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How Much Food Loss and Waste Do Countries with Problems with Food Security Generate?

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Abstract: Worldwide, the number of people suffering from hunger is around 702 and 828 million, and 2.3 billion people have moderate or severe food insecurity. This situation is striking, considering that the vast amount of food discarded globally equals 1.3 billion tons annually. For this reason, in 2015, world leaders agreed to a global agenda for 2030, adopting the Sustainable Development Goals (SDGs). Among its objectives, are to fight against poverty, hunger, and gender inequality worldwide and achieve environmental sustainability. With this framework, this article uses a top-down mass balance approach to calculate food loss and waste (FLW) by country's food security level. In addition, it explores the causes of FLW and its impacts on natural resources, climate change, food security, and the SDGs in countries with a weak and moderate level of food security. The estimated global FLW was 1498 million tons of food in 2017. The most food discarded was concentrated in countries with good food security, 894.3 million tons. In contrast, the lowest food discard occurred in countries with a weak level of food security, 11.4 million tons. The primary outcome of this paper is to establish a link between the levels of food security and food loss in different countries, which may serve as a guide for the design of specific public policies.

Keywords: food loss and waste; food security; food supply chain

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1. Introduction

Food poverty and insecurity affect broad population groups observing that in high-income countries, the everyday wastage of food has risen significantly, which has increased public attention [1]. In 2021, approximately 702 and 828 million people worldwide were affected by hunger, and around 2.3 billion people had moderate or severe food insecurity [2]. According to [3], in 2020, global hunger was moderate, with a Global Hunger Index (GHI) score of 18.2, down from a severe level of 28.2 in 2000. However, hunger is a significant issue throughout South Asia (26.0) and sub-Saharan Africa (27.8), partly because of undernourishment and child stunting. Moreover, the highest child mortality and wasting rates are in Africa (south of the Sahara) and South Asia. Looking by country, 31 countries have severe levels of hunger, and three countries have alarming levels. As [4] (pl. 263) points out, "a combination of global food crises [. . .] and pressing environmental concerns [. . .] have led to a food waste momentum". The COVID-19 pandemic and the prolonged war between Russia and Ukraine have caused a global economic recession and jeopardized food security, primarily related to the agricultural labor mobility restrictions [5] and changes in imports of Ukrainian grains and Russian fertilizers [6,7]. In this context, the attention to the importance of food loss and waste becomes relevant due to the enormous amount of food lost in value chains.

The Food and Agriculture Organization (FAO) estimated in 2011, that globally, the amount of food discarded annually is equivalent to 1.3 billion tons per year [8]. The situation is even more worrying when considering that for every ton of food produced and not consumed, significant amounts of labor, natural resources, and capital are also wasted [9,10]. Resultantly, the adverse effects of FLW on the environment are multiple [11]; they cause negative impacts on water, land, climate changes, and biodiversity [12,13].

The world's population will continue increasing significantly, consequently triggering pressures on natural resources to meet the population's food needs [14]. With constrained resources and changing climate, achieving food security for the world's population without compromising ecosystem quality and biodiversity [15] requires a worldwide strategy. The focus must consider all food security dimensions and an integrated orientation. The Food Supply Chain (FSC) must be more efficient, and the amount of FLW must reduce [16,17], and generate benefits for the environment [18].

During the term of the Millennium Development Goals (MDGs), worldwide efforts and initiatives were implemented to address the reduction in poverty and hunger and ensure trends of global environmental sustainability [19]. The Agenda 2030 is the continuity of these goals by establishing the 17 Sustainable Development Goals (SDGs). Among those objectives, there is one to end hunger, achieve food security and improved nutrition (SDG2), and a target for reducing food losses along production and supply chains (SDG 12.3) [19]. Therefore, accounting for FLW at the national, continental, or global level is crucial to prioritize interventions, design public policies for FLW reduction [14], and achieve the SDGs. This knowledge allows us to (1) build a guideline to measure progress in reducing FLW; (2) supervise food generation over time; (3) decide the way to reduce food waste along the FSC; and (4) establish the pathways for potential food waste valorization.

Nevertheless, although interest in this issue has grown recently, FLW accounting needs to be expanded [20], especially in developing countries. With this background, the research question that motivates this paper arises and is as follows: How much FLW do countries with problems with food security generate?

A literature review shows a proliferation in the last fifteen years of studies for estimating FLW worldwide. FAO (2011) and Gustavsson et al. (2013) [21] estimated that 1300 million tons of food per year are wasted worldwide, equivalent to 33% of the total food production. Kummu et al. (2012) and Alexander et al. (2017) [22,23] measure food waste in kilocalories, implying a percentage of food loss between 24% and 20% dumped in the FSC. Porter et al. (2016) [24] estimated that 1646 million tons of food were discarded in 2011. FAO (2019) [25], using the Food Loss Index, estimated that globally nearly 14% of the food producing worldwide is lost during production before being sold in stores. Regarding food waste, UNEP (2021) [26] estimated an amount of 931 million tons of waste each year from different sectors related to the human food supply chain, of which 570 million tons directly come from households. Other studies collected by [20] have focused on quantifying food loss in specific countries. In contrast, others, for example Schanes et al. (2018) [27], have focused on the household level with attention to types of food and food loss.

Furthermore, countries have different causes of FLW. In industrialized countries, most FLW occurs in the food supply chain's retail, food service, and household phases [28]. Examples include food not consumed in time, spoiling, burning, personal preferences, or leftover waste [29]. In developing and underdeveloped nations, FLW is primarily due to a lack of infrastructure, knowledge, and storage technology investment [30].

The previous studies have provided valuable knowledge on the trends and scale of FLW, although they have yet to be exempt from criticism, as compiled in the work of [31,32]. On the other hand, these studies have yet to estimate the FLW considering the countries' food security level.

This article addresses these limitations by estimating FLW by the country's level of food security, by different food groups, and including all stages of the FSC. Then, it analyses the causes of FLW according to the level of food security. Finally, it briefly explores FLW's impact on natural resources, climate change, food security, and the SDGs in countries with

a weak and moderate level of food security. In this sense, the primary outcome of this paper is the analysis of the relationship between FLW and levels of food security in different countries, which may serve as a guide for the design of specific public policies. The paper primarily organizes a literature review that discusses the FLW concept and its relationships with natural resources, climate change, and food security. Secondly, FLW, by different products at each FSC stage and by the country's level of food security, is estimated. Thirdly, the empirical results are provided, with a discussion of the causes of FLW. Finally, the last section concludes by summarizing the significant findings of this contribution and opening new panels and research lines connected with them.

2. Research Background and Literature Review

2.1. Definition of Food Losses and Waste

There needs to be a universal agreement on the FLW definition and its terminologies for food waste and loss. The literature has different meanings and is often controversial [33]. FLW definitions are expressed in different terms: intended or not for human consumption; in relation to the time (pre-harvest, ready for harvest, post-harvest); considering criteria such as the edibility, use, or nutrition; the perspective adopted (social, environmental, food security); and finally, the type (quantitative or qualitative) [34]. On the other hand, there is no consistent definition of food loss and food waste [35]. Most researchers distinguish both terms regarding the stage of FSC [36]. Food loss refers to the diminished bulk of consumable food that happens from production to the processing stages in the FSC [37,38]. Food waste indicates the amount of food with good quality that is unsuitable for human consumption and then wasted at the end of the FSC in distribution, retail, or consumption stages [38,39].

Despite these differences, at least two main approaches describe FLW. The food focus contemplates the discarded edible food destined initially for human consumption as FLW. The waste focus studies FLW as both edible and inedible food discarded; however, only some FLW approaches consider FLW food meant for other uses, such as animal feed, energy production, and seed [40].

This article uses, on the one hand, the FAO definition of FLW, which tries to harmonize different concepts and align them with SDG 12.3. Moreover, it defines it as the reduction in quality or quantity of food along the FSC, from harvest, slaughter, and catch-up, not including the retail level. The case of food waste occurs at the retail and consumption level [23]. This article focuses on three concepts to implement the above definition of FLW. First, the food loss and waste rate (FLWR) is the food loss and waste ratio to total food production; second, the allocation factors determine the proportion of food destined for human consumption; and finally, the conversion factors for assessing the percentage of edible food.

2.2. FLW and Its Relationship with Food Security, Resources Sustainability, Climate Change, and SDGs

Multiple and multidirectional relationships exist between FLW, food security, natural resources sustainability, climate change, and SDGs. In the last decades, progress in technology and transport, trade barriers reduction [41], and climate change impacts on food systems [42] have contributed to an FSC that is more globalized, specialized, and complex. Consequently, there is a mismatch between the places where food is produced and consumed [43], involving many horizontally and vertically connected actors. Then, the probability of FLW along FSC increases because of more transactions between different FSC actors. On the other hand, food security can improve because food producers and a population suffering from food insecurity increase their chances of connection.

Mitigating FLW has positive results in various aspects. Firstly, it can enhance food security levels by increasing high-quality food availability [44] and improving food utilization [45]. Furthermore, a sustainable food system that contributes to less FLW might reduce food costs, improving vulnerable people's food access [45] and the investment risk

for enterprises. For instance, Lemaire and Limbourg (2019) point out that FLW reduction or food donation can reduce the food cost if the cost of that action is lower than the cost of disposal of FLW. In addition, mitigating FLW at the consumption stage of the FSC might increase the consumers' food budget and improve their access to food. According to [27], the general intention behind FLW reduction at the family level is money-saving before environmental concerns. On the other hand, sustainable food systems may reduce food price volatility, increasing the food supply's stability [46].

Secondly, mitigation of FLW may improve the efficiency and productivity of natural resource uses. According to [47,48], the water–energy–food nexus shows a clear relationship between food and the depletion of resources. For example, Kummu et al. (2012) estimated that 24% of total freshwater used in crop production, 23% of the total global cropland area, and 23% of complete global fertilizer used are wasted, producing food that will not be consumed. Furthermore, FLW has enormous potential for resource sustainability. For example, for compost returning mineral nutrients into the soil [49], recovering and reusing phosphorus [50], or using FLW to produce energy.

On the other hand, FLW causes CO_2, methane, and nitrogen emissions that cause climate change and adverse effects on biodiversity [33] and humanity [51]. According to [52,53], prevention of FLW can save from 800 to 4400 kg CO_2 equivalent per ton of food waste. Environmental degradation adversely affects agriculture, causing a vicious circle [54]. Therefore, climate change events are already contributing to reducing the yield of agricultural and livestock production [55].

SDGs took up the commitment to achieve food security and solve environmental problems. FLW negatively impacts food security and the environment, hindering the achievement of SDGs [56]. SDG 1, "No Poverty," and SDG 2, "Zero Hunger", are food security related. SDGs 6, 7, 11, 12, 13, 14, and 15 are connected directly or indirectly to the environment. Sachs et al. (2019) elaborated on an SDG Global Rank based on the performance of SDG indicators by country.

Table 1 regrouped the SDGs performance according to the country's food security, considering GFSI as a base, where six countries were classified with weak food security and 36 with moderate. The SDG Global Rank points out that every country with a weak level of food security and the majority with a moderate level of food security has significant challenges in achieving SDGs 1 and 2. The situation with the SDG 6, SDG 7, and SDG 11 is similar. Namely, most countries have significant and major challenges to achieving the SDGs. The situation regarding SDGs 12, 13, 14, and 15 is slightly better, but the challenges remain or are significant.

In addition, this improvement can be better because there are complex relationships between food security, wealth, and environment, where weak and moderate food security countries are associated with mainly poor countries. There are some reasons why poor countries may have a better environment, for example, lower industrialization and demand for natural resources, which may keep clean environments, but at the same time keep poverty. Lack of industrial and transportation infrastructure may limit the capacity to pollute or degrade the environment but produce other social and economic problems. Depending on agriculture and traditional practices, this tends to be less chemically intensive and more sustainable, but more inefficient in quantity production. Lower consumption results in a lower generation of waste and pollution, but sometimes consumption is below the survival standards [57–59]. Therefore, considering that in countries with a weak and moderate level of food security, FLW accounted for 21% and 20% as a percentage of the domestic food supply, it is possible to argue that there is a gap contributing to the achievement of SDGs through reducing FLW.

Table 1. Performance of the countries with a moderate and weak level of food security in SDGs affected by FLW.

	N° of Countries with Weak Level of Food Security				N° of Countries with Moderate Level of Food Security				
SDGs/Category	**SDG Achievement**	**Challenges Remain**	**Significant Challenges Remain**	**Major Challenges Remain**	**SDG Achievement**	**Challenges Remain**	**Significant Challenges Remain**	**Major Challenges Remain**	**Data No Available**
SDG1: No poverty				5	1	5	8	22	1
SDG2: Zero Hunger				6			4	32	0
SDG6: Clean water and sanitation		1		5			6	30	0
SDG7: Affordable and clean energy		1		5		5	5	26	0
SDG11: Sustainable cities and communities			2	4	1	1	13	21	0
SDG12: Responsable consumption and production	2	3	1		12	22	2		0
SDG13: Climate action	1	4	1		6	23	6	1	0
SDG14: Life below water			4			3	15	6	14
SDG15: Life on land		2	3	1	1	10	23	2	0

Source: own elaboration based on [57].

3. Materials and Methods

3.1. Calculation of Food Loss and Waste

The mass balance method designed by [8,21] is used in this research. This method calculates the amount of FLW as the difference between inputs and outputs of food, their stock variations, and weight changes during the process [60].

This method presents several advantages as it allows calculating the FLW of liquid and solid food at each stage of the FSC, at the national level, or the more specific company level. Moreover, the data required are often easily accessible and readily available, e.g., in national statistics [61]. For the research scope, the mass balance method is appropriate. It covers FSC worldwide, in all stages, and includes a wide range of food products. In addition, the amount of FLW estimated for each country was associated with its level of food security, using the four clusters formed by the Global Food Security Index (GFSI) designed by The Economist Intelligence Unit. These clusters are "very good", "good", "moderate", and "weak", and a set of indicators calculates them based on four categories related to food security: affordability, availability, quality, and safety, and natural resources and resilience. The GFSI is calculated for 113 countries, while FLW is estimated for 171; therefore, the rest of the countries were classified in a "without EUI index" cluster. The accounting approach to estimate FLW is described in Figure 1 [62].

The following equations represent the estimation of FLW and pooling.

$$FLW_k = \sum_{i=1}^{n} QA_{ijk} * \alpha_{ijk} * \beta_{ijk} * \gamma_{ijk} \quad (1)$$

$$FLW = \sum_{l=1}^{5} FLW_{kl} \quad (2)$$

where

- i is the food group: fruit, cereals, milk, fish and seafood, meat, eggs, starchy roots, pulses, oil crops, and vegetables;
- j is the stage of the FSC: agricultural production, post-harvest, storage, processing and packaging, distribution, and consumption;
- k is the country;

- l is the level of food security according to the Global Food Security Index of The Economist Intelligence Unit, which are very good, good, moderate, weak, very weak, and without EIU Index;
- QA_{ijk} is the domestic food supply quantity, which is the quantity of food available in the food group i in stage j of the FSC in the country k.
- α_{ijk} is the food loss and waste rate (FLWR) in the food group i in stage j of the FSC in the country k, defined as the ratio of food loss and waste to the total amount of food production;
- β_{ijk} is the allocation factor in the food group i in stage j of the FSC in the country k, which defines the proportion of the food meant for human consumption.
- γ_{ijk} is the conversion factor in the food group i in stage j of the FSC in the country k, which defines the proportion of edible food;
- FLW_{kl} is the food loss and waste in the country k with the level l of security.

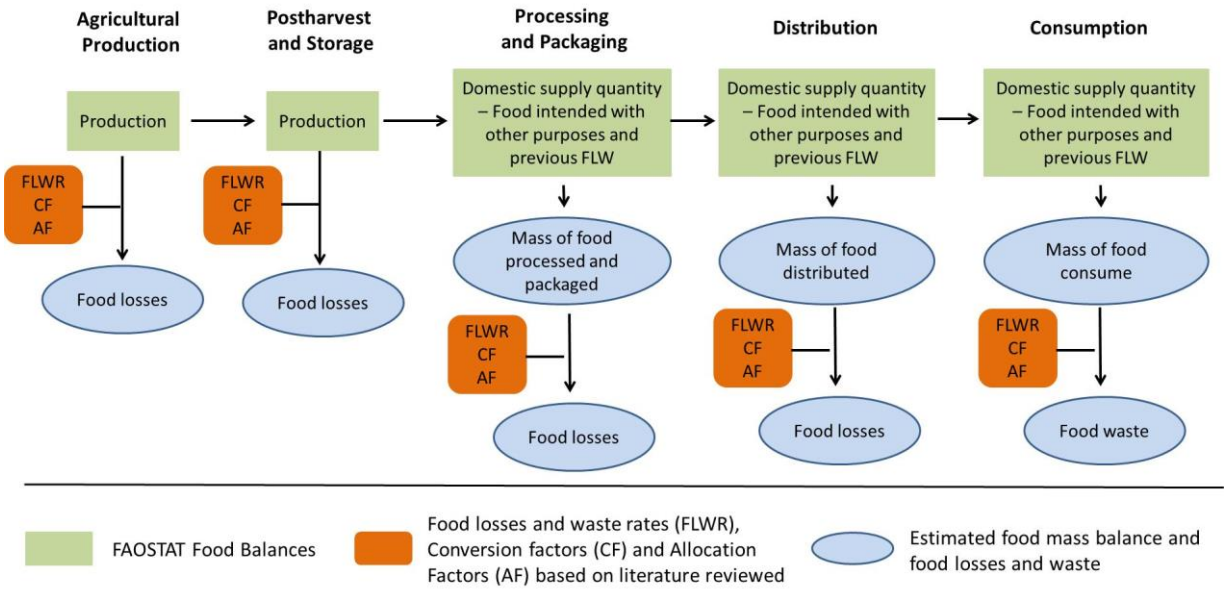

Figure 1. Accounting approach to estimate FLW.

The mass balance method distinguishes between edible and non-edible food. Regarding FLW, quantification only considers edible food and discordance in the FLW estimation. Several causes contribute to decreased edible food mass in FSC stages [63]. In this sense, food loss occurs at all stages except consumption, when food waste occurs [32,39].

Therefore, the FLW is calculated, multiplying the amount of food available at each step of the food chain by FLWR and the allocation and conversion factors. Finally, the FLW considers the country's level of food security.

Then, the following equation was used to calculate the per capita FLW.

$$FLW_{PC} = \frac{FLW}{P_n} \tag{3}$$

where FLW_{PC} is the per capita food loss and waste and P_n is the population.

3.2. Data

The geographical area selected for this study is worldwide, using the FAOSTAT datasets for 2017 for the production and yield of food information. The per capita results are calculated using population data from the World Bank. FLWR, conversion and allocation factors were taken from [8,21] and contrasted with [20]. The Global Food Security Index of December 2019, designed by The Economist Intelligence Unit, indicated the different countries' food security levels.

The method and data used have limitations that should be addressed in future research to obtain a more comprehensive and robust FLW accounting. These limitations are highlighted in the list below:

i. As pointed out, the research uses FAOSTAT data for various countries, food groups, and FSC stages of conducting this research. FAOSTAT data only for some of those variables have the same level of reliability and accuracy. This situation may be due to multiple reasons; for example, not all countries have the same incentive to deliver accurate and reliable information. In addition, not all countries have a national statistical institute that collects and processes national statistics. Moreover, some countries have a national statistical institute. Moreover, with a minimal budget preventing accurate information development, they must prioritize the agriculture and food data. Moreover, in many countries, FLW is considered a sensitive issue for policymakers, governments, citizens, and national and international organizations, which may cause the authorities an incentive to misinform accurate data regarding FLW. Therefore, future research addressing this problem might focus on developing more precise and reliable national statistical data, especially on countries with food security issues, usually countries with less developed statistical data.
ii. FLWR, conversion, and allocation factors for estimating FLW were taken from [8,21] and contrasted with data collected by [20] from 1943 to 2015. These factors were collected from scientific journals, statistical databases, non-governmental organizations, and national and international organizations, from 1997 to 2011. In Annex 1 to Annex 3, there are more details about data sources and methods used to estimate FLWR, conversion, and allocation factors [21]. Therefore, in some cases, the data needed to be updated, and it was necessary to make assumptions for their use. For example, when FLWR, conversion, or allocation factor were unavailable for a specific country, the regional FLWR, conversion, or allocation factor was used for the estimation, which introduces bias in the analysis. Nevertheless, by comparing the outcomes with research using primary data on food waste, these drawbacks can be eliminated [60,61]. However, despite these drawbacks, using these factors and the mass balance method is meaningful as it provides a more comprehensive picture of the structure of FLW in a country. Therefore, the results help to focalize future research resources on the country's main issues related to FLW and might focus on collecting primary food waste data in specific countries to improve the accuracy of the FLWR, conversion, and allocation factors.
iii. The Global Food Security Index of December 2019 was calculated for 113 countries, while the FLW was calculated for 176 countries in this research. As mentioned in this article's methodology section, the rest of the countries were grouped in the category without the EIU Index; therefore, some countries need an index, but with food security problems and a significant amount of FLW, future research might explore this in detail.

4. Results and Discussion

4.1. Descriptive Analysis

In this section, the analysis is conducted based on four levels of food security according to the classification of The Global Food Security Index: very good, good, moderate, and weak.

Moreover, it added a new category for countries where The Economist Intelligence Unit did not calculate the level of food security. This category was labelled as countries "without EIU Index". Thus, 171 countries were considered in this research, gathering a population of 7369 million people in 2017. The number of countries by category of food security is shown in Table 1. Except for countries without EIU Index (63 countries), the most significant number of countries are in the category of good and moderate levels of food security, in total 88 countries. Most of the world's population also lives in these two types of countries, that is 6345 million people, 86% of the world's population. A

considerable contribution to the population comes from China (1452 million people) and India (1338 million people) for good and moderate levels of food security, respectively.

Analyzing the absolute volume of total domestic food supply, countries with good food security hold the most significant amount of available food, 4734 million tons. Nevertheless, as expected in per capita terms, there is a positive correlation between food security and the amount of per capita food available.

Thus, countries with very good levels of food security had 1912 kg per capita, while countries with weak levels of food security had 481 kg per capita, which means four times less than countries with the highest level of food security.

Regardless of the level of food security, cereals represented the most significant food group available in every type of country. In contrast, the second largest food group available changes with the level of food security. In countries with very good food security, milk is the second largest food group available, followed by oil crops. In these countries, the number of vegetables, fruit, and meat is similar, around 115 kg per capita, higher than in countries with low levels of food security. In countries with moderate and weak levels of food security, the second largest food group available is starchy roots. Several reasons explain this situation, according to [64,65]: (i) the price of starchy root products is low, thus affordable for people from low socioeconomic strata; (ii) they provide protein, vitamin A, C, zinc, and iron that are nutritionally rich staple food; (iii) in comparison to other crops, they are versatile staples that produce more food per unit area of land; (iv) they have shorter crop cycles, about three or four months as is the case of potato and sweet potato; (v) yam and cassava are vital in the annual cycle of food availability due to their broader agroecological adaptation, diverse maturity period, and in-ground storage capability; (vi) they are far less susceptible to large-scale market shocks and price speculation experienced by more widely traded staples, such as grains.

In addition, countries with a moderate and weak level of food security have low availability of dairy products and meat, corroborating their poor diet [66], which supports the argument that countries with a high level of food security usually have high incomes per capita. They have access to a more varied, balanced, and healthy diet than those with a low level of food security (Table 2) [66].

Table 2. Domestic supply quantity in a million tons by country's level of food security and by each food group in 2017. Number of countries by level of food security and population in a million people. Own elaboration based on FAOSTAT data (2017), World Bank data (2019), and The Economist Intelligence Unit data (2019).

	Level of Food Security					
Food Group	**Very Good**	**Good**	**Moderate**	**Weak**	**Without EUI Index**	**Total**
Cereals-Excluding Beer	940.4	439.2	241.4	179.8	305.8	2106.6
Eggs	16.9	17.6	3.7	2.5	7.0	47.7
Fish, Seafood	29.2	35.3	9.3	9.2	10.9	93.9
Fruits-Excluding Wine	113.3	112.1	65.0	49.8	89.1	429.3
Meat	107.1	60.1	10.8	25.3	32.4	235.8
Milk-Excluding Butter	291.8	79.4	103.0	43.2	90.0	607.3
Oilcrops	198.9	197.6	46.7	18.6	31.1	492.9
Pulses	10.9	6.6	20.2	5.8	8.3	52.0
Starchy Roots	87.3	116.3	121.7	117.6	64.0	506.8
Vegetables	115.8	243.7	83.0	29.2	129.9	601.5
Total	1911.5	1307.9	704.8	481.0	768.6	5173.9
N° Countries	14	52	36	6	63	171
Population (Million people)	610.8	3619.7	2725.6	110.4	302.8	7369.3

4.2. Overall FLW by Food Security Level and Stage of the FSC

The total FLW was 1498.2 million tons of food in 2017. The greatest discard, 894.3 million tons, was concentrated in countries with good food security. In contrast, the lowest food discard, 11.4 million tons, occurred in countries with weak food security. This result is expected due to the difference in both countries' total domestic food supply. In addition, FLW in China, equivalent to 402 million tons, contributes significantly to the high amount of FLW in countries with good food security. FLW represents around 20% of the total domestic food supply in countries with good, moderate, and weak food security. In contrast, in countries with very good food security, FLW represents 14%.

The reasons that explain FLW in countries with different levels of food security vary from country to country. In general, countries with a very good and good level of food security are those with high and medium income, while countries with a moderate and weak level of food security are those with a reasonable and low-income level. The reasons for FLW in high/medium-income countries are related to consumer behavior and a lack of coordination between actors in the FSC [8,67,68]; for example, leftover waste, food not used in time, personal preferences, spoilage, or burning [20,29]. In contrast, in countries with moderate/low-income levels, the reasons for FLW are financial and managerial, some limitations are related to harvesting techniques, lack of storage, and cooling facilities in countries with difficult climatic conditions, infrastructure, packaging, and marketing systems [69,70].

Analyzing by stage of the FSC, the hotspots of FLW differ depending on the country's food security level (Table 3). In countries with a very good level of food security, FLW occurred mainly in the consumption stage of the FSC, around 43% of the total FLW in these countries. According to [71], FLW at the consumption stage of the FSC, is directly related to social factors, such as the level of education and cultural behaviors. In turn, [72] takes a more complex approach than [71], considering that psychological, socioeconomic, environmental, and regulatory factors affect consumers' attitudes towards FLW. Another reason that might explain FLW at the consumption stage is the inconsistency between the consumer's demand and a need for more general awareness of the existing waste problem.

Table 3. FLW in a million tons calculated for the country's level of food security and FSC stage in 2017.

		Food Losses and Waste (Mt)						
Level of Food Security	**Domestic Supply Quantity (Mt)**	**Agricultural Production**	**Postharvest and Storage**	**Processing and Packaging**	**Distribution**	**Consumption**	**Total FLW**	**Food Waste/Domestic Supply Quantity**
Very good	1167.6	46.3	15.7	11.9	18.2	68.3	160.5	14%
Good	4734.3	259.3	207.9	75.8	132.2	219.1	894.3	19%
Moderate	1921.1	122.3	130.5	22.3	76.5	36.8	388.3	20%
Weak	53.1	3.5	3.3	1.0	2.1	1.5	11.4	21%
Without EUI Index	232.7	13.5	10.3	2.7	8.8	8.4	43.7	19%
Total	8108.8	444.8	367.8	113.7	237.7	334.1	1498.2	18%

In countries with good food security, FLW mainly occurred at the end of the FSC, 259.3 (29%) and 219.1 (25%) million tons in the agricultural production and consumption stages, respectively. Nevertheless, post-harvest storage and distribution stages showed considerable FLW, 207.9 (23%) and 132.2 (15%) million tons, respectively. Therefore, FLW is distributed more equally among the stages of FSC in countries with a good level of security than in countries with other food security groups. One of the reasons to explain this pattern is that this category gathers countries with a high heterogeneity with each other. For instance, the most significant amount of FLW in this category of countries occurred in China. The FLW mainly happened at the end of the FSC, 129 (32%) and 109 (27%) million tons in the agricultural production and consumption stages, respectively, with considerable

FLW in post-harvest and storage and distribution stages, 89 (22%) and 63 (16%) million tons, respectively. However, in Chile, FLW mainly occurred at the first two stages of the FSC, namely, agricultural production and post-harvest and storage stages, with 2897 (60%) thousand tons of FLW. The other three stages represent a similar percentage, around 13% of total FLW.

In contrast with the countries with a very good level of food security, in countries with a moderate and weak level of food security, FLW occurred mainly in the first two stages of the FSC, namely, agricultural production and post-harvest and storage. The reasons that explain the FLW in these stages are several: for instance, difficulties in managing the factors that affect the agricultural production process, such as weather conditions [73]; lack of efficient irrigation systems [36]; insects, diseases, rodents, weeds, inefficient seeding, and severe weather conditions during planting [74]; death and disease, such as animal death during breeding for bovine, poultry, and pork meat, discards during fishing for fish, and decreases in milk production due to dairy cow diseases such as mastitis [74]; mechanical damage during harvesting [44]; market prices lower than the harvesting cost [44]; and poor storage facilities and lack of infrastructure [8].

4.3. Overall FLW by Food Security Level and Food Group

The analysis of FLW by food group and in terms of volume shows that in countries with very good levels of food security, FLW occurred mainly in five food groups (Figure 2). These are vegetables, milk, and starchy roots, with around 28 million tons of each food group, and cereals and fruit, with about 25 million tons of each food group. Pulses, eggs, fish, and seafood showed the lowest FLW, between 0.4 and 3.4 million tons. Food groups with the highest FLW as a percentage of the domestic food supply quantity were starchy root, vegetables, and fruit, 52%, 40%, and 36%, respectively. However, meat, fish and seafood, milk, and eggs also showed a significant amount of FLW compared with the domestic supply quantity, between 15% and 20%. In every food group, FLW occurred mainly in the consumption stage. However, for starchy root, vegetables, milk, and fruit, the agricultural production stage also concentrated a significant amount of FLW.

According to [75] some of the reasons that explain FLW in the production and consumption stage that might apply to this category of countries are: (i) unpredictable use of supply and demand volume and consequent overproduction and demand volatility, especially in perishable food, such as, starchy root, vegetable, and fruit; (ii) inappropriate use of fridge and storage systems in households; (iii) packaging renewals due to marketing campaigns; (iv) incorrect forecast of serving in food services and restaurants; (v) inadequacy of menus to consumer's preferences; (vi) insufficient information in menus; (vii) inflexibility in portion size and assortment; (viii) too short lunch breaks in schools; (ix) possibility of last-minute cancelations of orders; (x) cheap price of food compared with the salary in developed countries; (xi) marketing standards for fruit and vegetables; (xii) farm overproduction related to government subsidies; (xiii) difference in implementation and enforcement of safety rules among countries; (xiv) phytosanitary controls on imports; (xv) European restrictions on the possibility of using animal residuals food and animal feed preparations; (xvi) production of food that not achieve the marketing standards; (xvii) urbanization and related changing dietary habits; (xviii) household formed by few members or by one single person; (xix) and selective behavior of consumers with respect to food freshness.

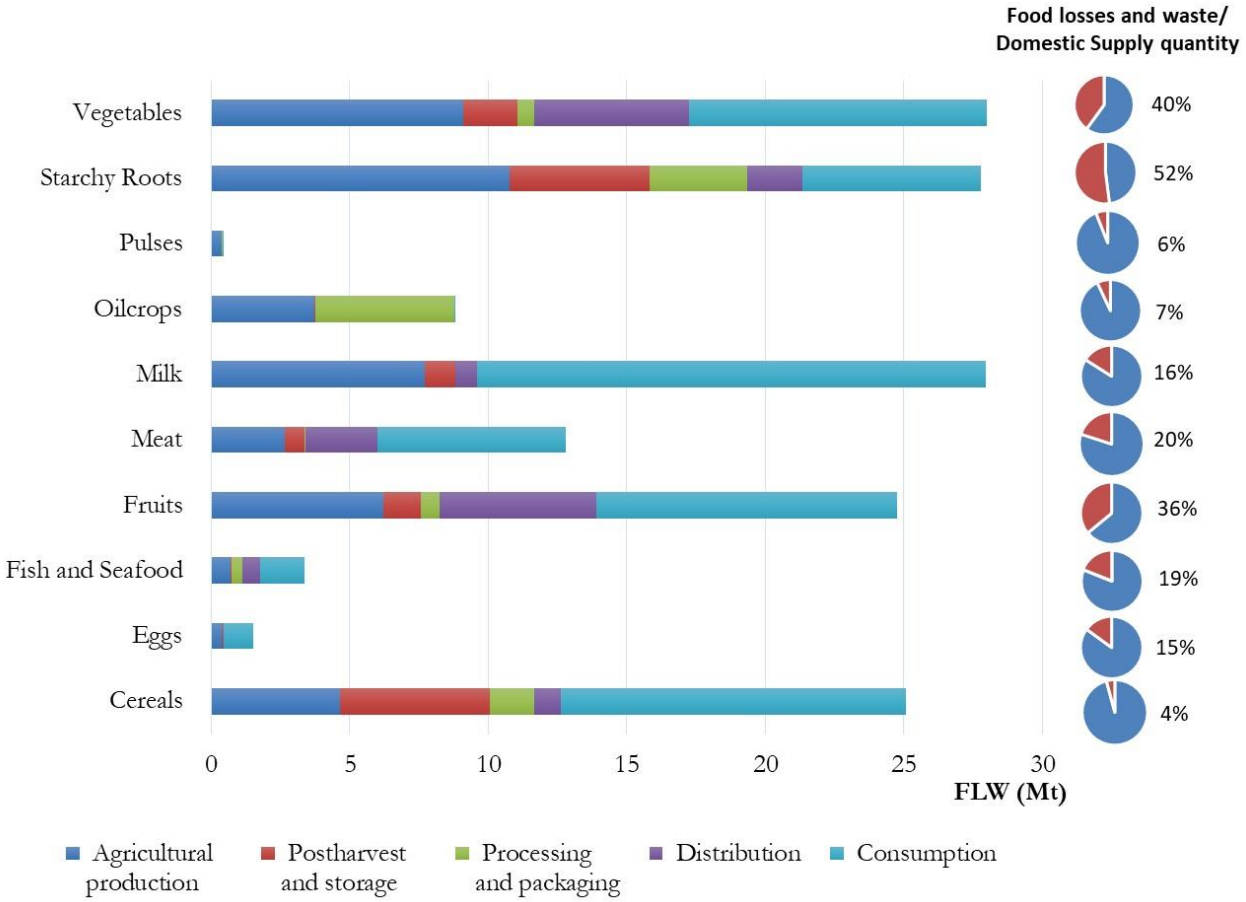

Figure 2. Left (bar chart): FLW calculated for each food group and FSC stage in countries with a very good level of food security in 2017. **Right** (pie chart): percentage of FLW as a fraction of the total domestic supply quantity in countries with a very good level of food security in 2017.

In countries with good food security, FLW mainly occurred in vegetables, 273.4 million tons, equivalent to 31% of the total FLW in this category of countries. An exceptional case is Chinese FLW which represents 66% of the total FLW of vegetables in this category of countries (Figure 3). The reasons are mainly due to weeds, diseases, rodents, insects, inefficient seeding, and severe weather conditions during planting [74] and the economic growth of the last four decades that has improved the living standards of the Chinese population, leading to careless behaviors resulting in FLW [76]. Other groups with a significant amount of FLW are fruit and cereals, with around 150 million tons each. Food groups with the highest FLW as a percentage of the domestic food supply quantity were fruit, vegetables, and starchy root, 37%, 31%, and 30%, respectively. However, the rest of the food groups also showed a significant amount of FLW compared with the domestic supply quantity, a range between 12% and 19%, except for cereals and pulses, which have a low level of FLW. Analyzing by stage of the FSC, in countries with a good level of food security, FLW is more equally distributed through the FSC than in countries with the best level of food security. The exception is the processing and packaging stage, which is small in every food group except for oil crops.

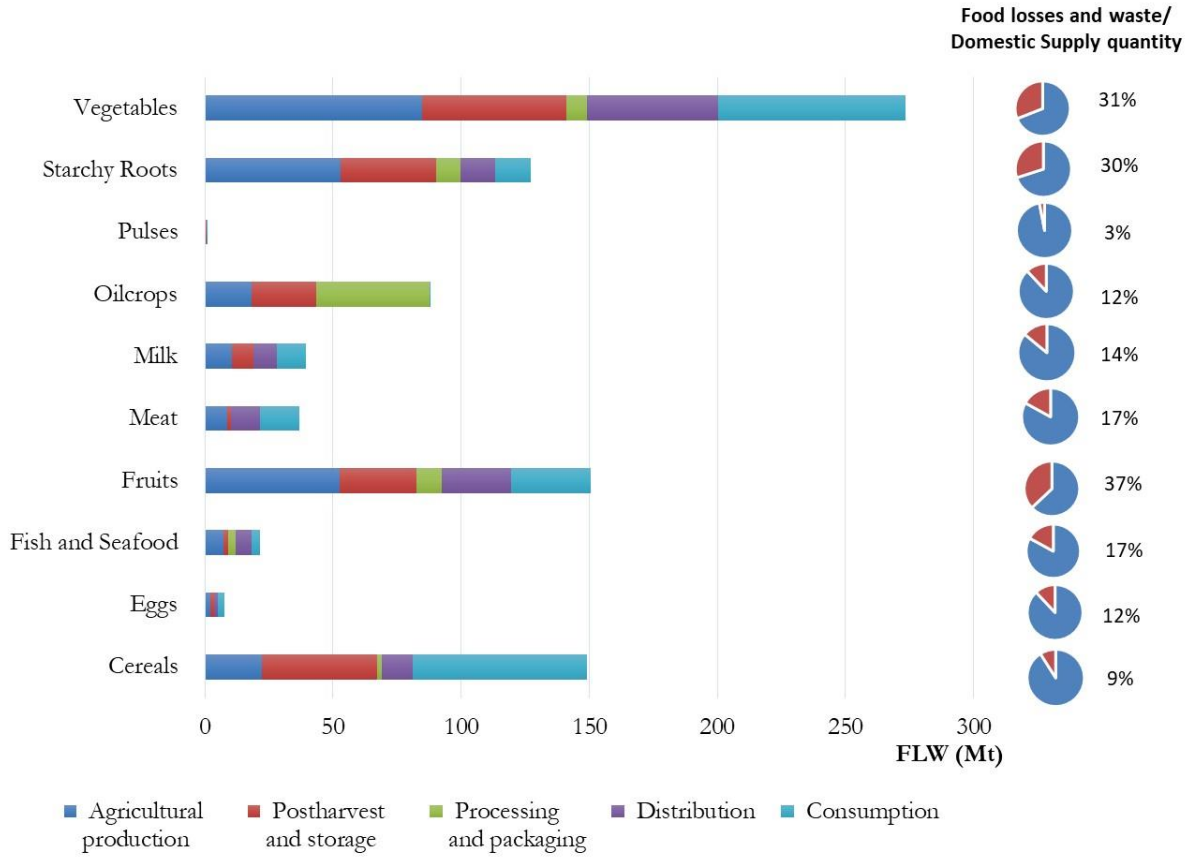

Figure 3. Left (bar chart): FLW calculated for each food group and FSC stage in countries with a good level of food security in 2017. **Right** (pie chart): percentage of FLW as a fraction of the total domestic supply quantity in countries with a good level of food security in 2017.

The reasons that explain FLW in this category of countries are like the causes that explain FLW in countries with a very good level of food security. Nevertheless, it is possible to mention some additional reasons related to the agricultural, post-harvest, and storage stages. Firstly, some characteristics of fruits, vegetables, starchy roots, and cereals production reduce the possibility of predicting supply and demand volumes. This situation hinders the capacity of FSC operators to adapt to changing markets, which generates FLW [75]. An example of this situation is at the agricultural production stage; the uncertainties in weather conditions, frosts, droughts, rodents, or disease might cause the FLW of fruits, vegetables, and starchy roots. This situation induces farmers to overplant to avoid the risks of not fulfilling their contract conditions.

Consequently, unsold and unharvested products are generated [77]. Secondly, many fruits and vegetables are delicate by nature, which renders them vulnerable to injury during automated or human harvesting and handling [75]. Thirdly, different conditions, such as bites of birds, frosts, droughts, and weather conditions, provoke the FLW of these products [78]. The conditions above also cause the vegetables, fruits, and starchy roots not to satisfy the market standards, such as appearance, shape, and weight. Hence, farmers discard them to avoid harvesting costs [79].

In countries with moderate food security, the largest FLW occurred in the starchy root, 106.6 million tons, equivalent to 27% of the total FLW in this category of countries (Figure 4). Other groups with a significant amount of FLW are vegetables, cereals, fruit, and milk. Starchy root, vegetables, and fruit groups have the highest FLW as a percentage of the domestic food supply quantity, around 32% of each group. However, the rest of the food groups also showed a significant amount of FLW compared with the domestic supply quantity, between 10% and 19%. Analyzing by stage of the FSC, in countries with moderate

food security, almost every food group FLW is concentrated mainly in the first two stages of the FSC. Nevertheless, a significant amount of FLW occurred in the distribution stage.

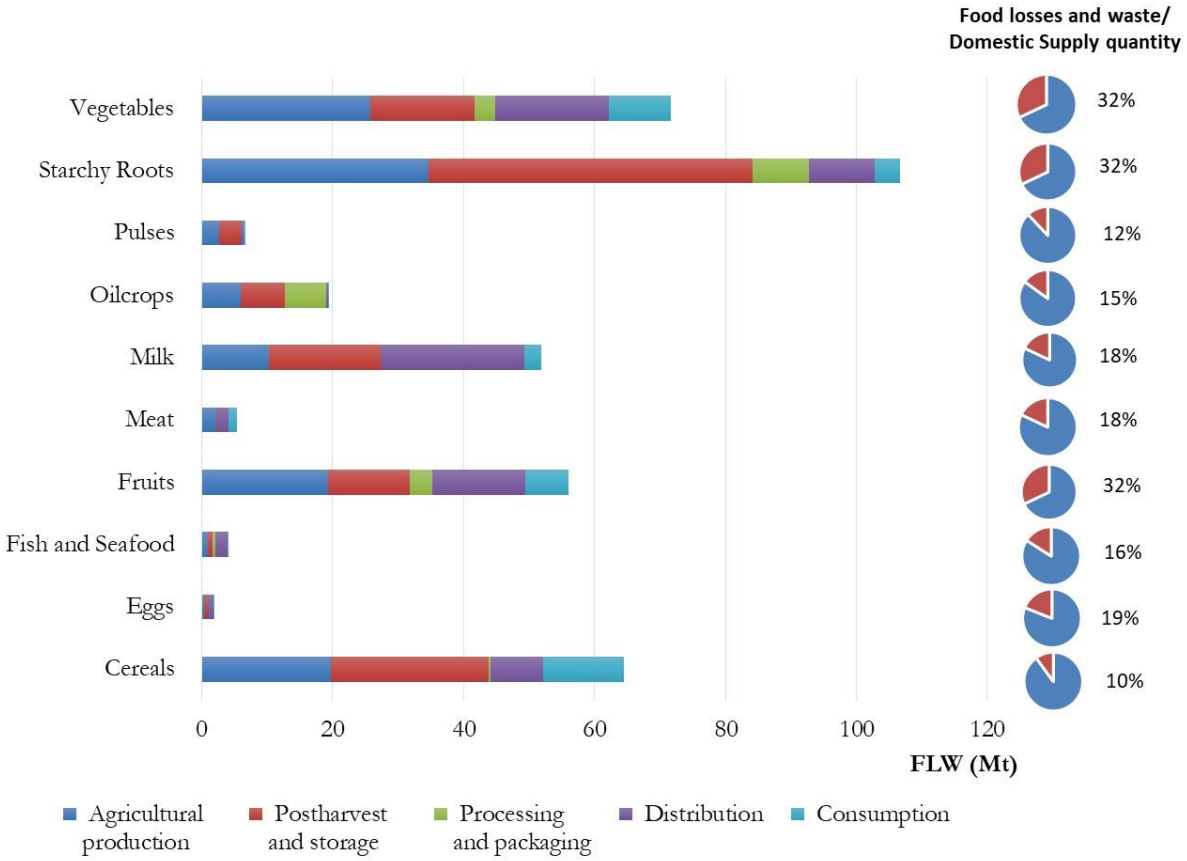

Figure 4. Left (bar chart): FLW calculated for each food group and FSC stage in countries with a moderate level of food security in 2017. **Right** (pie chart): percentage of FLW as a fraction of the total domestic supply quantity in countries with a moderate level of food security in 2017.

The causes that explain FLW at the agricultural and post-harvest and storage stages in this category of countries are related to the lack of infrastructure, knowledge, and investment in storage technologies [8,69,70] and limited capacity to face environmental and weather conditions and climate change [80,81], for instance: (i) inadequate systems of control in production and processing, for example, slaughtering and processing losses in the meat industry [82]; (ii) suboptimal operation and ease of use of equipment [79]; (iii) poor storage handling [80,83]; (iv) damage during transport due to suboptimal transport infrastructure [75]; (v) cold chain inefficiencies [83]; (vi) incorrect application or absence of inventory turnover [75]; (vii) and lack of finance that hinders the setting of facilities for proper conservation and processing of food [8,75].

In countries with the worst level of food security, the largest FLW occurred in the starchy root, 4.1 million tons, equivalent to 36% of the total FLW in this category of countries, a very high percentage compared with the other food groups (Figure 5). In this category, FLW occurred mainly in the first two stages of the FSC. Some reasons for this are the lack of storage infrastructure and technology to control pests, rodents, insects, diseases, weeds, inefficient seeding, and extreme weather conditions [74].

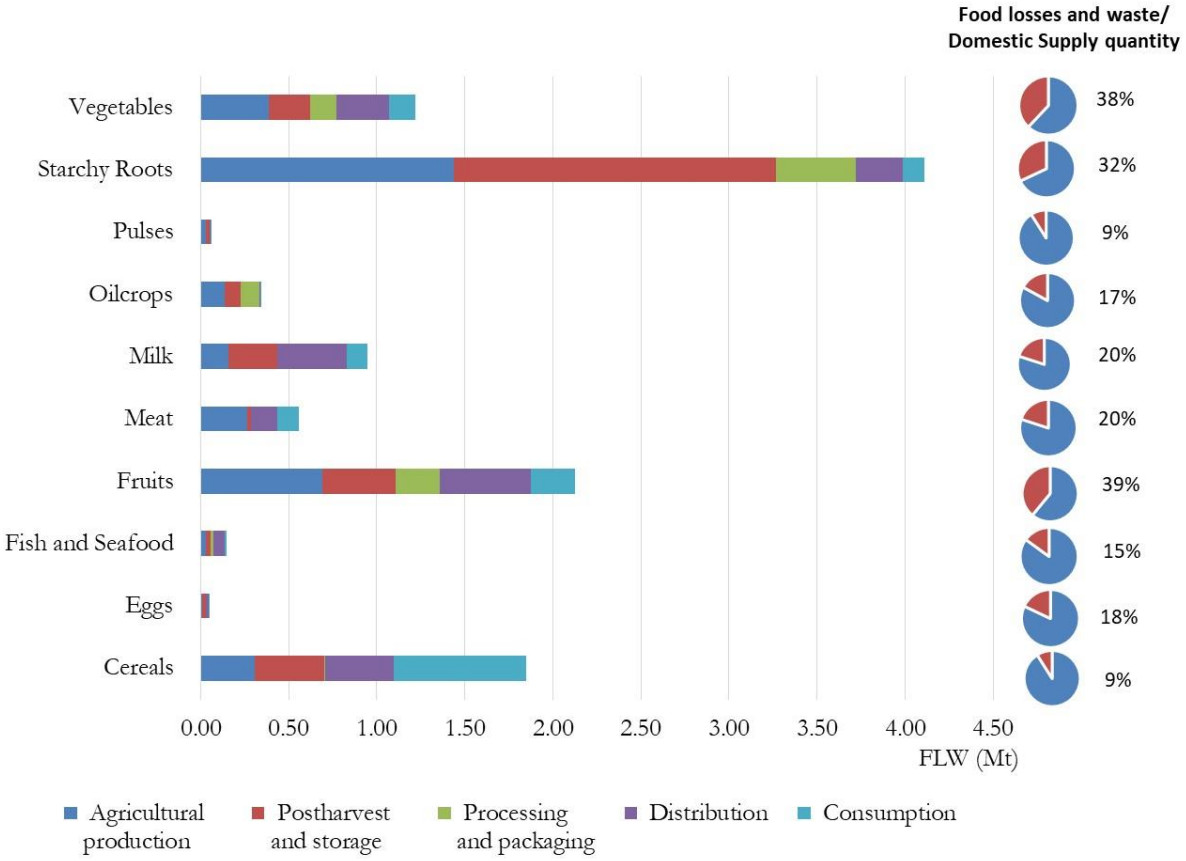

Figure 5. Left (bar chart): FLW calculated for each food group and FSC stage in countries with a weak level of food security in 2017. **Right** (pie chart): percentage of FLW as a fraction of the total domestic supply quantity in countries with a weak level of food security in 2017.

In fruit and cereals, a significant amount of FLW occurred, 2.13 and 1.85 million tons, respectively. Food groups of fruit, vegetables, and starchy root represent a high amount of FLW as a percentage of the domestic food supply quantity, 39%, 38%, and 32%, respectively. Nevertheless, the rest of the food groups also showed a significant amount of FLW compared with the domestic supply quantity, ranging between 15% and 20%. The only exceptions are cereals and pulses with 9% of FLW. As a percentage of the domestic food quantity, countries with a weak level of food security lost the same or even more fruit and vegetables than countries with a very good and good level of food security. This situation is consistent with the diet of these countries, which can be more diversified, mainly based on starchy roots, cereals, and vegetables due to their lower cost than other food groups, such as meat or fish. In this sense, the main reasons for FLW are the lack of storage infrastructure and investment in agricultural technologies, the lack of knowledge of proper technology use [69,70], and a limited ability to adapt to changing environmental and meteorological circumstances and climate change.

In countries with a weak level of food security, FLW is concentrated in distinct stages of the FSC, depending on the food group.

In the starchy root, 80% of FLW occurred in the first two stages of the FSC. FLW in fruit was concentrated in agricultural production and distribution, but a necessary amount of FLW also happened in the other stages. In cereals, the hotspot is the consumption stage, with 41% of the FLW in this food group. The causes that explain FLW in this category of countries are like those in countries with a moderate level of food security. Nevertheless, in countries with a weak level of food security, political instability or even wars significantly impact the sustainability of food systems, therefore, their FLW.

5. Conclusions

This article estimated the FLW by the country's level of food security, by different food groups, including all stages of the FSC.

It analyzed the causes of FLW according to the level of food security and explored the impact of FLW on natural resources, climate change, and SDGs. The estimated global FLW was 1498 million tons of food in 2017. The greatest discard was concentrated in countries with good food security, 894.3 million tons. In contrast, the lowest food discard occurred in countries with a weak level of food security, 11.4 million tons. FLW represents around 20% of the total domestic food supply in countries with good, moderate, and inadequate food security.

By contrast, in countries with a very good level of food security, FLW represents 14% of it, and the hotspot of FLW is mainly concentrated in the consumption phase. However, in countries with good food security, FLW is generated primarily in the last step of the FSC. On the other hand, in countries with moderate and weak food security, FLW occurred mainly in the first two stages of the FSC.

It was observed that countries with a moderate and weak level of food security must face significant challenges to achieve the SDGs. Another challenge for scientists, government, policymakers, and civil organisms is to improve statistical data on FLW, especially primary data. Efforts must be oriented to obtain more accurate FLWR, conversion, and allocation factors for every country, especially those with a weak and moderate level of food security that usually need more precise and reliable statistical information.

Furthermore, quantitative connections between FLW and the SDGs indicators are needed to comprehend better how they affect food safety, the environment, and broader sustainable development trajectories. Despite these challenges, the economic, social, and environmental impact of FLW is enormous. Therefore, considering that in countries with a weak and moderate level of food security, FLW accounted for 21% and 20% of the domestic food supply, respectively, it is possible to argue that there is a gap in contributing to the achievement of SDGs through reducing FLW. It is necessary to enhance food security, lift people from poverty, and achieve environmental sustainability.

For this purpose, public policies play a crucial role in designing measures according to the food security dimension to which they contribute. Public policies can improve the efficiency of productive processes, translating to decreased food costs and, therefore, a possible price reduction. Additionally, the design of public policies must consider each country's different economic, institutional, human resources, and infrastructure contexts.

Generally, some policy measures can be oriented to the first stages of the food chain, such as developing good manufacturing practices, preparation, and food hygiene, which contributes to reducing food loss. Regarding storage and conservation solutions, it is necessary to develop technologies on a smaller scale with lower costs so that small farmers can access them. Along with this, they must improve the means of transport from the producers to the retail buyers, making it necessary for them to have refrigeration systems.

Many causes lead to food loss and waste generation in the consumption stage. Therefore, from the public policies perspective, better regulation about the expiration date and the promotion of packaging in small quantities is necessary.

In addition to these public policy solutions, others are proposed for structural causes of food loss and waste. These measures involve the entire food chain and require the participation of multiple actors. Some of them are improvements in transport and energy infrastructures, adequate cold chain management, and conservation processes. What is essential is increasing both the training of farmers and the education of consumers to avoid food waste that, in the case of countries with severe food insecurity, revolves around the relevant role that women have in the agricultural sector. Food loss and waste reduction must be part of companies' social and environmental responsibility plans.

Finally, in the actual development of a circular economy, it is of great importance to provide value to the rescued surplus food and the by-products, which can be used in other

production processes as inputs, thus, contributing to better use of resources and reduction in environmental impact.

In this sense, possible future research lines are improving primary statistical data on FLW in weak and moderate food security countries and analyzing the quantitative relationships between FLW and the SDG's performance and investigating the impacts of the global food supply chain in the generation of FLW in weak and moderate food security countries and proposing circular economy models to reduce FLW in countries with problems of food security.

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