo-Bruinsma, 2014).

Literature also started to differentiate between avoidable and unavoidable FLW (Corrado et al., 2019; Omolayo et al., 2021; Teigiserova et al., 2020). The extent to which FLW can be avoided directly depends on whether it was originally edible material and later deteriorated or if it is naturally inedible (Monier et al., 2020; Papargyropoulou et al., 2014). What is originally edible can be avoided, whereas what is originally inedible cannot simply be prevented, but should rather be destined to other purposes (Teigiserova et al., 2020). Unavoidable FLW also englobes the parts of the food unavoidably discarded at the processing stage to obtain the processed products. Most of the research is still primarily focusing on the quantification of avoidable FLW (FAO, 2019b) or does not disaggregate between avoidable FLW and unavoidable FLW (Omolayo et al., 2021). There is currently no estimation on how much unavoidable FLW is being generated at the global level. At the national level, the first estimations mention that 20 to 35% of household food waste could be characterized as unavoidable (Salemdeeb et al., 2017; Schott & Andersson, 2015).

1.2.2. FLW valorisation

The other second main approach of research regarding FLW concerns the study of its valorisation. The aim is to optimise management of FLW to minimise its production along the food value chain and, if it cannot be prevented, to generate value from it, which can lead to new technologies and business opportunities (Boiteau & Pingali, 2023; Teigiserova et al., 2020), contributing to a circular bioeconomy.

One tool that has been used to provide guidance for waste management (and notably of FLW) is the waste management hierarchy. Represented as a pyramid (Figure 1.1), the various possible end-of-life (EoL) treatments are ordered from the most to the least favourable option, by prioritizing the most environmental-friendly ones and the most resource-efficient ones, and by also taking into account economic and health impacts and the quality of the waste (European Commission, 2008). The pyramid slightly varies across the literature (Moshtaghian et al., 2021), but it fundamentally recommends reduction, reuse and recycling over disposal (Van Ewijk & Stegemann, 2016).

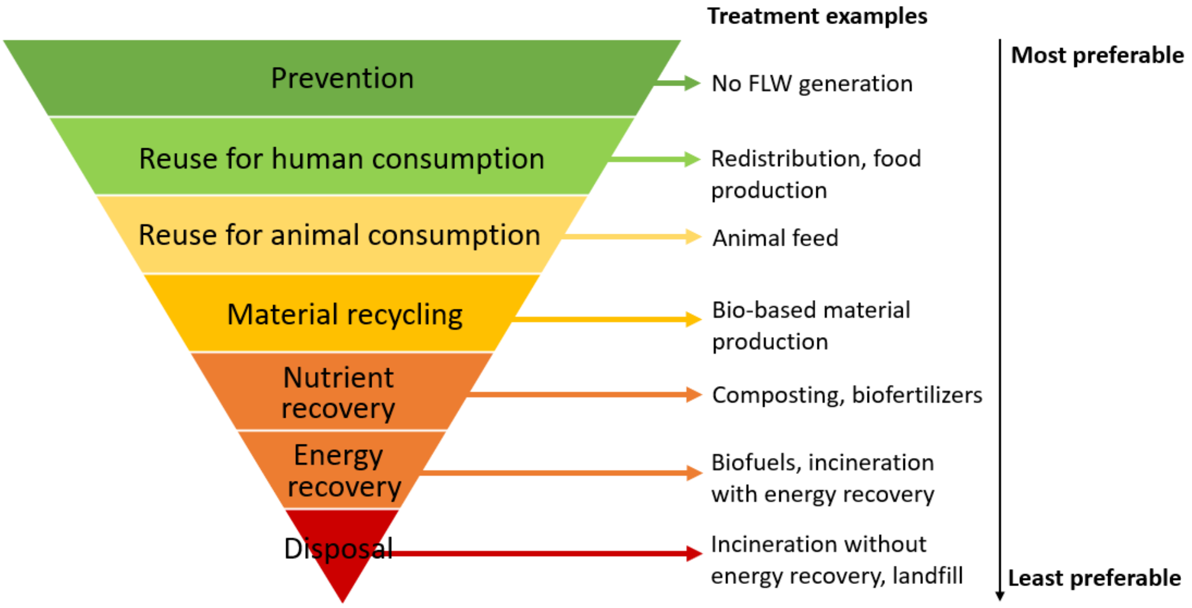

Figure 1.1: Food loss and waste (FLW) management hierarchy. Adapted from Teigiserova et al., 2020.

Prevention

Before even considering its valorisation, the most desirable option is clearly the prevention of the FLW generation (Imbert, 2017; Papargyropoulou et al., 2014). By definition, this is only possible for avoidable FLW. This includes a variety of actions throughout the food value chain, from better harvesting practices, an improved management of food stocks and greater care during transport, to better consumption behaviour (Garrone et al., 2017; Papargyropoulou et al., 2014).

Reuse for human consumption

Once the FLW has been generated, the second-best option comprises all the reuse activities. It includes redistribution organized by institutions, municipal authorities, the food sector itself such as discounts or donation of unsold food products from supermarkets or restaurants (Beretta & Hellweg, 2019; Eriksson et al., 2015), or citizen's initiatives, like food banks, shared refrigerators or food-sharing apps (Falcone & Imbert, 2017; Ferrari, 2016). Naturally, these actions only concern edible food that has been discarded but whose quality has not yet deteriorated (Priefer et al., 2016). Unavoidable FLW can rather be valorised as a source of extractable compounds that are then reused for food production (Dulo et al., 2022; Thani et al., 2019). Currently, this latter valorisation is hardly put into application due to health and safety precautions reflected in strict legal frameworks or, on the opposite, due to a lack of legislation allowing their use (Mateos-Aparicio & Matias, 2019). Reuse for human consumption should always be prioritized over reuse for animal consumption from an ethical point of view (Teigiserova et al., 2020).

Reuse for animal consumption

The consumption of animal-derived products is expected to grow in the future, further increasing the need for animal feed. Conventional sources of animal feed have become globally more expensive and area expansion for fodder production is limited by a growing human population and urbanization needs (Wadhwa & Bakshi, 2013). Hence, alternative sources are needed and explored (Esparza et al., 2020). Using FLW as animal feed does not represent a competition with human food production (Bakshi et al., 2016). Moreover, it represents a rich source of nutrients at a low cost (Wadhwa & Bakshi, 2013). Unavoidable food loss generated at the processing stage is already a commonly-accepted and used stream for animal feed production (Dou et al., 2018) and with a heat sterilizing treatment and the application of safety measures, food waste generated at the consumption stage can also be used as animal feed (Dou et al., 2018; Torok et al., 2021).

Material recycling

When the quality of the loss or waste stream does not allow fore the aforementioned options, recovery and recycling alternatives must be considered. Teigiserova et al. (2020) distinguish material recycling from nutrient recovery and energy recovery by stating that material recycling (or recovery) does not lead to complete degradation and to a loss of material value unlike the two latter. Hence, it is a preferable option, as it leads to obtaining higher value products (Imbert, 2017). As industries need to reduce their demand of fossil fuels and other petroleum derivatives, alternative sources such as FLW have gained interest for industrial purposes, such as the production of biobased materials (Cherubini, 2010). Material recycling typically concerns unavoidable FLW generated at the processing stage, which represents large amounts of homogeneous by-products (Teigiserova et al., 2019). Waste from household or food service is less suitable as, being generally a heterogenous mix, it is economically costly, time consuming and processing-intensive to extract high-value products from it, and thus unlikely to occur (Haldar et al., 2022; Teigiserova et al., 2020). In recent years, research on material recycling of unavoidable FLW has grown but most technologies are still at an early stage of research and currently mainly achieved at a lab or semi-industrial scale (Imbert, 2017).

Nutrient recovery

Mixed household waste that has already rotten or is unavoidable can preferably be nutritionally or energetically recovered, which in terms of GHG emissions have a comparable carbon footprint (Dou et al., 2018). Nutritional recovery is for instance composting, a valorization pathway already commonly applied (Esparza et al., 2020). Compost is obtained from the aerobic degradation of organic waste by microorganisms (Banks & Wang, 2006). It can then be used for manure or as biofertilizers that enriches the soil in nutrient and microbial diversity, improves water retention and thus reduces irrigation needs for the soil (Otles et al., 2015; Shilev et al., 2006). The biofertilizer global market is continuously growing, and production from FLW is increasingly gaining attention (Sharma et al., 2023).

Energy recovery

Energy recovery includes the production of renewable energy such as biofuels (Teigiserova et al., 2020), that are obtained from biomass and can be used as an alternative to fossil fuels in the transport sector and in heating and electricity generation. FLW represents an interesting source for a low carbon footprint and is not competing with food production (Antonopoulou et al., 2019; Esparza et al., 2020; Zhan et al., 2016). Biofuel production from FLW remains mainly achieved at a lab-scale, but interest is growing around this valorisation pathway (Zhan et al., 2016). Its production can be expected to increase in the coming years, notably to achieve the ambitious sustainable targets regarding biofuel production (from only 3.6% of the global energy for the transport sector in 2021 up to 15% by 2030 in the Net Zero Scenario) (IEA, 2022).

Incineration is another form of energy recovery (Teigiserova et al., 2020). Due to its high moisture content and heterogeneity, household food waste often ends up being incinerated (Zhu et al., 2023). This is one of the least desirable options in the FLW management hierarchy, as it can lead to important environmental hazards, such as atmospheric air pollution (although modern design of incineration plants only results in very low emissions) and toxic compound accumulation (Kajiwara et al., 2017). Preferably, the heat generated during the combustion can be partially preserved and valorised, either for power generation or reused in the process of incineration. In any case, it is a preferred EoL treatment to immediate landfill, as the FLW is significantly reduced when incinerated (Hanson et al., 2016; Zhu et al., 2023). The resulting solid residue (ash) is then generally landfilled but uses less volume (Esparza et al., 2020).

Disposal

At last, when no valorisation is possible, disposal practices are used to manage FLW. It is not desirable, and should be avoided whenever possible. It is the third most important source of anthropogenic methane emissions (Breeze, 2018). Leachate formation is also a common issue with landfill sites, a mixture of rainwater and waste moisture that accumulates heavy metals and needs to be purified in appropriate facilities to avoid contamination of water sources (Bhatt et al., 2017; Moody & Townsend, 2017).

The type of treatment is dependent on the type of waste feedstock. Knowing the amount of the various types of FLW generated can thus be a valuable information in the elaboration of valorisation pathways. Research has already been conducted at the national level on quantifying the amount of FLW generated and on identifying potential valorisation pathways by quantifying the amount of various compounds recoverable from FLW (Amicarelli, Bux, et al., 2021; Amicarelli, Rana, et al., 2021; Dulo et al., 2022). However, no study was found to have done such an evaluation at the global level.

1.3. Research approach

1.3.1. Scope

FAO (2011, 2019b) estimates that the efforts on reducing FLW should be focusing on what is avoidable. Nevertheless, it is important to address avoidable FLW and unavoidable FLW separately, as they cannot be managed the same way (Ishangulyyev et al., 2019). Furthermore, it is essential to address unavoidable FLW, as by its nature it cannot simply be prevented and their generation should thus be appropriately managed. Even more, they can represent opportunities for new and innovative valorisation pathways.

Additionally, the scope of this report is limited to the FLW generated by one food commodity group: fruits and vegetables. Although FLW is generated across all commodity groups, fruits and vegetables have a higher contribution to the total global FLW in terms of mass (37%) compared to cereals (24%), dairy (7%) and meat and fish (6%) (Chen et al., 2020). Meat becomes the largest contributor when contribution is quantified in terms of GHG emissions (57%) (Chen et al., 2020), however the choice is made here to focus on the amount of FLW generated in mass as a unit of measurement. Additionally, 45% to 55% of the initial production of fruits and vegetables becomes FLW in almost all regions of the world. For cereals, these percentages fall to 35% to 20% and for meat it is under 30% in all geographic regions (FAO, 2011). Considering these estimations, it is particularly important to reduce FLW generated in the food value chain of the fruit and vegetable commodity group.

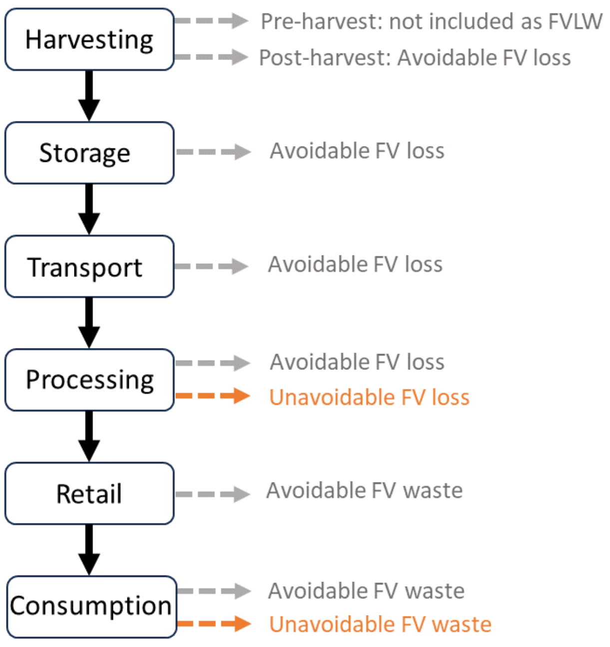

Figure 1.2: Fruit and vegetable (FV) supply chain and the consequent avoidable and unavoidable fruit and vegetable loss and waste (FVLW) generated. Black arrow = food flow; dashed orange arrow= FVLW quantified in the report; dashed grey arrow = FVLW not quantified in the report.

1.3.2. Research question

The aim of this thesis is twofold: first quantifying unavoidable FVLW as generated throughout the fruit and vegetable value chain, and second exploring potential valorisation pathways for unavoidable FVLW. A global perspective is aligned with recent literature which has asked for the adoption of more standardised and harmonised methods that would consider the food system as a whole (Corrado et al., 2019; M. Ju et al., 2017; Teigiserova et al., 2020).

Considering the aforementioned information, the following two research questions can be formulated:

1. ***How much unavoidable fruit and vegetable loss and waste (FVLW) is currently being generated at the global level ?***
2. ***How can unavoidable FVLW be valorised ?***

To answer these research questions, the research is further structured into sub-research questions (sRQs). For the FVLW quantification part of the research, it is relevant to analyse the fruit and vegetable value chain and to quantify the consequent unavoidable FVLW per world region. This allows to compare unavoidable FVLW generation across world regions and hence to identify geographical hotspots of global unavoidable FVLW. The following sRQ can thus be formulated:

1. *How much unavoidable FVLW is generated per world region ?*

Additionally, a better understanding of global unavoidable FVLW is given when it is not only expressed in terms of mass but also as a percentage of the global fruit and vegetable production. This allows to better grasp the magnitude of what is being globally lost and wasted. This leads to the following sRQ:

2. *How much of the global production of fruits and vegetables do unavoidable loss and unavoidable waste represent respectively ?*

As the type of valorisation treatment is dependent on the type of waste feedstock, each unavoidable FVLW stream quantified can be classified according to its nature (peel, seed, etc.) to assess what types of FVLW stream are generated and in which amounts. This leads to the following two SRQs:

3. *How much of each FVLW stream is generated globally ?*
4. *What is the largest FVLW stream ?*

For the FVLW valorisation part of the research, the FLW management hierarchy was shown to be a relevant tool to use, showing which valorisation pathways to prioritize depending on the waste feedstock. This leads to the following sRQ:

5. *How can the calculated FVLW be valorised following the FLW management hierarchy ?*

Lastly, unavoidable FVLW streams do not all have the same valorisation potential. To improve FVLW valorisation and to allow the allocation of financial, technical and time resources in the most optimal manner, it is relevant to determine which unavoidable FVLW streams have the highest potential for each valorisation pathway and should thus be prioritized, leading to the following sRQ:

6. *Which FVLW streams show the highest valorisation potential ?*

2
Method

2.1. Definitions

The terms related to FLW used in this report are defined in Table 2.1. The literature distinguishes food loss from food waste (FAO, 2019b). The definitions of food loss and food waste are in accordance with the phrasing of the SDG 12.3. Cultural edibility, nutritional edibility, unavoidable food loss and unavoidable food waste are the own definitions of the author of this report.

Avoidable FLW is generated at each stage of the food value chain, but unavoidable FLW is only generated at the processing and consumption stages. Indeed, unavoidable FLW is generated when food originally inedible is discarded, or when food is discarded as a consequence of processing food. Since pre-harvest loss is not included in the definition of food loss (Table 2.1), unavoidable food loss is only generated at the processing stage, where food goes through various transformation steps, such as drying, dehusking or deshelling steps (FAO, 2019b), with some parts unavoidably discarded to obtain the processed food products. In this report, the amount of food discarded during processing that could be saved with optimized processing technologies is not considered as avoidable.

Unavoidable food waste refers to food discarded by the end-consumer because perceived as inedible, following the definition of cultural edibility (Table 2.1). Note that this perceived edibility is about the original nature of the food, and does not include food that the end-consumer originally perceived as edible and once it has rotten becomes inedible. Furthermore, whereas food waste concerns both the retail and the consumption stages (FAO, 2019b), unavoidable food waste is generated by the end-consumer, thus only at the consumption stage.

Table 2.1: Terms used in this thesis report.

	Definition	Example
Food loss	Post-harvest decrease in the mass of food grown for human consumption, excluding retail and consumption stages (FAO, 2019b)	Mature crops left unharvested
Food waste	Decrease in the mass of food grown for human consumption at retail and consumption stages (FAO, 2019b)	Good food products discarded due to poor consumer behaviour
Cultural edibility	Food that is eaten (or not) by the end-consumer because culturally perceived as edible (or inedible)	Chicken feet are culturally edible in Asia but not in Europe
Nutritional edibility	Food that is actually edible (or inedible) for humans, based on its digestibility and nutritional value	Chicken feet are nutritionally edible
Unavoidable food loss	Food loss generated at the processing stage as a consequence of the production of processed food products	Olive pits from olive oil production, orange peels from orange juice production
Unavoidable food waste	Food waste generated as a consequence of cultural edibility	Cherry pits, banana peels, chicken feet in Europe

2.2. Data collection

The data needed for the unavoidable FVLW quantification part of the research can be divided into three groups: the data need for the database on fruit and vegetable parts (Section 2.2.1), the data need for the calculations of unavoidable fruit and vegetable loss (Section 2.2.2), and lastly the data need for the calculations of unavoidable fruit and vegetable waste (Section 2.2.3). The data need for the part of the research on FVLW valorisation is explained in Section 2.2.4.

2.2.1. Data collection for the database on fruit and vegetable parts

The database on fruit and vegetable parts had to contain the following information: the categories of fruits and vegetables covered in the study and the percentage for each parts composing fruits and vegetables.

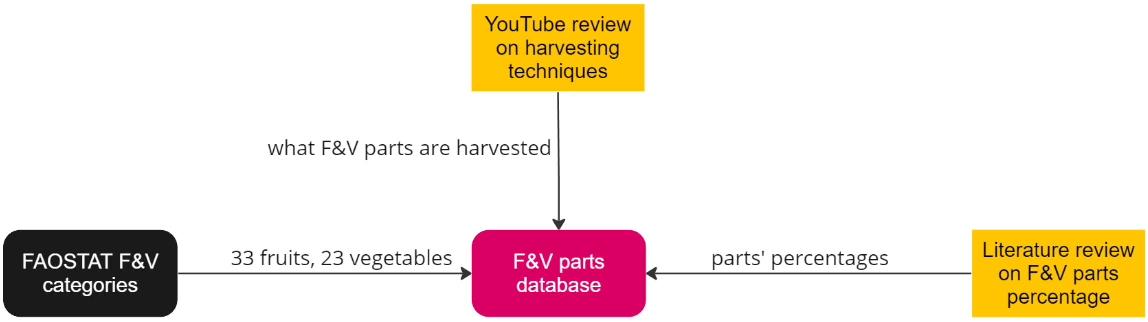

Figure 2.1: Part I of the FVLW quantification: Creation of the fruit and vegetable parts database. Sources of the references for the weight and parts' percentages can be found in Appendix A.

Fruits and vegetables

This report follows the commodity groups as defined by the FAOSTAT. In FAOSTAT, the fruit primary category covers 33 fruits (excluding six categories called "other fruits") and the vegetable primary category 23 vegetables (excluding two categories called "other vegetables"), which are listed in Table 2.3.

Parts of fruits and vegetables

An inventory was made of the various parts composing the fruits and the vegetables respectively as well as the percentage they represent in the fruit or the vegetable. As the FAOSTAT data only accounts for the production actually harvested, it excludes pre-harvest loss. These losses are left on the harvest site. Only food parts that leave the harvest site was considered in the inventory. This was determined by reviewing current harvesting techniques for all fruits and vegetables included in the study. For most food items, flowers, leaves, stems, branches and roots are not harvested or are immediately discarded on the harvest site and were thus not taken into account. This is also in accordance with Dulo et al. (2022), who performed a similar study on three food products. The composition in parts of each fruit and vegetable and the percentages these parts represent of the whole fruit or vegetable was found in the literature and if not possible, based on personal assumptions. All the sources and assumptions can be found in Appendix A.

For simplicity, peel, skin and rind are three words encountered in the literature to designate similar structures and were thus all grouped under the term peel. Similarly, stem, peduncle, and stalk were all grouped under the term stem. Seed and kernel were both grouped under the term seed, and pit shell (also called sometimes the stone) is what encloses the seed in some fruits, for example apricot (hence, the outside layer is the pit, and inside is the seed). Flesh was divided in juice and pomace components, with pomace (or bagasse, marc, press-cake) being further divided in pulp, peel and seed (Table 2.2).

Table 2.2: Names of parts used in this report. In parenthesis are other names used in the literature for the same part.

Fruit parts	Vegetables parts
juice, pulp, peel (skin, rind), seed (kernel), stem (peduncle, stalk), core, calyx, pit shell (stone), husk, crown	juice, pulp, peel (skin, rind), seed (kernel), stem (peduncle, stalk), core, calyx, leaf (outer leaf, inner leaf), choke, tip, root, bulb, cap, pea, pod

The edibility of these parts was also noted. As discussed in Section 2.1, this report uses the definitions of edibility both from a nutritional perspective and from a cultural perspective. The latter was based on what the author of this report eats, who is a French woman living in the Netherlands without any specific health and diet condition. However, cultural edibility varies across cultures and individuals (Teigiserova et al., 2020). The status on the cultural and nutritional edibility of all parts can be found in the Supplementary Information. References can be found in Appendix A for parts generally not eaten although showed to be nutritionally edible in the literature.

Table 2.3: Fruit and vegetable categories from the FAOSTAT and studied in this report.

Fruits	Vegetables
Apples	Artichokes
Apricots	Asparagus
Avocados	Broad beans and horse beans, green
Bananas	Cabbages
Blueberries	Carrots and turnips
Cantaloupes and other melons	Cassava leaves
Cashewapples	Cauliflowers and broccoli
Cherries	Chillies and peppers, green (Capsicum and Pimenta spp.)
Cranberries	Cucumbers and gherkins
Currants	Eggplants (aubergines)
Dates	Green corns (maize)
Figs	Green garlic
Gooseberries	Leeks and other alliaceous vegetables
Grapes	Lettuce and chicory
Kiwi fruits	Mushrooms and truffles
Lemons and limes	Okras
Locust beans (carobs)	Onions and shallots, dry (excluding dehydrated)
Mangoes, guavas and mangosteens	Onions and shallots, green
Oranges	Peas, green
Papayas	Pumpkins, squashes and gourds
Peaches and nectarines	Spinach
Pears	String beans
Persimmons	Tomatoes
Pineapples	
Plantains and cooking bananas	
Plums and sloes	
Pomelos and grapefruits	
Quinces	
Raspberries	
Sour cherries	
Strawberries	
Tangerines, mandarins, clementines	
Watermelons	

2.2.2. Data collection for unavoidable fruit and vegetable loss' modelling

Since the focus is on unavoidable FVLW, only information on the processing stage needed to be collected for unavoidable fruit and vegetable loss. The processed quantities were downloaded from the supply utilisation accounts of FAOSTAT, for each fruit and vegetable and for all countries. The processed quantity of a commodity is the quantity of the commodity from the total domestic supply of a country that is used for all processed products produced in the country from that commodity, knowing that domestic supply of a country is calculated as follows in FAOSTAT (Gustavsson et al., 2013):

$$\textit{Domestic Supply (t)} = \textit{Production (t)} + \textit{Import (t)} - \textit{Export (t)} - \textit{Stock Variation (t)} \tag{2.1}$$

The data is from 2020, the most recent year for which data is available. The production quantities for each processed product for each fruit and vegetable in 2020 was also downloaded from FAOSTAT for all countries. Last, technical conversion factors (TCFs), which are the coefficients expressing how much of the fruit or the vegetable is necessary to obtain 1 unit of the processed product, were kindly provided by A. Coudard. These TCFs were calculated for the year 2019, and it was assumed here that they were also valid for data from 2020.

2.2.3. Data collection for unavoidable fruit and vegetable waste's modelling

For unavoidable fruit and vegetable waste, information on the consumption stage needed to be collected. Quantities of fruits and vegetables consumed per country was collected from FAOSTAT (named 'Food' on the website) in the supply utilization accounts. The most recent data available was downloaded, which is from 2020. 'Food', which is the food available as fresh to the end-consumer, is calculated as follows in FAOSTAT (Gustavsson et al., 2013):

$$\textit{Food (t)} = \textit{Domestic Supply (t)} - \textit{Processed Commodity (t)} - \textit{Feed (t)} - \textit{Seed (t)} \tag{2.2}$$

However, the data from FAOSTAT does not disaggregate between the retail and the consumption (R&C) stages. Indeed, the FAO specifies that the data refers to "the quantities of food available for human consumption at the retail level by the country's resident population". This means that unavoidable fruit and vegetable waste had to be calculated from the consumption stage as well as the retail stage in this report.

2.2.4. Data collection for unavoidable fruit and vegetable valorisation

As explained previously, it is impossible to prevent the generation of unavoidable FVLW, hence excluding the first level of the waste management hierarchy. Hence, possibility of valorisation was quantified for the next five levels of the waste hierarchy: reuse for human consumption, reuse for animal consumption, material recycling, nutrient recovery and energy recovery.

For each stream of loss and waste (LW) studied for the valorisation assessment, the dry matter content and the extraction yields of the compounds of interest for material recycling were gathered in the recent literature. Extraction yield values were taken whenever possible instead of total content percentage values to reflect the current feasibility of the recovery and the valorisation of compounds rather than the total possible recovery with a future improved technology. When no extraction yield could be found, the total content percentage value was taken. Additionally, the total content percentage values of the compounds of interest for reuse for human and animal consumption and nutrient recovery were gathered in the recent literature. Lastly, the production yields of the biofuels of interest for energy recovery were gathered from the recent literature. The same conversion factors as in Dulo et al. (2022) were taken for the bioenergy potential of biofuels. When the literature was giving a range of values, the average was taken. All the references can be found in Appendix B.

2.3. MFA modelling

Material Flow Analysis (MFA) is a method that allows for the quantification of the material flows and stocks in a defined system, and is one of the core methodologies in the IE field (Brunner & Rechberger, 2016). Applied to the context of the agro-food industry, MFA allows for the accounting of FLW produced at each stage by modelling the food value chain, and thus allows for the identification of loss and waste hotspots. This has already been made in scientific research, notably at the European level (Caldeira et al., 2019), or at the national level (Amicarelli, Rana, et al., 2021; Beretta et al., 2013; Garcia-Herrero et al., 2018; M. Ju et al., 2017). Current MFAs focused on assessing the amount of FLW generated as a whole, but only a few distinguished the waste generated according to their quality (Amicarelli, Bux, et al., 2021; Bux & Amicarelli, 2022; Dulo et al., 2022) and none addressed this at a global level. Python was used to model the MFA and the code can be found in the Supplementary Information.

2.3.1. Calculations of fruit and vegetable loss generated during processing

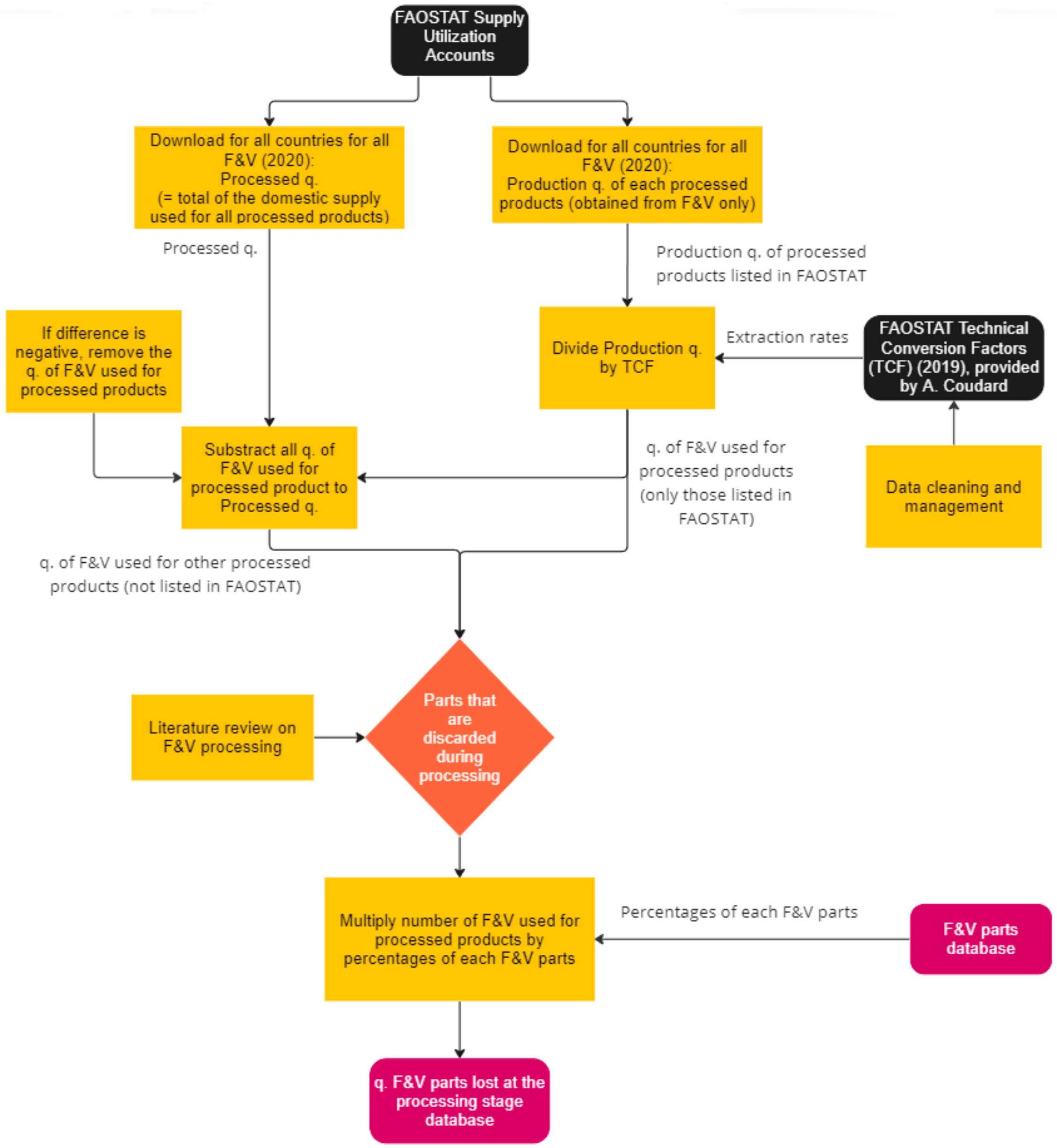

Figure 2.2: Part II of the FVLW quantification: Calculation of unavoidable fruit and vegetable loss. (q. = quantity)

The production quantities of all processed products from fruits and vegetables were divided by the TCFs to determine the quantities of fruits or vegetables used to obtain these production quantities. The obtained mass was then substracted from the total processed quantities data from FAOSTAT. What remained from the processed quantities are all the fruits and vegetables that were also used to obtained processed products but from which FAOSTAT does not have the production quantities, or from which no TCF could be found. In some cases, it can also be that the processed product is obtained from more than one type of fruit or vegetable.

The processed items for which there is data on FAOSTAT and for which data on extraction rates could be found were aggregated into categories. The categories for processed fruits and the fruit parts discarded to obtain them are summarized in Table 2.4 and the ones for processed vegetables in Table 2.5.

Table 2.4: Processed fruit categories.

Fruit, dried	The moisture of the food is removed by evaporation (Zepp et al., 2023) and the juice hence discarded cannot be considered as a waste. The peel is usually rinsed but not necessarily peeled if edible (Zepp et al., 2023). In our case, it was considered to be kept if edible. Stem, husk, calyx, seed (if inedible) and pit shell are also removed from the fruit in the process (Kendall & Sofos, 2023) and were considered as waste. The exception was the date, for which the seed is usually left in the dried fruit, although generally not eaten by the end-consumer (following our assumption on cultural edibility, using the diet of the author of this report). The lemon and orange peels are also left in the dried fruit, although generally not eaten by the end-consumer. For the pineapple, the core and crown are removed.
Fruit, juice or juice concentrated	Although fresh juice and juice concentrate vary in the amount of original food needed, in their steps and in their components (the latter having had its water components evaporated until reaching a certain level of concentration before being reincorporated with possible additives (A. K. Singh et al., 2012)), their process results in similar discarded waste. Steps can vary for the preparation of juice or juice concentrate. Here, I follow the generalized juice flow scheme represented by the FAO in Hingston and Noseworthy (2001), where the fruit is peeled, cored and deseeded. Basically, only juice and pulp are kept. Although centrifugation might be used to discard the pulp from the juice (Rabenhorst, n.d.), many juices are now commercialized with pulp, and even if removed, fruit pulp is also a commercialized product that is thus not considered to be lost during processing.
Fruit, pulp	This is the most basic processed product, where all the parts of the fruit are discarded except its pulp and its juice (de Farias Silva & de Souza Abud, 2017).
Alcohol	The maceration releases the juice which is then naturally fermented. The by-products are skins and seeds (Maroun et al., 2017). Inedible parts are also discarded.
Fruit, otherwise prepared or preserved	All the remaining processed products that do not fall in the aforementioned categories are grouped in 'otherwise prepared or preserved'. For this category, it was assumed that only inedible parts were discarded.

Table 2.5: Processed vegetable categories.

Vegetable, dried	All inedible parts are generally removed (Herringshaw & Hill, 2015).
Vegetable, juice	A similar process to fruit is followed, with sorting of edible from inedible parts and possible peeling (Toushik et al., 2017).
Vegetable, peeled	It was considered that inedible parts and peel were removed.
Vegetable, canned	The inedible parts of the vegetables are discarded before being canned. The vegetables can also be heated before being put in a jar but that is optional; in any case, the potential water loss is not considered as a food loss (Treadaway & Crayton, 2019).
Vegetable, paste	The water content of the vegetable is reduced and the peel and seeds are discarded to obtain concentrated pulp (A. K. Singh et al., 2012). The water evaporated is not considered a waste.
Vegetable, otherwise prepared or preserved	All the remaining processed products that do not fall in the aforementioned categories are grouped in 'otherwise prepared or preserved'. For this category, it was assumed that only inedible parts were discarded.

Using the database on fruit and vegetable parts, specifically information on their percentages , it was calculated how much of each fruit and vegetable parts are discarded during the processing stage.

2.3.2. Calculations of fruit and vegetable waste generated during consumption

FAOSTAT data on food availability to end-consumers was merged with the database on fruit and vegetable parts to obtain the quantity available to end-consumers for each part. Then, a database with only parts that are considered culturally inedible (and thus are unavoidable waste) was obtained.

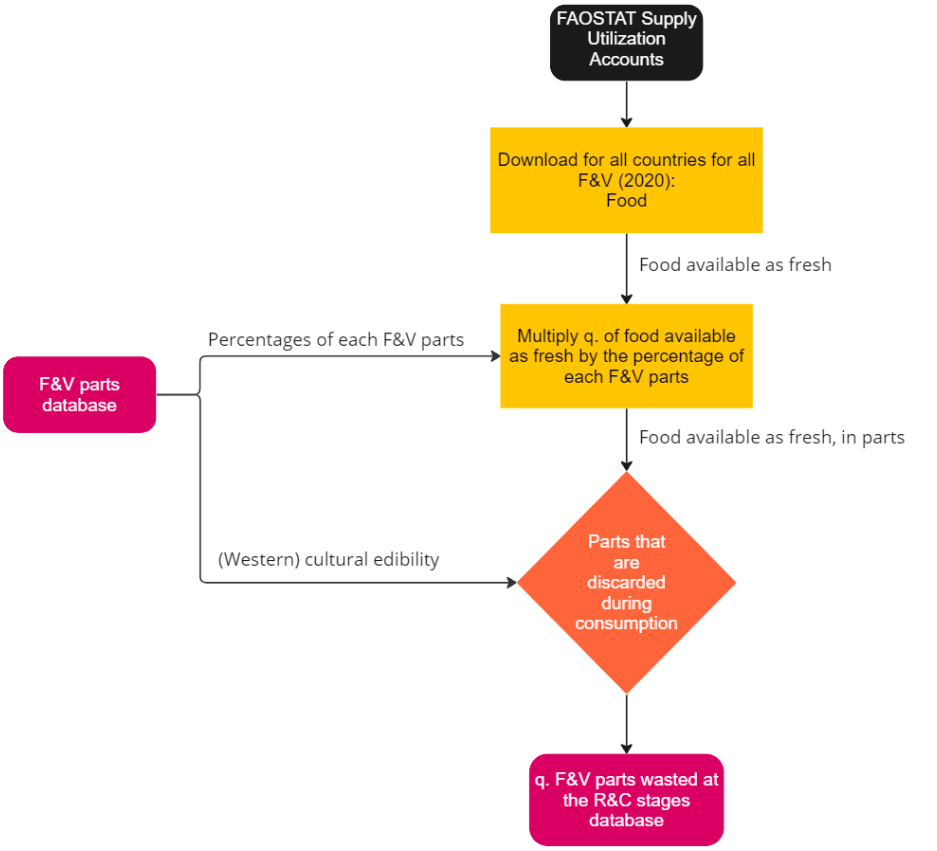

Figure 2.3: Part III of the FVLW quantification: Calculation of unavoidable fruit and vegetable waste. (q. = quantity)

2.3.3. Aggregation of results into world regions and categories of parts

The MFA results regarding unavoidable fruit and vegetable loss as well as waste were aggregated into world regions (Table 2.6). These regions were determined firstly geographically and secondly taking into account the level of income of countries, as the literature mentions differences in FLW generation pattern between developed and developing countries (FAO, 2011; Iordachescu et al., 2019; Kitinoja et al., 2010; Porat et al., 2018).

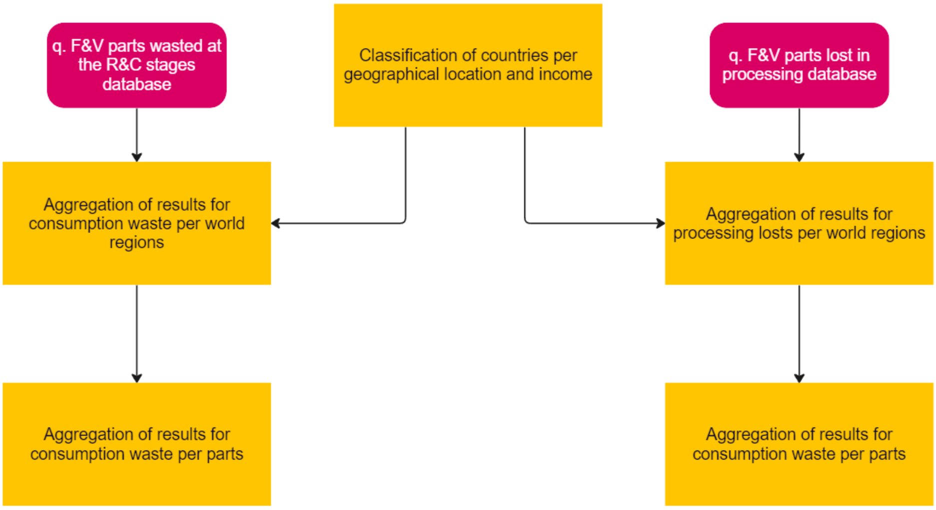

Figure 2.4: Part IV of the FVLW quantification: Data management by aggregating the MFA results into world regions and categories of waste streams.

The level of income and the number of inhabitants for each country (information used to obtained results per capita) can be found in the Supplementary Information.

Additionally, the MFA results for fruits were also grouped according to main categories of LW streams. For fruits, the categories are peel, seed, stem, core, calyx, pit shell, husk and crown. For vegetables, the categories are peel, seed, stem, core, calyx, leaf, choke, tip and root.

Table 2.6: Regional divisions of countries used in this report.

Europe	Albania, Austria, Belarus, Belgium, Bosnia and Herzegovina, Bulgaria, Croatia, Cyprus, Czechia, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Iceland, Ireland, Italy, Latvia, Lithuania, Luxembourg, Malta, Montenegro, Netherlands, North Macedonia, Norway, Poland, Portugal, Republic of Moldolva, Romania, Russian Federation, Serbia, Slovakia, Slovenia, Spain, Sweden, Switzerland, Ukraine, United Kingdom of Great Britain and Northern Ireland
North America	Canada, United States of America
Industrialised Asia	China, Japan, Republic of Korea, Singapore
Latin America	Antigua and Barbuda, Argentina, Bahamas, Barbados, Belize, Bolivia, Brazil, Chile, Colombia, Costa Rica, Cuba, Dominica, Dominican Republic, Ecuador, El Salvador, Grenada, Guatemala, Guyana, Haiti, Honduras, Jamaica, Mexico, Nicaragua, Panama, Paraguay, Peru, Puerto Rico, Saint Kitts and Nevis, Saint Lucia, Saint Vincent and the Grenadines, Suriname, Trinidad and Tobago, Uruguay, Venezuela
Oceania (high income countries)	Australia, New Caledonia, New Zealand, French Polynesia, Nauru
Oceania (low and middle income countries)	Fiji, Kiribati, Micronesia, Papua New Guinea, Samoa, Solomon Islands, Tonga, Tuvalu, Vanuatu, Cook Islands, Niue, Tokelau
Sub-Saharan Africa	Angola, Benin, Botswana, Burkina Faso, Burundi, Cabo Verde, Cameroon, Central African Republic, Chad, Comoros, Congo, Côte d'Ivoire, Democratic Republic of the Congo, Equatorial Guinea, Eswatini, Ethiopia, Gabon, Gambia, Ghana, Guinea, Guinea-Bissau, Kenya, Lesotho, Liberia, Madagascar, Malawi, Mali, Mauritania, Mauritius, Mozambique, Namibia, Niger, Nigeria, Rwanda, Sao Tome and Principe, Senegal, Seychelles, Sierra Leone, Somalia, South Africa, South Sudan, Sudan, Togo, Uganda, United Republic of Tanzania, Zambia, Zimbabwe
Central Asia	Armenia, Azerbaijan, Goergia, Kazakhstan, Mongolia, Taijikistan, Turkey, Turkmenistan, Uzbekistan
South-east Asia	Afghanistan, Bangladesh, Bhutan, Cambodia, Democratic People's Republic of Korea, India, Indonesia, Lao People's Democratic Republic, Malaysia, Maldives, Myanmar, Nepal, Pakistan, Philippines, Sri Lanka, Thailand, Timor-Leste, Vietnam
North Africa	Algeria, Bahrain, Djibouti, Egypt, Iran, Iraq, Israel, Jordan, Kuwait, Lebanon, Libya, Morocco, Oman, Qatar, Saudi Arabia, Syrian Arab Republic, Tunisia, United Arab Emirates, Yemen

2.4. Valorisation assessment

The valorisation assessment was conducted following the waste management hierarchy (Section 1.2.2) and the research categories used in Dulo et al. (2022). This is the only paper found in literature to have made such a type of assessment, where FLW is first quantified with MFA and then its valorisation potential is quantified.

Due to time constraints, the valorisation assessment focused on one main category of LW streams. The category that resulted in the highest generation of LW according to the MFA results was further analysed in the valorisation part of the report.

2.4.1. Selection of valorisation pathways

In Dulo et al. (2022), the types of compounds that can be extracted or products that can be made from FLW were classified into categories similar to the levels of the FLW management hierarchy. The only level of the hierarchy that was not covered is nutrient recovery. Due to time constraints, only two valorisation pathways were selected from Dulo et al. (2022) per level of the waste management hierarchy.

Nutrient recovery was included in the present report by including phosphorus (P), potassium (K) and nitrogen (N) content in FLW, hence allowing to assess the potential of FLW as biofertilizers. Pectin was also selected although not included in Dulo et al. (2022), as research is showing a growing interest for its valorization from FLW. Regarding biofuel production, other valorisation pathways have received attention, such as biohydrogen, biobutanol and biodiesel. It was however decided to not include them in the valorisation assessment, due to a lower feasibility and knowledge compared to bioethanol and biogas. Biohydrogen production is still difficult to scale up due to a low yield achieved and knowledge gaps, especially when using FLW, whose composition is complex (Algapani et al., 2018; S. Rahman et al., 2016). Biobutanol is a biofuel with a higher energy density than bioethanol (Zhan et al., 2016), but it has been less researched for FLW valorisation (Esparza et al., 2020). Lastly, FLW can be used in the production of biodiesel (Barik et al., 2018; Pleissner et al., 2013), but remains a challenge, as the yield is also low (Karmee & Lin, 2014) and residual water usually present in FLW interferes with the production process (Esparza et al., 2020).

In Table 2.7, the valorisation pathways selected for each level of the waste management hierarchy are shown and the reasons to include them in this valorisation assessment are given.

Table 2.7: Compounds or product selected for each level of the waste management hierarchy for the valorisation assessment.

Reuse for human and animal consumption	Protein	Unavoidable FVLW can be a relevant source of protein supplement to be used in food production (Dulo et al., 2022). Additionally, FVLW possible use for feed production has already been investigated (Dulo et al., 2022; Nath et al., 2023).
	Sugar	Sugar of processing fruit and vegetable by-products can be extracted and used as a natural sweetener in the production of food and beverages (Scordino et al., 2007). Additionally, FVLW use for feed production has already been investigated (Dulo et al., 2022; Thani et al., 2019).
Material recycling	Flavonoid	Secondary metabolite present in plants (Luna et al., 2020), which is beneficial to human health thanks to its numerous bioactive effects, notably anti-inflammatory, anti-carcinogenic and cardio-protective (Dias et al., 2021; Fraga et al., 2019; Jucá et al., 2018; Saini et al., 2017). These properties make it attractive for industrial applications, notably in the food, pharmaceutical and cosmetic sectors (S. Kumar & Pandey, 2013), and its recovery from FVLW has already shown to be successful (Doria et al., 2021).
	Tannin	Natural compound found in basically all parts of plants, and which is currently mainly recovered for leather tanning, but is also used in the food and pharmaceutical industries for its health benefits, notably against cancer and cardiovascular problems, as well as in the production of biobased materials (Pizzi, 2019), such as flexible plastic films (Basso et al., 2014) or fireproof insulating foams (Celzard et al., 2014). Research has already assessed the feasibility of tannin extraction from FVLW (Fraga-Corral et al., 2021).
	Pectin	Polysaccharide naturally present in most plants (Khamsucharit et al., 2017), it is a high-value compound interesting for the food industry as a gelling agent, a stabiliser or a source of dietary fibers. Research is growing on its recovery from FVLW and on other potential industrial applications, notably as an encapsulating agent for drug delivery or for edible food packaging production (Frosi et al., 2023; Kanmani, 2014; Maric et al., 2018; Perussello et al., 2017a).
Nutrient recovery	P, K, N	Phosphorus (P), Potassium (K) and Nitrogen (N) are essential nutrients for plant growth. P, K, N fertilizers thus help in agriculture to enhance yield crops (Sinha & Tandon, 2020). Composting of FVLW produces stable compounds, which can then be used as biofertilizers that enriches the soil in nutrients, notably in P, K, N (Otles et al., 2015; Shilev et al., 2006).
Energy recovery	Bioethanol	Bioethanol is a well-studied biofuel, for which current efforts are on using other substrates than corn to avoid conflict with food production (Esparza et al., 2020; Zhan et al., 2016). FVLW is a promising alternative feedstock for biofuel production (Khandaker et al., 2018).
	Biogas	Can be used in a variety of ways, but it is mainly upgraded and purified to obtain biomethane via anaerobic digestion to then be incorporated to the natural gas grid or used as an alternative fuel for vehicles (Esparza et al., 2020; Kannah et al., 2020). Biogas production from FVLW has been studied for a long time (Knol et al., 1978), and current studies demonstrate both an enourmous potential as well as financial and environmental advantages (Esparza et al., 2020; Masebinu et al., 2018).

2.4.2. Valorisation's calculations

As explained in Section 1.2.2, only unavoidable loss is suitable for extraction of specific compounds to be used for reuse for human consumption or animal consumption, or for material recycling. Unavoidable waste is more suitable for nutrient or energy recovery. According to the waste management hierarchy, nutrient and energy recovery must be considered for unavoidable loss only when upper levels, so reuse for human and animal consumption or material recycling, are not suitable.

The following equations show the calculations for the total content of compounds for food and feed productions (Equation 2.3), the potential recovery of high value compounds for biobased material production (Equation 2.4), the total content of nutrients for biofertilizer production (Equation 2.5), the bioenergy potential from bioethanol production (Equations 2.6 & 2.7) and the bioenergy potential from biogas production (Equations 2.8 & 2.9) from the category of LW streams of interest. All the extraction yield and total content values can be found in Appendix B.

$$\textit{Compound content (t)} = \textbf{\textit{Loss (t)}} \textit{ x DM x CP} \tag{2.3}$$

$$\textit{Potential Extraction (t)} = \textbf{\textit{Loss (t)}} \textit{ x DM x Extraction Yield (t/t)} \tag{2.4}$$

$$\textit{Nutrient content (t)} = \textbf{\textit{(Loss (t) + Waste (t))}} \textit{ x DM x CP} \tag{2.5}$$

$$\textit{Bioethanol (t)} = \textbf{\textit{(Loss (t) + Waste (t))}} \textit{ x DM x Production Yield (t/t)} \tag{2.6}$$

$$\textit{Bioenergy Potential of bioethanol (kWh)} = \textit{Bioethanol (t) x Conversion Factor (kWh/t)} \tag{2.7}$$

$$\textit{Biogas } (m^3) = \textbf{\textit{(Loss (t) + Waste (t))}} \textit{ x DM x Production Yield } (m^3/t) \tag{2.8}$$

$$\textit{Bioenergy Potential of biogas (kWh)} = \textit{Biogas } (m^3) \textit{ x Conversion Factor } (kWh/m^3) \tag{2.9}$$

Where:

- *DM* is the Dry Matter content (%)
- *CP* is the Content Percentage (t/t)
- **Loss (t)** and **Waste (t)** are the amounts of LW streams calculated in the first part of the research on FLW quantification using MFA

3

Results

3.1. Fruit and vegetable loss and waste quantification

Globally, 26.5 Mt of unavoidable fruit loss was generated at the processing stage, whereas 175.2 Mt of unavoidable fruit waste was generated at the retail and consumption (R&C) stages in 2020. Compared to the total production of fruits destined to human consumption in 2020[1], this represented 3.0% loss and 20.0% waste respectively. For the vegetables, 4.2 Mt of unavoidable loss was generated at the processing stage, and 52.8 Mt of unavoidable waste was generated at the R&C stages. Compared to the total production of vegetables destined to human consumption in 2020[2], this represented 0.4% loss and 4.8% waste respectively. Figures 3.1 and 3.3 show these results disaggregated at the regional level.

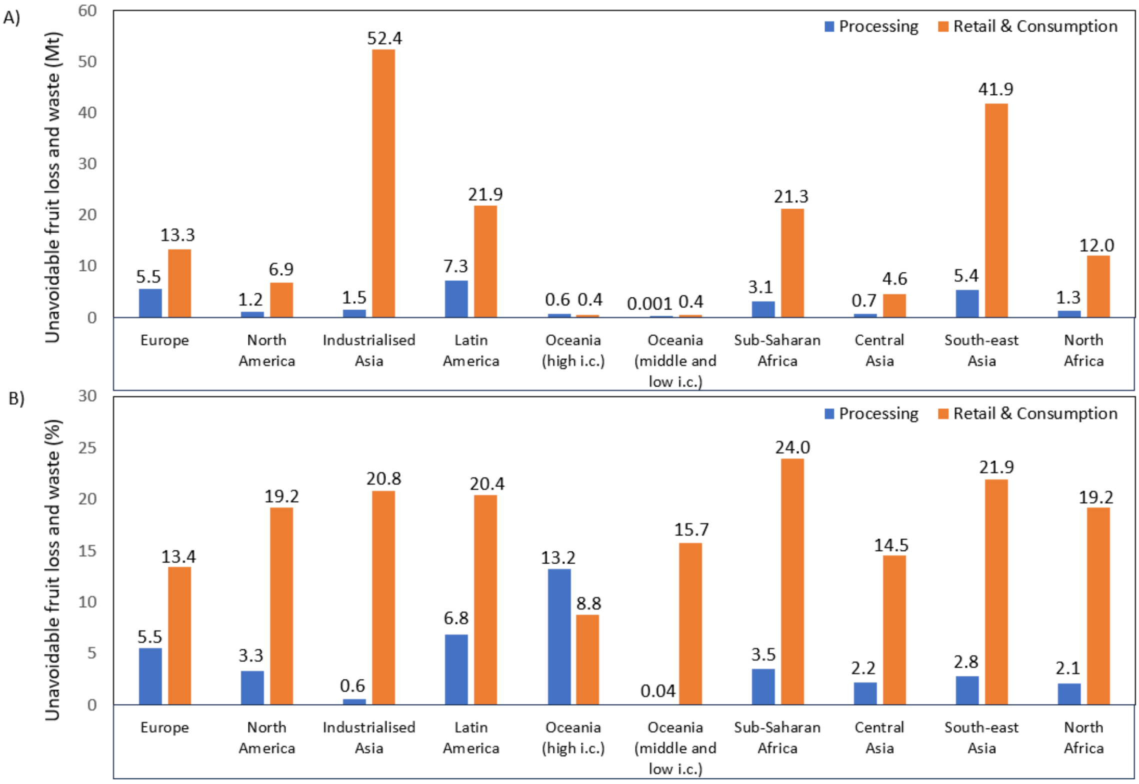

Figure 3.1: Unavoidable fruit loss and waste per world region in 2020: a) in mass generated b) in percentage they represent of the total domestic supply. (i.c. = income countries)

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[1] For the 33 fruits covered in this study.

[2] For the 23 vegetables covered in this study.

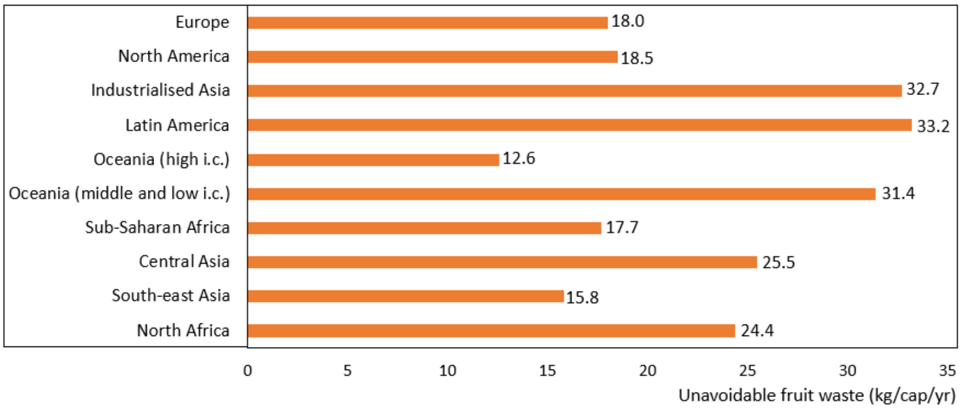

Figure 3.2: Per capita, unavoidable fruit waste generated per world region in 2020. (i.c. = income countries)

Across all regions except one, unavoidable fruit waste was higher than unavoidable fruit loss in 2020 (Figure 3.1). Unavoidable fruit waste was 2.5 to 400 times higher than unavoidable fruit loss depending on the region. Oceania (middle and low i.c.[3]) represented the region with the lowest generation of unavoidable fruit loss, and Latin America the highest. Oceania in general (both high i.c.[3] and middle and low i.c.[3]) had the lowest generation of unavoidable fruit waste, whereas industrialized Asia had the highest. However, at a per-capita level, Latin America was the highest-generating region of unavoidable fruit waste (Figure 3.2). The region having the highest percentage of unavoidable fruit loss compared to its total domestic supply (the initial fruit availability for both processing and the R&C stages) was Oceania (high i.c.) and the region with the highest percentage of unavoidable fruit waste compared to its total domestic supply was Sub-Saharan Africa.

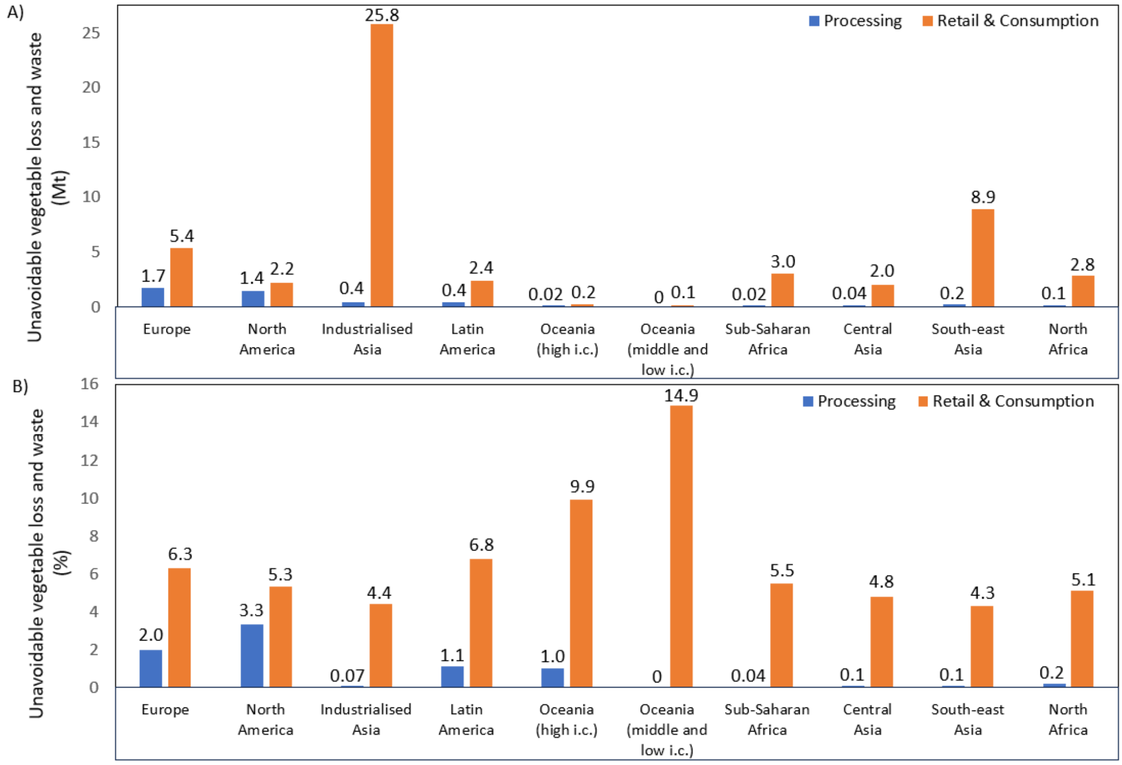

Figure 3.3: Unavoidable vegetable loss and waste per world region in 2020: a) in mass generated b) in percentage they represent of the total domestic supply. (i.c. = income countries)

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[3] income countries.

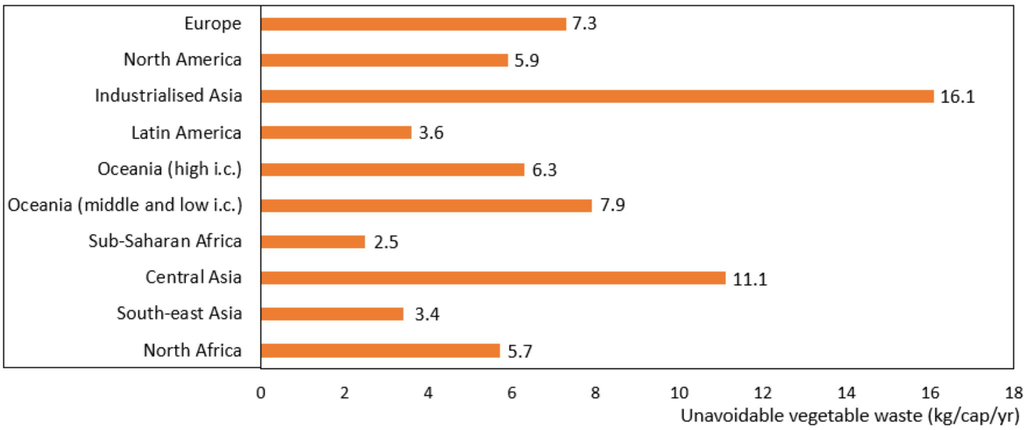

Figure 3.4: Per capita, unavoidable vegetable waste generated per world region in 2020. (i.c. = income countries)

Regarding vegetables, all regions were generating more unavoidable waste than unavoidable loss in 2020 (Figure 3.3), from 1.6 to 150 times higher depending on the region. No unavoidable loss generation is reported for Oceania (middle and low i.c.[3]). The region generating the highest unavoidable loss was Europe in terms of mass, but North America had the highest unavoidable loss in terms of percentage of total domestic supply lost. Concerning unavoidable waste of vegetables, Oceania (middle and low i.c.[3]) was the lowest-generating region, and industrialised Asia the highest-generating one, although Oceania ranked first when looking at the percentage of total domestic supply wasted. At a per-capita level (Figure 3.4), industrialised Asia had the highest unavoidable waste generation.

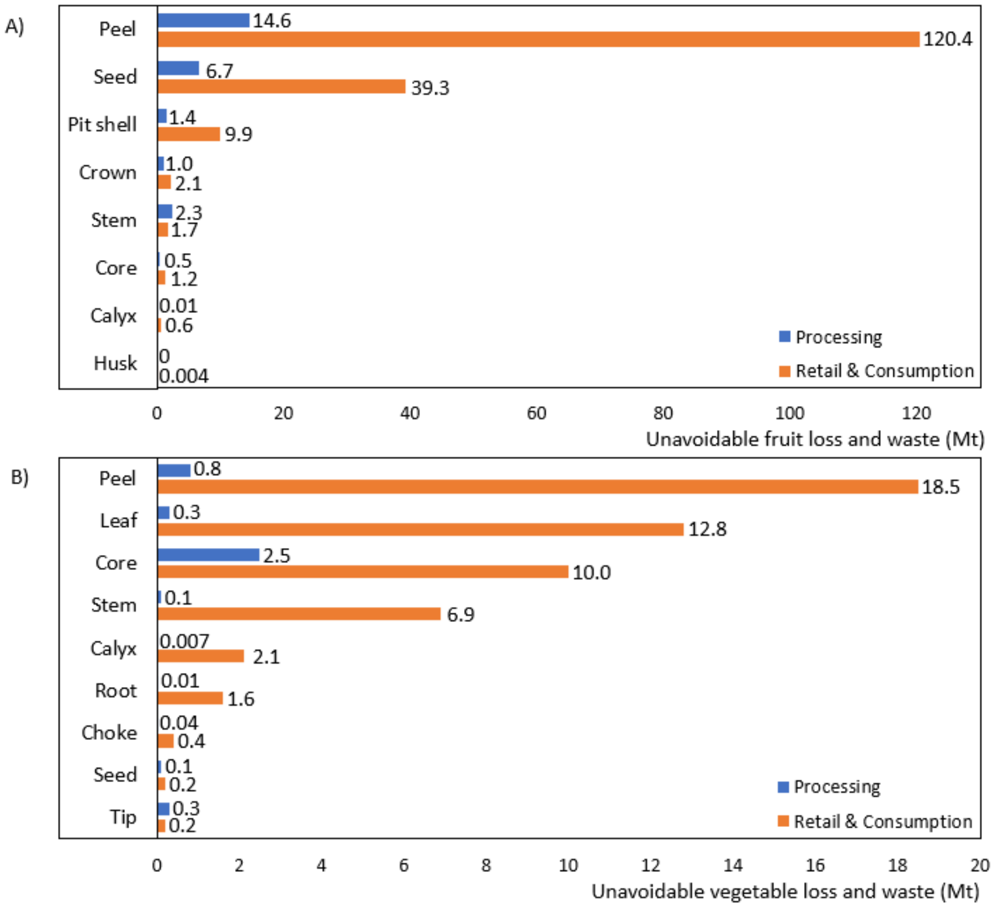

Figure 3.5: Unavoidable loss and waste generated at the global level in 2020 and aggregated into part categories: a) for fruits b) for vegetables.

In Figure 3.5, types of LW streams are aggregated into categories of fruit and vegetable parts. For unavoidable vegetable loss generated in 2020, core was the dominant category, which includes artichoke, cabbage, cauliflower, broccoli, green corn, lettuce, chicory and okra cores. However, for unavoidable fruit LW as well as for unavoidable vegetable waste, peel was the highest category, and it ranked second for unavoidable vegetable loss. Peel represented 55.1% of all unavoidable fruit loss, 68.7% of all unavoidable fruit waste, 19.2% of all unavoidable vegetable loss and 35.1% of all unavoidable vegetable waste in 2020.

This is further visible in Figures 3.9, 3.10, 3.11 and 3.12, where all the unavoidable LW streams for fruits and for vegetables at a global level are ranked from the highest generated amount in 2020 to the lowest one. 12 out of the 40 streams for unavoidable fruit loss and 13 out of the 46 streams for unavoidable fruit waste are peels. For vegetables, 6 out of the 27 streams for unavoidable loss and 5 out of the 28 streams for unavoidable waste are peels. The highest generated unavoidable streams were orange peels for unavoidable fruit loss (18.5% of the total fruit loss) and banana peels for unavoidable fruit waste (19.2%). For vegetables, green corn cores were the highest stream for unavoidable loss (57.1%) and onion and shallot peels the highest stream for unavoidable waste (17.6%). In Appendix C, the 10 most generated LW streams for fruits and for vegetables can be found disaggregated per world region to provide further information.

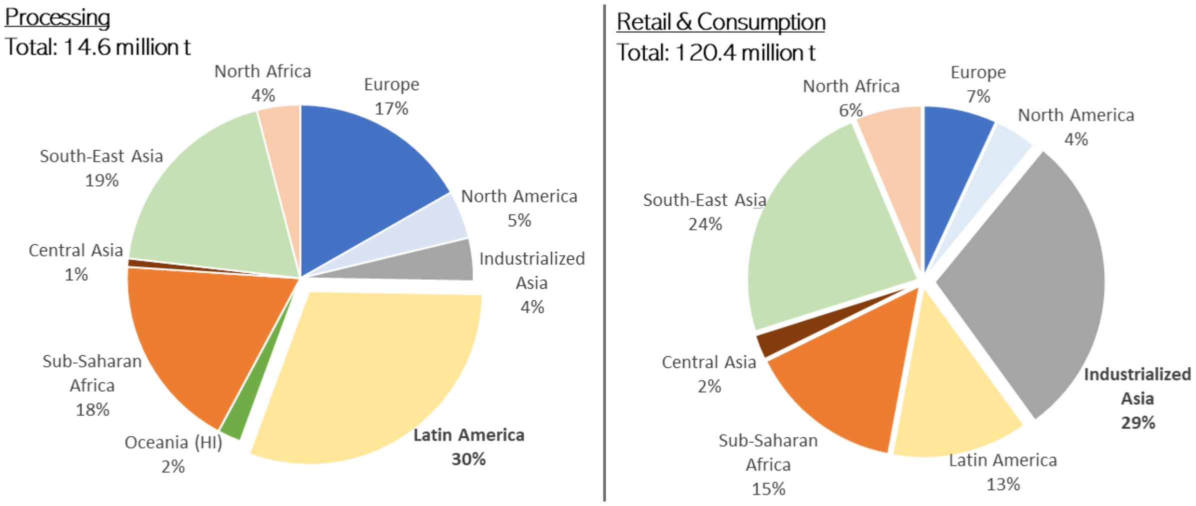

Figure 3.6: Fruit peel loss and waste generated at the regional level in 2020. (HI = high income)

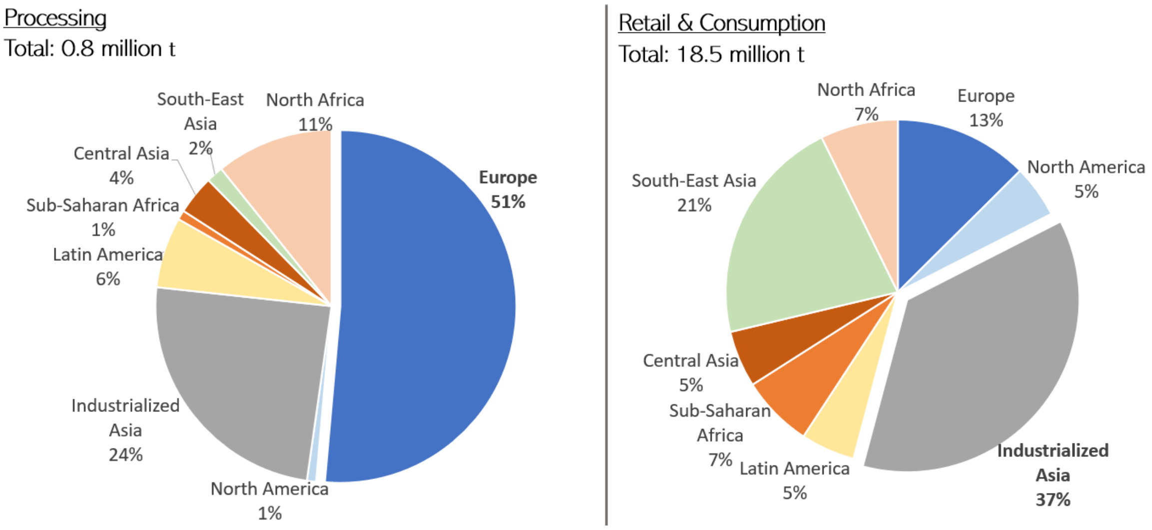

Figure 3.7: Vegetable peel loss and waste generated at the regional level in 2020.

In Figures 3.6 and 3.7, the contribution of each world region to the global generation of fruit and vegetable peels is shown. Latin America was the region with the highest contribution when it comes to unavoidable fruit peel loss generated in 2020 whereas industrialised Asia had the highest generation of unavoidable fruit peel waste. Regarding vegetables, Europe was dominant for unavoidable vegetable peel loss, while industrialised Asia was again the main contributor for unavoidable vegetable peel waste. In Appendix D, the contribution of each world region to the global generation of fruit and vegetable for the remaining categories can be found.

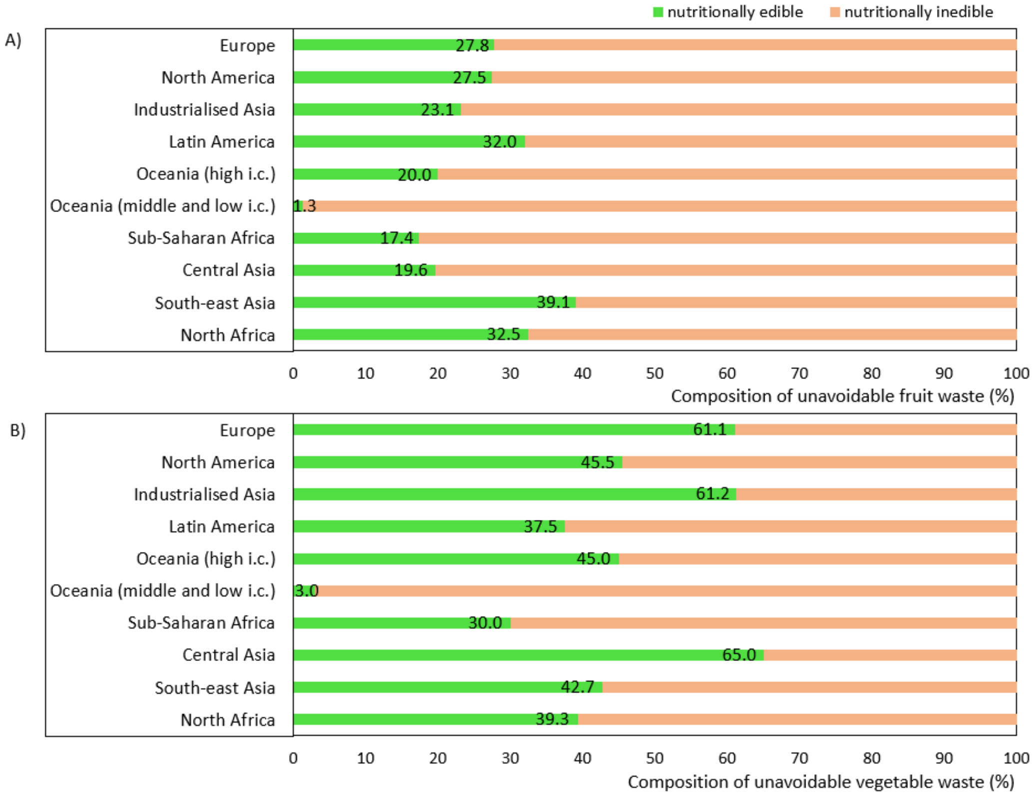

Figure 3.8: Per capita, percentage of the total unavoidable waste generated that is nutritionally edible, at the regional level in 2020: a) for fruits b) for vegetables. (i.c. = income countries)

From the global unavoidable fruit waste, 49.6 Mt was nutritionally edible, meaning that it was discarded by the consumer (according to the assumption on cultural edibility) although the fruit part discarded could have been eaten or even represented health benefits. This amount represents 28.3% of the total unavoidable fruit waste for 2020. Regarding global unavoidable vegetable waste, 28.3 Mt was nutritionally edible, representing 53.6% of the total unavoidable vegetable waste for 2020. Figure 3.8 shows these results per region.

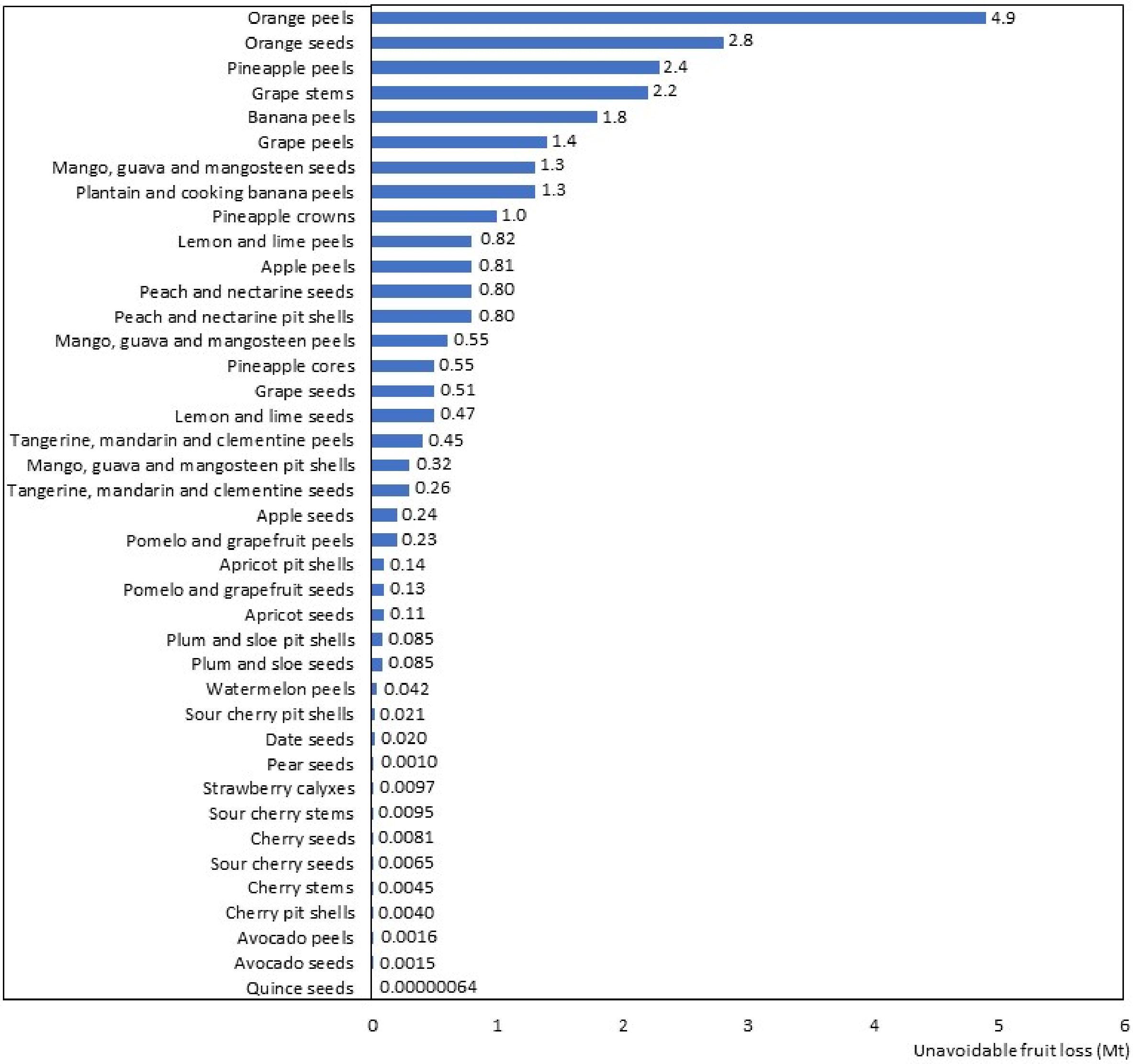

Figure 3.9: All the types of unavoidable fruit loss generated at a global level in 2020.

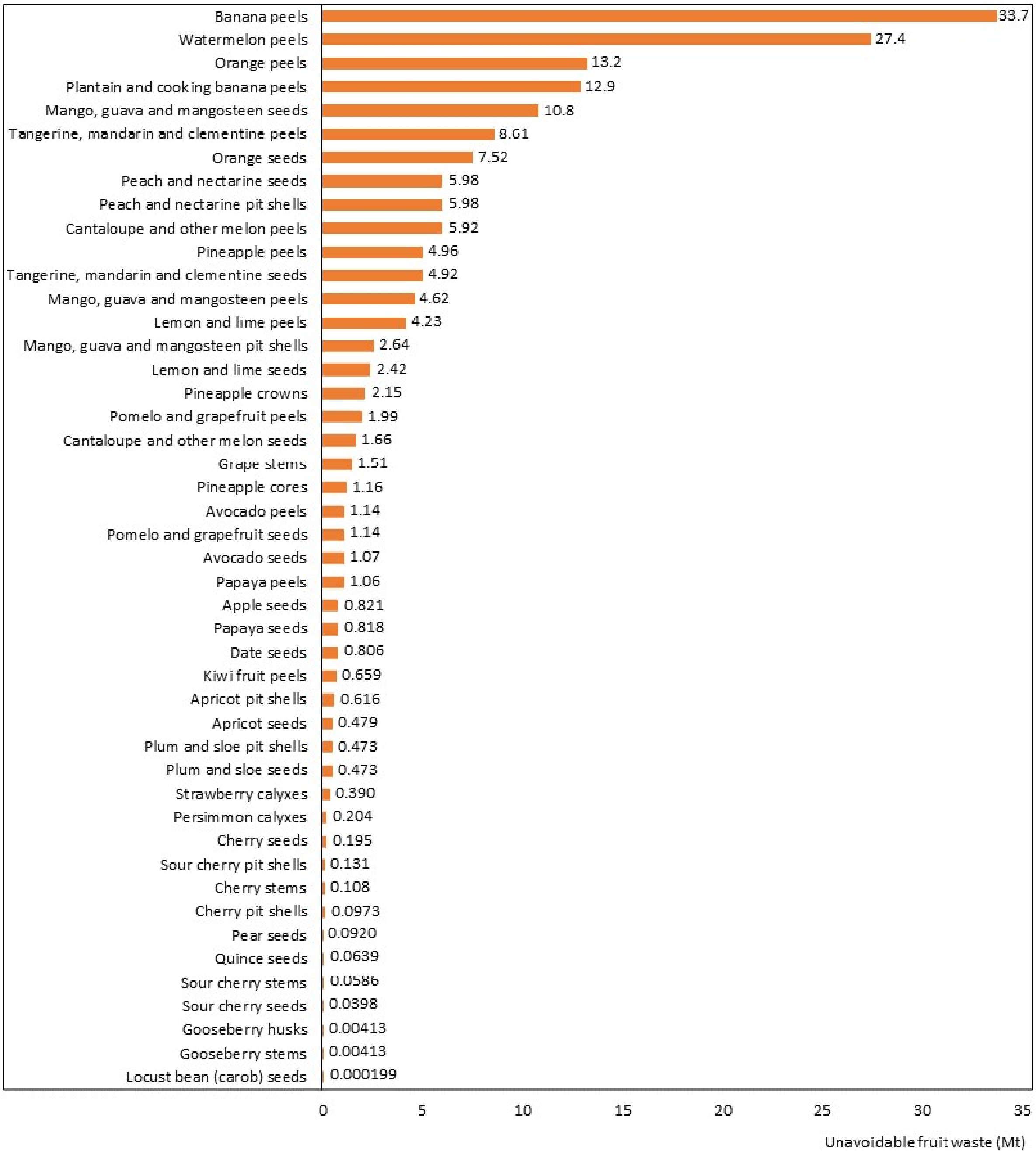

Figure 3.10: All the types of unavoidable fruit waste generated at a global level in 2020.

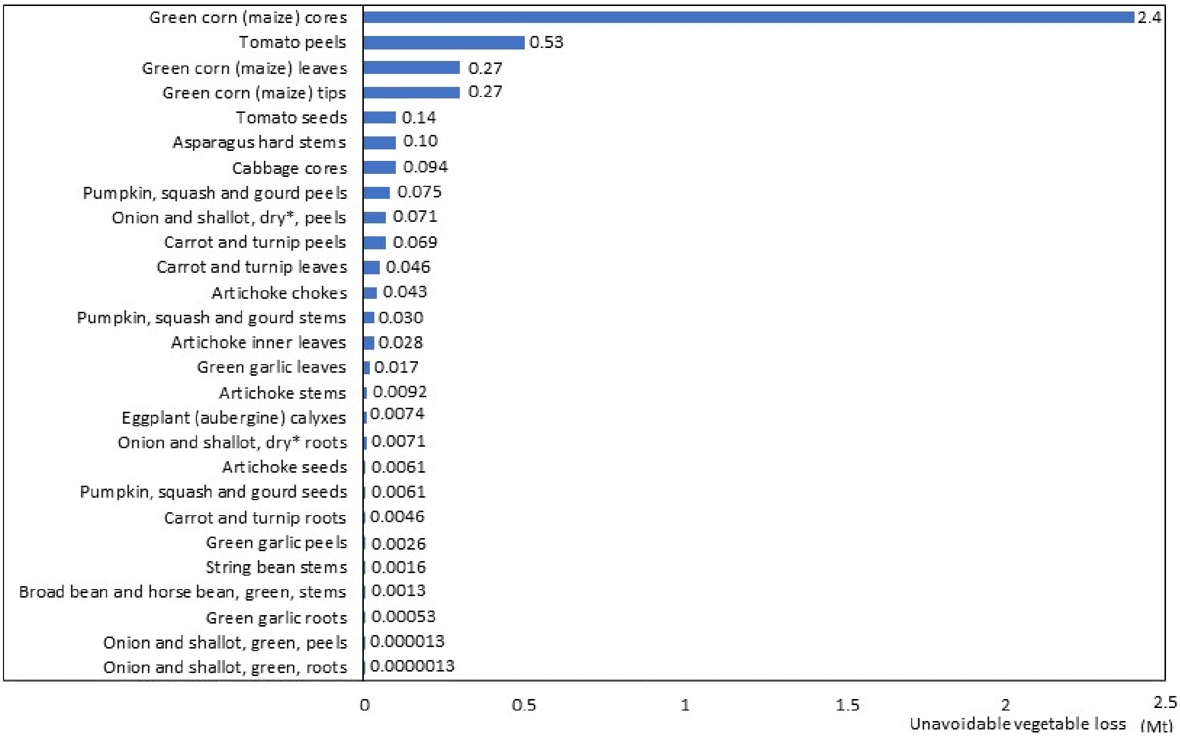

Figure 3.11: All the types of unavoidable vegetable loss generated at a global level in 2020. (* excluding dehydrated)

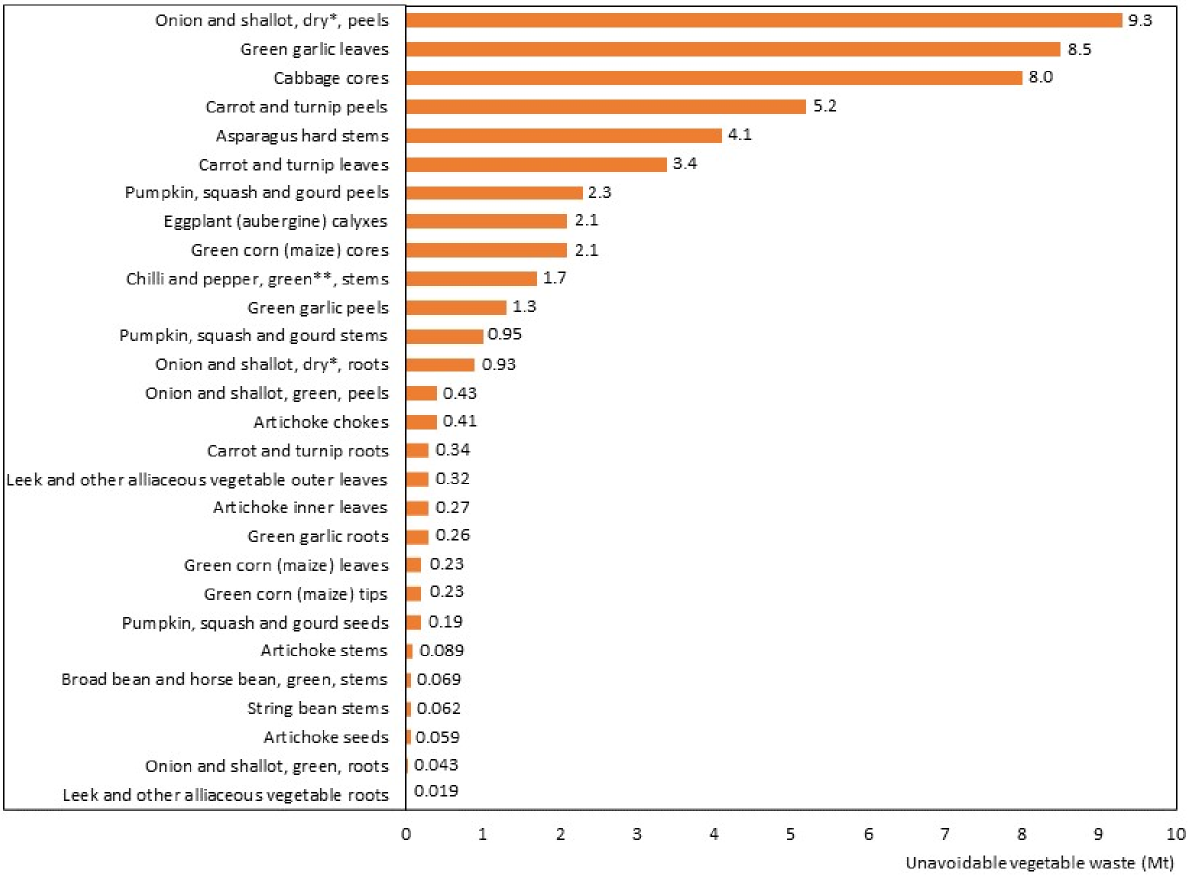

Figure 3.12: All the types of unavoidable vegetable waste generated at a global level in 2020. (* excluding dehydrated; ** Capsicum spp. and Pimenta spp.)

3.2. Fruit and vegetable peel loss and waste valorisation

The MFA results reveal that peel was one of the highest generated categories of LW streams in 2020. The valorisation part of the report is only focusing on this category. This was done at a global level, without consideration of variation in technological development across the world. The results of the valorisation assessment of fruit and vegetable peel loss and waste are summarized in Table 3.1.

Table 3.1: Summary of the potential of biomaterial recovery from unavoidable peel loss and waste generated in 2020. (Limited = less than 0.1 kt or 0.1 GWh; n.f. = not found; P = Phosphorus; K = Potassium; N = Nitrogen; * excluding dehydrated)

FLW management hierarchy level	Reuse for human and animal consumptions		Material recycling			Nutrient recovery			Energy recovery	
Valorisation pathway	Food and feed productions		Biobased material production			Biofertilizer production			Biofuel production	
Feedstock	Unavoidable peel loss		Unavoidable peel loss			Unavoidable peel loss and waste			Unavoidable peel loss and waste	
Compound/nutrient/energy potential	Protein (kt)	Sugar (kt)	Flavonoid (kt)	Tannin (kt)	Pectin (kt)	P (kt)	K (kt)	N (kt)	Bioethanol (GWh)	Biogas (GWh)
Fruits										
Apples	0.3	14.6	0.6	0.5	11.3	0.1	48.6	113.5	242.2	422.5
Avocados	limited	limited	limited	limited	limited	0.7	26.5	3.3	17.3	2.9
Bananas, plantains and cooking bananas	24.6	147.8	17.2	98.6	98.6	19.9	0.4	0	2225.6	19559.5
Cantaloupes and other melons	-	-	-	-	-	n.f.	48.5	n.f.	2175.5	n.f.
Grapes	47.2	209.6	5.2	1.6	36.7	1.6	limited	3.1	156.6	1703.4
Kiwi fruits	-	-	-	-	-	0.5	13.6	n.f.	n.f.	n.f.
Lemons and limes	3.6	50.4	28.8	0.7	431.9	1.3	44.5	13.3	996.2	limited
Mangoes, guavas and mangosteens	5.8	66.5	1.7	13.3	41.6	6.2	6.2	n.f.	812.0	3330.9
Oranges	0.9	117.1	11.7	17.6	339.5	1.3	43.3	13.0	970.6	6108.8
Papayas	-	-	-	-	-	0.2	0.2	1.3	0.1	38.1
Pineapples	21.1	70.5	2.3	94.0	3.5	0.7	0.7	7.3	272.9	1837.9
Pomelos and grapefruits	0.2	4.5	0.2	limited	14.1	0.2	5.6	1.7	124.4	limited
Tangerines, mandarins and clementines	0.1	9.4	limited	limited	9.4	0.6	19.0	5.7	426.1	limited
Watermelons	0.2	1.3	limited	0.2	0.4	49.4	13.2	33.0	24.6	4923.8
Vegetables										
Carrots and turnips	0.6	1.9	0.2	limited	1.2	1.4	2.4	n.f.	211.1	398.0
Green garlic	limited	limited	limited	limited	0.2	limited	3.6	160.2	209.4	n.f.
Onions and shallots, dry* and green	limited	3.1	0.5	limited	0.7	1.0	10.7	n.f.	321.0	2792.9
Pumpkins, squashes and gourds	0.5	0.5	limited	limited	1.4	limited	limited	n.f.	54.3	188.2
Tomatoes	10.7	85.3	0.3	limited	20.8	0.3	1.1	32.0	39.8	173.3

Following the FLW management hierarchy, the highest levels must be prioritized, and when they are not suitable, the lowest levels must be considered.

The first level studied is reuse for human consumption and animal consumption, which can be valorised by extracting protein and sugar from unavoidable peel loss for food production and feed production. The peel losses that are the most promising sources for this valorisation pathway are grape peels and banana peels, which showed the highest and second-highest amounts of protein and sugar respectively. This is also the best valorisation pathway for unavoidable loss of tomato peels and mango, guava and mangosteen peels, as for these peels the amounts of compounds usable for food and feed productions were higher than the ones of compounds usable for material recycling.

The second level studied is material recycling, which can be valorised by extracting flavonoid, tannin and pectin from unavoidable peel loss for the production of biobased materials. The most promising sources for flavonoid extraction are lemon and lime peels, followed by banana peels and orange peels. The highest amounts of tannin extraction were from banana peels and pineapple peels. However, banana peels showed a high potential for food and feed productions, which rank higher in the hierarchy and should thus be prioritized over material recycling. Regarding pectin extraction, lemon and lime peels and orange peels have the highest potential.

The third level is nutrient recovery, which can be valorised by producing biofertilizers from unavoidable peel loss and waste rich in phosphorus (P), potassium (K) and nitrogen (N). Watermelon peels were the highest source for P, apple peels for K and green garlic peels for N.

At the same level of prioritisation as nutrient recovery is energy recovery, which can be valorised by producing biofuels from unavoidable peel loss and waste, such as bioethanol and biogas. Banana peels showed the highest bioenergy potential with both bioethanol and biogas productions. Orange peels and mango, guava and mangosteen peels also have a high potential for both biofuel productions. Other promising sources for bioethanol production are cantaloupe and other melon peels and lemon and lime peels, whereas watermelon peels, onion and shallot peels, pineapple peels and grape peels are promising sources for biogas production. However, fruit or vegetable peel losses that can be valorised on upper levels of the FLW management hierarchy should be prioritized on those levels.

The aforementioned information are summarized in Table 3.2, where the most promising sources are given for each valorisation pathway.

Table 3.2: Unavoidable peel loss and waste showing the highest potential for each level of the food loss and waste management hierarchy according to the valorisation assessment.

Food loss and waste management hierarchy	Feedstock
Reuse for human and animal consumptions	Banana, plantain and cooking banana peel loss Grape peel loss Mango, guava and mangosteen peel loss Tomato peel loss
Material recycling	Lemon and lime peel loss Orange peel loss Pineapple peel loss
Nutrient recovery	Apple peel loss and waste Watermelon peel loss and waste Green garlic peel loss and waste
Energy recovery	Banana, plantain and cooking banana peel waste Cantaloupe and other melon peel loss and waste Lemon and lime peel waste Mango, guava and mangosteen peel waste Orange peel waste Pineapple peel waste Onion and shallot peel loss and waste

In general, the highest values for a specific valorisation pathway were among fruit peels rather than vegetable peels. The valorisation assessment shows a more limited potential of valorisation for the following LW streams: avocado peels, pomelo and grapefruit peels, tangerine, mandarin and clementine peels, carrot and turnip peels, and pumpkin, squash and gourd peels. Avocado peels have a limited potential for reuse for human and animal consumptions and material recycling, but could be used in biofertilizer production as a source of K. Pomelo and grapefruit peels, tangerine, mandarin and clementine peels as well as carrot and turnip peels have a low potential for upper levels of the FLW management hierarchy, and represent a moderate potential for bioethanol production. Pumpkin, squash and gourd peels also have a low potential for upper levels, and represent a moderate potential for biogas production.

The valorisation assessment was also limited by the fact that values necessary to quantify the valorisation potential could not be found in the literature for some LW streams (noted n.f. in Table 3.1).

4

Discussion

4.1. General discussion

This Section elaborates on how the results of the FVLW quantification (Section 4.1.1) and the FVLW valorisation (Section 4.1.2) answer the research questions and the sRQs formulated in Chapter 1.

4.1.1. Fruit and vegetable loss and waste quantification

Higher generation of unavoidable LW from fruits than vegetables

Regarding the results from the MFA, a first observation that can be made is that the value chain of fruits produced more unavoidable LW than the one of vegetables in 2020. This is visible both at the global level and at the regional level. This was not the result of a higher production of fruits compared to vegetables, as the data from FAOSTAT shows for 2020 an actual higher total production in mass of vegetables (876.7 Mt) than fruits (1104.2 Mt). Thus, the processing and R&C stages of the fruit value chain resulted in a higher unavoidable LW generation than the processing and R&C stages of the vegetable value chain.

In the literature, fruits and vegetables are often associated into a single category, making it difficult to compare them (FAO, 2019b; Magalhaes et al., 2021; Mayo-Bruinsma, 2014). However, in Chen et al. (2020), one of the few MFA studies on FLW conducted at a global level, the results show opposite trends to the present report, with fruits representing 12% of the global FLW and vegetables 25%. This can possibly be explained by the fact that only unavoidable LW is included in the present study, which would mean that the value chain of fruits represents mostly unavoidable LW whereas the one of vegetables is mostly avoidable LW. A second explanation could be that the data used by Chen et al. (2020) is from 2011 and that trends have changed over the last decade. The latter seems however less likely, as recent numbers show an overall increase of global FLW generation over the years (Hegnsholt et al., 2018) rather than an increase of LW generation specifically from the global fruit value chain and a decrease of LW generation from the vegetable value chain.

Hence, the value chain of fruits represents a hotspot of unavoidable LW generation, where global action should be prioritized to reduce efficiently and rapidly global FLW generation.

Higher generation of unavoidable LW from the R&C stages than the processing stage

In regard to sRQ 2, the MFA results show that the R&C stages generate higher quantities of unavoidable waste than the processing stage of unavoidable loss, and this is true for both fruits and vegetables. Indeed, global unavoidable fruit waste was almost 7 times higher than unavoidable fruit loss in 2020, and global unavoidable vegetable waste was more than 17 times higher than unavoidable vegetable loss. Additionally, this trend can be observed across all regions except for unavoidable fruit LW generated by Oceania (high i.c.[3]).

This is partly in accordance with the literature, such as Calvo-Porral et al. (2017) or Teuber and Jensen (2020), which generally state that the consumption stage produces the highest amount of FLW in the food value chain in high income countries. However, research said for lower income countries that most of the FLW generation occurs at earlier stages, such as processing (FAO, 2019b; Hodges et al., 2011). This difference in trends could again be explained by the fact that literature generally does not disaggregate

FLW between avoidable and unavoidable. Avoidable food loss is generated at all stages before retail, and is caused mainly by a lack of good logistics and storage and cooling equipment, which is mostly an issue in lower income countries due to technical, financial or managerial limitations (Kitinoja et al., 2010). On the other hand, unavoidable food loss is only generated at the processing stage, caused by food discarded in the production of processed food products. The level of development of processing technologies can partially influence food loss generation (Jermann et al., 2015) and thus lead to differences across countries, but processing food unavoidably leads to the generation of food by-products (Teigiserova et al., 2019). Regarding food waste, the avoidable type is caused by unsustainable consumption behaviour, such as over-purchasing (Porat et al., 2018; WRAP, 2013), as well as more complex factors, notably socio-economic and demographic ones (Parfitt et al., 2010). It is an issue mostly observed in developed countries (Hodges et al., 2011), although with increasingly higher income and living standards, it is also growing in developing regions (FAO, 2019b; Keser et al., 2012). Regarding unavoidable food waste, it is defined here as being caused by end-consumers discarding inedible food. In this report, the assumption made on cultural edibility does not take into account differences in edibility perception across regions, which could have led to underestimating variation across regions in fruit and vegetable waste generation (more on the implications of the assumptions is discussed in Section 4.3.2). Nevertheless, nutritionally inedible parts of food are unlikely to be eaten despite cultural or individual eating preferences. When food is being processed, these inedible parts are discarded at the processing stage, but since a high proportion of the fruit and vegetable productions is not processed before the R&C stages, these inedible parts are discarded during consumption, resulting in higher global unavoidable waste than unavoidable loss.

To confirm these results, more research is needed at the global level that disaggregates between avoidable and unavoidable FLW. Some recent studies have now included the avoidance status of the waste in their results (De Laurentiis et al., 2018; Fredes et al., 2023), and it should be even more encouraged in the future. For now, the MFA results show that there is no visible relationship between the income level of regions and the stage of their fruit and vegetable value chain generating the most unavoidable FVLW. For all regions, it is essential to target unavoidable fruit and vegetable waste generated at the R&C stages, which is more problematic than unavoidable fruit and vegetable loss generated at the processing stage.

Trends at the geographical level

To answer sRQ 1, a closer look needs to be taken at the results aggregated into world regions.

Regarding the fruit value chain, Latin America was the region with the highest generation of unavoidable loss and the second-highest in terms of percentage of the domestic supply unavoidably lost during processing. Loss generated from the processed fruit production has already been identified as problematic for this region (León-Roque et al., 2023). Latin America has one of the highest shares in the global market of processed fruit production, after industrialized Asia and Europe (FAO, 2020). The reason behind Latin America generating more fruit loss than industrialized Asia and Europe could be that processed fruit production in Latin America is accelerating and is increasingly optimized, but that the processing technologies used have not yet caught up with the level of development of the two other regions (Hernández-Hernández et al., 2019). This is however only a supposition since such a correlation between processing techniques and loss generation is not studied in this report.

For vegetables, Europe and North America generated significantly higher amounts of unavoidable loss compared to the rest of the world. Europe was the highest in terms of mass generated and North America the highest in terms of percentage that the unavoidable loss generated represents of the total domestic supply. This can be explained by the fact that these two regions rank second and third respectively in terms of processed vegetable production in the world (FAO, 2020). Although industrialised Asia is by far the largest producer of processed vegetables, especially China and Japan (Facts and Factors Research, 2021; FAO, 2020; Insights, 2022), it only ranked third in unavoidable loss generation, and in significantly smaller proportions than the two other regions. This is because North America and Europe are respectively the first and second biggest producers of processed maizes (FAO, 2020), whereas industrialised Asia only ranks fifth. Processing maize generates high amounts of maize cores (Miranda et al., 2018), which are particularly heavy compared to other types of vegetable waste.

At the R&C stages, industrialised Asia largely produces both the most fruit and vegetable waste. This is notably due to the important population living in this region (for instance, Latin America has a higher fruit waste per-capita), but it is not the only reason. The major fruit waste of industrialised Asia was by far watermelon peels, with 98.7% of watermelon peel waste in this region being generated by China alone. China is the largest global consumer of watermelon (W. Liu et al., 2016), generating alone 60.9% of the global R&C waste of watermelon peels, and the peel is relatively heavy compared to other fruit wastes.

Regarding vegetables, the main waste of industrialised Asia is leaves of green garlic, followed by cabbage cores, asparagus hard stems, carrot and onion peels, carrot leaves and eggplant calyxes. For all of them, more than 90% was generated by China. A recent literature review on FLW in China (Li et al., 2022) demonstrated the lack of information on FLW generation pattern in China, but what is known is that the recent boom in the Chinese catering industry led to an increase of food waste (Cheng et al., 2018), and that this food waste is mostly constituted of vegetables and staple foods. According to the case studies reviewed, vegetable waste represents from 29% up to 44% of waste generated by households and restaurants (Qi et al., 2020; Wang et al., 2017; Zhang et al., 2016; Zhang et al., 2015; Zhang et al., 2017). This aligns with the results of this report, although no specific mention of unavoidable FLW is made in this literature review.

Hence, the MFA conducted in this report not only quantifies the extent of unavoidable FVLW generated at a global level, but also helps identifying which regions and which specific LW streams contribute the most to the overall unavoidable FLVW generation. However, the results show different trends when looking at the percentage of the domestic supply unavoidably wasted. Indeed, for fruits, Sub-Saharan Africa has the highest percentage, whereas for vegetables Oceania (both regions) has the highest percentage, followed by Latin America. Such information is hard to compare with the current literature looking at global FLW, who does not disaggregate between avoidable and unavoidable, or between fruits and vegetables, or who has different world region division (such as Dulo et al. (2022)) or who simply is lacking such data (Chen et al., 2020). More research studying global FLW generated at each stage of the food value chain for each food commodity group and disaggregating between avoidable and unavoidable FLW is thus needed.

Peel as the highest generated category of unavoidable loss and waste

To answer sRQ 3 and 4, the results were presented per categories of fruit and vegetable parts. Peel stands out as the dominant category of unavoidable FVLW, especially for fruits. This aligns with Parry et al. (2015) and Teuber and Jensen (2020), who had reached a similar conclusion.

Among fruit peels, banana peel was the highest-generated one. Bananas are indeed consumed in high amounts all over the world, with the highest generation of peels from the R&C stages in South-East Asia. In this region, 62% of the banana peels were generated by India, which is the largest producer and consumer of bananas (FAO, 2019a; Gowri & Shanmugam, 2015).

Orange peel ranked third as unavoidable waste after watermelon peels (which was already discussed) and ranked first as unavoidable loss. Latin America had the highest generation of orange peel loss, and most specifically Brazil, which was responsible for 88.9% of the total orange peel loss in this region. Brazil is indeed the world leading country in orange juice production (Neves et al., 2020). Orange peel waste was the highest in South-East Asia, specifically in India, where consumption of orange juice has grown fast in the last decades (Neves et al., 2020), with a peak particularly visible in 2020. This peak in demand was possibly due to the COVID-19 pandemic, as orange juice contains micronutrients boosting the immune system, which was particularly seeked by consumers at that time (K. Kumar & Babu, 2021).

More generally, peel is a significant category of by-products from food processing industries (Suhag et al., 2022) and a significant category of waste from the R&C stages, discarded because inedible or due to unpleasant texture or aftertaste (Lau et al., 2021). It can cause serious pollution and disposal issues if not properly managed. However, its abundance and its low cost coupled to its high content of many bioactive compounds of interest for industrial applications makes it an interesting feedstock that can offer a wide range of opportunity for valorization (Suhag et al., 2022).

Nutritional edibility of unavoidable waste

Lastly, a noticeable share of what is considered unavoidable in the FVLW calculated is actually edible from a pure nutritional perspective, meaning that it is not harmful to human health and can even represent nutritional benefits. For example, citrus peel discarded at the R&C stages (28.0 Mt) could have been used to produce 48.2 Mt of marmalade[1].

Again, there was no clear distinction between high and lower income regions in terms of the percentage of nutritionally edible FV waste. Such quantification of edible food being thrown away could not be found in the literature, which is also is due to a lack of consistent definition and coherent approach regarding edibility and the quantification of edible versus inedible food waste (Teigiserova et al., 2020).

However, as aforesaid, it should be kept in mind that these calculations do not take into account variation of eating preferences across regions following the assumption made on cultural edibility. Hence, they do not reflect exactly the reality but rather provides an idea of the importance of consumer behaviour in the generation of food waste. Many factors are found to influence the perceived edibility of food by the consumer, such as its age, culture, knowledge of food, concern of environmental issues as well as its own eating preferences (Melbye et al., 2016; Nicholes et al., 2019; Teigiserova et al., 2020). Campaigns raising awareness is a strategy of food waste prevention that has proven to be efficient, when implemented alongside structural and economical strategies (Priefer et al., 2016), and could notably educate on the edibility of food parts generally discarded and on ways of valorising them in our diet.

4.1.2. Fruit and vegetable peel loss and waste valorisation

The valorisation part of this report aimed at answering sRQ 5 and 6. Each level of the food waste management hierarchy was explored. As unavoidable FLW cannot by definition be prevented, the first level of the waste hierarchy is not feasible. Additionally, the majority being already currently incinerated and landfilled, and the other upper levels of the waste hierarchy being preferable FLW management alternatives, these two last levels of the hierarchy were not covered.

Valorising via reuse for human and animal consumptions

One type of food that can be enriched with protein is pasta, which are low in amino acids (Alzuwaid et al., 2021). 472 kt of spaghetti meal could have been made using protein extracted from grape peel loss, 246 kt using banana, plantain and cooking banana peel loss, 107 kt using tomato peel loss and 58 kt using mango, guava and mangosteen peel loss[2], the four streams identified as having the highest potential for food and feed productions. In total, this could have substituted the use of 88.3 kt of soy protein to make spaghetti-enriched meal, and prevent the use of 1 942.6 km^2 of land[3] and 526.3 million m^3 of water[4] as well as the release of 1.8 Mt of CO_2 emissions[5] to grow soy.

Additionally, 167.7 kt of natural sweetener could have been made using sugar extracted from grape peel loss, 118.2 kt using banana, plantain and cooking banana peel loss, 68.2 kt using tomato peel loss and 53.2 kt using mango, guava and mangosteen peel loss[6]. This could have been used in food and beverage productions to substitute the use of 407.3 kt of aspartame, an artificial sweetener associated to a potential carcinogenic risk for human health (Riboli et al., 2023).

Regarding reuse for animals, banana peel loss has already been largely researched in the literature as a a feed additive for various animal species (Abel et al., 2015; Justine et al., 2014; Nuriyasa et al., 2019). Grape peel is also already used as a dietary supplement for animals, being a great source of antioxidants (Maamoun, 2022; Zentek et al., 2014). Additionally, tomato peel (Lu et al., 2019) and mango, guava and mangosteen peel (Sanon & Kanwe, 2010) have both also been studied as relevant animal feed ingredients. The results in this report further support the valorisation of these peels in this valorisation pathway.

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[1] Using the conversion factors (c.f.) in Andress and Harrison (2014): 450g of citrus peels used to obtain 775g of marmalade

[2] Using the same assumptions as in Dulo et al. (2022): spaghetti meal can be obtained from 10% protein supplement mixed with spaghetti flour (Alzuwaid et al., 2021)

[3] Using the c.f. calculated in Poore and Nemecek (2018): 2.2 m^2 of land are needed to produce 100g of soy protein

[4] Using the c.f. calculated in Mekonnen and Hoekstra (2011): 596 litres of water are needed to produce 100g of soy protein

[5] Using the c.f. calculated in Poore and Nemecek (2018): 2 kg CO_2 are released in the production of 100g of soy protein

[6] Using the c.f. calculated in Scordino et al. (2007): 80% of the processing by-product sugar is recovered as natural sweetener

Valorising via material recycling

One possible application for flavonoid and tannin is to use them as a natural alternative to synthetic dyes (Dulo et al., 2022). With the aim of moving towards more sustainable textile practices, natural dyes are increasingly gaining interest (Mirjalili et al., 2011), as some synthetic dyes have been associated to a toxic risk for humans and environmental pollution (Mirjalili et al., 2011). Flavonoid from lemon and lime peel loss could have been used as a dye for 236.1 million m^2 of wool fabric, and another 95.9 million m^2 of wool fabric could have been dyed using orange peel loss[7], the two streams identified as having the highest potential for flavonoid valorisation. From pineapple peel loss, which is the stream identified as having the highest potential for tannin valorisation, tannin could have been extracted and used to tan 9.4 Mt skin[8].

Regarding pectin, lemon and lime peel as well as orange peel losses were found to be the best sources for pectin recovery. Citrus peel loss is already being exploited for pectin recovery, but this remains at a laboratory and semi-industrial scale of production (Fidalgo et al., 2016). The results in this report show that citrus peel loss represents a significant feedstock for pectin extraction for industrial purposes, and that research should persevere in developing this valorisation pathway to a larger scale.

Valorising via nutrient recovery

Research has already been achieved on assessing the potential of biofertilizer production from watermelon peel LW (Erugo et al., 2022; Hassan & Abdulsalam, 2017), which was found to be the highest source for phosphorus, and shows a good efficiency of the biofertilizers with significant crop growth rate. Apple peel LW, the highest in potassium content, and garlic peel LW, the highest in nitrogen content, have been less studied, but the results of Halpatrao et al. (2019) showed an improvement of protein concentration in plants who had received apple peel powder and those of Mahmood et al. (2020) an improvement of nutrient concentration in plants who had received spraying garlic extract. In light of the results, more research should be conducted on the potential of these two LW streams for biofertilizer production.

Valorising via energy recovery

The results show generally a higher potential for biogas production than bioethanol production from fruit and vegetable peel LW, which is in accordance with the findings of Dulo et al. (2022). Biogas energy from unavoidable banana, plantain and cooking banana peel waste, which was calculated to have the highest potential, could have produced 7 435.6 GWh electricity and 9 294.5 GWh heat[9]. This is equivalent to 6.6% of the annual consumption in electricity and 34.1% of the annual consumption in heat of the Netherlands (CBS, 2022; RVO, 2020). This could have supported 12.0 million households in electricity and 15.5 million households in heat per year[10]. Other interesting LW feedstock for biogas production are orange peel waste (which could have provided 2.9 million households in electricity and 3.7 million households in heat), mango, guava and mangosteen peel waste (which could have provided 1.9 million households with electricity and 2.5 million households with heat per year), onion and shallot peel LW (which could have provided 1.8 million households with electricity and 2.3 million households with heat per year), and pineapple peel waste (which could have provided 0.8 million households with electricity and 1.0 million households with heat per year)[9][10].

Regarding the best sources for bioethanol production determined in this report, energy from bioethanol could have supported 3.6 million households using cantaloupe and other melon peel LW, 3.5 million households in heat using banana, plantain and cooking banana peel waste, 1.4 million households using lemon and lime peel waste, 1.2 million households using mango, guava and mangosteen peel waste and 1.2 million households using orange peel waste[10].

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[7] Using the same assumptions as in Dulo et al. (2022): 1:5 (w/w) flavonoid dye to fabric ratio and 610g/m^2 wool fabric weight (Guinot et al., 2008)

[8] Using the same assumptions as in Dulo et al. (2022): 1% (w/w) tanning process from tannin (Pinto et al., 2013)

[9] Using the same assumptions as in Dulo et al. (2022), where biogas energy can be converted up to 40% as electricity and up to 50% as heat (Pöschl et al., 2010)

[10] Assuming an average consumption of 620 kWh electricity and 600 KWh heat annually for an household as in Dulo et al. (2022)

4.2. Relevance of the research

Although research has thrived in recent decades on identifying causes and finding solutions to tackle FLW generation, unavoidable FLW has been neglected. This is notably due to a confusion in definitions on what should be considered as FLW (Boiteau & Pingali, 2023; FAO, 2019b; Teigiserova et al., 2020). The definitions given by the FAO (2019b) do not explicitly refer to the degree of avoidability of FLW. Nevertheless, unavoidable FLW is being generated worldwide, and needs to be correctly managed to achieve more sustainable global waste management systems.

For the first time in research, unavoidable FVLW was quantified at the global level, and the results show that this is generated in significantly high amounts. If not handled properly, this rises environmental issues similar to avoidable FLW. This research also identifies hotspots in the fruit and vegetable value chains, showing that the fruit value chain results in higher unavoidable LW than the vegetable value chain, and that the R&C stages results in higher unavoidable waste than the processing stage in unavoidable loss. Regions generating the highest FLW generations were also identified. These results contribute to the achievement of the SDG 12.3 by quantifying the extent of unavoidable FVLW generation and by identifying hotspots that need to be prioritized by measures of intervention.

However, this also shows a significant feedstock that could offer a high potential of valorisation. Valorisation assessment of FLW are a necessary step to move away from landfill and incineration, which are unsustainable EoL treatments (Slorach et al., 2019; Talan et al., 2021), and to investigate the potential of more value-creating pathways which contribute to a circular bioeconomy for a more sustainable future (Said et al., 2023; Sharma et al., 2021). Additionally, whereas FLW generation has environmental, social, and economic impacts (FAO, 2019b; UN, 2015), FLW valorisation could represent environmental, social, and economic benefits. Indeed, whereas industries need to reduce their demand of fossil fuels and other petroleum derivatives, FLW can be used as an alternative feedstock to primary materials, which reduces pressure on natural resources (Cherubini, 2010; Plazzotta & Manzocco, 2019). Moreover, this offers the possibilities for new businesses and creates job opportunities (Boiteau & Pingali, 2023; Teigiserova et al., 2020). Specifically, valorisation of unavoidable FLW is necessary as what is unavoidable cannot simply be prevented (Teigiserova et al., 2019). Whereas global efforts should most importantly aim at the reduction of avoidable FLW generation (FAO, 2019a), unavoidable FLW is a feedstock that is not expected to significantly fluctuate and is thus more stable and consequently more reliable to be used for innovative products and technologies. This report shows that unavoidable FVLW has the potential to be valorised in many ways. If strict safety measures are applied, FVLW can be used in food and feed as a substitute to some supplements and additives, reducing resources use to produce them. The continuously growing body of research as well as the present results show that FVLW has a high potential to be used as a low-cost feedstock in biobased material production, if challenges of scaling-up are overcome. FVLW can also contribute to the continuously growing global markets of biofertilizers and biofuels. Taking into account the nature of the FLVW streams, the results suggest that an optimal FLW management system should be an adequate mix of various valorisation pathways, as previously argued (Esparza et al., 2020). In regard to the SDG 12.3, efforts should aim at preventing FLW that can be avoided and at valorising FLW that cannot be avoided. Moreover, these results bring a positive contribution to other international aspirations, such as SDG 7.2 on increasing the renewable energy share in the global energy mix by developing FLW-based biofuels, and SDG 8.4 on promoting sustainable production and resource efficiency.

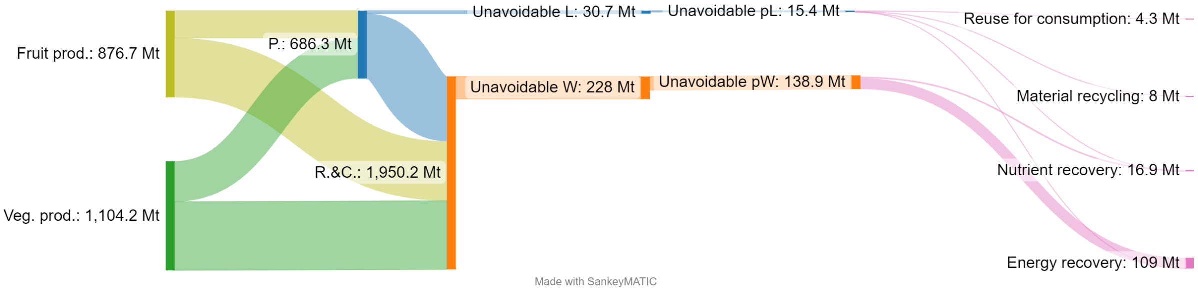

Figure 4.1: Fruit and vegetable value chain at the global level in 2020. In pink is the unavoidable FVLW that could have been valorised based on the valorisation assessment. Avoidable FVLW is not included. (Veg. = vegetable; prod. = production; P. = processing stage; R.&C. = retail and consumption stages; L. = loss; W. = waste; pL = peel loss; pW = peel waste)

4.3. Limitations

The results and the conclusions of this report have to be nuanced regarding the actual feasibility of the valorisation possibilities assessed for unavoidable FVLW (Section 4.3.1) and regarding the limitations of the research approach (Section 4.3.2).

4.3.1. Limitations of the valorisation assessment

Food loss and waste management hierarchy: from concept to application

The (food) loss and waste management hierarchy is an attractive tool, as it provides a clear message on the preference and the prioritization of the EoL treatments. For this matter, it has already been used to guide legislation on waste management, notably in the United States or the European Union (Dijkgraaf & Vollebergh, 2004; Ewijk & Stegemann, 2016). However, its practical application is yet to be proven. In reality, decision-makers and actors of the waste management sector are still prioritizing more practical aspects, such as ensuring safe transportation and disposal of waste (Ewijk & Stegemann, 2016; Wilkinson, 2002). Generally, current efforts are concentrated on avoiding landfill by imposing tax (Mazzanti & Zoboli, 2008), or on supporting recycling of non-biodegradable material waste and composting of FLW (Gertsakis & Lewis, 2003). Policies are still hardly addressing the upper-ranked options of the hierarchy, such as prevention (Ewijk & Stegemann, 2016).

Moreover, the hierarchy only offers partial guidance on waste management. Indeed, Ewijk and Stegemann (2016) pointed out that the hierarchy advices on a direction to take for managing waste, by assessing which EoL treatment to favour over another one, but does not provide a clear end-goal at which to aim in order to have a sustainable waste management system. This leaves the possibility for a wide interpretation of what to consider to be the best possible management practices (Ewijk & Stegemann, 2016), which prevents an harmonization of policies towards the achievement of common objectives, notably regarding the SDGs (Bandola-Gill et al., 2022).

Additionally, the waste management hierarchy completely overlooks any possible trade-offs, notably financial ones, that could arise between the application of the various EoL treatments and potential impacts this would have on other sectors, such as energy and transport. These are however essential information for decision-makers, and thus prevents the use of the waste management hierarchy in legislation (Ewijk & Stegemann, 2016; Papargyropoulou et al., 2014).

To reinforce its relevance in legislation, it would thus be important to demonstrate how the waste management hierarchy can concretely guide in the achievement of international waste reduction goals, such as the SDG 12.3. The environmental, social and economical benefits that would occur from its application should be more transparently communicated, especially regarding the adoption of upper-ranked EoL treatments. In this regard, other tools could be used additionally to the hierarchy, as for instance Cost-Benefit Analysis, Life Cycle Assessment (LCA), and Social Life Assessment (s-LCA) (Mak et al., 2020; Papargyropoulou et al., 2014).

Technical and legislative challenges of fruit and vegetable loss and waste valorisation

The extent to which the valorisation pathways evaluated are currently applicable is another limitation of the valorisation assessment. Indeed, most of the innovative technologies covered in this report are still at an early stage of research (Imbert, 2017) and many barriers for their expansions still remain. The high heterogeneity of their composition, their low-calory content, their fast perishability, and the difficulty of extraction and separation of compounds of interest are all factors affecting the valorisation of unavoidable FVLW (Esparza et al., 2020; Otles & Kartal, 2018; Sagar et al., 2018). Additionally, there are still insufficient legislative supports for these innovative technologies, high financial costs related to their development and an insufficient market demand (Mak et al., 2020). For some sectors, such as the cosmetic industry or the pharmaceutical one, it is also of uttermost importance to guaranty the purity of their products, which is still a technological and an economical difficulty when working with FLW (Freitas et al., 2011). More investments are thus needed to support research and accelerate the development of FLW-based technologies (Kretschmer et al., 2013; Lin et al., 2013). Moreover, strict legislation is needed around FLW use in food, feed and bio-based productions to ensure a safe use and the good quality of the products (Mak et al., 2020).

Logistics of food loss and waste management

Another main challenge that adds to the complexity of FVLW waste management and that has not been covered in this report is the logistics needed for FVLW disposal, collection, transport and treatment. Due to the nature of FVLW and to avoid further deterioration of the quality, efficient and organized logistics that prioritize short circuits are needed (Dulo et al., 2022; Galanakis, 2012; Karmee, 2016). This is still a significant challenge in most parts of the world, as this requires a high level of coordination of a wide range of stakeholders (Kretschmer et al., 2013; Lin et al., 2013). Planning such logistics is done at the national and local levels by examining context-specific factors, such as population density, type of area (urban or rural) and climate, which would result in different local optimal FLW management systems (Panaretou et al., 2021). However, this needs to be achieved with a common global vision, and monitoring is essential to track progress towards the achievement of the SDGs (Wilson et al., 2015).

Consumer perception

Lastly, public perception on these innovative technologies is an important factor for their acceptance and development (Morone & Imbert, 2020), which can thus affect the feasibility of FVLW valorisation. Consumers are still insufficiently informed on possibilities of FVLW valorisation (Mak et al., 2020), which can lead to mistrust and challenge market penetration of FVLW-based products (Moshtaghian et al., 2021). This is especially true for valorisation pathways aiming at the extraction and the use of FVLW compounds for food production. Even with strict regulations on FVLW reuse for food production purposes, consumers tend to show aversion towards new types of food products or new food technologies (Cox & Evans, 2008). Many factors can affect consumer's perception on FVLW-based products (Moshtaghian et al., 2021), but informing on these innovative products surely increases their social acceptance (Morone & Imbert, 2020). It is thus essential to promote communication of these valorisation pathways, and this can be coupled to as a supporting policy framework through subsidies to help their entry to the market (Dabbert et al., 2017; Dietz et al., 2018).

4.3.2. Limitations of the research approach

FAOSTAT database

The data used in this report is retrieved from FAOSTAT, which relies on some assumptions, as some data points are imputed or estimated. Nevertheless, it remains a reliable database that has been extensively used in scientific research, notably for FLW quantification (Amicarelli, Bux, et al., 2021; Caldeira et al., 2019; Mayo-Bruinsma, 2014). Additionally, FAOSTAT does not disaggregate data between the retail stage and the consumption stage. This is in accordance with the definitions of food loss and food waste as phrased in the SDG 12.3, where food loss includes all reductions in mass of food before retail (excluding pre-harvest loss) and where food waste includes all reductions of food at the retail and consumption stages. However, some trends in the results regarding unavoidable waste that were interpreted as generated at the consumption stage might actually be generated at the retail stage for reasons that are thus not identified in this report. Conducting a similar research with data disaggregating between these two stages could thus bring additional information.

Assumption on cultural edibility

It is possible that the assumption on cultural edibility used in this report to determine fruit and vegetable parts discarded by the end-consumer (based on what the author of this report eats, who is a French woman living in the Netherlands without any specific health and diet condition) influenced the results for unavoidable waste and led to an overestimation. For example, mango peel was considered in this report as inedible and thus discarded by the end-consumer, although it is typically used to add flavour to meals in some countries of industrialised Asia and South-east Asia (Fasoli & Righetti, 2013). However, in the database on fruit and vegetable parts used in this report, the same edibility status is given from a cultural and nutritional perspective for most parts (only 21 out of the 209 fruit and vegetable parts in the database are considered culturally inedible and nutritionally edible). The majority of the parts that are culturally inedible in the database are thus also nutritionally inedible. This means that the potential overestimation of unavoidable waste due to a variation in cultural edibility across world regions is limited. Future studies could conduct a similar research as the present report with data reflecting more accurately cultural edibility for each world region to determine whether this would lead to a different trend in the results. However, such an analysis would also be limited by the fact that edibility perception is not only cultural-dependent, but also varies across individuals from a same cultural background (Teigiserova et al., 2020). This is well illustrated in Zhao et al. (2023), who conducted a survey of consumption preferences of the Chinese population regarding fruit peels, and whose results show a high variation of eating habits across individuals.

Already implemented strategies for valorisation of unavoidable loss and waste

The MFA made in this report to quantify unavoidable FVLW did not take into account potential strategies already implemented by industries, end-consumers or actors of the waste management sector to valorise unavoidable FVLW. For instance, composting is already a commonly-applied EoL treatment (Esparza et al., 2020; Tlais et al., 2020), by end-consumer and industries (Barrena et al., 2014). Use of food loss as animal feed is also an already applied valorisation pathway (Dou et al., 2018), and food waste is also commonly used in rural areas to feed their livestock (Rajeh et al., 2021). Regarding bio-based products, an increasing number of businesses are slowly emerging using FVLW as an opportunity to create value from it (Donner & de Vries, 2023). However, these initiatives remain at a small-scale level. The results of this report remain a relevant indication of all the potential opportunities of valorisation possible from unavoidable FVLW at a global level.

Scope of the valorisation assessment

It was decided for this report to only study one category of FVLW stream in the valorisation assessment due to time constraints. Based on the MFA results, peel was chosen. Nonetheless, this does not mean that other categories do not represent opportunities of valorisation. For instance, research has also grown regarding potential valorisation pathways of seed (Almasi et al., 2021; do Nascimento Marques et al., 2019; Lucarini et al., 2018; Tesfaye et al., 2022). Future research could investigate these other categories to provide further information on the valorisation potential of FVLW.

Along the same lines, not all existing valorisation pathways were covered in this study, and many more could have been included, such as other high value compounds also attractive for industrial applications (e.g., fiber, starch, carotenoid, limonene, lactic acid or acetic acid) or other biofuels (e.g., biohydrogen, biodiesel or biobutanol). This research aimed at providing a first overview of the possibilities of valorisation of FVLW, and future studies could conduct a more complete valorisation assessment.

Lastly, the valorisation part was conducted at the global level, as this is a relevant scope in the achievement of the SDG 12.3. However, it is also relevant to adopt a similar approach at a more disaggregated level, such as a regional or national level, as it also can provide more accurate information on solutions that are feasible locally taking into account context-specific conditions, such as logistics and technological development.

5

Conclusion

> *"Inevitable food waste, if quantified and valorised rightly, ultimately leads to the economic, environmental and social sustainability."*
> *Talan et al. (2021).*

5.1. Answers to the research questions

In this Section is provided a summary of the answers provided in Chapters 3 and 4 to the sRQs and the main research questions. The sRQs were as follows:

1. *How much unavoidable FVLW is generated per world region ?*

Figure 3.1 shows for each world region the amount of unavoidable fruit loss and unavoidable food waste generated in 2020, both in terms of mass and in terms of percentage of the total domestic supply lost and wasted. Latin America generated the most unavoidable fruit loss. This can be due to the region being one of the highest global producers of processed fruits and a potential lower development of processing technologies compared to other regions. Industrialised Asia generated the most unavoidable fruit waste, which is mainly due to an important amount of watermelon peels being discarded.

Figure 3.3 shows these results for vegetables. Europe and North America generated the most unavoidable vegetable loss. This can be explained by the fact that these two regions are among the highest processed vegetable producers, especially of maize. Industrialised Asia generated the most unavoidable vegetable waste, which could have been caused by the recent boom in the Chinese catering industry.

2. *How much of the global production of fruits and vegetables do unavoidable loss and unavoidable waste represent respectively ?*

26.5 Mt of unavoidable fruit loss was generated globally in 2020, which represented 3.0% of the total fruit production for that year. Additionally, 175.2 Mt of unavoidable fruit waste was generated which represented 20.0% of the total fruit production. 4.2 Mt of unavoidable vegetable loss and 52.8 Mt of unavoidable vegetable waste were generated, which represented 0.4% and 4.8% respectively of the total vegetable production of that year.

Overall, there was a higher generation of unavoidable LW from the R&C stages that the processing stage, observable both for fruits and vegetables and across almost all regions. These trends are different than the ones observed in research on avoidable FLW. Inedible parts of food are discarded when being processed, but since a higher proportion is directly brought to the retail stage as fresh, these parts are discarded at the consumption stage, resulting in higher amounts of unavoidable waste than unavoidable loss.

3. *How much of each FVLW stream is generated globally ?*

Figure 3.5 shows the amount of unavoidable fruit and vegetable loss as well as unavoidable fruit and vegetable waste generated globally in 2020 aggregated into categories of streams.

4. *What is the largest FVLW stream ?*

Peel stands out as the category of LW streams having been the most generated in 2020. Peel represented 55.1% of all unavoidable fruit loss, 68.7% of all unavoidable fruit waste, 19.2% of all unavoidable vegetable loss and 35.1% of all unavoidable vegetable waste in 2020. Peel is a significant category of by-products from food processing industries and a significant category of waste from the R&C stages, discarded because inedible or due to unpleasant texture or aftertaste.

5. *How can the calculated FVLW be valorised following the FLW management hierarchy ?*

The valorisation assessment was only focusing on fruit and vegetable peel loss and waste. The first level of the hierarchy is prevention, which cannot be considered for unavoidable FVLW as what is unavoidable cannot simply be prevented. The second level of the hierarchy is reuse for human consumption. Following strict safety measures to ensure its good quality, unavoidable fruit and vegetable loss can be used by extracting protein and sugar and by using it in food production, such as in the making of spaghetti protein-enriched or to produce natural sweetener to be used in drinks and food. The third level of the hierarchy is reuse for animal consumption. Again, with strict measures, unavoidable fruit and vegetable loss can be used as additives in feed production. In total, it was calculated that 4.3 Mt of unavoidable fruit and vegetable loss generated in 2020 could have been valorised in food and feed productions. The fourth level of the hierarchy is material recycling. Unavoidable fruit and vegetable loss can be used by extracting flavonoid, tannin and pectin, which are high-value compounds interesting to use in the production of biobased materials. It was calculated that 8 Mt of unavoidable fruit and vegetable loss generated in 2020 could have been valorised according to this valorisation pathway. The fifth level of the hierarchy is nutrient recovery. Unavoidable FVLW can be used to produce biofertilizers rich in P, K and N. It was calculated that 16.9 Mt of unavoidable FVLW generated in 2020 could have been valorised according to this valorisation pathway. The sixth level of the hierarchy is energy recovery. Unavoidable FVLW can be used to produce biofuels, notably bioethanol and biogas. It was calculated that 109 Mt of unavoidable FVLW generated in 2020 could have been valorised according to this valorisation pathway. The last level of the hierarchy is disposal. It is not desirable, and should be avoided whenever possible.

6. *Which FVLW streams show the highest valorisation potential ?*

Table 3.2 shows the streams of unavoidable fruit and vegetable peel loss and waste showing the highest potential for each valorisation pathway. According to the FLW management hierarchy, the highest levels must be prioritized, and when they are not suitable, the lowest levels must be considered.

Considering the aforementioned information, the two research questions can be answered:

1. ***How much unavoidable fruit and vegetable loss and waste (FVLW) is currently being generated at the global level ?***

In 2020, a total of 258.7 Mt of unavoidable FVLW was generated. This represents 13.1% of the global fruit and vegetable production for that year.

2. ***How can unavoidable FVLW be valorised ?***

Unlike avoidable FVLW, unavoidable FVLW cannot simply be prevented. To avoid landfill and incineration, it can rather be valorised to contribute to a circular bioeconomy. Hence, environmental, social, and economic impacts from FVLW generation can be turned into environmental, social, and economic benefits, by using FVLW as an alternative feedstock to primary materials, which reduces pressure on natural resources, to create innovative products and new businesses, which create job opportunity. FVLW can be valorised in a variety of ways, whether in food and feed productions, with material recycling in the production of biobased materials, with nutrient recovery in the production of biofertilizers, or in energy recovery in the production of biofuels. Hence, the optimal FLW management system is found to be a mix of various valorisation pathways. This contributes to the achievement of the SDG 12.3, by showing that global efforts should aim at preventing FLW that can be avoided and valorising FLW that cannot be avoided.

5.2. General conclusion

These results bring new information to the discussion of global FLW and the challenge of achieving SDG 12.3. It shows the importance of disaggregating in research between what can be considered avoidable and unavoidable, as unavoidable FLW cannot simply be prevented, and in order to evaluate the best management strategies, quantifying it and identifying hotspots is necessary. For the first time, an overview and a comparison of valorisation pathways for unavoidable fruit and vegetable loss and waste is provided at the global level. By quantifying at the level of fruit and vegetable parts, more detailed information is given on the generation of LW and on the possibilities for their valorisation. Recently, research has grown around different ways of getting value from FLW, and such an overview as the one done in this report allows to bring further information by classifying the relevant valorisation pathways and identifying the FLW feedstocks with the highest potentials.

More similar research is needed in the future, covering other food commodities and more valorisation strategies to allow for an even better perspective on the current situation regarding global FLW and on the possibilities of valorisation.

Additionally, it is important to mobilize resources for the technological progress of high-value compound recovery from food loss, as most of the current extraction yields reported remain at a lab-scale. And although loss generated at the processing stage is already being valorised, waste generated at the consumption stage remains in higher proportions. It is thus necessary to support the current research investigating its valorisation in other ways than incineration and landfill.

5.3. Personal reflections

In this Section, the author summarizes what she has learned during this research.

Regarding planning, the author realised how important it is to carefully prepare all parts of the research before starting. Whereas the first part of the report on FLW quantification was well planned and the choice of the method to achieve the goals was clearly decided prior to starting the research, the method to conduct the second part on FLW valorisation was not clearly determined from the beginning. This has led to confusion half-way of the research on how to conduct the second part, due to a lack of a clear overview on the overall goals of the research. Hence, it would have been more time-efficient to take extra time at the start to formulate a clear plan, even if some details are modified along the way and if it would have meant slightly delaying the start of the research.

Regarding the methodology, conducting the MFA part has been a nice challenge. The process has been a continuous learning process, during which the author has been capable of finding solutions rather autonomously. For the valorisation part, finding the suitable methodology has been difficult, as it is a type of research that has hardly been done before, and especially at the global level. Nevertheless, the author feels that this report brings an innovative approach and results to the current research on food loss and waste.

Concerning the results, although the MFA code has been written to ensure that mistakes could be debugged and data abnormalities could be identified, a data anomaly was found at a late stage of the research. This resulted in unexpected time needed to fix the problem, which impacted the research planning. A particular attention should thus be brought in checking all possible outputs from the code to ensure the validity of the results, rather than discovering bad surprises at a later stage of the research.

Overall, this project has taught the author how to conduct a relatively long research project independently, as well as valuable skills in her future career of industrial ecologist.

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A

Fruit and vegetable parts: References

When a range of values for the percentage of a part was given, the average was taken.

A.1. Fruits

Apples

(1) Parts: juice (70-75%), stem (0,25-0,3%), peel (13%), seed (1-1,2%), pulp (10,75%-15,5%)
(2) Harvest: only fruit harvested

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Apricots

(1) Parts: pit shell (20-25%), seed (15-20%)
What remains is assumed to be 2/3 of juice and 1/3 of pulp+peel (with equal shares for pulp and peel).
(2) Harvest: only fruit harvested

References
(1)

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(2)

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Avocados

(1) Parts: peel (16%), seed (15%), pulp (69%)
(2) Harvest: only fruit harvested

References
(1)

Charles, A. C., Dadmohammadi, Y., & Abbaspourrad, A. (2022). Food and cosmetic applications of the avocado seed: A review. *Food and Function*, *13*(13), 6894–6901. https://doi.org/10.1039/d1fo02438h

(2)

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Bananas

(1) Parts: peel (35%), pulp (65%)
(2) Harvest: Tree is cut to get the fruits that are high or just the branch holding the bananas is cut, but the FAOSTAT only includes the fruit itself in its account.

References
(1)

Zou, F., Tan, C., Zhang, B., Wu, W., & Shang, N. (2022). The valorization of banana by-products: Nutritional composition, bioactivities, applications, and future development. *Foods*, *11*(20), 3170. https://doi.org/10.3390/foods11203170

(2)

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Blueberries

(1) Parts: peel+pulp (15-25%), juice (70%-80%), seed (5%)
Equal shares are assumed between peel and pulp.
(2) Harvest: only fruit harvested

References
(1)

Chang, Y., Wu, T., Chu, X., Tang, S., Cao, W., Liang, F., Fang, Y., Pan, S., & Xu, X. (2020). Fermented blueberry pomace with antioxidant properties improves fecal microbiota community structure and short chain fatty acids production in an in vitro mode. *LWT*, *125*, 109260. https://doi.org/10.1016/j.lwt.2020.109260

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Cantaloupes and other melons

(1) Parts: peel (25%), seed (7%)
What remains is assumed to be 1/3 of pulp and 2/3 of juice.
(2) Harvest: only fruit harvested
(3) Edibility: melon seed is generally discarded in Western-culture diet although nutritionally edible

References
(1)

Gómez-Garcıa, R., Campos, D. A., Aguilar, C. N., Madureira, A. R., & Pintado, M. (2020). Valorization of melon fruit (cucumis melo l.) by-products: Phytochemical and biofunctional properties with emphasis on recent trends and advances. *Trends in Food Science and Technology*, *99*, 507–519. https://doi.org/10.1016/j.tifs.2020.03.033

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Populer WrldVideo. (2020). World's Largest Watermelon Farm. - Tons of Watermelon Growing Like This. — youtube.com [[Accessed 19-Apr-2023]]. https://www.youtube.com/watch?v=mG3unLGxWMY

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Cashewapple

(1) Parts: It is assumed that 2/3 of the fruit is juice and 1/3 is peel+pulp (with equal shares between peel and pulp).
(2) Harvest: fruit harvested with the nut, but FAOSTAT has a separate category for the nut and here only the fruit is taken into account.

References
(2)

Access Agriculture. (2020). Preparing cashew apple juice (Summary) — youtube.com [[Accessed 19-Apr-2023]]. https://www.youtube.com/watch?v=jmOk7xGu-k0
Noal Farm. (2020a). How Cashew Nut Farming and Processing - Cashew Cultivation Asian Technology — youtube.com [[Accessed 19-Apr-2023]]. https://www.youtube.com/watch?v=DEEpLsleTls

Cherries

(1) Parts: pit shell+seed (12-15%)
Of the given percentage, it is assumed that 2/3 is seed and 1/3 is pit shell. Peel, pulp and stem are assumed to be in similar shares than for sour cherries. What remains is assumed to be juice.
(2) Harvest: fruit harvested with its stem

References
(1)

Korlesky, N. M., Stolp, L. J., Kodali, D. R., Goldschmidt, R., & Byrdwell, W. C. (2016). Extraction and characterization of montmorency sour cherry (prunus cerasus l.) pit oil. *Journal of the American Oil Chemists' Society*, *93*(7), 995–1005. https://doi.org/10.1007/s11746-016-2835-4

(2)

Noal Farm. (2021b). Cherries Harvest by hand and Harvest by machine - Cherry sorting and packaging Factory — youtube.com [[Accessed 19-Apr-2023]]. https://www.youtube.com/watch?v=4eAe_z0FsJQ&vl=fr

Cranberries

(1) Parts: juice (65-90%), peel+seed+pulp (10-35%)
It is assumed that peel, pulp and seed share equal parts.
(2) Harvest: only fruit harvested

References
(1)

Dienaitė, L., Pukalskienė, M., Pereira, C. V., Matias, A. A., & Venskutonis, P. R. (2020). Valorization of european cranberry bush (viburnum opulus l.) berry pomace extracts isolated with pressurized ethanol and water by assessing their phytochemical composition, antioxidant, and antiproliferative activities. *Foods*, *9*(10), 1413. https://doi.org/10.3390/foods9101413

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Ocean Spreay. (2015). The Life Cycle of a Cranberry Harvest — youtube.com [[Accessed 19-Apr-2023]]. https://www.youtube.com/watch?v=F1m7tCAA8Zk

Currants

(1) Parts: It is assumed that 2/3 is juice and 1/3 peel+seed (with equal shares between peel and seed).
(2) Harvest: only fruit harvested

References
(2)

Tractorspotter. (2017). Red & Black Currant Harvest - MaVeBo Lewedorp | SFM Technology Harvester — youtube.com [[Accessed 19-Apr-2023]]. https://www.youtube.com/watch?v=9eXbPcNVW2M

Dates

(1) Parts: seed (5-15%), pulp (85-95%)
(2) Harvest: only fruit harvested
(3) Edibility: date seed is generally discarded in Western-culture diet although nutritionally edible

References
(1)

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Kamal, H., Habib, H. M., Ali, A., Show, P. L., Koyande, A. K., Kheadr, E., & Ibrahim, W. H. (2023). Food waste valorization potential: Fiber, sugar, and color profiles of 18 date seed varieties (phoenix dactylifera, l.) *Journal of the Saudi Society of Agricultural Sciences*, *22*(2), 133–138. https://doi.org/10.1016/j.jssas.2022.11.001

(2)

Noal Farm. (2018a). Dates palm Harvesting by Shaking Machine - Packing Dates Modern Agricultural Technology — youtube.com [[Accessed 19-Apr-2023]]. https://www.youtube.com/watch?v=i8qpqiWc00g

(3)

Kamal-Eldin, A., B Hashim, I., & O Mohamed, I. (2012). Processing and utilization of palm date fruits for edible applications. *Recent Patents on Food, Nutrition & Agriculture*, *4*(1), 78–86.

Figs

(1) Parts: It is assumed that 1/3 is juice, 1/3 is seed and 1/3 is peel and pulp (with equal shares between peel and pulp).
(2) Harvest: only fruit harvested

References
(2)

Noal Farm. (2020b). Japan Fig Farm and Harvest - Giant Fig Cultivation Technology — youtube.com [[Accessed 19-Apr-2023]]. https://www.youtube.com/watch?v=gbQt3uGEONw

Gooseberries

(1) Parts: seed+peel (27,4%)
It is assumed that seed and peel have equal shares. It is further assumed that 5% is husk and 5% is stem, and what remains is 2/3 juice.
(2) Harvest: Fruit is harvested with its stem and its husk

References
(1)

Popova, V., Petkova, Z., Ivanova, T., Stoyanova, M., Mazova, N., & Stoyanova, A. (2021). Lipid composition of different parts of cape gooseberry (physalis peruviana l.) fruit and valorization of seed and peel waste. *Grasas y Aceites*, *72*(2), e402. https://doi.org/10.3989/gya.1256192

(2)

Fischer, G., & Melgarejo, L. M. (2020). The ecophysiology of cape gooseberry (physalis peruviana l.) - an andean fruit crop. a review. *Revista Colombiana de Ciencias Hortícolas*, *14*, 76–89. https://doi.org/10.17584/rcch.2020v14i1.10893

Grapes

(1) Parts: juice (75%), pulp (6,5-9,5%), peel (12,5%), seed (3-6%), stem (2,5-7,5%)
(2) Harvest: fruit harvested with its stem

References
(1)

Dávila, I., Robles, E., Egüés, I., Labidi, J., & Gullón, P. (2017). The biorefinery concept for the industrial valorization of grape processing by-products. In *Handbook of grape processing by-products* (pp. 29–53). Elsevier. https://doi.org/10.1016/b978-0-12-809870-7.00002-8

Gómez-Brandón, M., Lores, M., Insam, H., & Domınguez, J. (2019). Strategies for recycling and valorization of grape marc. *Critical Reviews in Biotechnology*, *39*(4), 437–450. https://doi.org/10.1080/07388551.2018.1555514

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New Holland North America. (2019). Modern Grape Harvesting - Amazing Totals — youtube.com [[Accessed 19-Apr-2023]]. https://www.youtube.com/watch?v=1I6AF24zfSM

Noal Farm. (2022b). Amazing Grape Harvesting and Processing Grape Juice - Modern agricultural harvesting machines — youtube.com [[Accessed 19-Apr-2023]]. https://www.youtube.com/watch?v=mIDof6rrqqM

Kiwi fruits

(1) Parts: It is assumed that 1% is seed, 2/3 is juice and 1/3 is peel+pulp (with equal shared between peel and pulp).
(2) Harvest: only fruit harvested
(3) Edibility: kiwi fruit peel is generally discarded in Western-culture diet although nutritionally edible

References
(2)

Noal Farm. (2018b). Kiwi Fruit Harvesting Picking and Packing - Amazing Agriculture Kiwi Farm Technology — youtube.com [[Accessed 19-Apr-2023]]. https://www.youtube.com/watch?v=NIwLvshWyAw

(3)

Julson, E. (2018). Can You Eat Kiwi Skin? — healthline.com [[Accessed 07-08-2023]]. https://www.healthline.com/nutrition/eating-kiwi-skin

Lemons and limes

(1) Parts: juice (50%), peel (25-27,5%), seed (10-20%), pulp (2,5-15%)
(2) Harvest: only fruit harvested
(3) Edibility: lemon peel is generally discarded in Western-culture diet although nutritionally edible

References
(1)

Suri, S., Singh, A., & Nema, P. K. (2022). Current applications of citrus fruit processing waste: A scientific outlook. *Applied Food Research*, *2*(1), 100050. https://doi.org/10.1016/j.afres.2022.100050

(2)

The Produce Nerd. (2017a). How Mandarins are Harvested and Packed at Cuties Citrus — youtube.com [[Accessed 19-Apr-2023]]. https://www.youtube.com/watch?v=0Hl-VCExpd4

(3)

Lang, A. (2019). 9 Benefits and Uses of Lemon Peel — healthline.com [[Accessed 07-08-2023]]. https://www.healthline.com/nutrition/lemon-peel

Locust beans (carobs)

(1) Parts: pulp (90%), seed (10%)
(2) Harvest: only fruit harvested

References
(1)

Zhu, B.-J., Zayed, M. Z., Zhu, H.-X., Zhao, J., & Li, S.-P. (2019). Functional polysaccharides of carob fruit: A review. *Chinese Medicine*, *14*(1). https://doi.org/10.1186/s13020-019-0261-x

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AustralianCarobCo. (2013). The Australian Carob Co. Harvesting Carobs — youtube.com [[Accessed 19-Apr-2023]]. https://www.youtube.com/watch?v=8tGJ2ZJ3_KY

Mangoes, guavas and mangosteens

For simplicity, only data from mangoes were taken.
(1) Parts: peel (7-14%), pit shell (6%), seed (9-40%), pulp+juice (33-85%)
Of the given percentage, it is assumed that 1/2 is pulp and juice 2/3 is juice.
(2) Harvest: only fruit harvested
(3) Edibility: mango peel and seed are generally discarded in Western-culture diet although nutritionally edible

References
(1)

Okino-Delgado, C., Prado, D., Pereira, M. S., Camargo, D. A., Koike, M. A., & Fleuri, L. F. (2020). Mango. In *Valorization of fruit processing by-products* (pp. 167–181). Elsevier. https://doi.org/10.1016/b978-0-12-817106-6.00008-3

(2)

Noal Farm. (2021c). How to Harvest Mango fruit and Processing - Awesome Mango Juice Processing - Mango Farm — youtube.com [[Accessed 19-Apr-2023]].

(3)

Kubala, J. (2020). Can You Eat Mango Skin? — healthline.com [[Accessed 07-08-2023]]. https://www.healthline.com/nutrition/mango-skin#benefits

Torres-León, C., Rojas, R., Contreras-Esquivel, J. C., Serna-Cock, L., Belmares-Cerda, R. E., & Aguilar, C. N. (2016). Mango seed: Functional and nutritional properties. *Trends in Food Science &amp Technology*, *55*, 109–117. https://doi.org/10.1016/j.tifs.2016.06.009

Oranges

(1) Parts: juice (50%), peel (25-27,5%), seed (10-20%), pulp (2,5-15%)
(2) Harvest: only fruit harvested
(3) Edibility: orange peel is generally discarded in Western-culture diet although nutritionally edible

References
(1)

Suri, S., Singh, A., & Nema, P. K. (2022). Current applications of citrus fruit processing waste: A scientific outlook. *Applied Food Research*, *2*(1), 100050. https://doi.org/10.1016/j.afres.2022.100050

(2)

Matrix Farm. (2022). Awesome Orange Farming and Harvesting Modern Technology How Orange Juice Is Made In Factory — youtube.com [[Accessed 19-Apr-2023]]. https://www.youtube.com/watch?v=EQGj7GH5qPg

The Produce Nerd. (2017b). How Mandarins are Harvested and Packed at Cuties Citrus — youtube.com [[Accessed 19-Apr-2023]]. https://www.youtube.com/watch?v=0Hl-VCExpd4

(3)

McGrane, K., & Warwick, K. (2021). Can You Eat Orange Peels, and Should You? — healthline.com [[Accessed 07-08-2023]]. https://www.healthline.com/nutrition/can-you-eat-orange-peels

Papayas

(1) Parts: juice (52,96%), peel (8,47%), seeds (6,51%), pulp (32,06%)
(2) Harvest: only fruit harvested
(3) Edibility: papaya seed is generally discarded in Western-culture diet although nutritionally edible

References
(1)

Ayala-Zavala, J., Rosas-Dominguez, C., Vega-Vega, V., & Gonzalez-Aguilar, G. (2010). Antioxidant enrichment and antimicrobial protection of fresh-cut fruits using their own byproducts: Looking for integral exploitation. *Journal of Food Science*, *75*(8), R175–R181. https://doi.org/10.1111/j.1750-3841.2010.01792.x

(2)

Farm Machinery. (2021b). Incredible Modern Agriculture Papaya Harvesting Processing - Amazing Farming Harvest Fruit Process — youtube.com [[Accessed 19-Apr-2023]]. https://www.youtube.com/watch?v=ZMebzeG9_WM

(3)

Ajmera, R., & Arnason, A. (2023). Can You Eat Papaya Seeds? — healthline.com [[Accessed 07-08-2023]]. https://www.healthline.com/nutrition/papaya-seeds#:~:text=Papaya%20is%20a%20fruit%20beloved,edible%20but%20also%20highly%20nutritious.

Peaches and nectarines

(1) Parts: pit shell+seed (60%)
Equal shares between pit shell and seed are assumed. What remains is 2/3 of juice and 1/3 of peel+pulp (with equal shares between peel and pulp).
(2) Harvest: only fruit harvested

References
(1)

Farag, M. A., Eldin, A. B., & Khalifa, I. (2022). Valorization and extraction optimization of prunus seeds for food and functional food applications: A review with further perspectives. *Food Chemistry*, *388*, 132955. https://doi.org/10.1016/j.foodchem.2022.132955

(2)

The Produce Nerd. (2017c). Peach Harvest and Packing — youtube.com [[Accessed 19-Apr-2023]]. https://www.youtube.com/watch?v=kOlqMDEIfU8

Pears

(1) Parts: It is assumed that 0.5% is seed, and what remains is 2/3 of juice and 1/3 of peel+pulp (with equal shares between peel and pulp).
(2) Harvest: only fruit harvested

References
(2)

Complete Agriculture. (2021d). How To Harvest Pears? - Pears Harvesting and Pears Farming - Pears Agriculture Technology — youtube.com [[Accessed 19-Apr-2023]]. https://www.youtube.com/watch?v=lZvaE1m-3vI

Frumaco Agriculture Technology. (2017). Industrie-Fruit-Harvester (Apple, Pears, Sherry etc) continue driving and harvesting system — youtube.com [[Accessed 19-Apr-2023]]. https://www.youtube.com/watch?v=Wv01nfSRQiw

Persimmons

(1) Parts: It is assumed that 5% is calyx, 2/3 is juice and what remains is pulp+peel (with equal shared between pulp and peel).
(2) Harvest: fruit harvested with its calyx

References
(2)

Complete Agriculture. (2021b). Amazing Dried Persimmon Agriculture Technology - Persimmon Farming and Persimmon Harvesting -Dry Kaki — youtube.com [[Accessed 19-Apr-2023]]. https://www.youtube.com/watch?v=cVox4oN6-Hc

Pineapples

(1) Parts: crown (13%), core (7%), pulp (50%), peel (30%), juice (37%)
(2) Harvest: fruit harvested with its crown
(3) Edibility: pineapple core is generally discarded in Western-culture diet although nutritionally edible

References
(1)

Campos, D. A., Ribeiro, T. B., Teixeira, J. A., Pastrana, L., & Pintado, M. M. (2020). Integral valorization of pineapple (ananas comosus l.) by-products through a green chemistry approach towards added value ingredients. *Foods*, *9*(1), 60. https://doi.org/10.3390/foods9010060

(2)

DOLETube. (2013). DOLE - Harvesting Pineapples — youtube.com [[Accessed 19-Apr-2023]]. https://www.youtube.com/watch?v=wFYEeFpvik8

Modern Tech. (2021). Most Modern Pineapple Harvesting Technology On The World - Amazing Pineapple Juice Processing Line — youtube.com [[Accessed 19-Apr-2023]]. https://www.youtube.com/watch?v=sUubYHj5bC0

(3)

Weiss, J. (2022). Is It Safe to Eat the Core of a Pineapple? — eatingwell.com [[Accessed 07-08-2023]]. https://www.eatingwell.com/article/7965731/is-it-safe-to-eat-the-core-of-a-pineapple/#:~:text=Pineapples%20are%20a%20juicy%2C%20tropical,edible%20and%20filled%20with%20nutrients.

Plantains and cooking bananas

(1) Parts: peel (35%), pulp (65%)
(2) Harvest: Tree is cut to get the fruits that are high or just the branch holding the bananas is cut, but the FAOSTAT only includes the fruit itself in its account.

References
(1)

Zou, F., Tan, C., Zhang, B., Wu, W., & Shang, N. (2022). The valorization of banana by-products: Nutritional composition, bioactivities, applications, and future development. *Foods*, *11*(20), 3170. https://doi.org/10.3390/foods11203170

(2)

DoleTube. (2013). DOLE - Harvesting Bananas — youtube.com [[Accessed 19-Apr-2023]]. https://www.youtube.com/watch?v=_l7sak6Vlq8

Kanaris, P. (2020). Harvesting Bananas! Everything You Need To Know To Grow Your Own Fruit! — youtube.com [[Accessed 19-Apr-2023]]. https://www.youtube.com/watch?v=NsxLZUKm--s

Plums and sloes

For simplicity, only data for plums is taken.
(1) Parts: seed (5%), peel/pulp (15-45%)
For the given percentage, peel and pulp are given equal shares and it is assumed that 5% is pit shell.
(2) Harvest: only fruit harvested

References
(1)

Savic, I. M., & Gajic, I. M. S. (2020). Optimization study on extraction of antioxidants from plum seeds (prunus domestica l.) *Optimization and Engineering*, *22*(1), 141–158. https://doi.org/10.1007/s11081-020-09565-0

(2)

Harvest — Oprema za berbu voca. (2021). Plum Harvest 2020 | Fruit Harvesting Tools — youtube.com [[Accessed 20-Apr-2023]]. https://www.youtube.com/watch?v=eUU-u98KFDY

Weremczuk Agromachines. (2020). Plums (Prune) harvest with FELIX Z harvester | Masina de scuturat prune — youtube.com [[Accessed 20-Apr-2023]]. https://www.youtube.com/watch?v=WMIvfjH_ZZQ

Pomelos and grapefruits

For simplicity, only data for grapefruits is taken.
(1) Parts: juice (50%), peel (25-27,5%), seed (10-20%), pulp (2,5-15%)
(2) Harvest: only fruit harvested
(3) Edibility: peel and seed are generally discarded in Western-culture diet although nutritionally edible

References
(1)

Suri, S., Singh, A., & Nema, P. K. (2022). Current applications of citrus fruit processing waste: A scientific outlook. *Applied Food Research*, *2*(1), 100050. https://doi.org/10.1016/j.afres.2022.100050

(2)

Complete Agriculture. (2019b). How to Harvest Pomelo ? Pomelo Harvesting and Agriculture and Processing Technology — youtube.com [[Accessed 20-Apr-2023]]. https://www.youtube.com/watch?v=WqHosQpJpNs

Grow Plants. (2017). Grapefruit tree - grow, harvest and eat — youtube.com [[Accessed 20-Apr-2023]]. https://www.youtube.com/watch?v=UFobTB3s-cg

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Busch, S. (n.d.). Grapefruit Peel Benefits | Livestrong.com — livestrong.com [[Accessed 07-08-2023]]. https://www.livestrong.com/article/114945-grapefruit-peel-benefits/

Price, A. (2017). 6 Grapefruit Seed Extract Benefits You Won't Believe | Dr.Axe.com — draxe.com [[Accessed 07-08-2023]]. https://draxe.com/nutrition/grapefruit-seed-extract/

Quinces

(1) Parts: It is assumed that 10% is seed, and what remains is 2/3 of juice and 1/3 of peel+pulp (with equal shares between peel and pulp).
(2) Harvest: only fruit harvested

References
(2)

Relaxing Village. (2022). Harvesting quince in the village! cooking pomegranate and quince compote and jam — youtube.com [[Accessed 20-Apr-2023]]. https://www.youtube.com/watch?v=bL3LJwJ5A6A

Raspberries

(1) Parts: It is assumed that 5% is seed, and what remains is given equal shares between juice and pulp.
(2) Harvest: fruit harvested its stem

References
(2)

Noal Farm. (2022f). Red Raspberry Harvesting and Processing - Red Raspberry Cultivation Technology - Raspberry Factory — youtube.com [[Accessed 20-Apr-2023]]. https://www.youtube.com/watch?v=VKh1tW1Ttm4

Sour cherries

(1) Parts: pulp+juice (85,4%), pit shell (11,2%), seed (3,4%)
It is assumed that 5% is stem and what remains is 2/3 of pulp+peel (with equal shares between pulp and peel) and 1/3 of juice.
(2) Harvest: only fruit harvested

References
(1)

Yılmaz, C., & Gökmen, V. (2013). Compositional characteristics of sour cherry kernel and its oil as influenced by different extraction and roasting conditions. *Industrial Crops and Products*, *49*, 130–135. https://doi.org/10.1016/j.indcrop.2013.04.048

(2)

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Strawberries

(1) Parts: It is assumed that 1% is seed, 5% is calyx ans what remains is 2/3 of juice and 1/3 of pulp.
(2) Harvest: fruit harvested with its calyx

References
(2)

AGROBOT. (2018). AGROBOT Robotic Strawberry Harvester — youtube.com [[Accessed 20-Apr-2023]]. https://www.youtube.com/watch?v=M3SGScaShhw

Florida Department of Agriculture and Consumer Services. (2015). Strawberries - Harvesting — youtube.com [[Accessed 20-Apr-2023]]. https://www.youtube.com/watch?v=-53fxf7jdHU

Tangerines, mandarins, clementines

(1) Parts: juice (50%), peel (25-27,5%), seed (10-20%), pulp (2,5-15%)
(2) Harvest: only fruit harvested
(3) Edibility: peel is generally discarded in Western-culture diet although nutritionally edible

References
(1)

Suri, S., Singh, A., & Nema, P. K. (2022). Current applications of citrus fruit processing waste: A scientific outlook. *Applied Food Research*, *2*(1), 100050. https://doi.org/10.1016/j.afres.2022.100050

(2)

The Produce Nerd. (2017a). How Mandarins are Harvested and Packed at Cuties Citrus — youtube.com [[Accessed 19-Apr-2023]]. https://www.youtube.com/watch?v=0Hl-VCExpd4

(3)

Lang, A. (2019). 9 Benefits and Uses of Lemon Peel — healthline.com [[Accessed 07-08-2023]]. https://www.healthline.com/nutrition/lemon-peel

Watermelons

(1) Parts: juice (40-75%), peel (33%), pulp+seed (27%)
It is assumed that pulp and seed have equal parts.
(2) Harvest: only fruit harvested

References
(1)

Hashem, A. H., Hasanin, M. S., Khalil, A. M. A., & Suleiman, W. B. (2019). Eco-green conversion of watermelon peels to single cell oils using a unique oleaginous fungus: Lichtheimia corymbifera AH13. *Waste and Biomass Valorization*, *11*(11), 5721–5732. https://doi.org/10.1007/s12649-019-00850-3

Vinhas, A., Sousa, C., Matos, C., Moutinho, C., & Vinha, A. (2021). *World Journal of Advance Healthcare Research*, *5*, 302–309.

(2)

Maryland Farm and Harvest. (2022). How Watermelons are Harvested | MD FandH — youtube.com [[Accessed 20-Apr-2023]]. https://www.youtube.com/watch?v=hoL1JnxH-2w

Tantum Tech HD. (2022b). Incrível Processo de Cultivo, Colheita e Processamento de Melancias em Estufa e Agricultura Moderna — youtube.com [[Accessed 20-Apr-2023]]. https://www.youtube.com/watch?v=EQHbI7VKmxs

A.2. Vegetables

Artichokes

(1) Parts: choke (30-40%), cup+inner bracts (35-55%), stem+seed+external bracts (5-35%)
It is assumed that there are equal shares between cup and inner bract, that 5% is seed, and that there are equal shares between stem and outer bracts.
(2) Harvest: vegetable harvested with its stem
(3) Edibility: artichoke stem is generally discarded in Western-culture diet although nutritionally edible

References
(1)

Zayed, A., & Farag, M. A. (2020). Valorization, extraction optimization and technology advancements of artichoke biowastes: Food and non-food applications. *LWT*, *132*, 109883. https://doi.org/10.1016/j.lwt.2020.109883

(2)

Food Processing Channel. (2022). Harvesting and Processing Artichokes | Modern Artichoke Harvesting Machine | How to Grow Artichoke — youtube.com [[Accessed 20-Apr-2023]]. https://www.youtube.com/watch?v=YXZGITR4frg

Noal Farm. (2022a). Amazing Agriculture Technology : Artichoke Cultivation - Artichokes Harvest and Processing in Factory — youtube.com [[Accessed 20-Apr-2023]]. https://www.youtube.com/watch?v=K8UQnWP5Q_A

OceanMistFarms. (2008). Artichoke Harvest — youtube.com [[Accessed 20-Apr-2023]]. https://www.youtube.com/watch?v=GjZTvgR-Nfs

(3)

Kleiman, E. (2014). Artichokes: Don't Forget the Stems — evankleiman.com [[Accessed 07-08-2023]]. https://www.evankleiman.com/artichokes-dont-forget-the-stems/

Asparagus

(1) Parts: stem (25-50%)
It is assumed that 10% is tip and what remains is the hard stem.
(2) Harvest: all the aboveground parts are harvested

References
(1)

Chitrakar, B., Zhang, M., Devahastin, S., Adhikari, B., & Zhang, X. (2022). Valorization of asparagus leafy by-product by ionic-liquid extraction and characterization of bioactive compounds in the extracts. *Food Bioscience*, *46*, 101600. https://doi.org/10.1016/j.fbio.2022.101600

Santiago, B., Feijoo, G., Moreira, M. T., & González-Garcıa, S. (2021). Identifying the sustainability route of asparagus co-product extraction: From waste to bioactive compounds. *Food and Bioproducts Processing*, *129*, 176–189. https://doi.org/10.1016/j.fbp.2021.08.005

(2)

Farm Machinery. (2021a). Amazing Growing and Harvesting Asparagus Technology.Asparagus Processing in Factory. Asparagus Farming — youtube.com [[Accessed 20-Apr-2023]]. https://www.youtube.com/watch?v=Yw09uk87YmU

Broad beans and horse beans, green

(1) Parts: pod (20%), husk (10%)
It is assumed that 5% is stem and what remains is pea.
(2) Harvest: only vegetable harvested

References
(1)

Krenz, L. M. M., Grebenteuch, S., Zocher, K., Rohn, S., & Pleissner, D. (2023). Valorization of faba bean (vicia faba) by-products. *Biomass Conversion and Biorefinery*. https://doi.org/10.1007/s13399-023-03779-9

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Dutch Agriculture. (2019). Harvesting broad beans XL | 3X FMC 979 AT | Tuinbonen dorsen | Rijko BV Helmond — youtube.com [[Accessed 20-Apr-2023]]. https://www.youtube.com/watch?v=wIQ5ClWCcVw

Organic Gardening Lovers. (2020). How to Harvest Broad Beans — youtube.com [[Accessed 20-Apr-2023]]. https://www.youtube.com/watch?v=IgB8hUAB37E

Cabbages

(1) Parts: core+outer leaves (20%), inner leaves (80%)
What remains is assumed to be 1/3 of outer leaves and 2/3 of core.
(2) Harvest: only vegetable harvested
(3) Edibility: core is generally discarded in Western-culture diet although nutritionally edible

References
(1)

Nasrin, T. A. A., & Matin, M. A. (2017). Valorization of vegetable wastes. *Food Processing By-Products and their Utilization*, 53–88.

(2)

Agrifoto. (2020). Automatic cabbage harvesting | How sauerkraut is made | Asa-Lift TK-1000E I — youtube.com [[Accessed 20-Apr-2023]]. https://www.youtube.com/watch?v=yFiZYPagYJc

Bonnie Plants. (2020). How To Harvest Cabbage — youtube.com [[Accessed 20-Apr-2023]]. https://www.youtube.com/watch?v=mSDMyA96ip4

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Tokuyasu, K., Yamagishi, K., Ando, Y., & Shirai, N. (2022). Cabbage core powder as a new food material for paste preparation with “nata puree”. *Journal of Applied Glycoscience*, *69*(4), 91–95. https://doi.org/10.5458/jag.jag.jag-2022_0003

Carrots and turnips

For simplicity, only data from carrots is taken.
(1) Parts: it is assumed that 1% is root, 10% is leaf, and what remains is 2/3 of juice and 1/3 of pulp+peel (with equal shares between pulp and peel).
(2) Harvest: the entire plant is harvested
(3) Edibility: leaf and peel are generally discarded in Western-culture diet although nutritionally edible

References
(2)

Complete Agriculture. (2019a). How To Harvest Carrot ? - Carrot Harvesting and Farming — youtube.com [[Accessed 20-Apr-2023]]. https://www.youtube.com/watch?v=zqBYV0jymxM

Insider Tech. (2017). This monster machine is the ultimate carrot harvester — youtube.com [[Accessed 20-Apr-2023]]. https://www.youtube.com/watch?v=xDsZC-s6V9g

(3)

Fincher, M. (2020). Can You Eat Carrot Greens? And What to Do With Them? — allrecipes.com [[Accessed 09-08-2023]]. https://www.allrecipes.com/article/can-you-eat-carrot-greens/

Lama, S., & Renee, J. (2020). Should Carrots Be Peeled or Are They More Nutritious With the Peel Left On? | Livestrong.com — livestrong.com [[Accessed 09-08-2023]]. https://www.livestrong.com/article/518814-should-carrots-be-peeled-or-are-they-more-nutritious-with-the-peel-left-on/

Cassava leaves

(1) Parts: leaves (100%)

Cauliflowers and broccoli

(1) Parts: core (64%), leaves (18%), stems (18%)
(2) Harvest: all the aboveground parts are harvested but the majority of the leaves are immediately discarded on the harvesting site

References
(1)

Kowalski, A., Agati, G., Grzegorzewska, M., Kosson, R., Kusznierewicz, B., Chmiel, T., Bartoszek, A., Tuccio, L., Grifoni, D., Vågen, I. M., & Kaniszewski, S. (2021). Valorization of waste cabbage leaves by postharvest photochemical treatments monitored with a non-destructive fluorescence-based sensor. *Journal of Photochemistry and Photobiology B: Biology*, *222*, 112263. https://doi.org/10.1016/j.jphotobiol.2021.112263

Llorach, R., Espın, J. C., Tomás-Barberán, F. A., & Ferreres, F. (2003). Valorization of cauliflower: By-products as a source of antioxidant phenolics. *Journal of Agricultural and Food Chemistry*, *51*(8), 2181–2187. https://doi.org/10.1021/jf021056a

(2)

The Produce Nerd. (2018a). How Cauliflower is Harvested and Packed in the Field — youtube.com [[Accessed 20-Apr-2023]]. https://www.youtube.com/watch?v=9BwpM6prR8s

Chillies and peppers, green (Capsicum spp. and Pimenta spp.)

For simplicity, only data for chillies is taken.
(1) Parts: pulp (63-85%), placenta (10%), seeds (5-23%)
It is assumed that placenta is included in pulp and that 5% is stem.
(2) Harvest: by hand, vegetable harvested with its stem, and with machine all the aboveground parts are harvested but leaves and stems are discarded on the harvesting site

References
(1)

Guillen, N., Tito, R., & Mendoza, N. (2018). Capsaicinoids and pungency in capsicum chinense and capsicum baccatum fruits. *Pesquisa Agropecuária Tropical*, *48*(3), 237–244.

(2)

Complete Agriculture. (2021a). Amazing Chili Farming Technology chili Harvesting chili Cultivation chili Agriculture chili Process — youtube.com [[Accessed 20-Apr-2023]]. https://www.youtube.com/watch?v=Hiyfep4tEbA

Noal Farm. (2022c). How Tons of Red Chili Pepper Harvesting by Machine - Paprika Chili Powder Processing in Factory — youtube.com [[Accessed 20-Apr-2023]]. https://www.youtube.com/watch?v=eSiyh47JD_k

Cucumbers and gherkins

For simplicity, only data from cucumbers is taken.
(1) Parts: 95% of water content
It is assumed that 1% is pulp and 1% is seed.
(2) Harvest: by hand, only vegetable harvested, and with machine all the aboveground parts are harvested but leaves and stems are discarded on the harvesting site

References
(1)

Dillon, K. (2021). *15 health benefits of cucumber water plus recipes and helpful tips*. Retrieved June 3, 2021, from https://lajollamom.com/drink-cucumber-water-health/

(2)

Noal Farms. (2021). Million Tons Cucumber Harvest Machine - How Pickles are made - Cucumber pickles processing factory — youtube.com [[Accessed 20-Apr-2023]]. https://www.youtube.com/watch?v=sQnzZzqxMto

Eggplants (aubergines)

(1) Parts: calyx (4%), peel (14%), flesh (82%)
(2) Harvest: vegetable harvested with its calyx

References
(1)

Karimi, A., Kazemi, M., Samani, S. A., & Simal-Gandara, J. (2021). Bioactive compounds from by-products of eggplant: Functional properties, potential applications and advances in valorization methods. *Trends in Food Science &amp Technology*, *112*, 518–531. https://doi.org/10.1016/j.tifs.2021.04.027

(2)

Matrix Farm. (2021). Greenhouse Eggplant Farming and Harvesting - Eggplant Growing Cultivation Agriculture Technology — youtube.com [[Accessed 20-Apr-2023]]. https://www.youtube.com/watch?v=A8ULLZK9t8k

Green corn (maize)

(1) Parts: kernel (45%)
It is assumed that 5% is leaves and 5% is tip (5%), and what remains is core.
(2) Harvest: with machine, all the aboveground parts are harvested, but some of the by-products are immediately discarded on the harvesting site

References
(1)

Nasrin, T. A. A., & Matin, M. A. (2017). Valorization of vegetable wastes. *Food Processing By-Products and their Utilization*, 53–88.

(2)

Hauswald Farms. (2021). Harvesting green corn!? — youtube.com [[Accessed 20-Apr-2023]]. https://www.youtube.com/watch?v=so4vK37sf4M
Tantum Tech HD. (2022a). Incrível Processo de Colheita e Processamento de Milho Verde - Máquinas de agricultura moderna — youtube.com [[Accessed 20-Apr-2023]]. https://www.youtube.com/watch?v=p8Oq-6WYZBU

Green garlic

(1) Parts: it is assumed that 1/3 is leaf, 1% is root, 10% is bulb, 5% is husk, and what remains is stem
(2) Harvest: the entire plant is harvested
(3) Edibility: leaf and root are generally discarded in Western-culture diet although nutritionally edible

References
(2)

ASA-LIFT. (2013). ASA-LIFT - PO-90 - Spring Onion harvester — youtube.com [[Accessed 20-Apr-2023]]. https://www.youtube.com/watch?v=CAhap80v8Zs

Practical Farmers of Iowa. (2021). Garlic Production at Grade A Garden: Harvest, Bunching, Hanging and Curing - Virtual Field Day — youtube.com [[Accessed 20-Apr-2023]]. https://www.youtube.com/watch?v=EAP2rXiaDKc

(3)

Are Garlic Leaves Edible? - Garlic Store — garlicstore.com [[Accessed 09-08-2023]]. (2022). https://garlicstore.com/are-garlic-leaves-edible/#google_vignette

Folgert, J. (2018). Eating Garlic Roots — groeat.com [[Accessed 09-08-2023]]. https://www.groeat.com/post/eating-garlic-roots#:~:text=Garlic%20roots%20can%20be%20used,give%20them%20a%20crunchy%20texture.

Leeks and other alliaceous vegetables

(1) Parts: it is assumed that 1% is root, 2/3 is stem, and what remains is shared equally between inner and outer leaves.
(2) Harvest: with machine, the whole plant is harvested but the upper part of long leaves are immediately discarded on the harvesting site, or by hand, where the roots and the majority of the leaves are immediately discarded on the harvesting site

References
(2)

Noal Farm. (2022d). Leek, Okra, Green Plum Harvesting Machine - World Modern Agriculture Technology - Harvest vegetables — youtube.com [[Accessed 20-Apr-2023]].

Lettuce and chicory

For simplicity, only the data for lettuce is taken.
(1) Parts: core+outer leaves (10%), inner leaves (90%)
Equal shares between core and outer leaves are assumed.
(2) Harvest: all the aboveground parts are harvested.

References
(1)

Nasrin, T. A. A., & Matin, M. A. (2017). Valorization of vegetable wastes. *Food Processing By-Products and their Utilization*, 53–88.

(2)

Food Wishes. (2012). How Lettuce Gets Harvested — youtube.com [[Accessed 20-Apr-2023]]. https://www.youtube.com/watch?v=oxbJVqfIK1U

Ortomec Italia. (2018). Harvester for lettuce | Self-propelled harvester Ortomec — youtube.com [[Accessed 20-Apr-2023]]. https://www.youtube.com/watch?v=VjAXX-PCwjI

Mushrooms and truffles

(1) Parts: stem (30%), cap+peel (70%)
Of the given percentage, it is assumed that 5% is peel and 65% is cap.
(2) Harvest: the whole plant is harvested and the lower part is cut at the harvest site

References
(1)

Guo, J., Zhang, M., & Fang, Z. (2022). Valorization of mushroom by-products: A review. *Journal of the Science of Food and Agriculture*, *102*(13), 5593–5605. https://doi.org/10.1002/jsfa.11946

(2)

Agrimat USA. (2013). MUSHROOM HARVESTING (part 1) — youtube.com [[Accessed 20-Apr-2023]]. https://www.youtube.com/watch?v=tvfCvI925rs

Noal Farm. (2021d). How to Harvest Million Mushroom with Machine - Modern Mushroom Farm, Mushroom cultivation Technology — youtube.com [[Accessed 20-Apr-2023]].

Okra

(1) Parts: it is assumed that 5% is seed and what remains is 2/3 of peel and 1/3 of pulp
(2) Harvest: only the okra in the plant is harvested

References
(2)

NC A and T Community Gardens. (2012). How To Harvest Okra — youtube.com [[Accessed 20-Apr-2023]]. https://www.youtube.com/watch?v=-SZmXlYsjGA

Noal Farm. (2022e). Leek, Okra, Green Plum Harvesting Machine - World Modern Agriculture Technology - Harvest vegetables — youtube.com [[Accessed 20-Apr-2023]]. https://www.youtube.com/watch?v=Gqnjyh2NsaM

Onions and shallots, dry (excluding dehydrated)

(1) Parts: it is assumed that peel is 10% and root is 1%, and what remains is bulb.
(2) Harvest: the whole plant is harvested but the leaves are immediately discarded on the harvest site

References
(2)

The Produce Nerd. (2018b). Onion Harvest in California: Onion Harvesting by Hand — youtube.com [[Accessed 20-Apr-2023]]. https://www.youtube.com/watch?v=Trl02ZBEbEY

Onions and shallots, green

(1) Parts: it is assumed to be the same as the category above
(2) Harvest: same as the category above

References
(2)

The Produce Nerd. (2018b). Onion Harvest in California: Onion Harvesting by Hand — youtube.com [[Accessed 20-Apr-2023]]. https://www.youtube.com/watch?v=Trl02ZBEbEY

Peas, green

(1) Parts: peas (100%)
(2) Harvest: all the aboveground parts are harvested but only the peas are kept and the rest is discarded on the harvest site

References
(2)

Eat Happy Project. (2016). Frozen peas: From farm to fork — youtube.com [[Accessed 20-Apr-2023]]. https://www.youtube.com/watch?v=qnhqkhEVZuI

Pumpkins, squash and gourds

(1) Parts: pulp (82,98%), peel (12,36%)
It is assumed that 1% is seed and 5% is stalk.
(2) Harvest: all the aboveground parts are harvested, but the leaves and a part of the stem is immediately discarded on the harvest site
(3) Edibility: peel and seed are generally discarded in Western-culture although nutritionally edible

References
(1)

Mahmoud, E. A., & Mehder, A. O. A. (2022). The manufacture of three types of organic butternut squash flour and their impact on the development of some oat gluten-free products. *Arabian Journal of Chemistry*, *15*(9), 104051. https://doi.org/10.1016/j.arabjc.2022.104051

(2)

The new pumpkin harvester — youtube.com [[Accessed 20-Apr-2023]]. (n.d.). https://www.youtube.com/watch?v=kWC9xHMSU6g

(3)

Butler, N., & Streit, L. (2023). Can You Eat Pumpkin Seed Shells? — healthline.com [[Accessed 09-08-2023]]. https://www.healthline.com/nutrition/can-you-eat-pumpkin-seed-shells
Can You Eat Pumpkin Skin? Hokkaido, Butternut Squash and More — utopia.org [[Accessed 09-08-2023]]. (2022). https://utopia.org/guide/edible-pumpkin-skin-quick-recipes/

Spinach

(1) Parts: leaves (100%)
(2) Harvest: only mature leaves harvested

References
(2)

Seedsheet. (2019). How To Harvest Spinach — youtube.com [[Accessed 20-Apr-2023]]. https://www.youtube.com/watch?v=7EPU1T1DmW0&t=18s
texasfarmbureau. (2014). Strong to the Finish | Spinach Harvest — youtube.com [[Accessed 20-Apr-2023]]. https://www.youtube.com/watch?v=cV9KY6jnQAc

String beans

(1) Parts: the same data as horse beans is taken
(2) Harvest: all the aboveground parts are harvested but the leaves and stem are immediately discarded on the harvesting site

References
(2)

Picking Green Beans | New Ploeger BP2140e Bean Picker | Laarakker Well | Harvesting Haricot Verts — youtube.com [[Accessed 20-Apr-2023]]. (2020).

Tomatoes

(1) Parts: seed (1%), pulp+peel (4%), juice (95%)
For the given percentage, it is assumed that 2/3 is peel and 1/3 is pulp.
(2) Harvest: all the aboveground parts are harvested but the leaves and stem are immediately discarded on the harvesting site

References
(1)

Kiralan, M., & Ketenoglu, O. (2022). Utilization of tomato (solanum lycopersicum) by-products: An overview. In *Mediterranean fruits bio-wastes* (pp. 799–818). Springer International Publishing. https://doi.org/10.1007/978-3-030-84436-3_34

(2)

Complete Agriculture. (2021e). How To Harvest Tomato? - Tomato Harvesting and Tomato Farming — youtube.com [[Accessed 20-Apr-2023]]. https://www.youtube.com/watch?v=OQdX7vU56aY
Penn State Extension. (n.d.). Tomato Harvesting — youtube.com [[Accessed 20-Apr-2023]]. https://www.youtube.com/watch?v=t-koSjUj7kU

B

Peel loss and waste valorisation: References

Conversion factors:

- bioenergy potential of bioethanol: 7470 kWh/t (from Wobiwo et al. (2019), as in Dulo et al. (2022))
- bioenergy potential of biogas: 6.5 kWh/m^3 (from Tomperi et al. (2014), as in Dulo et al. (2022))

B.1. Fruit peel

Apple peel

- dry matter content: 20.0 % (Ma et al., 2021)
- flavonoid: 0.004 t NAE/t (Park et al., 2022)
- tannin: 0.003 t/t (Wahyudiono et al., 2022)
- pectin: 0.04-0.1 t/t (Perussello et al. (2017a); (!) this yield was obtained from apple pomace, thus not specifically from the peel)
- protein: 0.002 t/t (Zheng et al., 2007)
- sugar: 0.09 t/t (Kalinowska et al., 2020)
- phosphorus: 0.0007 t/t (Skinner et al. (2018); (!) this yield was obtained from apple pomace, thus not specifically from the peel)
- potassium: 0.3 t/t (Kalinowska et al., 2020)
- nitrogen: 0.7 t/t (Henrıquez et al., 2010)
- bioethanol: 0.2 t/t (Borujeni et al., 2022)
- biogas: 401 m^3/t (Suhartini et al., 2020)

Avocado peel

- dry matter content: 29.0 % (Bullo, 2021)
- flavonoid: 0.05-0.06 t QE/t (Castillo-Llamosas et al., 2021)
- tannin: 0.0004 t/t (N. Rahman et al., 2022)
- pectin: 0.03 t/t (Bamba et al., 2020)
- protein: 0.04 t/t (Araujo et al. (2021): (!) this is a total content, no extraction could be found)
- sugar: 0.01 t/t (Garcia-Vargas et al., 2020)
- phosphorus: 0.002 t/t (Haas et al., 1949)
- potassium: 0.08 t/t (Rotta et al., 2015)
- nitrogen: 0.01 t/t (Garcia-Vargas et al., 2020)
- bioethanol: 0.007 t/t (Kerebh, 2022)
- biogas: 0.9 Nm^3/kg (Garcia-Vallejo et al., 2023)

Banana peel

- dry matter content: 28.0 % (Dulo et al., 2022)
- flavonoid: 0.03-0.04 t/t (Putra et al., 2022)
- tannin: 0.2 t/t (Wu et al., 2014)
- pectin: 0.16-0.24 t/t (Khamsucharit et al., 2017)
- protein: 0.05 t/t (Deb et al., 2022; Pyar & Peh, 2018)
- sugar: 0.3 t/t (Mohapatra et al., 2010)
- phosphorus: 0.002 t/t (Hikal et al., 2022)
- potassium: 0.00004 t/t (Hikal et al., 2022)
- nitrogen: 0 t/t (Hikal et al., 2022)
- bioethanol: 0.03 t/t (Dulo et al., 2022)
- biogas: 303 m^3/t (Dulo et al., 2022)

Cantaloupe and other melon peel

- dry matter content: 82.0 % (Jekayinfa et al., 2015)
- phosphorus: not found
- potassium: 0.01 t/t (Silva et al., 2020)
- nitrogen: not found
- bioethanol: 0.06 t/t (Rico et al., 2023)
- biogas: not found

Grape peel

- dry matter content: 37.0 % (Sokač et al., 2022)
- flavonoid: 0.01 t CE/t (Casazza et al., 2011)
- tannin: 0.003 t/t (Fournand et al., 2006; Y.-l. Ju et al., 2021)
- pectin: 0.04-0.1 t/t (Spinei & Oroian, 2022)
- protein: 0.09 t/t (Iuga & Mironeasa, 2020)
- sugar: 0.4 t/t (Corbin et al., 2015)
- phosphorus: 0.003 t/t (Corbin et al., 2015)
- potassium: 0.00002 t/t (Corbin et al., 2015)
- nitrogen: 0.006 t/t (T. Hussain et al., 2023)
- bioethanol: 0.04 t/t (Favaro et al. (2013): (!) this yield was obtained from grape pomace, thus not specifically from the peel)
- biogas: 500 m^3/t (R. Oliveira et al. (2022); (!) this yield was obtained from grape pomace, thus not specifically from the peel)

Kiwifruit peel

- dry matter content: 23.0 % (Boghossian et al., 2023)
- phosphorus: 0.003 t/t (Boghossian et al., 2023)
- potassium: 0.09 t/t (Boghossian et al., 2023)
- nitrogen: not found
- bioethanol: not found
- biogas: not found

Lemon and lime peel

- dry matter content: 88.0 % (Miran et al., 2016)
- flavonoid: 0.04 t/t (Londoño-Londoño et al., 2010)
- tannin: 0.001 t CE/t (Olfa et al., 2021)
- pectin: 0.6 t/t (Kanmani, 2014)
- protein: 0.005 t/t (Baker & Charlton, 2020; Janati et al., 2012)
- sugar: 0.07 t/t (Boluda-Aguilar & López-Gómez, 2013)
- phosphorus: 0.0003 t/t (T. Hussain et al., 2023)
- potassium: 0.01 t/t (T. Hussain et al., 2023)
- nitrogen: 0.003 t/t (T. Hussain et al., 2023)
- bioethanol: 0.03 t/t (Patsalou et al., 2019)
- biogas: 0.0004 m^3/t (Patsalou et al., 2019)

Mango, guava and mangosteen peel

Information for mango was taken, and assumed to be applicable for all fruits of this category.

- dry matter content: 30.0 % (Puligundla et al., 2014)
- flavonoid: 0.01 t QE/t (Lanjekar et al., 2022)
- tannin: 0.08 t/t (Kanatt & Chawla, 2017)
- pectin: 0.2-0.3 t/t (do Nascimento Oliveira et al., 2018)
- protein: 0.035 t/t tPuligundla et al. (2014); (!) this is a total content, no recovery yield could be found)
- sugar: 0.4 t/t (Puligundla et al., 2014)
- phosphorus: 0.004 t/t (Kaur & Srivastav, 2018)
- potassium: 0.004 t/t (J. Singh et al., 2016)
- nitrogen: not found
- bioethanol: 0.007 t/t (Tlais et al., 2020)
- biogas: 330 m^3/t (Puligundla et al., 2014)

Orange peel

- dry matter content: 24.0 % (M'hiri et al., 2015)
- flavonoid: 0.01 t rutin/t (M'hiri et al., 2015)
- tannin: 0.02 t/t (Martati & Ciptadi, 2020)
- pectin: 0.29 t/t (Tovar et al., 2019)
- protein: 0.0008 t/t (Baker & Charlton, 2020; Isibika et al., 2021)
- sugar: 0.1 t/t (Boluda-Aguilar & López-Gómez, 2013)
- phosphorus: 0.0003 t/t (T. Hussain et al., 2023)
- potassium: 0.01 t/t (T. Hussain et al., 2023)
- nitrogen: 0.003 t/t (T. Hussain et al., 2023)
- bioethanol: 0.03 t/t (Vázquez et al., 2017)
- biogas: 217 m^3/t (Wikandari et al., 2015)

Papaya peel

- dry matter content: 3.0 % (Dahunsi et al., 2017)
- phosphorus: 0.005 t/t (Dahunsi et al., 2021)
- potassium: 0.007 t/t (Dahunsi et al., 2021)
- nitrogen: 0.04 t/t (Dahunsi et al., 2021)
- bioethanol: 0.0005 t/t (Abdulla et al., 2018)
- biogas: 183.9 m^3/t (Dahunsi et al., 2017)

Pineapple peel

- dry matter content: 10.0 % (Mucra et al., 2023)
- flavonoid: 0.01 t QE/t (Bansod et al., 2023)
- tannin: 0.4 t TAE/t (Bansod et al., 2023)
- pectin: 0.01-0.02 t/t (Rodsamran & Sothornvit, 2019)
- protein: 0.09 t/t tHuang et al. (2011); (!) this is a total content, no recovery yield could be found)
- sugar: 0.3 t/t (Casabar et al., 2019)
- phosphorus: 0.001 t/t (ila Teixeira Souza Raiane et al., 2016)
- potassium: 0.001 t/t (Vieira et al., 2021)
- nitrogen: 0.01 t/t (Sutikarini et al., 2023)
- bioethanol: 0.05 t/t (Casabar et al., 2019)
- biogas: 387 m^3/t (Suhartini et al., 2020)

Pomelo and grapefruit peel

Information for grapefruit was taken, and assumed to be applicable for all fruits of this category.

- dry matter content: 25.0 % (Mohamed, 2016)
- flavonoid: 0.003 t QE/t (Nishad et al., 2019)
- tannin: 0.0000004 t/t (Czech et al., 2021)
- pectin: 0.2-0.3 t/t (Xu et al., 2014)
- protein: 0.003 t/t (Baker & Charlton, 2020; Karataş & Arslan, 2016)
- sugar: 0.08 t/t (Boluda-Aguilar & López-Gómez, 2013)
- phosphorus: 0.0003 t/t (T. Hussain et al., 2023)
- potassium: 0.01 t/t (T. Hussain et al., 2023)
- nitrogen: 0.003 t/t (T. Hussain et al., 2023)
- bioethanol: 0.03 t/t (Patsalou et al., 2019)
- biogas: 0.0004 m^3/t (Patsalou et al., 2019)

Tangerine, mandarin, and clementine peel

Information for mandarin was taken, and assumed to be applicable for all fruits of this category.

- dry matter content: 21.0 % (Ghanem et al., 2012)
- flavonoid: 0.00006 t/t (A. Kumar et al., 2022)
- tannin: 0.0000003 t/t (Czech et al., 2021)
- pectin: 0.1 t/t (Karbuz & Tugrul, 2020)
- protein: 0.001 t/t (Baker & Charlton, 2020; Magda et al., 2008)
- sugar: 0.1 t/t (Boluda-Aguilar & López-Gómez, 2013)
- phosphorus: 0.0003 t/t (T. Hussain et al., 2023)
- potassium: 0.01 t/t (T. Hussain et al., 2023)
- nitrogen: 0.003 t/t (T. Hussain et al., 2023)
- bioethanol: 0.03 t/t (Patsalou et al., 2019)
- biogas: 0.0004 m^3/t (Patsalou et al., 2019)

Watermelon peel

- dry matter content: 6.0 % (Bazié et al., 2022)
- flavonoid: 0.0004 t CE/t (Shahid et al., 2021)
- tannin: 0.06 t/t (Neglo et al., 2021)
- pectin: 0.1-0.2 t/t (Petkowicz et al., 2017)
- protein: 0.07 t/t (Feizy et al. (2020): (!) this is a total content, no recovery yield could be found)
- sugar: 0.5 t/t (Kassim et al., 2021)
- phosphorus: 0.03 t/t (Chenn et al., 2017)
- potassium: 0.008 t/t (Chenn et al., 2017)
- nitrogen: 0.02 t/t (Chenn et al., 2017)
- bioethanol: 0.002 t/t (Chaudhary et al., 2023)
- biogas: 460 m^3/t (Jekayinfa et al., 2015)

B.2. Vegetable peel

Carrot and turnip peel

Information for carrot was taken, and assumed to be applicable for all vegetables of this category.

- dry matter content: 9.0 % (Jayesree et al., 2021)
- flavonoid: 0.03 t/t (Nguyen & Le, 2018)
- tannin: 0.003 t/t (Shyamala and Jamuna (2010): (!) this is a total content, no extraction could be found)
- pectin: 0.2 t/t (Jafari et al., 2017)
- protein: 0.1 t/t (Chantaro et al. (2008): (!) this is a total content, no recovery yield could be found)
- sugar: 0.3 t/t (Chantaro et al., 2008)
- phosphorus: 0.003 t/t (Shyamala & Jamuna, 2010)
- potassium: 0.005 t/t (J. Singh et al., 2016)
- nitrogen: not found
- bioethanol: 0.06 t/t (Aimaretti et al., 2012)
- biogas: 130 m^3/t (Austin (2013); (!) this yield was obtained from grape pomace, thus not specifically from the peel)

Green garlic peel

- dry matter content: 31.0 % (Bisnoi et al., 2008)
- flavonoid: 0.009-0.01 t QE/t (Carreón-Delgado et al., 2023)
- tannin: 0.02 t/t (Pardede et al. (2020): (!) this is a total content, no extraction could be found)
- pectin: 0.2 t/t (Şen et al. (2022): (!) this yield was obtained from garlic waste (peel, stem, and straw), thus not specifically from the peel)
- protein: 0.08 t/t (Lyngdoh and Ray (2022): (!) this is a total content, no recovery yield could be found)
- sugar: 0.07 t/t (Zhivkova, 2021)
- phosphorus: 0.0001 t/t (Khalid et al. (2014): (!) this yield was obtained from garlic, thus not specifically from the peel)
- potassium: 0.009 t/t (Zhivkova, 2021)
- nitrogen: 0.4 t/t (and, 2021)
- bioethanol: 0.07 t/t (Hartini & Kristijanto, 2018)
- biogas: not found

Onion and shallot peel

- dry matter content: 11.0 % (Garcia et al., 2019)
- flavonoid: 0.06 t QE/t (Chadorshabi et al., 2022)
- tannin: 0.0006 t/t (Sukor et al., 2021)
- pectin: 0.09 t/t (Benito-Román et al., 2022)
- protein: 0.01 t/t (Ko et al., 2011)
- sugar: 0.4 t/t (Choi et al., 2015)
- phosphorus: 0.0009 t/t (Zhivkova, 2021)
- potassium: 0.01 t/t (M. Kumar et al., 2022)
- nitrogen: not found
- bioethanol: 0.04 t/t (Robati, 2013)
- biogas: 400 m^3/t (Gunaseelan, 2004)

Pumpkin, squash and gourd peel

- dry matter content: 6.0 % (Czubaszek et al., 2022)
- flavonoid: 0.0002 t QE/t (J. Singh et al., 2016)
- tannin: 0.00007 t CE/t (Yang et al. (2022): (!) this is a total content, no extraction could be found)
- pectin: 0.3 t/t (Hamed & Mustafa, 2018)
- protein: 0.1 t/t (Rico et al. (2020): (!) this is a total content, no recovery yield could be found)
- sugar: 0.1 t/t (Kim et al., 2012)
- phosphorus: 0.003 t/t (Mala & Kurian, 2016)
- potassium: 0.005 t/t (A. Hussain et al., 2021)
- nitrogen: not found
- bioethanol: 0.05 t/t (Chouaibi et al., 2020)
- biogas: 199 m^3/t (Czubaszek et al., 2022)

Tomato peel

- dry matter content: 20.0 % (Albanese et al., 2014)
- flavonoid: 0.0009-0.004 t RE/t (Grassino et al., 2020)
- pectin: 0.09-0.3 t/t (Sengar et al., 2020)
- tannin: 0.000002 t/t (Oyetayo and Ibitoye (2012): (!) this is a total content, no extraction could be found)
- protein: 0.001-0.2 t/t (Lu et al., 2019)
- sugar: 0.8 t/t (Elbadrawy & Sello, 2016)
- phosphorus: 0.003 t/t (Knoblich et al., 2005)
- potassium: 0.01 t/t (Elbadrawy & Sello, 2016)
- nitrogen: 0.3 t/t (Stevens et al., 1986)
- bioethanol: 0.05 t/t (Hijosa-Valsero et al. (2019): (!) this yield was obtained from tomato pomace, thus not specifically from the peel)
- biogas: 250 m^3/t (Scaglia et al., 2020)

CE = catechin equivalent; NAE = naringin equivalent; QE = quercetin equivalent; RE = rutin equivalent

References for Appendix B

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C

MFA results: most generated types of fruit and vegetable loss and waste

Only the 10 most generated types of unavoidable fruit or vegetable loss and waste per world region are shown here. The totality of loss and waste flows are available in the Supplementary Information of this report.

C.1. Fruits: Most generated types of unavoidable loss and waste

Table C.1: 10 most generated types of unavoidable fruit loss and waste generated in Europe in 2020.

Processing		Retail & Consumption	
1) Grape stems	1.2 Mt	1) Banana peels	2.8 Mt
2) Grape peels	1.1 Mt	2) Orange peels	1.4 Mt
3) Orange peels	0.4 Mt	3) Watermelon peels	1.3 Mt
4) Grape seeds	0.4 Mt	4) Tangerine, mandarin and clementine peels	1.0 Mt
5) Peach and nectarine pit shells	0.3 Mt	5) Orange seeds	0.8 Mt
6) Peach and nectarine seeds	0.3 Mt	6) Peach and nectarine pit shells	0.7 Mt
7) Apple peels	0.3 Mt	7) Peach and nectarine seeds	0.7 Mt
8) Orange seeds	0.2 Mt	8) Tangerine, mandarin and clementine seeds	0.6 Mt
9) Banana peels	0.2 Mt	9) Lemon and lime peels	0.6 Mt
10) Tangerine, mandarin and clementine peels	0.2 Mt	10) Cantaloupe and other melon peels	0.4 Mt

Table C.2: 10 most generated types of unavoidable fruit loss and waste generated in North America in 2020.

Processing		Retail & Consumption	
1) Orange peels	0.4 Mt	1) Banana peels	1.5 Mt
2) Orange seeds	0.2 Mt	2) Orange peels	0.8 Mt
3) Grape stem	0.2 Mt	3) Watermelon peels	0.7 Mt
4) Tangerine, mandarin and clementine peels	0.1 Mt	4) Lemon and lime peels	0.5 Mt
5) Tangerine, mandarin and clementine seeds	0.1 Mt	5) Orange seeds	0.4 Mt
6) Pomelo and grapefruit peels	0.04 Mt	6) Pineapple peels	0.4 Mt
7) Banana peels	0.03 Mt	7) Lemon and lime seeds	0.3 Mt
8) Pomelo and grapefruit seeds	0.02 Mt	8) Cantaloupe and other melon peels	0.3 Mt
9) Grape peels	0.01 Mt	9) Avocado peels	0.2 Mt
10) Plum and sloe seeds	0.01 Mt	10) Tangerine, mandarin and clementine peels	0.2 Mt

Table C.3: 10 most generated types of unavoidable fruit loss and waste generated in industrialized Asia in 2020.

Processing		Retail & Consumption	
1) Apple peels	0.3 Mt	1) Watermelon peels	17.0 Mt
2) Peach and nectarine pit shells	0.2 Mt	2) Tangerine, mandarin and clementine peels	5.6 Mt
3) Peach and nectarine seeds	0.2 Mt	3) Banana peels	4.2 Mt
4) Grape stems	0.2 Mt	4) Peach and nectarine pit shells	4.1 Mt
5) Pineapple peels	0.2 Mt	5) Peach and nectarine seeds	4.1 Mt
6) Apple seeds	0.1 Mt	6) Tangerine, mandarin and clementine seeds	3.2 Mt
7) Pineapple crowns	0.07 Mt	7) Cantaloupe and other melon peels	3.0 Mt
8) Lemon and lime peels	0.04 Mt	8) Orange peels	1.9 Mt
9) Pineapple cores	0.04 Mt	9) Pomelo and grapefruit peels	1.2 Mt
10) Mango, guava and mangosteen seeds	0.03 Mt	10) Orange seeds	1.1 Mt

Table C.4: 10 most generated types of unavoidable fruit loss and waste generated in Latin America in 2020.

Processing		Retail & Consumption	
1) Orange peels	3.4 Mt	1) Banana peels	4.5 Mt
2) Orange seeds	1.9 Mt	2) Orange peels	2.8 Mt
3) Lemon and lime peels	0.4 Mt	3) Plantain and cooking banana peels	1.9 Mt
4) Pineapple peels	0.3 Mt	4) Orange seeds	1.6 Mt
5) Lemon and lime seeds	0.3 Mt	5) Pineapple peels	1.5 Mt
6) Grape stems	0.2 Mt	6) Watermelon peels	1.2 Mt
7) Banana peels	0.1 Mt	7) Mango, guava and mangosteen seeds	1.1 Mt
8) Pineapple crowns	0.1 Mt	8) Lemon and lime peels	1.0 Mt
9) Apple peels	0.1 Mt	9) Tangerine, mandarin and clementine peels	0.7 Mt
10) Grape peels	0.07 Mt	10) Pineapple crowns	0.6 Mt

Table C.5: 10 most generated types of unavoidable fruit loss and waste generated in Oceania (high income countries) in 2020.

Processing		Retail & Consumption	
1) Grape peels	0.2 Mt	1) Banana peels	0.1 Mt
2) Grape stems	0.1 Mt	2) Watermelon peels	0.05 Mt
3) Grape seeds	0.08 Mt	3) Cantaloupe and other melon peels	0.04 Mt
4) Orange peels	0.04 Mt	4) Tangerine, mandarin and clementine peels	0.02 Mt
5) Orange seeds	0.02 Mt	5) Orange peels	0.02 Mt
6) Apple peels	0.02 Mt	6) Avocado peels	0.02 Mt
7) Peach and nectarine seeds	0.02 Mt	7) Avocado seeds	0.02 Mt
8) Peach and nectarine pit shells	0.02 Mt	8) Mango, guava and mangosteen seeds	0.02 Mt
9) Pineapple peels	0.02 Mt	9) Cantaloupe and other melon seeds	0.01 Mt
10) Banana peels	0.02 Mt	10) Tangerine, mandarin and clementine seeds	0.01 Mt

Table C.6: 10 most generated types of unavoidable fruit loss and waste generated in Oceania (middle and low income countries) in 2020.

Processing		Retail & Consumption	
1) Mango, guava and mangosteen seeds	0.3 kt	1) Banana peels	397.6 kt
2) Pineapple peels	0.3 kt	2) Pineapple peels	9.0 kt
3) Mango, guava and mangosteen peels	0.1 kt	3) Pineapple crowns	3.9 kt
4) Pineapple crowns	0.1 kt	4) Watermelon peels	2.2 kt
5) Mango, guava and mangosteen pit shells	0.08 kt	5) Pineapple cores	2.1 kt
6) Pineapple cores	0.06 kt	6) Plantain and cooking banana peels	2.0 kt
7) Avocado peels	0.02 kt	7) Orange peels	1.0 kt
8) Avocado seeds	0.02 kt	8) Mango, guava and mangosteen seeds	0.7 kt
9) -		9) Orange seeds	0.6 kt
10) -		10) Papaya peels	0.5 kt

Table C.7: 10 most generated types of unavoidable fruit loss and waste generated in Sub-Saharan Africa in 2020.

Processing		Retail & Consumption	
1) Plantain and cooking banana peels	1.3 Mt	1) Plantain and cooking banana peels	9.0 Mt
2) Banana peels	1.0 Mt	2) Banana peels	4.7 Mt
3) Pineapple peels	0.2 Mt	3) Mango, guava and mangosteen seeds	1.6 Mt
4) Pineapple crowns	0.1 Mt	4) Pineapple peels	1.2 Mt
5) Grape stems	0.09 Mt	5) Watermelon peels	0.9 Mt
6) Orange peels	0.08 Mt	6) Mango, guava and mangosteen peels	0.7 Mt
7) Pineapple cores	0.05 Mt	7) Orange peels	0.6 Mt
8) Orange seeds	0.05 Mt	8) Pineapple crowns	0.5 Mt
9) Lemon and lime peels	0.04 Mt	9) Mango, guava and mangosteen pit shells	0.4 Mt
10) Pomelo and grapefruit peels	0.04 Mt	10) Orange seeds	0.4 Mt

Table C.8: 10 most generated types of unavoidable fruit loss and waste generated in Central Asia in 2020.

Processing		Retail & Consumption	
1) Grape stems	0.1 Mt	1) Watermelon peels	1.3 Mt
2) Peach and nectarine pit shells	0.09 Mt	2) Cantaloupe and other melon peels	0.5 Mt
3) Peach and nectarine seeds	0.09 Mt	3) Banana peels	0.3 Mt
4) Apricot pit shells	0.09 Mt	4) Orange peels	0.3 Mt
5) Apricot seeds	0.07 Mt	5) Tangerine, mandarin, clementine peels	0.2 Mt
6) Banana peels	0.03 Mt	6) Apricot pit shells	0.2 Mt
7) Grape peels	0.02 Mt	7) Grape stems	0.2 Mt
8) Apple peels	0.02 Mt	8) Peach and nectarine pit shells	0.2 Mt
9) Apple seeds	0.01 Mt	9) Peach and nectarine seeds	0.2 Mt
10) Watermelon peels	0.01 Mt	10) Lemon and lime peels	0.2 Mt

Table C.9: 10 most generated types of unavoidable fruit loss and waste generated in South-East Asia in 2020.

Processing		Retail & Consumption	
1) Pineapple peels	1.6 Mt	1) Banana peels	14.0 Mt
2) Mango, guava and mangosteen seeds	1.0 Mt	2) Mango, guava and mangosteen seeds	7.1 Mt
3) Pineapple crowns	0.7 Mt	3) Orange peels	3.8 Mt
4) Mango, guava and mangosteen peels	0.4 Mt	4) Mango, guava and mangosteen peels	3.0 Mt
5) Pineapple cores	0.4 Mt	5) Orange seeds	2.2 Mt
6) Banana peels	0.3 Mt	6) Watermelon peels	2.1 Mt
7) Mango, guava and mangosteen pit shells	0.2 Mt	7) Mango, guava and mangosteen pit shells	1.7 Mt
8) Orange peels	0.2 Mt	8) Plantain and cooking banana peels	1.6 Mt
9) Orange seeds	0.1 Mt	9) Pineapple peels	0.9 Mt
10) Lemon and lime peels	0.1 Mt	10) Lemon and lime peels	0.9 Mt

Table C.10: 10 most generated types of unavoidable fruit loss and waste generated in North Africa in 2020.

Processing		Retail & Consumption	
1) Orange peels	0.3 Mt	1) Watermelon peels	2.9 Mt
2) Mango, guava and mangosteen seeds	0.2 Mt	2) Orange peels	1.6 Mt
3) Orange seeds	0.2 Mt	3) Banana peels	1.1 Mt
4) Lemon and lime peels	0.1 Mt	4) Orange seeds	0.9 Mt
5) Mango, guava and mangosteen peels	0.09 Mt	5) Cantaloupe and other melon peels	0.6 Mt
6) Tangerine, mandarin, clementine peels	0.06 Mt	6) Tangerine, mandarin and clementine peels	0.6 Mt
7) Lemon and lime seeds	0.06 Mt	7) Date seeds	0.6 Mt
8) Mango, guava and mangosteen pit shells	0.05 Mt	8) Peach and nectarine pit shells	0.5 Mt
9) Grape stems	0.04 Mt	9) Peach and nectarine seeds	0.5 Mt
10) Tangerine, mandarin, clementine seeds	0.03 Mt	10) Lemon and lime peels	0.4 Mt

C.2. Vegetables: Most generated types of unavoidable loss and waste

Table C.11: 10 most generated types of unavoidable vegetable loss and waste generated in Europe in 2020.

Processing		Retail & Consumption	
1) Green corn (maize) cores	0.9 Mt	1) Carrot and turnip peels	1.0 Mt
2) Tomato peels	0.2 Mt	2) Cabbage cores	0.9 Mt
3) Green corn (maize) leaves	0.1 Mt	3) Onion and shallot, dry*, peels	0.9 Mt
4) Green corn (maize) tips	0.1 Mt	4) Carrot and turnip leaves	0.7 Mt
5) Tomato seeds	0.06 Mt	5) Pumpkin, squash and gourd peels	0.4 Mt
6) Carrot and turnip peels	0.06 Mt	6) Green garlic leaves	0.3 Mt
7) Pumpkin, squash and gourd peels	0.05 Mt	7) Chilli and pepper, green**, stems	0.2 Mt
8) Onion and shallot, dry*, peels	0.04 Mt	8) Pumpkin, squash and gourd stems	0.2 Mt
9) Artichoke chokes	0.04 Mt	9) Asparagus hard stems	0.2 Mt
10) Carrot and turnip leaves	0.04 Mt	10) Artichoke chokes	0.1 Mt

Table C.12: 10 most generated types of unavoidable vegetable loss and waste generated in North America in 2020.

Processing		Retail & Consumption	
1) Green corn (maize) cores	1.1 Mt	1) Onion and shallot, dry*, peels	0.4 Mt
2) Green corn (maize) leaves	0.1 Mt	2) Carrot and turnip peels	0.3 Mt
3) Green corn (maize) tips	0.1 Mt	3) Green corn (maize) cores	0.3 Mt
4) Tomato peels	0.006 Mt	4) Cabbage cores	0.2 Mt
5) Tomato seeds	0.001 Mt	5) Pumpkin, squash and gourd peels	0.2 Mt
6) -		6) Carrot and turnip leaves	0.2 Mt
7) -		7) Asparagus hard stems	0.2 Mt
8) -		8) Green garlic leaves	0.09 Mt
9) -		9) Chilli and pepper, green**, stems	0.09 Mt
10) -		10) Pumpkin, squash and gourd stems	0.08 Mt

Table C.13: 10 most generated types of unavoidable vegetable loss and waste generated in industrialized Asia in 2020.

Processing		Retail & Consumption	
1) Tomato peels	0.2 Mt	1) Green garlic leaves	5.9 Mt
2) Green corn (maize) cores	0.07 Mt	2) Cabbage cores	4.4 Mt
3) Tomato seeds	0.06 Mt	3) Asparagus hard stems	3.7 Mt
4) Cabbage cores	0.03 Mt	4) Carrot and turnip peels	2.5 Mt
5) Green corn (maize) leaves	0.008 Mt	5) Onion and shallot, dry*, peels	2.3 Mt
6) Green corn (maize) tips	0.008 Mt	6) Carrot and turnip leaves	1.7 Mt
7) Pumpkin, squash and gourd peels	0.0005 Mt	7) Eggplant (aubergine) calyxes	1.4 Mt
) Asparagus hard stems	0.0005 Mt	8) Pumpkin, squash and gourd peels	0.9 Mt
9) Pumpkin, squash and gourd stems	0.0003 Mt	9) Green garlic peels	0.9 Mt
10) String bean stems	0.0003 Mt	10) Chilli and pepper, green**, stems	0.8 Mt

Table C.14: 10 most generated types of unavoidable vegetable loss and waste generated in Latin America in 2020.

Processing		Retail & Consumption	
1) Green corn (maize) cores	147.5 kt	1) Onion and shallot, dry*, peels	477.3 kt
2) Asparagus hard stems	99.9 kt	2) Green corn (maize) cores	477.0 kt
3) Tomato peels	33.4 kt	3) Carrot and turnip peels	235.8 kt
4) Green corn (maize) leaves	16.4 kt	4) Green garlic leaves	235.5 kt
5) Green corn (maize) tips	16.4 kt	5) Carrot and turnip leaves	157.2 kt
6) Pumpkin, squash and gourd peels	14.7 kt	6) Pumpkin, squash and gourd peels	138.4 kt
7) Tomato seeds	6.2 kt	7) Chilli and pepper, green**, stems	112.0 kt
8) Pumpkin, squash and gourd stems	6.0 kt	8) Cabbage cores	898.7 kt
9) Green garlic leaves	3.6 kt	9) Asparagus hard stems	835.8 kt
10) Cabbage cores	1.6 kt	10) Pumpkin, squash and gourd stems	560.0 kt

Table C.15: 10 most generated types of unavoidable vegetable loss and waste generated in Oceania (high income countries) in 2020.

Processing		Retail & Consumption	
1) Green corn (maize) cores	9.3 kt	1) Green corn (maize) cores	34.8 kt
2) Pumpkin, squash and gourd peels	1.6 kt	2) Carrot and turnip peels	34.4 kt
3) Green garlic leaves	1.5 kt	3) Carrot and turnip leaves	22.9 kt
4) Green corn (maize) leaves	1.0 kt	4) Onion and shallot, dry*, peels	22.4 kt
5) Green corn (maize) tips	1.0 kt	5) Cabbage cores	18.0 kt
6) Pumpkin, squash and gourd stems	0.7 kt	6) Pumpkin, squash and gourd peels	10.3 kt
7) Green garlic peels	0.2 kt	7) Asparagus hard stems	5.2 kt
8) Tomato peels	0.2 kt	8) Green garlic leaves	4.8 kt
9) Pumpkin, squash and gourd seeds	0.1 kt	9) Pumpkin, squash and gourd stems	4.2 kt
10) Tomato seeds	0.06 kt	10) Green corn (maize) leaves	3.9 kt

Table C.16: 10 most generated types of unavoidable vegetable loss and waste generated in Oceania (middle and low income countries) in 2020.

Processing		Retail & Consumption	
1) -		1) Green corn (maize) cores	94.5 kt
2) -		2) Green corn (maize) leaves	10.5 kt
2) -		3) Green corn (maize) tips	10.5 kt
3) -		4) Onion and shallot, dry*, peels	1.2 kt
4) -		5) Green garlic leaves	1.0 kt
5) -		6) Cabbage cores	0.9 kt
6) -		7) Onion and shallot, green peels	0.6 kt
7) -		8) Carrot and turnip peels	0.6 kt
8) -		9) Carrot and turnip leaves	0.4 kt
9) -		10) Pumpkin, squash and gourd peels	0.2 kt

Table C.17: 10 most generated types of unavoidable vegetable loss and waste generated in Sub-Saharan Africa in 2020.

Processing		Retail & Consumption	
1) Green corn (maize) cores	10.4 kt	1) Onion and shallot, dry*, peels	782.9 kt
2) Tomato peels	4.3 kt	2) Green corn (maize) cores	703.7 kt
3) Onion and shallot, dry*, peels	2.2 kt	3) Cabbage cores	368.9 kt
4) Green corn (maize) leaves	1.2 kt	4) Pumpkin, squash and gourd peels	184.1 kt
5) Green corn (maize) tips	1.2 kt	5) Carrot and turnip peels	157.3 kt
6) Tomato seeds	1.1 kt	6) Onion and shallot, green, peels	106.1 kt
7) Onion and shallot, dry*, roots	0.2 kt	7) Carrot and turnip leaves	104.9 kt
8) -		8) Green garlic leaves	87.9 kt
9) -		9) Onion and shallot, dry*, roots	78.3 kt
10) -		10) Green corn (maize) leaves	78.2 kt

Table C.18: 10 most generated types of unavoidable vegetable loss and waste generated in Central Asia in 2020.

Processing		Retail & Consumption	
1) Onion and shallot, dry*, peels	20.2 kt	1) Carrot and turnip peels	488.4 kt
2) Eggplant (aubergine) calyxes	6.1 kt	2) Onion and shallot, dry*, peels	401.4 kt
3) Pumpkin, squash and gourd peels	5.4 kt	3) Carrot and turnip leaves	325.6 kt
4) Pumpkin, squash and gourd stems	2.2 kt	4) Cabbage cores	222.6 kt
5) Onion and shallot, dry*, roots	2.0 kt	5) Green garlic leaves	138.6 kt
6) Tomato peels	1.3 kt	6) Chilli and pepper, green**, stems	122.8 kt
7) Pumpkin, squash and gourd seeds	0.4 kt	7) Pumpkin, squash and gourd peels	54.5 kt
8) Tomato seeds	0.4 kt	8) Leek and other alliaceous vegetable outer leaves	46.6 kt
9) -		9) Onion and shallot, dry*, roots	40.1 kt
10) -		10) Carrot and turnip roots	32.6 kt

Table C.19: 10 most generated types of unavoidable vegetable loss and waste generated in South-East Asia in 2020.

Processing		Retail & Consumption	
1) Green corn (maize) cores	0.2 Mt	1) Onion and shallot, dry*, peels	3.2 Mt
2) Cabbage cores	0.03 Mt	2) Cabbage cores	1.6 Mt
3) Green corn (maize) leaves	0.02 Mt	3) Green garlic leaves	1.6 Mt
4) Green corn (maize) tips	0.02 Mt	4) Eggplant (aubergine) calyxes	0.5 Mt
5) Tomato peels	0.006 Mt	5) Onion and shallot, dry*, roots	0.3 Mt
6) Carrot and turnip peels	0.003 Mt	6) Green corn (maize) cores	0.3 Mt
7) Carrot and turnip leaves	0.002 Mt	7) Pumpkin, squash and gourd peels	0.3 Mt
8) Pumpkin, squash and gourd peels	0.002 Mt	8) Green garlic peels	0.2 Mt
9) Pumpkin, squash and gourd stems	0.0008 Mt	9) Carrot and turnip peels	0.2 Mt
10) Tomato seeds	0.0007 Mt	10) Chilli and pepper, green**, stems	0.2 Mt

Table C.20: 10 most generated types of unavoidable vegetable loss and waste generated in North Africa in 2020.

Processing		Retail & Consumption	
1) Tomato peels	0.06 Mt	1) Onion and shallot, dry*, peels	0.8 Mt
2) Tomato seeds	0.01 Mt	2) Carrot and turnip peels	0.3 Mt
3) Carrot and turnip peels	0.01 Mt	3) Green garlic leaves	0.2 Mt
4) Carrot and turnip leaves	0.007 Mt	4) Pumpkin, squash and gourd peels	0.2 Mt
5) Green corn (maize) cores	0.006 Mt	5) Carrot and turnip leaves	0.2 Mt
6) Onion and shallot, dry*, peels	0.006 Mt	6) Artichoke chokes	0.2 Mt
7) Cabbage cores	0.002 Mt	7) Cabbage cores	0.2 Mt
8) Artichoke chokes	0.0009 Mt	8) Chilli and pepper, green**, stems	0.1 Mt
9) Pumpkin, squash and gourd peels	0.0008 Mt	9) Artichoke inner leaves	0.1 Mt
10) Green garlic leaves	0.0008 Mt	10) Eggplant (aubergine) calyxes	0.1 Mt

* excluding dehydrated.
** Capsicum spp. and Pimenta spp..

D

MFA results: Fruit and vegetable loss and waste by category and region

D.1. Fruits: unavoidable loss and waste by category and region

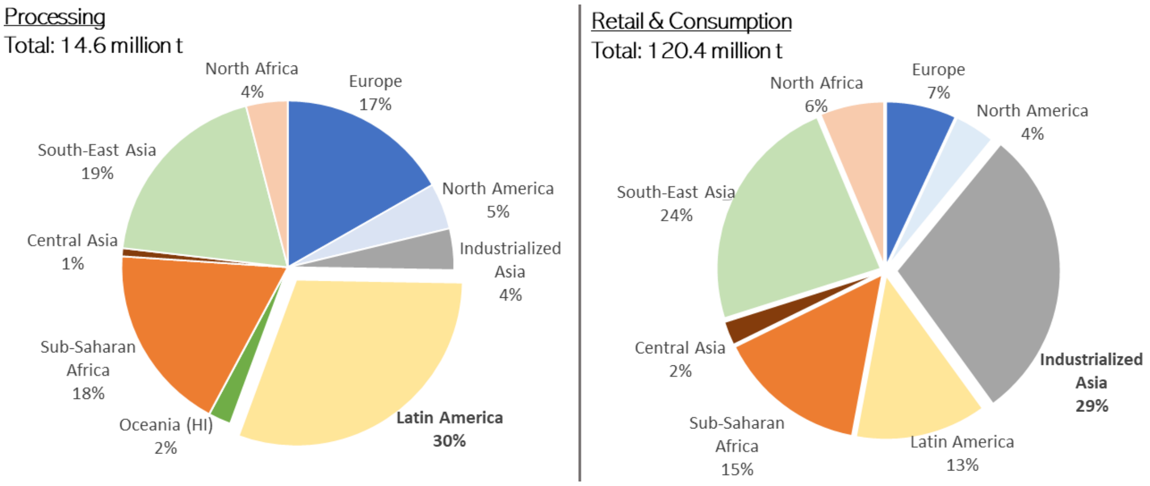

Figure D.1: Fruit peel loss and waste, at the regional level in 2020.

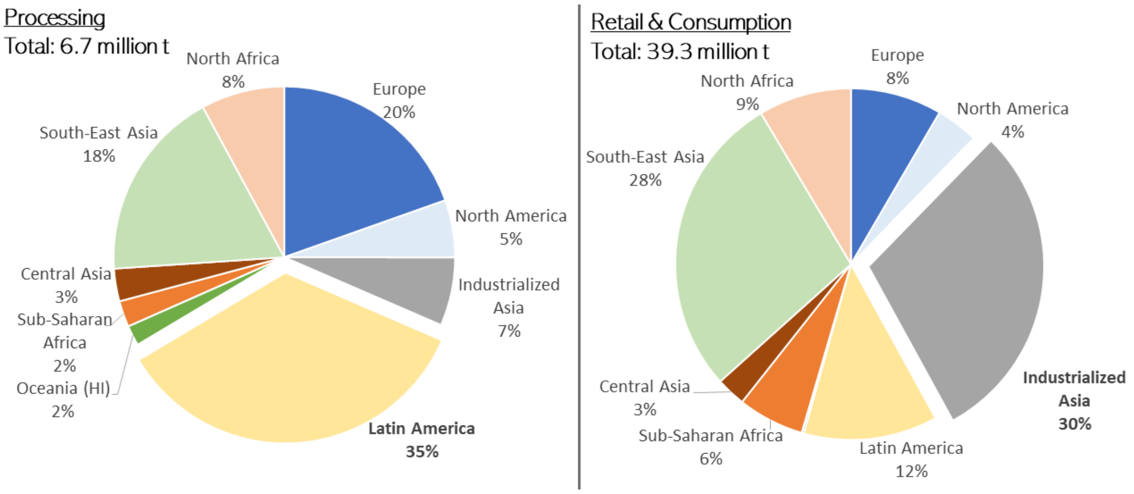

Figure D.2: Fruit seed loss and waste, at the regional level in 2020.

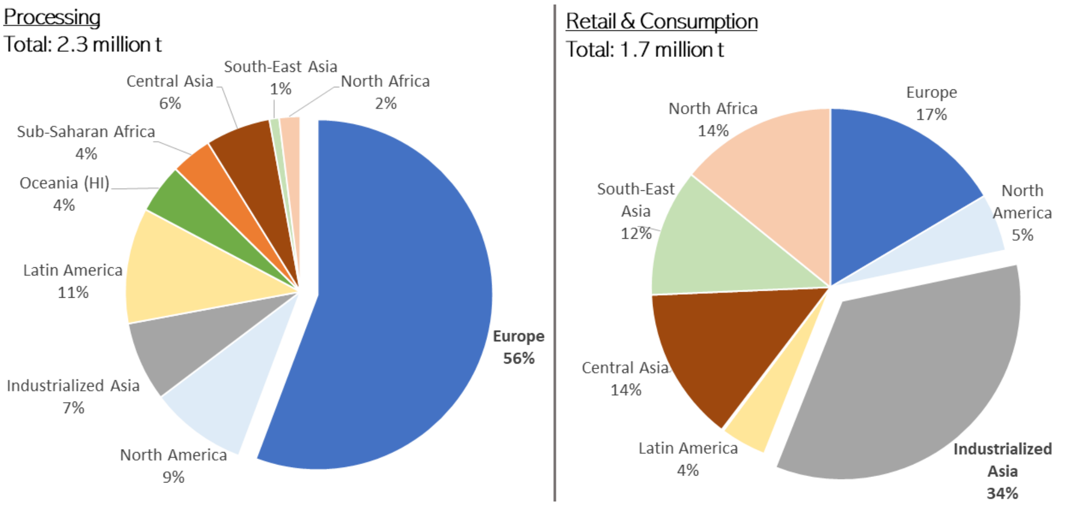

Figure D.3: Fruit stem loss and waste, at the regional level in 2020.

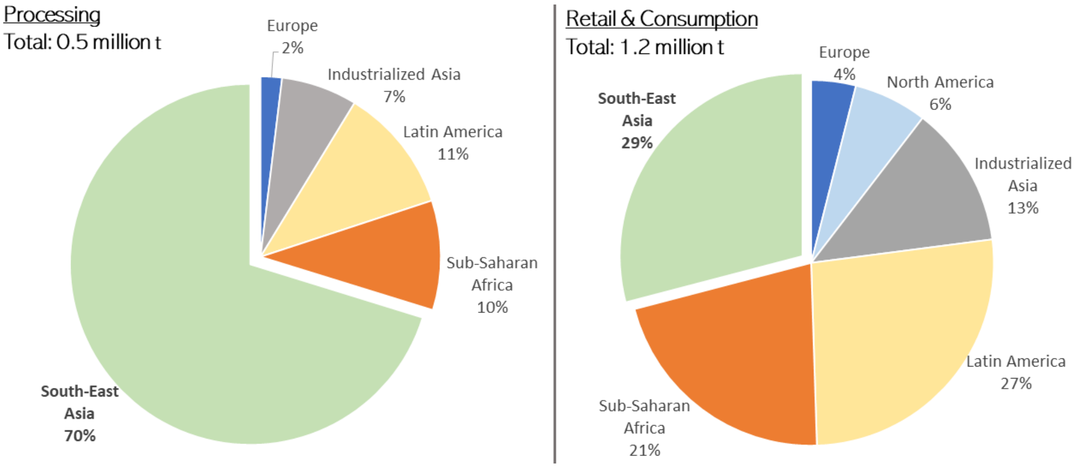

Figure D.4: Fruit core loss and waste, at the regional level in 2020.

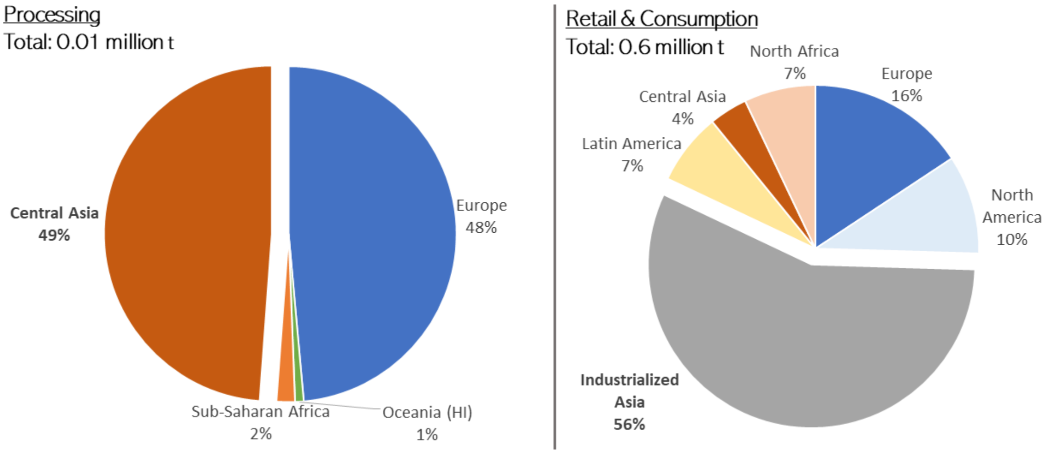

Figure D.5: Fruit calyx loss and waste, at the regional level in 2020.

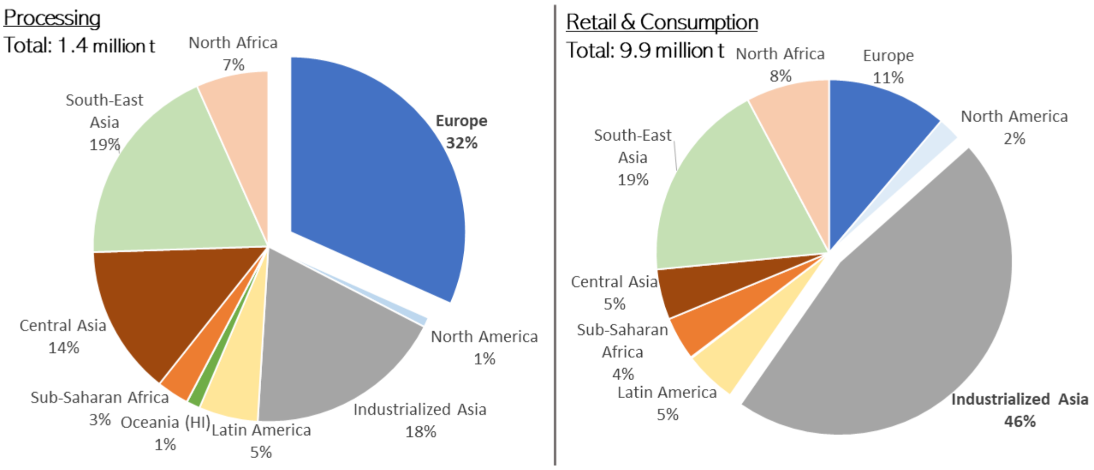

Figure D.6: Fruit pit shell loss and waste, at the regional level in 2020.

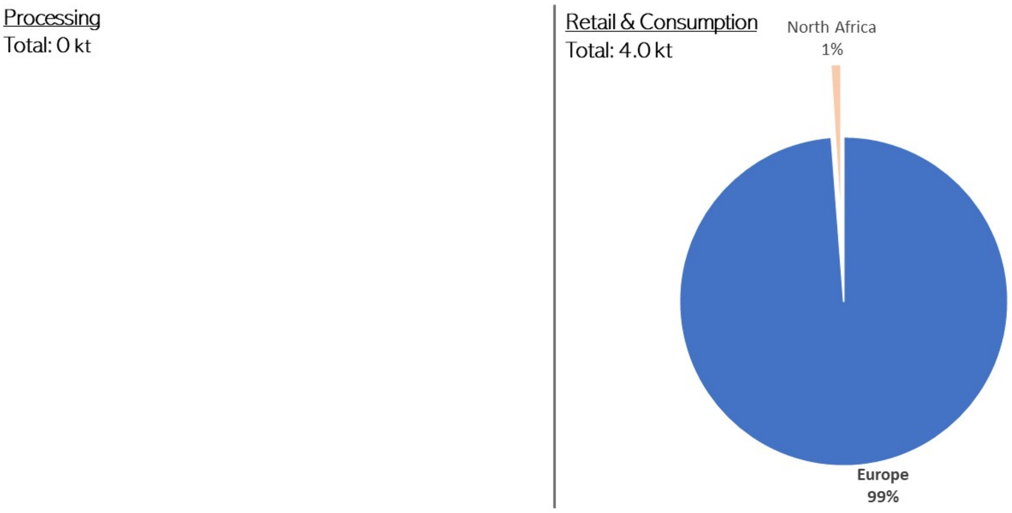

Figure D.7: Fruit husk loss and waste, at the regional level in 2020.

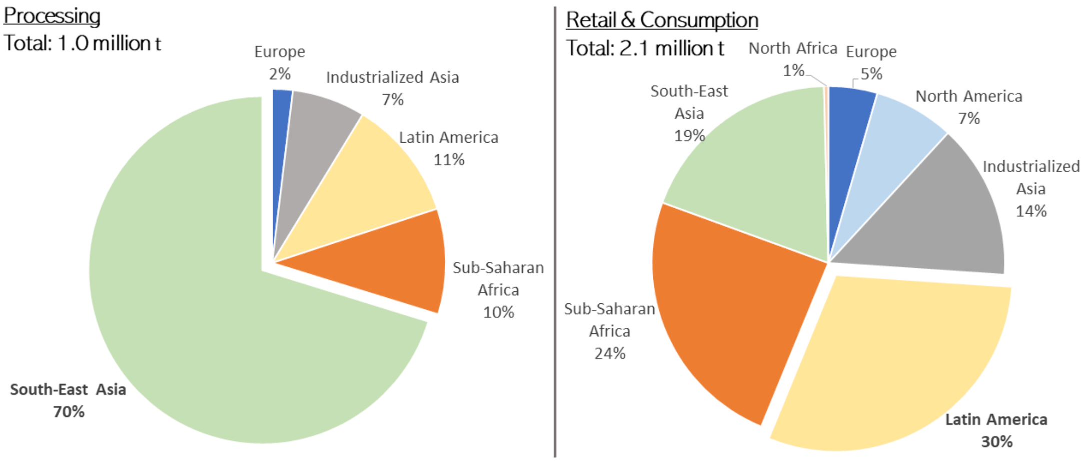

Figure D.8: Fruit crown loss and waste, at the regional level in 2020.

D.2. Vegetables: unavoidable loss and waste by category and region

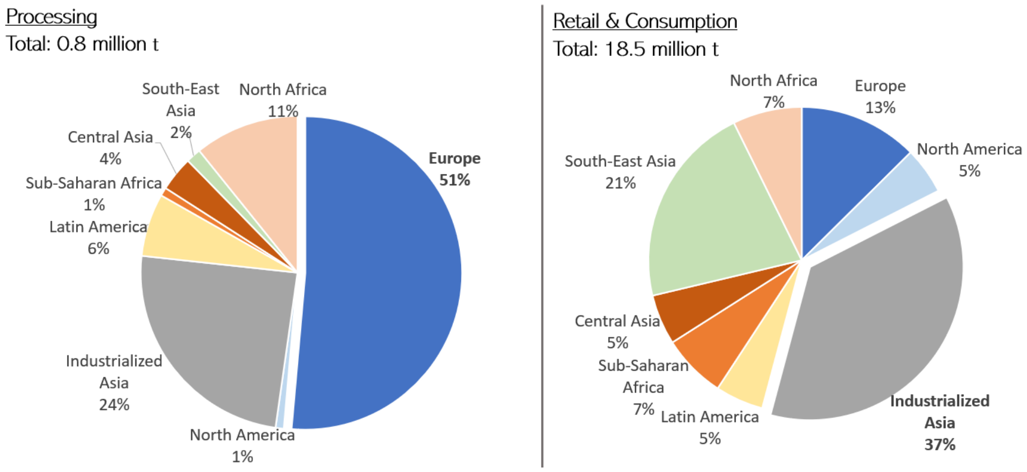

Figure D.9: Vegetable peel loss and waste, at the regional level in 2020.

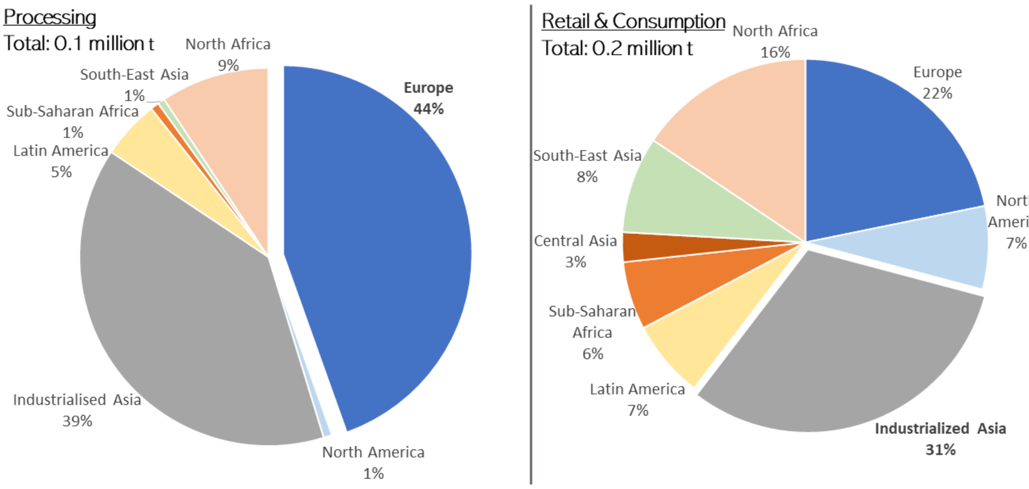

Figure D.10: Vegetable seed loss and waste, at the regional level in 2020.

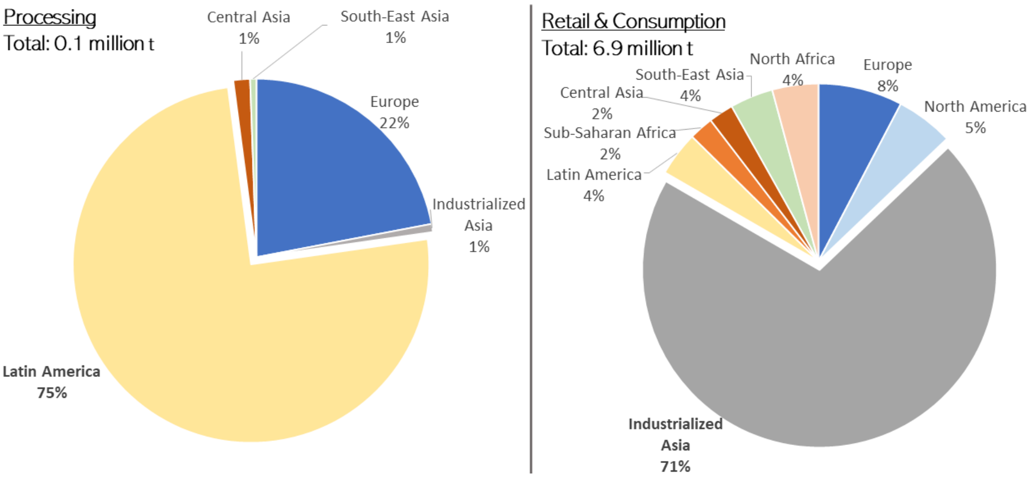

Figure D.11: Vegetable stem loss and waste, at the regional level in 2020.

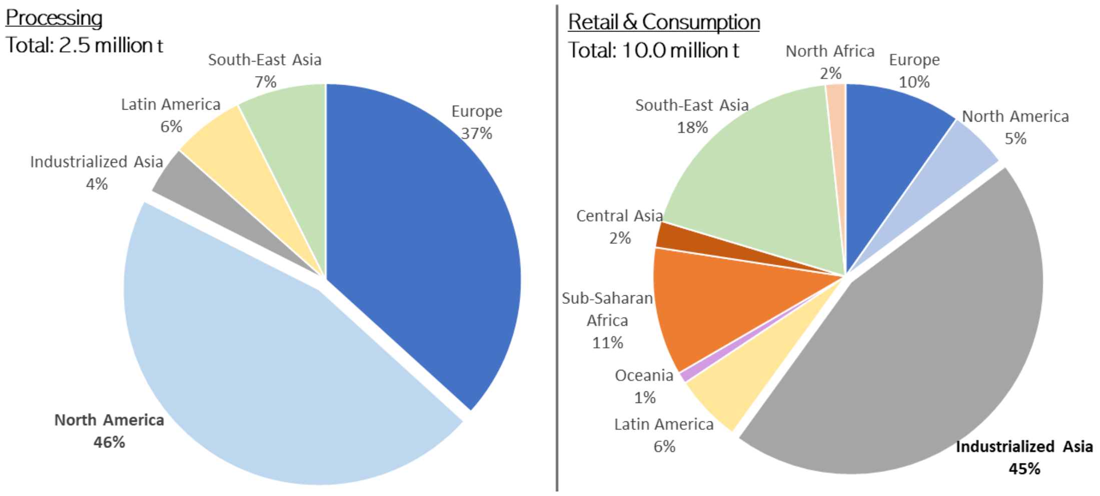

Figure D.12: Vegetable core loss and waste, at the regional level in 2020.

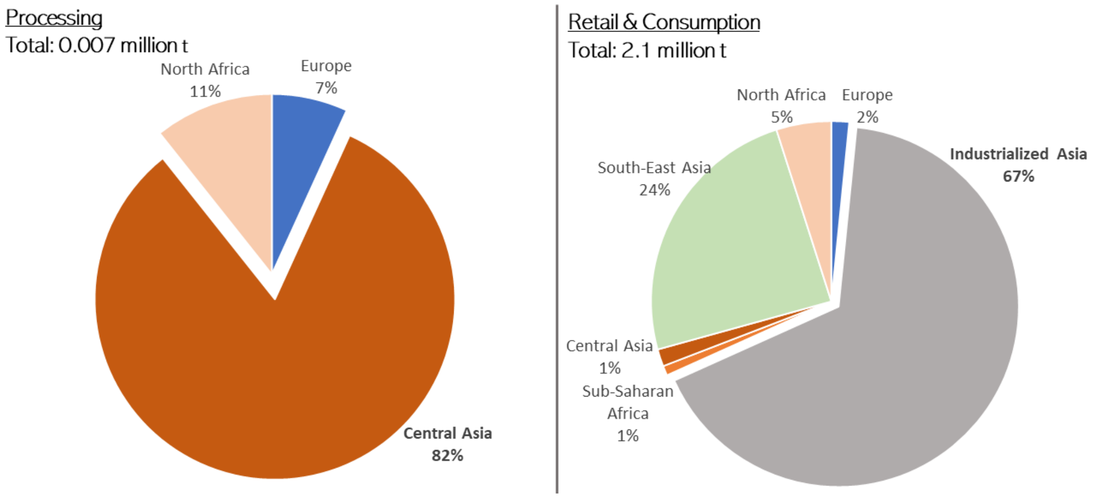

Figure D.13: Vegetable calyx loss and waste, at the regional level in 2020.

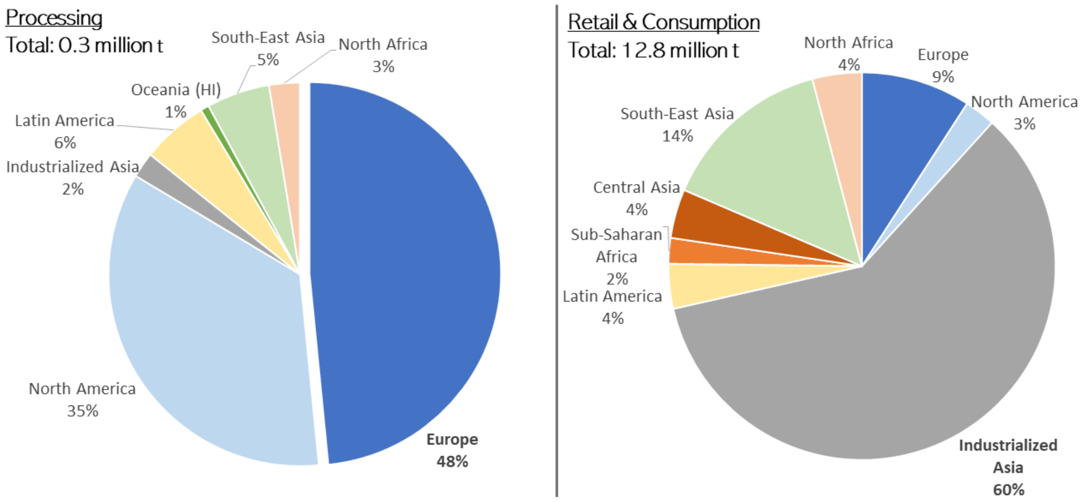

Figure D.14: Vegetable leaf loss and waste, at the regional level in 2020.

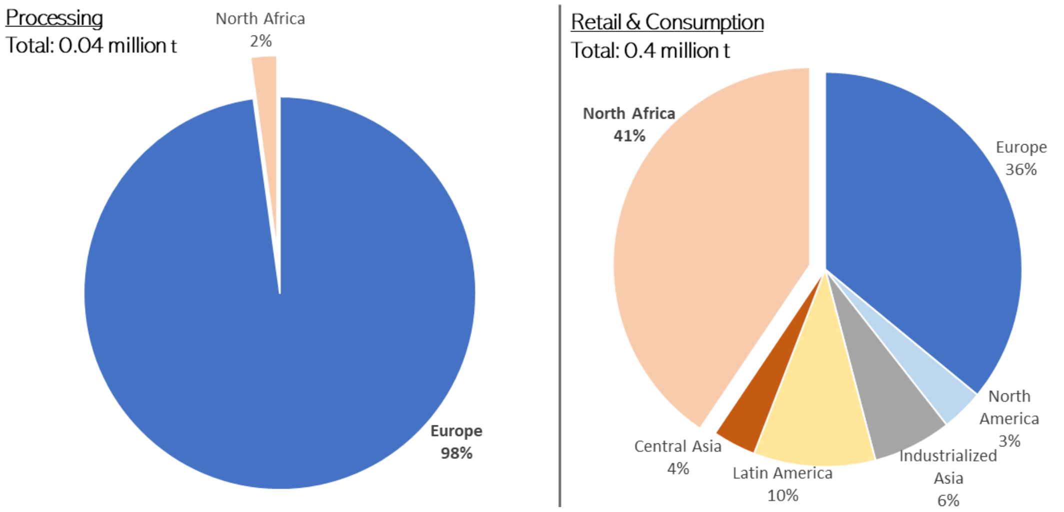

Figure D.15: Vegetable choke loss and waste, at the regional level in 2020.

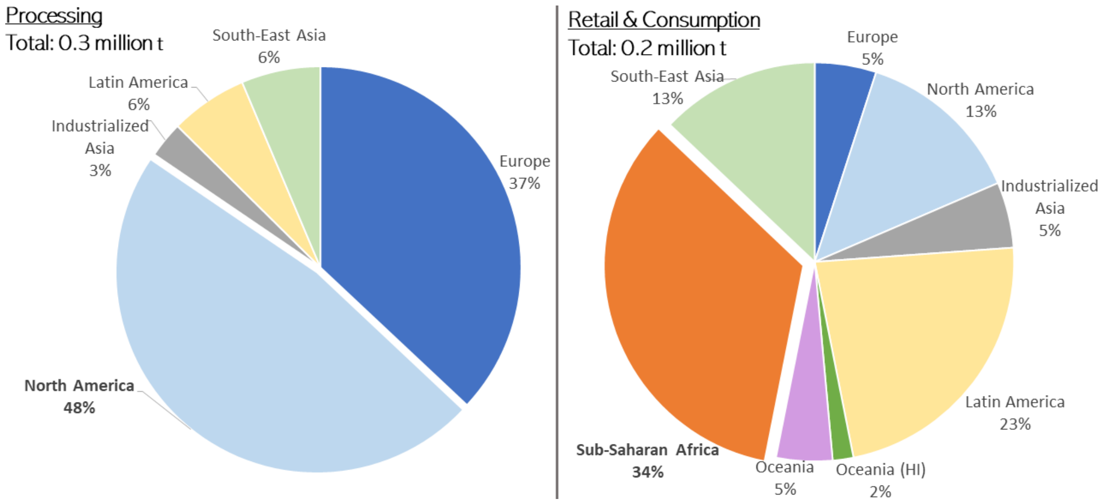

Figure D.16: Vegetable tip loss and waste, at the regional level in 2020.

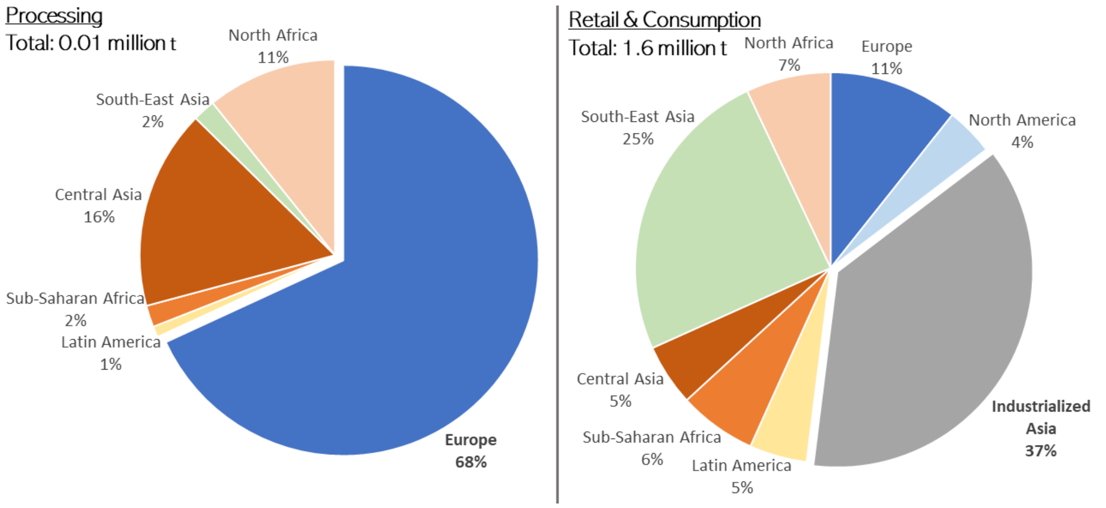

Figure D.17: Vegetable root loss and waste, at the regional level in 2020.