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Food Loss and Waste Across the Supply Chain: A Comparative Analysis of Developed and Developing Countries

Pérdidas y desperdicios de alimentos a lo largo de la cadena de suministro: análisis comparativo de países desarrollados y en desarrollo

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Abstract

Food loss and waste (FLW) is a major global challenge with significant social, environmental, and economic impacts. The Food and Agriculture Organization (FAO) estimates that one-third of food produced for human consumption is lost or wasted annually, amounting to 1.3 billion tonnes. This study analyzes FLW variations across supply chain stages in developed and developing countries using the FAO 2022 database (21,736 observations, 149 countries). Inferential statistical analysis (Kruskal-Wallis tests) evaluates differences in FLW by stage and country development level. Results show higher FLW in developed countries (39.67%) than in developing ones (21.87%). Developed nations experience more waste in Distribution (10.0%) and Consumption (17.0%), while developing nations face losses in Agricultural Production (2.5%) and Postharvest Handling. Findings highlight the need for tailored interventions: infrastructure and technology enhancements in developing nations, and policy-driven consumer behavior changes in developed ones. Solutions include improved supply chain transparency, AI-driven demand forecasting,

food donation programs, and consumer awareness campaigns. This research advances FLW understanding and informs policies for their elimination. Future studies should refine quantification methods, assess policy impacts, and explore technological solutions to mitigate FLW's environmental and economic effects.

Keywords: Food loss; food waste; food supply chain; developed and developing countries; Sustainable Development Goal.

Resumen

Las pérdidas y desperdicios de alimentos (FLW, por sus siglas en inglés) constituyen un importante reto mundial con importantes repercusiones sociales, medioambientales y económicas. La Organización de las Naciones Unidas para la Agricultura y la Alimentación (FAO) estima que un tercio de los alimentos producidos para el consumo humano se pierde o desperdicia anualmente, lo que supone un volumen de 1.300 millones de toneladas. Este estudio analiza las variaciones de FLW en las distintas fases de la cadena de suministro en países desarrollados y en desarrollo utilizando la base de datos FAO 2022 (21.736 observaciones, 149 países). El análisis estadístico inferencial (pruebas de Kruskal-Wallis) evalúa las diferencias en las FLW por etapa y nivel de desarrollo del país. Los resultados muestran mayores FLW en los países desarrollados (39,67%) que en los países en desarrollo (21,87%). Los países desarrollados sufren más pérdidas en la distribución (10,0%) y el consumo (17,0%), mientras que los países en vías de desarrollo se enfrentan a pérdidas en la producción agrícola (2,5%) y la manipulación postcosecha. Los resultados ponen de manifiesto la necesidad de intervenciones a medida: mejoras de las infraestructuras y la tecnología en los países en desarrollo, y cambios en el comportamiento de los consumidores impulsados por las políticas en los países desarrollados. Las soluciones incluyen una mayor transparencia de la cadena de suministro, la previsión de la demanda basada en la inteligencia artificial, programas de donación de alimentos y campañas de concienciación de los consumidores. Esta investigación avanza en el conocimiento de las FLW y sirve de base a las políticas para su eliminación. Los estudios futuros deberán perfeccionar los métodos de cuantificación, evaluar las repercusiones políticas y explorar soluciones tecnológicas para mitigar los efectos medioambientales y económicos de las FLW.

Palabras clave: Pérdida de alimentos; desperdicio de alimentos; cadena de suministro alimentario; países desarrollados y en desarrollo; Objetivo de Desarrollo Sostenible.

JEL Classification / Clasificación JEL: D63, I32, L66, Q01.

1. Introduction

The problem of food loss and waste (FLW) is one of the world's most significant social, environmental and economic challenges (Abiad & Meho, 2018). The Food and Agriculture Organisation of the United Nations (FAO) estimates that one-third of food intended for human consumption is lost or wasted along the entire supply chain, equivalent to 1.3 billion tonnes of food per year (Gustavsson et al., 2011). The environmental impact of FLW is 3.3 Gigatonnes of CO_2 equivalent per year, 6% of total greenhouse gas emissions (Amicarelli et al., 2021). The water consumed in producing food crops that is subsequently wasted accounts for 24% of the planet's total freshwater and 23% of the global cropland area (Kummu et al., 2012). The monetary value of these losses and wastes amounts to 940 billion USD (FAO, 2014a). More detail, 14% of all food produced worldwide is lost along the supply chain before it reaches the retail level (United Nations, 2021). Target 12.3 of the Sustainable Development Goals (SDGs), included in SDG 12, "Responsible production and consumption", formulates the aim by 2030 to "halve global per capita food waste at the retail and consumer level, and reduce food losses in production and supply chains, including Postharvest losses" (United Nations, n.d.). The reduction of FLW has, in turn, an impact on other SDGs of the Agenda in addition to the number 12 as mentioned above, namely those aiming at more efficient use of resources, reducing hunger by increasing food availability or reducing greenhouse gas emissions (FAO, 2017) and also have a direct impact on the triple bottom line of sustainability: economy (SDG 1, no poverty), society (SDG 2, zero hunger, and SDG 3, good health and well-being), and environment (SDG 6, clean water and sanitation, SDG 11, sustainable cities and communities, SDG 13, climate action and SDG 15, life on land), as shown in Figure 1.

Despite their frequent use, the terms "Food losses" and "Food waste" in the food supply chain are not clearly defined in the literature about the stages of the chain, varying according to the bodies that define them, as shown below:

- FAO and the World Resources Institute (WRI) differentiate between losses (FL) and wastes (FW), the former being those produced in the Postharvest, handling, storage, processing and transport stages, and the latter being those produced in commercialization (retail) and consumption (FAO, 2018;

Lipinski et al., 2013; FAO, 2013; Ishangulyyev et al., 2019; Luo et al., 2021; Porter et al., 2016).

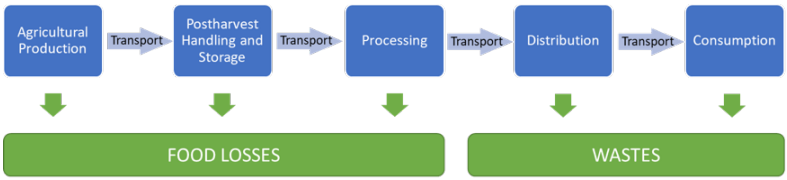
- The United States Department of Agriculture (USDA) considers wastage as the unconsumed part of an edible item during marketing and consumption. It is part of all losses that occur along the entire supply chain, from Postharvest to final consumption (Buzby et al., 2014).
- The European Commission (EC), through the FUSIONS project and other authors, consider all food losses at any stage of the supply chain as waste, except for plants that have not been harvested (European Commission, 2019; FUSIONS, 2014; Sheahan & Barrett, 2017).

Figure 1. Impact of FLW on the SDGs

Source: Own elaboration.

This research has adopted the FAO and WRI model (FAO, 2013; Ishangulyyev et al., 2019; Luo et al., 2021; Porter et al., 2016), as shown in Figure 2. In this figure, the food Transport activities that occur between each of the stages have been added. Specifically, these are the movements of food produced on the farm and from the farm to final consumption through each stage of the supply chain: Postharvest, Handling and Storage, Processing, Distribution and Consumption. Losses and waste occur during transport, depending on the corresponding stages of product movement (FAO, 2019).

Figure 2. Stages of the supply chain, losses and waste



Source: Own elaboration based on FAO model.

On the other hand, each of the stages mentioned above of the supply chain can be divided into sub-stages, and these, in turn, into more specific and more detailed activities, which is very effective in locating the root cause of losses and wastes and proposing specific solutions to minimise or eliminate them.

FAO recommends collecting data from different stages to help countries adapt programmes to improve the efficiency and functioning of their food supply system. In addition, the European Commission also recommends a sustainable food systems approach, addressing FLW in the context of other policy priorities (European Commission, 2020). Better data availability on where loss or waste occurs will support the design and development of policies, strategies and interventions to reduce FLW. Consideration of food disposed of in stages will focus on related policies and help focus data collection efforts.

The stages of the supply chain at which losses and waste are generated have been addressed in the scientific literature, although most of the existing publications deal with FW at the stages related to distribution - sales to wholesalers and retailers - and consumption, with less research on FL at the stages of Agricultural Production, Handling and Storage, and Processing, as reported by Dora et al. (2020).

The different stages of the supply chain, from Agricultural Production of food to final Consumption, can take place in different countries and regions of the world (Magalhães et al., 2021). In some cases, the Agricultural Production and Postharvest, Handling, and Storage stages occur in developing countries, while the Processing, Distribution and Consumption stages occur in developed countries. The opposite may also be the case, but it is less frequent. There are very few articles for which FLW generated at all stages of the chain are analysed and which also take into account the different levels of development of the countries. Fabi et al. (2021) indicate that poorly developed countries have higher losses. However, most existing scientific articles analyse losses in developed countries like the US and Great Britain (Xue et al., 2017). Studies such as Gustavsson et al. (2011) and Lipinski et al. (2013) show that in developed countries, losses and wastes occur mainly at the Distribution and Consumption stages and that in developing countries, the most significant losses and wastes occur at the Agricultural Production, Postharvest, Handling and Storage stages (Papargyropoulou et al., 2014). Such studies have been referenced to date, although the lack of data on losses and wastes disaggregated by stage and activity must be considered, especially in the emerging BRICS economies — Brazil, Russia, India, China, and South Africa (Kummu et al., 2012; Parfitt et al., 2010; Xue et al., 2017). However, the United Nations Environment Programme (UNEP, 2021) measured household, food service and retail waste by income level across countries and concluded that per capita household FW is very similar across countries, regardless of income group. On the other hand, FAO has updated its 2022 loss and waste database (FAO, 2022), providing a larger volume of records than the previous version published in 2018.

It is, therefore, of great interest to be able to check whether the trend set out in the UNEP report at the final consumption stage is reproduced in the rest

of the stages of the supply chain and whether it is maintained at the consumption stage with a greater volume of more up-to-date data. In short, the aim is to show whether the percentage of FLW is currently independent of the income level of the country in which it is generated. This evidence would make it possible to guide public policies promoting the reduction of FLW more accurately.

This is precisely the main objective of this research: to analyse whether FLW produced at the different stages of the supply chain vary significantly, depending on the level of development of the countries in which they are generated, taking as a reference the updated FAO database and the level of development of the countries established by the United Nations Development Programme (UNDP, 2022), and identifying not only their magnitude but also the underlying factors that explain their occurrence. This main objective is further broken down into three specific goals: i) to know the percentage of FLW in each of the stages and sub-stages of the supply chain,–ii) to check whether there are significant differences in the generation of these losses and waste depending on the level of development of the countries and the stages and sub-stages of the supply chain, and iii) to analyse and discuss the underlying causes of losses and waste in those stages and sub-stages where differences are observed in relation to the level of development of the countries.

If the trend mentioned above is confirmed, i.e. if there is equality in the FLW generated in different countries, regardless of their level of development, this could have social, economic and political repercussions.

This article is structured as follows: after the introduction, an analysis of the information available in the FAO database is carried out in section 2. In section 3, an inferential statistical analysis is carried out, which allows us to identify the existence of significant differences in FLW by stages, sub-stages and level of development of the countries, as well as to generalise the conclusions obtained from the analysis of the database. The discussion and conclusions derived from the study are detailed in sections 4 and 5, respectively.

2. Materials and methods

2.1. FAO database descriptive analysis

The FAO database is a panel database in which observations refer to the loss or waste generated in a specific food, expressed as a percentage, in a given country or area, in a particular stage and/or sub-stage of the supply chain, in different annual periods. For this research, the analysis period from 2000 to 2021 was considered, and it initially included 27,650 observations. From these observations, 5,914 observations have not been included in this research due to the lack of concreteness of the stage in which the losses or wastes occurred. Therefore, the sample analysed consists of 21,736 observations, averaging 988 observations/year. However, from 2018 onwards, the database contains a lower average number of observations per year.

All the observations come from different sources or databases, both external to FAO, such as the African Postharvest Losses Information System (APHLIS), the World Bank, the Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ), Food Balance Sheets from Ministries of Agriculture and National Statistics Offices, as well as expert opinions and surveys carried out by FAO itself (FAO, 2022).

The database contains information on 149 countries, 76% of the world's nations, according to the M49 classification (UNSD — Methodology, n.d.), grouped into 15 sub-regions on five continents. Despite this tremendous geographical diversity, there is a high concentration of data. A Pareto analysis showed that 80% of the observations belong to Sub-Saharan Africa (18,666 observations, 67.5%), Southern Asia (2,152 observations, 7.8%), and North America (1,844 observations, 6.7%). In terms of the level of development of the countries, they have been classified into developed and developing countries. Table 1 shows the number of observations for each stage and sub-stage of the supply chain for developed, developing and total countries. It can be seen that there is a large disproportion between the observations for developed countries (672) versus the observations for developing countries (21,064), which are much more numerous.

Table 1. Stages and sub-stages of the FAO database

		OBSERVATIONS		
Stage	Sub-Stage	Developed countries	Developing countries	Total
Agricultural production	Farm	98	12266	12364
	Harvest	57	3630	3687
	Pre-Harvest	9	2	11
Postharvest, handling and storage	Grading	11	0	11
	Post-harvest	0	22	22
	Stacking	0	1	1
	Storage	29	2413	2442
Processing	Processing	53	209	262
	Packing	17	0	17
Distribution	Distribution	0	10	10
	Export	15	35	50
	Market	2	7	9
	Retail	207	231	438
	Trader	0	76	76
	Wholesale	17	240	257
	Food Services	6	8	14
Consumption	Households	136	31	167
Transport	Transport	4	1845	1849
Blank	Blank	11	38	49
TOTAL		672	21064	21736

Source: Own elaboration based on FAO information.

Focus on the data available in the country database shows limited representation of BRICS countries, despite their significant global economic and demographic weight. Specifically, the dataset includes only 16 observations from Brazil, 47 from Russia, and 98 from China, in stark contrast to 1,173 from India and 365 from South Africa. This uneven coverage is particularly striking considering that BRICS countries account for approximately 30% of global GDP and 46% of the world's population. Moreover, projections from the World Economic Outlook (International Monetary Fund, 2023) estimate that by 2028, China alone will contribute 22.6% of global GDP growth, with Brazil and Russia contributing 1.7% and 1.6%, respectively. Including the new BRICS members as of 2023 (Argentina, Egypt, Ethiopia, Iran, Saudi Arabia, and the United Arab Emirates), the total number of observations rises to 2,797, or only 12.87% of the dataset. This underrepresentation highlights the need for caution when interpreting results for emerging economies with such geopolitical and economic relevance.

The database also provides information on the causes of food losses for each observation; although only 3% of the observations contain such information, a total of 632 causes are available for supply chain stages Agricultural Production to Distribution. A grouping of the main causes collected in the database has been made, which are set out in Table 2 for each stage of the supply chain (FAO, 2022):

Table 2. Main food waste causes in the stages of the supply chain

Agricultural production	• Climatic and biological factors. • Factors related to product quality and commercial standards. • Technical and operational factors. • Planning and production factors. • Commercial and market factors.
Postharvest handling and storage	• Pests and diseases (insects, rodents, mould). • Adverse climatic conditions (heat, humidity, rain). • Poor infrastructure (storage, refrigeration, transport). • Inadequate post-harvest handling (harvesting, handling, drying). • Human and organizational factors (lack of training, traditional practices, supply-demand mismatch).
Processing	• Poor handling and mechanical damage. • Inadequate or outdated technology. • Losses due to infestation and spoilage. • Unfavourable environmental conditions. • Problems in grading and visual quality. • Imbalance between supply and demand. • Lack of training and know-how.
Distribution	• Physical and mechanical damage. • Deterioration due to biological factors. • Inadequate storage conditions. • Poor handling, sorting and marketing. • Socio-economic and organisational factors.
Transport	• Improper handling and physical damage. • Poor transport conditions. • Storage problems during transport. • Problems in the logistics and distribution chain. • Product quality and condition.

Source: Own elaboration from FAO database.

The FLW in the database represents the percentage decrease in food mass for each of the observations. From these data, the aggregation of the FLW values of all the observations of a stage has been done by calculating the median of the observations, as discussed in the next sub-sections. For the calculation of the global results, the aggregation criterion for losses along the FAO supply chain has been considered (FAO, 2018).

2.2. Statistical treatment of the information obtained

The statistical treatment of the database comprises two phases: 1) exploratory and descriptive analysis of the data, and 2) inferential statistical analysis. The exploratory analysis allows us to know the distribution of the data and the detection of atypical data. The inferential statistical analysis begins with the testing of the hypotheses required by parametric statistics, and the subsequent application of the most appropriate statistical tests to identify the existence of significant differences in the FLWs according to the stage and degree of development of the countries in which they are generated, extrapolating the results to the rest of the population analysed.

2.2.1. Descriptive statistical analysis

The descriptive analysis carried out contains the frequency distribution of the variable (FLW), expressed as a percentage, as well as the mean value, median, standard deviation of losses and waste, and the coefficient of variation (standard deviation/mean) for the stages and sub-stages of the supply chain, depending on the degree of development of the countries.

The calculated coefficients of variation range from 47% to more than 200%, so the median will be used to represent the losses at each stage, rather than the mean, which is not very representative due to the wide dispersion of the loss percentages. The use of the median avoids the influence of outliers.

2.2.2. Inferential statistical analysis

Prior to the loss comparison analysis, the normality of the variable and the equality of variances in the different groups were analysed to check the applicability of the ANOVA analysis. Both the Kolmogorov test (to study normality) and the Levene test (to study homogeneity of variance) resulted in the rejection of both assumptions ($p < 0.05$), normality and homogeneity, so it was decided to apply the Kruskal-Wallis test. This test compares ranges of the variable rather than means, which is, in turn, more accurate given the large heterogeneity of the variable, as discussed above.

The Kruskal-Wallis test has been carried out with the observations recorded between the years 2000 and 2021 using two hypothesis tests that try to verify whether there are significant differences in FLW by stages and sub-stages, depending on the level of development of the countries. The results are as follows:

- Regarding the stages, losses and wastes are different depending on the corresponding stage ($p = 0$).
- About the sub-stages, depending on the sub-stages being compared, there are not always significant differences depending on the level of development ($p > 0.05$) (as will be seen in detail in section 3.1).

The results for each stage of the supply chain and its corresponding sub-stages are presented below. For each stage, the results are presented according to the two specific objectives of this research.

3. Results

The first results relate to the total losses and waste generated in the different stages of the supply chain, according to the level of development of the countries where they occur. These values are shown in Table 3. In this table, it can be seen that developed countries have higher losses and waste than developing countries, both at the global level, 39.67% versus 21.87%, and at each stage of the supply chain. The total loss and waste is 31.38%. In the Postharvest, Handling and Storage stage, there is a substantial imbalance in the number of observations in each sub-stage that compose it. Precisely, 98.5% of the observations in this stage correspond to the Storage sub-stage, compared to 1% of the observations in Postharvest, which has the highest losses, so the overall result of the stage cannot be established.

Table 3. Median percentage of losses and waste by stage and level of development of the countries in which they occur

	Developed	Developing	Global result
Agricultural production	6.90	2.50	2.50
Postharvest, handling and storage	-	-	-
Processing	5.00	3.04	3.44
Distribution	10.00	6.30	7.50
Consumption	17.00	5.00	15.00
Transport	4.51	1.00	1.00
Global result	39.67	21.87	31.38

Source: Own elaboration.

If the total losses and wastes are grouped according to the FAO concepts, this results in the values shown in Table 4:

Table 4. Median percentage of loss and waste by the level of country development

	Developed	Developing	Total
Losses	18.15	8.69	9.09
Wastes	29.25	11.80	23.00
Global result	39.67	21.87	31.38

Source: Own elaboration

The results for each stage of the supply chain and its corresponding sub-stages are presented below, in Table 5, and are discussed in the following subsections. For each stage, the results are presented according to the two specific objectives of this research.

Table 5. Percentage of losses and wastes in the stages and sub-stages of the supply chain for developed and developing countries

		Developed countries		Developing countries		Total countries		
Stage	Sub-Stage	FLW Median (%)	Observations	FLW Median (%)	Observations	Total Median (%)	Observations	FLW Global (%)
Agricultural production	Farm	10.00	98	2.50	12266	2.50	12364	2.50
	Harvest	4.30	57	4.43	3630	4.43	3687	
	Pre-Harvest	4.00	9	4.33	2	4.00	11	
Postharvest handling and storage	Grading	7.00	11	-	0	7.00	11	2.65
	Post-harvest	-	0	30.00	22	30.00	22	
	Stacking	-	0	2.10	1	2.10	1	
	Storage	4.00	29	2.65	2413	2.65	2442	
Processing	Packing	2.50	17	-	0	2.50	17	3.44
	Processing	5.00	53	3.04	209	3.49	262	
Distribution	Distribu-tion	-	0	4.75	10	4.75	10	7.50
	Export	9.00	15	8.00	35	9.00	50	
	Food Service	18.50	6	4.65	8	2.50	14	
	Market	30.25	2	1.10	7	8.30	9	
	Retail	10.90	207	6.60	231	5.11	438	
	Trader	-	0	5.11	76	7	76	
	Wholesale	5.00	17	6.19	240	4.50	257	
Consumption	House-holds	17.00	136	5.00	31	15.00	167	15.00
Transport	Transport	4.51	4	1.00	1845	1.00	1849	1.00

Source: Own elaboration.

3.1. Agricultural production

The median of the FL produced in the Agricultural Production stage is 2.50%. A more detailed analysis of the Agricultural Production sub-stages shows that the sub-stages with the highest losses are Harvest, with a median of 4.43% and Preharvest, with a median of 4.00%, as shown in Table 5.

In the Agricultural Production stage, the number of observations relating to developed countries is considerably lower than those from developing countries, as seen in Table 5. Observations from developed countries account

for only 0.01% of the total observations, among other reasons, due to the lower weight of agriculture in their economic activity. However, the most significant losses correspond precisely to developed countries, especially in the Farm sub-stage (10%) (FAO, 2014b).

Regarding the significant differences between sub-stages according to the level of development, the tests concluded no significant differences in Harvest ($p = 0.44$) and Preharvest ($p = 1.00$). In the sub-stages mentioned above, losses are similar in developed and developing countries; in the case of Preharvest, the losses are 4.00%, and in the case of Harvest, they are 4.43%. On the other hand, there are significant differences in the case of Farm ($p = 0$) depending on the level of development of the countries: 10% for developed countries compared to 2.50% for developing countries.

3.2. Postharvest, handling and storage

The analysis of the data related to the Postharvest, Handling and Storage stage leads to the result that the highest losses in this stage occur in Postharvest, 30%, and Grading, 7%, as shown in Table 5. However, there is a substantial imbalance in the number of observations in each sub-stage, as discussed above.

In the case of Postharvest, there are only observations for developing countries, where losses are 30%, as seen in Table 5; in the case of Grading, there are only observations for developed countries, and in Stacking, only for developing countries, so it is impossible to test the hypotheses in the previous sub-stages. In the case of Storage, there are significant differences ($p = 0$), and losses are 4.00% in developed countries versus 2.65% for developing countries.

3.3. Processing

The processing stage has a median loss of 3.44%. Regarding the sub-stages, Processing and Packing, the most critical losses occur in Processing, with 3.49%, compared to 2.50% in Packing, as shown in Table 5.

At this stage, the comparative analysis of losses according to the level of development of the countries results in the highest losses in the Processing sub-stage in developed countries, 5.00%. There are no observations for the Packing sub-stage in developing countries. In the Processing sub-stage, there are significant differences in losses depending on the level of development of the countries ($p < 0.05$), standing at 5.00% for developed countries compared to 3.04% in developing countries.

3.4. Distribution

Food waste caused in the Distribution stage is 7.50%, as shown in Table 5. Within the Distribution sub-stages, the most notable data are those produced in Export, 9.00%, and Retail, 8.30%. Regarding the Wholesale and Trader sub-

stages, waste is 6.17% and 5.11%, respectively. The lowest losses are in the Food Services, 4.90%, and Market, 2.50%.

The hypothesis test carried out in the sub-stages indicates that there are no significant differences according to the level of development of the countries in the cases of Export ($p = 0.95$), Food Services ($p = 0.59$), Market ($p = 0.17$), Wholesale ($p = 0.99$). In the case of Trader, there are only observations for developing countries, so it is not possible to test the hypothesis. Regarding Retail, the difference in waste in developed and developing countries is significant ($p < 0.05$), with 10.90% and 6.60%, respectively.

3.5. Consumption

The waste produced in the Consumption stage accounts for 15.00% and is produced during domestic consumption, as shown in Table 5.

The highest waste is produced in developed countries, 17%, although there are few observations for developing countries, which does not allow parametric tests for hypothesis testing.

3.6. Transport

Transport losses are 1.00%, as shown in Table 5. The losses produced during transport in developed countries are a median of 4.51%, compared to the losses made in developing countries, which are 1%. The low number of observations in developed countries does not allow parametric tests for hypothesis testing.

4. Discussion

This research shed light on the critical aspects of FLW across various supply chain stages, offering insights into regional differences and trends over time. These results are discussed from four key perspectives: total FLW, FL and FW in relation to the level of development of countries, FL and FW by stages, and FL and FW by sub-stages and level of development.

4.1. Total FLW

A comparison of the total FLW observed in this study with previous FAO estimates (Gustavsson et al., 2011) reveals a noteworthy decline in the overall FLW of the supply chain, with a reduction of 5.85% compared to earlier figures. This positive trend reflects the significant efforts made by farmers, businesses, and consumers to curb FLW, driven by the growing recognition of its environmental, economic, and social benefits. Such efforts indicate a concerted movement toward greater sustainability in food systems, suggesting that public awareness campaigns and policy interventions are beginning to bear fruit (Lipinski, 2023).

However, when FLW is disaggregated by the level of development of the countries, significant differences emerge. Developed countries report a total FLW of 39.67%, which is considerably higher than the 21.87% observed in developing countries. This aligns with findings by Lipinski et al. (2013) and has been used as a reference in other subsequent research (Ishangulyyev et al., 2019; Nicastro & Carillo, 2021), who also observed higher FLW in more developed countries, and reinforces the notion that industrialized food systems are more prone to waste, particularly at the distribution and consumption stages.

When we compare the results for FL and FW, it is evident that food losses account for a lower percentage (9.09%) than the 14% reported by the UN (United Nations, 2021). This discrepancy is likely due to differences in the scope of data sources used—this research relies on FAO's broader database, which encompasses a wider range of food categories and geographical areas, whereas the UN focuses on more specific data sets (FAO, 2018). On the other hand, food waste in this study (23%) exceeds the UN's estimate (17%), pointing to an increasing trend in waste, particularly at the consumer level, largely due to a lack of awareness of food waste in households and the service sector (Lipinski, 2023; UNEP, 2021).

4.2. FL and FW as a function of countries' level of development

According to the disaggregation of this research, the analysis of FL and FW between developed and developing countries leads to the fact that FL in developed countries has decreased; in developing countries, no conclusions can be drawn on FL due to the lack of observations of some sub-stages. Regarding FW, these are lower than previous FAO estimates in both developed and developing countries, but the differences arising from the level of development of the countries are attenuated. This trend may continue in the coming years as the achievements of strategies taken by the European Commission, the World Bank, and other multilateral agencies become apparent. As an example of this, in 2020, the EC launched the "Farm to Fork Strategy" Programme (European Union, 2020); in September 2021, the Inter-American Development Bank approved the Food Loss and Waste Reduction Programme for Latin America and the Caribbean, #SinDesperdicio, with an investment of US$1 million and interventions in Argentina, Mexico, and Colombia (We Team et al., 2023). In September 2023, the World Bank announced an investment of $10 billion in Sustainable Development Bonds (World Bank Group, 2020), highlighting FWL in developing countries and taking a diagnosis carried out in Rwanda, Vietnam, Nigeria and Guatemala as a starting point. The implications of narrowing the gap between losses in different countries arise from food security, education, technology, and sustainability policies, as explained below:

- Reducing FLW can increase food availability without additional production resources and contribute to rural development, particularly in less developed countries (Hodges et al., 2011).
- Investment in technology and machinery is emerging as an opportunity to reduce losses and waste in developed countries, although their use has certain limitations (Krishna Bahadur et al., 2016). Technologies such as blockchain, IoT, or the use of radio frequency tags to track information, improve traceability and avoid potential sources of contamination in the supply chain are technologically available; however, the significant investment required and the gap between technology and users limit the adoption of these technologies, especially at the agricultural production stage in developing countries (Benyam et al., 2021). Another limitation of the use of technology is that its deployment for FLW reduction is conditional on increasing process efficiency. Other available technological options arise from using Apps for waste recovery and valorisation, which are more available in developed countries, especially in the distribution and consumption stages (Hong et al., 2024).
- Regarding sustainability policies, economic development shows a positive correlation with the sustainability of food systems. Policies targeting the social and food security dimensions can impact sustainability more than those focusing on the environmental or economic domains (Béné et al., 2022).

4.3 FL and FW by stages of supply chain

The results of FLW by stage confirm previous research that food losses and waste are closely tied to the specific stages in which they occur (Corrado & Sala, 2018; Ishangulyyev et al., 2019; Luo et al., 2022; Porter et al., 2016). For instance, significant losses are observed in the agricultural production and postharvest handling stages in developing countries, while developed countries see higher levels of food waste during the distribution and consumption stages. These patterns underscore the need for tailored interventions at each stage.

4.4. FL and FW by sub-stages and level of development

The breakdown of FLW by sub-stages provides a more granular view of where losses and waste occur, highlighting the varied causes and implications for different regions. The most critical percentages of losses are postharvest, in line with Bräutigam et al.(2014), Manufacturing, Export and Retail. Regarding the differences in the losses produced in the sub-stages according to the level of development, as shown in table 6, there are significant differences in the Farm, Storage, Processing and Retail sub-stages and that there are no significant differences in the Harvest, Export, and Wholesale sub-stages; in the rest of the sub-stages, there are not enough observations.

Table 6. Significant and Non-Significant Differences in Food Losses by Supply Chain Sub-Stages According to Development Level

Stage	Sub-stages with significant differences	Sub-stages with no significant differences
Agricultural production	Farm	Harvest
Post-harvest handling and storage	Storage	-
Processing	Processing	-
Distribution	Retail	Export Wholesale

Source: Own elaboration.

For the sub-stages listed in Table 6, the causes that may explain the differences found both in the literature and in FAO's own database are presented and analysed below.

4.4.1 Farm and harvest

Food losses differ significantly between developed and developing countries in the Farm sub-stage. In developing countries, losses in this sub-stage are attributed to the next factors:

- Pests and diseases, which alone cause 38% of global agricultural losses (FAO, 2022; Junaid & Gokce, 2024).
- Climate change, which accounts for 10-25% of global agricultural losses (FAO, 2022).
- Limited access to equipment, credit and markets (Delgado et al., 2018; Hodges et al., 2011; Parfitt et al., 2010).

In developed countries, the Farm sub-stage is one of the primary sources of FL in the supply chain (van der Werf & Gilliland, 2017). In this sub-stage, the FL produced in the database observations are a mismatch between supply and demand, aesthetic and quality problems, overproduction due to supply agreements with retailers, and damage during harvesting (Priefer et al., 2016).

Addressing these issues requires different approaches depending on the typology of countries: developing countries need better education of farmers (Delgado et al., 2018), improved infrastructure and more efficient value chains, while developed countries need to focus on consumer education, improvements in supply chain coordination between retail and the farmer, review tax regulations to remove any incentives that may encourage the generation of FW, replace quality and marketing standards related to a product's external appearance with standards that refer to its quality for human consumption and growing conditions (Priefer et al., 2016), and use digital agricultural technologies.

The FL in the Harvest sub-stage does not show significant differences, so a reduction in FL could increase food availability and generate economic

benefits (da Costa et al., 2015). Losses in Harvest are due to poor handling and the use of poor or inadequate technical equipment (Buzby et al., 2015; Cicatiello et al., 2016; Dora, Biswas, et al., 2020). Technological advances in harvesting processes can contribute to reducing losses in this sub-stage. However, introducing new technologies must be emphasised with staff training and capacity building (Dumitru et al., 2020), especially in developing countries.

So, in the Agricultural Production stage, losses seem predominantly driven by external factors such as pests, diseases, and climate change in developing countries. In contrast, in developed countries, FL is often caused by factors such as overproduction, poor coordination between farmers and retailers, and quality issues that are not directly related to the food's safety or nutritional value.

4.4.2 Storage

The FL produced in the Storage sub-stage differs between developed and developing countries. However, for developed countries, the database only contains observations from Denmark, Norway, and the United Kingdom, so the differences should be treated with caution. For developing countries, FL is due to the next factors:

- Poor storage facilities cause significant losses, especially in cereals (Magalhães et al., 2021). Lack of refrigeration technology is a key issue that generates significant losses in developing countries (Dora, Biswas, et al., 2020).
- Microbial infestation, which leads to mould growth and insect pests (Dora, Biswas, et al., 2020; FAO, 2022).
- Other causes, such as rodents, spillage and theft: lack of proper control, preservation and security technologies contribute to the generation of losses during storage. (Affognon et al., 2015).

4.4.3 Processing

In the Processing stage, the causes of food losses differ between developed and developing countries. Hence, the implications of this are also different from country to country.

In developing countries, the causes identified are as follows:

- Poor facilities (FAO, 2022).
- Uncontrolled or poorly defined manual processes, as reported by Magalhães et al. (2021).
- Inefficient processing techniques (Dora, Biswas, et al., 2020).
- Human errors (FAO, 2022).

- A combination of financial, managerial and technical limitations, especially in countries like Sub-Saharan Africa and Southeast Asia (Wunderlich & Martinez, 2018).

In developed countries, the leading causes are:

- Non-compliance with quality standards regarding size, shape, and appearance (De Steur et al., 2016).
- The inadequate definition of production processes (Dora, Wesana, et al., 2020).

4.4.4 Export, retail and wholesale

The Export sub-stage shows little difference in FW across countries, suggesting that international trade regulations and quality standards —ISO 22000, BRC, IFS, mainly— apply universally, though logistical inefficiencies still contribute to waste. The FW is caused by long transit times, inadequate transport conditions, inefficient supply chain management, and breakage of the cold chain, resulting in loss of physical (maturity) and chemical properties of the products and size variations (Blanckenberg et al., 2022). Innovation and the implementation of new technologies provide a basis for reducing export losses, such as intelligent climate control systems using digital twins in refrigerated containers or "reefer containers" (Lukasse et al., 2023); the investment, which is paid for by logistics and transport companies, as well as electronic systems for generating orders by predicting demand through the use of machine learning (Miguéis et al., 2022).The FW produced in the Retail and Wholesale sub-stages are, in the case of Retail, different depending on the level of development of the countries, and in the case of Wholesale, they are the same. Although it seems contradictory, this fact is because, in the case of Wholesale, there are very few observations from developed countries, especially from the USA, which only contributes one observation. At the same time, there are 157 observations from the country mentioned above in Retail. Furthermore, the causes of losses in developed and developing countries differ, but are the same for Retail and Wholesale. In developed countries, the leading causes indicated in the database are a mismatch between supply and demand, aesthetic problems, and quality problems. In contrast, in developing countries, losses are caused by mechanical damage, diseases, deterioration, and rotting caused by facility deficiencies, which is in line with Santos et al. (2020).

The limitations of this research are due to the lack of observations in some sub-processes: in the case of developing countries, data are scarce in grading and packing; while in developed countries, the gap is found in grading, stacking, distribution and trader. The database lacks data from China, Russia and Brazil. This lack of data makes it difficult to calculate the losses in these sub-stages and find significant differences according to the level of development of the countries.

Future research may arise from analysing other databases that precisely measure waste, especially at the Consumption stage, and also from obtaining data from sub-stages where there are no records in the FAO database, namely Grading, Stacking, and Packing.

Further research can be undertaken to analyse further the causes of differences between sub-stages and by country type.

In summary, addressing FLW requires targeted interventions at both global and local levels. In developing countries, the focus should be on improving agricultural practices, infrastructure, and postharvest management. In contrast, in developed countries, attention should be directed toward reducing waste at the retail and consumption stages. Technological advancements, such as digital tools and intelligent systems, can play a pivotal role in lowering FLW across all stages. However, their implementation will need to be tailored to the specific context and capacity of each country.

Reducing FLW requires a multifaceted approach that includes technological innovation, policy interventions, and changes in consumer behaviour. While developed countries face challenges related to consumption and retail waste, developing countries must address inefficiencies in the early stages of the supply chain. Bridging these gaps and adopting targeted strategies based on the specific needs of each region will be essential in achieving the global SDG targets for food sustainability.

5. Conclusions

This study demonstrates that food losses and waste (FLW) remain significantly higher in developed countries compared to developing ones. However, the narrowing gap in food waste observed in recent studies suggests progress in mitigation efforts. Analyzing the supply chain at its various sub-stages offers a more precise understanding of where losses occur, though comprehensive data collection across regions and food categories remains a significant challenge. The difficulty in obtaining high-quality, standardized data across different contexts underscores the need for more coordinated international data harmonization and monitoring efforts.

FLW in developing countries is related to structural and technical factors, such as the incidence of pests and diseases, the impact of climate change, lack of access to equipment and finance, as well as poor storage and processing infrastructure. These countries also face difficulties in post-harvest handling and the use of appropriate technologies, resulting in significant losses before food reaches markets.

In contrast, in developed countries, losses occur more commonly downstream, especially in distribution and retail. Although there are also losses in agricultural production, these are mainly due to trade mismatches, overproduction and rejection of products due to aesthetic criteria and quality standards unrelated to food safety. During processing, losses are also linked to surface quality issues rather than structural problems. In addition, the

harvesting sub-phase and export show similar levels of losses between the two groups of countries.

To address FLW effectively, a multi-pronged approach is necessary, incorporating targeted interventions at each stage of the supply chain depending on the level of development. Key strategies would include the following, for developing countries:

- Enhancing farmer education and capacity building, providing small-scale and large-scale farmers with training on post-harvest handling, storage techniques, and sustainable farming practices that can significantly reduce losses. Governments and NGOs should develop tailored educational programs and offer financial incentives to promote the adoption of best practices.
- Improving Infrastructure and Storage Facilities. Inadequate transportation, cold chain logistics, and storage facilities contribute to significant food losses in these regions. Investments in modernized infrastructure, such as refrigerated transportation and climate-controlled warehouses, are crucial. Public-private partnerships can play a critical role in funding and scaling these improvements.

In the case of developing countries, the strategies are as follows:

- Optimizing value chains through efficient logistics. Strengthening coordination between producers, distributors, and retailers can help minimize inefficiencies that lead to food spoilage. Just-in-time inventory management, better forecasting techniques, and dynamic pricing models can help reduce excess supply at various points in the food system, especially in developed countries.
- Leveraging digital technologies for waste reduction. The integration of blockchain for supply chain transparency, artificial intelligence for demand forecasting, and IoT sensors for real-time monitoring of food quality can enhance decision-making and reduce avoidable losses. Digital platforms connecting surplus food to food banks and redistribution networks should be further expanded to maximize resource efficiency.
- Implementing policy reforms and incentives. Governments must enforce stricter regulations on food waste reduction, such as mandating clearer expiration date labelling and discouraging overproduction through targeted subsidies. Tax incentives for food donation programs and penalties for excessive waste at the retail and consumer levels could drive more responsible behaviour.
- Transforming consumer awareness and behaviour. Public awareness campaigns, educational programs, and behavioural nudges—such as portion control strategies in restaurants and supermarkets encouraging ‘ugly’ produce consumption—can significantly reduce household food

waste. Schools should integrate FLW education into curricula to instil long-term change.

While these strategies offer promising solutions, their effectiveness will depend on regional contexts and levels of economic development. Policymakers, businesses, and researchers must collaborate to adapt interventions to the specific needs of each country or sector.

Considering these findings, continued research is essential to refine FLW quantification methods further and uncover more precise root causes. Future studies should focus on evaluating the real-world impact of waste reduction policies, measuring the effectiveness of emerging technologies, and developing scalable solutions for diverse socio-economic conditions. FLW remains a pressing global challenge with profound economic, social, and environmental implications, reinforcing the urgency of a coordinated, data-driven approach to sustainable food system management.

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