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RESEARCH

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Socioeconomic factors of global food loss

Daniel Chrisendo[1*], Johannes Piipponen[1], Matias Heino[1] and Matti Kummu[1]

Abstract

A considerable amount of food produced is lost globally. Food loss indicates not only the amount of edible food that humans do not consume but also the waste of resources used in production and distribution, linked with multifold problems such as climate change, biodiversity loss, and economic loss. While there has been a growing body of literature about magnitudes and technical solutions to reduce food loss, little is known about how different socioeconomic factors are potentially related to the losses. Here we assess the relationships between various relevant socioeconomic factors and food loss within the early stages of the food supply chain (i.e., farm, harvest, storage, and transport parts of it) using the most comprehensive data available. We found that factors such as high gross national income (GNI) per capita and high employment in agriculture are significantly associated with low food loss. It suggests that income might be invested in technology or infrastructure while labor is still vital to reduce food loss, especially in technology-inferior countries. Other important factors related to low food loss are access to electricity in rural areas and export volume index, although the significance and directions vary in each commodity and food supply stage. Our results provide valuable insights into socioeconomic factors around food loss that are beneficial to formulating relevant policy, especially in countries where substantial food losses in the early stages of the food supply chain considerably risk to food security.

Keywords Food loss, Socioeconomic factors, Loss reduction, Food supply chain, Sustainable food systems

Introduction

It is widely emphasized that around one-third (in terms of weight) or one-fourth (in terms of calories) of human food is being lost and wasted globally [8, 29, 30, 55]. These numbers reflect not only the proportion of edible food that humans do not consume but also the waste of resources used in production and distribution that contribute to unnecessary negative externalities. Notably, food production emits greenhouse gasses, uses considerable amounts of land and water, and uses fertilizers—which can all harm biodiversity and ecosystem services [13, 17]. In addition, food loss and waste signal misspent time and financial investment by producers, resulting in income reduction and high consumer expenses [55]. Kummu et al. [29] reveal that almost a quarter of freshwater resources, total global cropland area, and total fertilizer use are wasted due to food loss and waste. Porter et al. [40] claim that greenhouse gas emissions due to food loss were 2.2 Gt CO_2e in 2011 and predict a steady increase, resulting in 5.7–7.9 Gt CO_2e emissions in 2050. The emission in 2011 was around 5% of total CO_2e [43].

In this study, we concentrate on food loss, which refers to the loss of food meant for human consumption that takes place at production until, but not including, the retailer level [19]. Meanwhile, food waste, which also poses a big problem, occurs at the retailer and consumption level. Therefore, assessing separately the loss and waste is meaningful and justified. Global food loss has also been recognized in sustainable development goals (SDGs), and its reduction has become a political agenda. SDG 12 Target 3 aims to reduce food losses in production and supply chain, including post-harvest losses [53]. Reducing food loss can also contribute to

*Correspondence:
Daniel Chrisendo
daniel.chrisendo@aalto.fi
[1] Water and Development Research Group, Aalto University, Espoo, Finland

Table 1 Variables used as dependent and independent variables in the study

Variables	Unit	Definitions	Source
Dependent variable			
Food loss	% of total food production	Measures of food loss across food products, stages of the supply chain, and countries reported in various literature	[20]
Independent variables			
GNI per capita	International $	Per capita values for gross national income	[60]
Agriculture share of GDP	% of GDP	Contributions of the agricultural sector to GDP	[60]
Employment in agriculture	% of total employment	Share of working age persons who were engaged in the agricultural sector to total employment	[60]
Education	Years	Average number of years of education received by people ages 25 and older	[23, 51, 52]
Access to electricity in rural area	% of rural population	Percentage of rural population with access to electricity	[60]
Mobile cellular subscription	Per 100 people	Subscription to a public mobile telephone service that offers voice communication, both prepaid and postpaid	[60]
Political stability and absence of violence	Index (low value = less stable; high value = more stable)	Perceptions of the likelihood that the government will be destabilized by violent means, including politically-motivated violence and terrorism, that might have implications for national food security	[21]
Export volume index	Index (low value = less export; high value = more export)	Measures of export volume of individual countries on a constant price basis	[60]

the achievement of SDG 2 "zero hunger", as the food loss reduction could directly and indirectly (if saved food could be distributed to food insecure areas from where there is enough food) increase food availability in food insecure places [29]. By roughly halving food loss and waste globally and reallocating the saved food, an extra one billion people could be fed, thus increasing food security without increasing the use of agricultural resources [29]. Reducing food loss and waste would also lower the need for production increase in the future [30].

There has been a growing body of literature about food loss in recent years [8, 47, 48, 61]. Some studies present food loss magnitude and offer measurement method improvements, which have received the most attention in food loss-related topics (e.g., [14, 15, 18, 40, 61]). In their latest comprehensive review, Cattaneo et al. [8] summarize what is known so far about the causes of food loss. They list food prices relative to production costs and economic incentives as drivers of loss. Others discuss approaches to reducing losses by proposing technical solutions such as establishing adequate storage, employing adequate harvesting techniques, and providing biological interventions [7, 30, 31]. However, while many technical solutions have been offered, little is known about the socioeconomic factors needed for successful implementation. Some studies discuss the socioeconomic aspects through reviews (e.g., [47, 48]). Few try to prove the correlations with data focusing on a particular country or local region and specific commodities (e.g., [3, 9, 36]). Those studies are contributive and important to particular areas, yet their results might not be applicable elsewhere due to heterogeneity in local settings. Therefore, a broader-level study is needed to make a meaningful contribution to a larger population with more general validity.

In this study, we are interested in understanding where food loss has occurred in the food supply chain based on different commodities using the Food Loss and Waste Database [20], which is the most extensive collection of national food loss and waste data. To then understand how different socioeconomic factors correlate with food loss, we link the food loss data with various national-level data on the most relevant factors, such as gross national income (GNI) per capita, employment in agriculture, access to electricity, and export volume index, among others. This is worth paying attention to since policymakers could use the findings to form the best intervention strategy and prioritize their limited resources to mitigate food loss.

Materials and methods

We used openly available datasets to investigate the links between food loss and various socioeconomic variables (Table 1). In the following subsections, we explain in more detail the variables, their relevance to this study, and how we conducted the analyses.

Food loss variable

Challenges in conducting research on food loss include limited data availability and unharmonized measurement methods [18, 61]. Furthermore, there is still no unanimous definition of food loss, what is considered loss across regions, and what food supply stage should be included [8, 14]. In this study, we consider food loss that occurs along the production side of the food supply chain. In other words, it starts from the moment that crops are ripe on the farm until before they reach the retailer or market [19]. We used food loss data from the Food Loss and Waste Database [20], which FAO collected through an extensive review of literature from openly accessible databases, sub- and national reports, and scientific articles in the public domain, including reports from various organizations such as the World Bank, GIZ, and IFPRI. Those publications used different food loss measurement methods, including case studies, controlled experiments, modeled estimates, survey-based estimates, census data, literature reviews, and expert opinions. To date, FAO has included more than 700 publications to produce the Food Loss and Waste Database across food products, stages of the value chain, and geographical areas.

Though the FAO database still has many uncertainties and limitations, the provided loss estimates are the most comprehensive global numbers currently available. The losses are expressed in percentage (proportion) at the country level in a specific year and stages of the food supply chain, from farm to households. They refer to the physical quantity loss of edible food, excluding feed and the inedible parts, divided by the amount produced for various crops and other food commodities. These are divided into five different commodity groups, namely (1) cereals and pulses, (2) fruits and vegetables, (3) roots, tubers, and oil crops, (4) animal products, and (5) others (such as stimulants and spices).

We slightly modified the commodity groups in our analysis. Wheat, maize, and rice, which have the most observations in the dataset and are the most grown cereals worldwide, were separated from the cereals and pulses group. The more granular groups for cereals and pulses are now wheat, maize, rice, and other cereals and pulses. By doing this, we could understand the effects of socioeconomic factors on losses of the most important crops in the world. On the other hand, due to data limitations and the small number of observations, we excluded animal products and others (such as stimulants and spices) from our analysis. The rest of the groups stay the same. Therefore, we have six commodity groups, which are (1) wheat, (2) maize, (3) rice, (4) other cereals and pulses, (5) fruits and vegetables, and (6) roots, tubers, and oil crops (Fig. 1).

We included four main food supply stages: farm, harvest, storage, and transport (Fig. 2). At the farm level, losses may occur because of several activities, including shelling, threshing, and winnowing. Losses at this level also include ripe but unharvested crops, so they stay on the farm [4]. It can happen when there is a failure to meet quality standards (market conformity reasons), pests attack, or simply uneconomical to harvest the ripe crops [6, 25, 45, 47]. During harvest, losses can happen during the gathering and drying, possibly because of poor harvesting techniques and equipment [3, 30]. Storage here is meant to be exclusively on the stage after harvest, not on the retailer or supermarket. Losses might occur due to low storage quality that triggers the presence of pests, fungi, and diseases [11, 15]. Finally, transport is a stage where the crops are brought to a processing facility, retailer, or market. Food might be left behind, damaged, or expired in the transporting facilities due to inadequate containers and poor road quality, prolonging the time to reach the market [3, 44].

The database consists of food loss from 81 countries (Figs. 1 and 2), with 10100 observations ranging from the year 2000 until 2020. One-point data observation refers to the average loss of one specific commodity in one specific stage of one particular country. However, not all countries possess loss data for all food supply stages (e.g., the loss of maize reported in Indonesia is only at the farm level). Figures 1 and 2 show how losses fluctuate between different commodity groups and along different stages of the value chains in different countries. As food loss has been disproportionately experienced in lower-income countries and continues to increase [40, 48], it is relevant to compare the losses in low-income countries and middle- & high-income countries. It is also meaningful to analyze the loss separately based on different commodities and stages, especially where the losses occur the most, in order to focus on effective interventions and policy. For example, intervention might be different if there are more losses on the farm level than during the transport stage. Moreover, if a country wants to enhance the population's nutritional status and reduce environmental pressure, reducing losses in fruits and vegetables can be the best strategy as they are rich in micronutrients but require resources more intensively than other crops in production [28, 34]. However, we should acknowledge that different measurement methodologies and small sample sizes of certain groups might complicate efficient analysis at this granular level. Therefore, while we looked at food loss data in detailed groups, we also analyzed the aggregate losses.

Socioeconomic variables

We were interested to understand the socioeconomic factors of food loss occurrence. We selected socioeconomic variables of related years that were proven to be important factors related to food loss (Table 1 and Fig. 3). The first explanatory variable is Gross National Income (GNI)

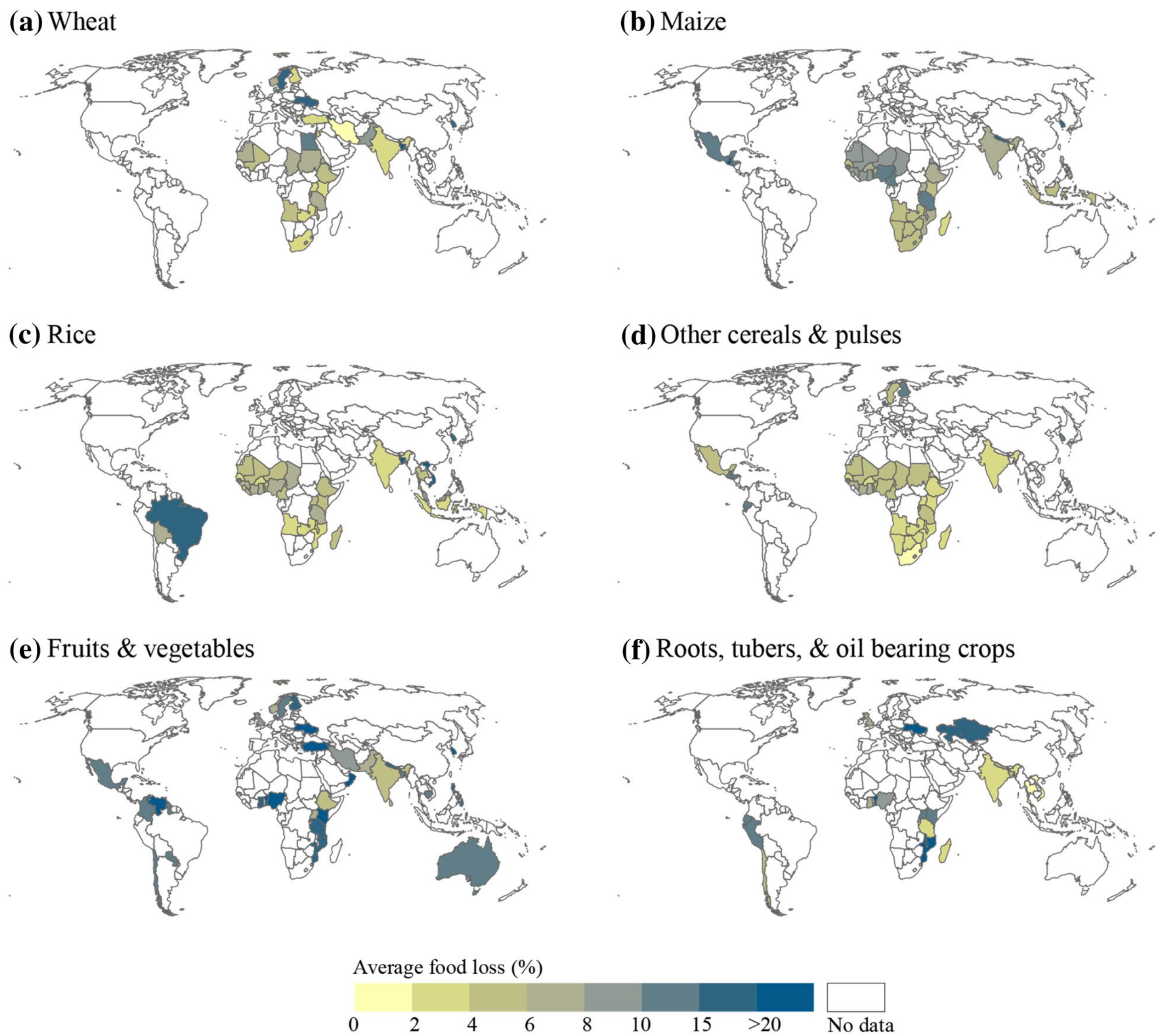

Fig. 1 Average food loss data distribution based on different commodities across food supply stages: wheat **a**, maize **b**, rice **c**, other cereals & pulses **d**, fruits & vegetables **e**, and roots, tubers, & oil crops **f**. Not all countries have food loss data for certain commodities in all supply stages. The map is the authors' illustration based on data from FAO [20]

per capita, as income may correlate negatively with food loss. High income indicates countries' ability to invest in equipment or facilities that can be useful in reducing food losses. For instance, efficient harvesting equipment or cooling facilities reduce food losses but can be costly [30]. We estimated GNI per capita (monetary values) in logarithmic form, which often provides a better empirical fit than the standard linear model.

We also used agriculture shares of GDP and employment in agriculture. Lower-income countries mainly rely on agriculture. Therefore, agriculture contributions to GDP have a considerable proportion of the total GDP, the opposite of many higher-income countries where agriculture often plays a relatively minor role in the economy. The higher importance of agriculture is usually indicated by less modern agriculture (inferior technology), higher employment in the sector, and lower farming efficiency [2, 12]. It involves much manual work and less mechanization, affecting food loss, especially during harvest and post-harvest handling [4].

Another important variable is education. Higher education correlates with lower food loss as it links to skills and knowledge that enable producers to manage farms more efficiently [15, 26]. Education also increases farmers' opportunities and access to production, especially in developing countries with still yield gaps to close [37]. On

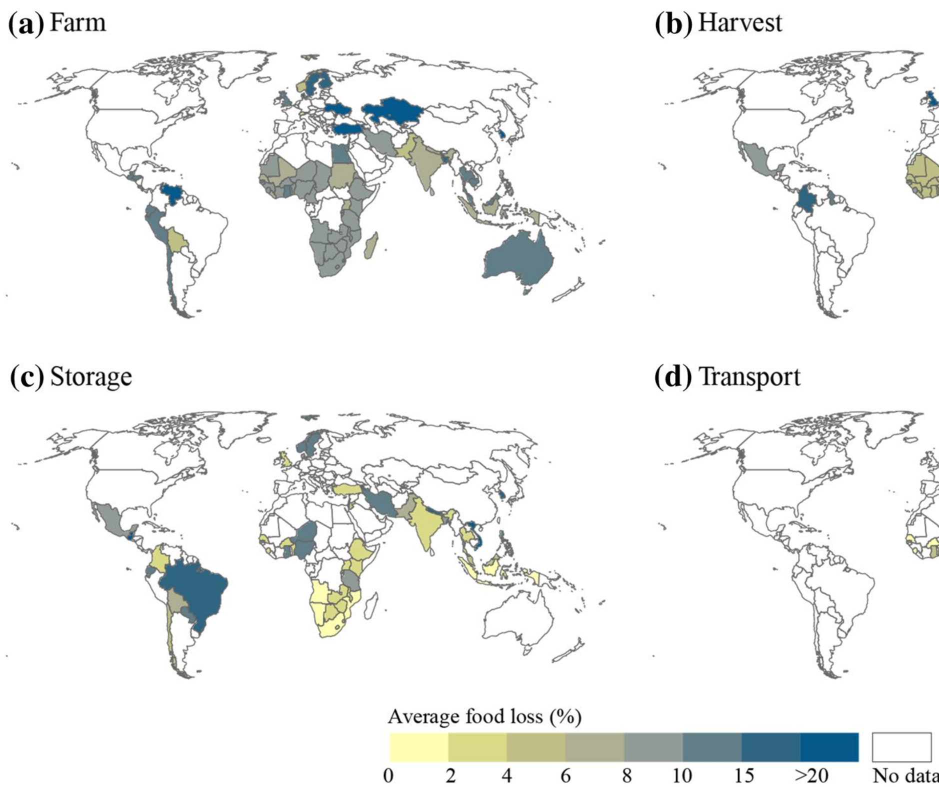

Fig. 2 Average food loss data distribution based on different food supply stages across commodities: farm **a**, harvest **b**, storage **c**, and transport **d**. Not all countries have food loss data for certain commodities in all supply stages. The map is the authors' illustration based on data from FAO [20]

average, countries with higher educated populations are observed to have larger farms than those with lower education [1, 32]. As farms get larger, the chance of losing food along the supply chain also increases [42], meaning that a positive correlation between education and food loss might be observed. It is also important to note the trend of current and future farming: people with better education tend to leave agriculture and take up better off-farm economic opportunities [56, 57]. If that is the case, education might not be correlated with low food loss.

Access to electricity has also been shown to affect food losses [22, 44]. The existence of electricity may signal the use of electric-powered harvesting equipment, refrigeration, and other technologies, thus decreasing food losses, especially during harvesting and storage, by preventing on-farm losses and spoilage [30]. Electricity usually comes to a village after the establishment of roads. It means that electricity is also a proxy for better infrastructure, which is vital for farmers to get to the market more quickly to sell their products, thus preventing loss. In this study, we use access to electricity in rural areas as food is usually produced there.

We used mobile cellular subscription as an explanatory variable as it indicates connectivity. Studies have shown that the spread of mobile phones is likely to reduce food losses over time [31, 41]. Through mobile phones, farmers get a wide range of services and information such as selling prices, input subsidies, farmers' meetings, and even banking, where farmers, notably in Sub-Saharan Africa, are typically underserved by traditional banking [27, 39]. In other words, mobile phones give farmers information about options related to their crops that can affect food loss.

(See figure on next page.)

Fig. 3 Distributions of different socioeconomic variables: GNI per capita **a**, agriculture shares of GDP **b**, employment in agriculture **c**, education **d**, access to electricity in rural area, mobile cellular subscriptions **f**, political stability & absence of violence **g**, and export volume index **h**. The map is the authors' illustration based on data from FAO [21], GDL [23], UNDP [51], UNESCO [52], and World Bank [60]. The Figure only shows data for countries included in this study

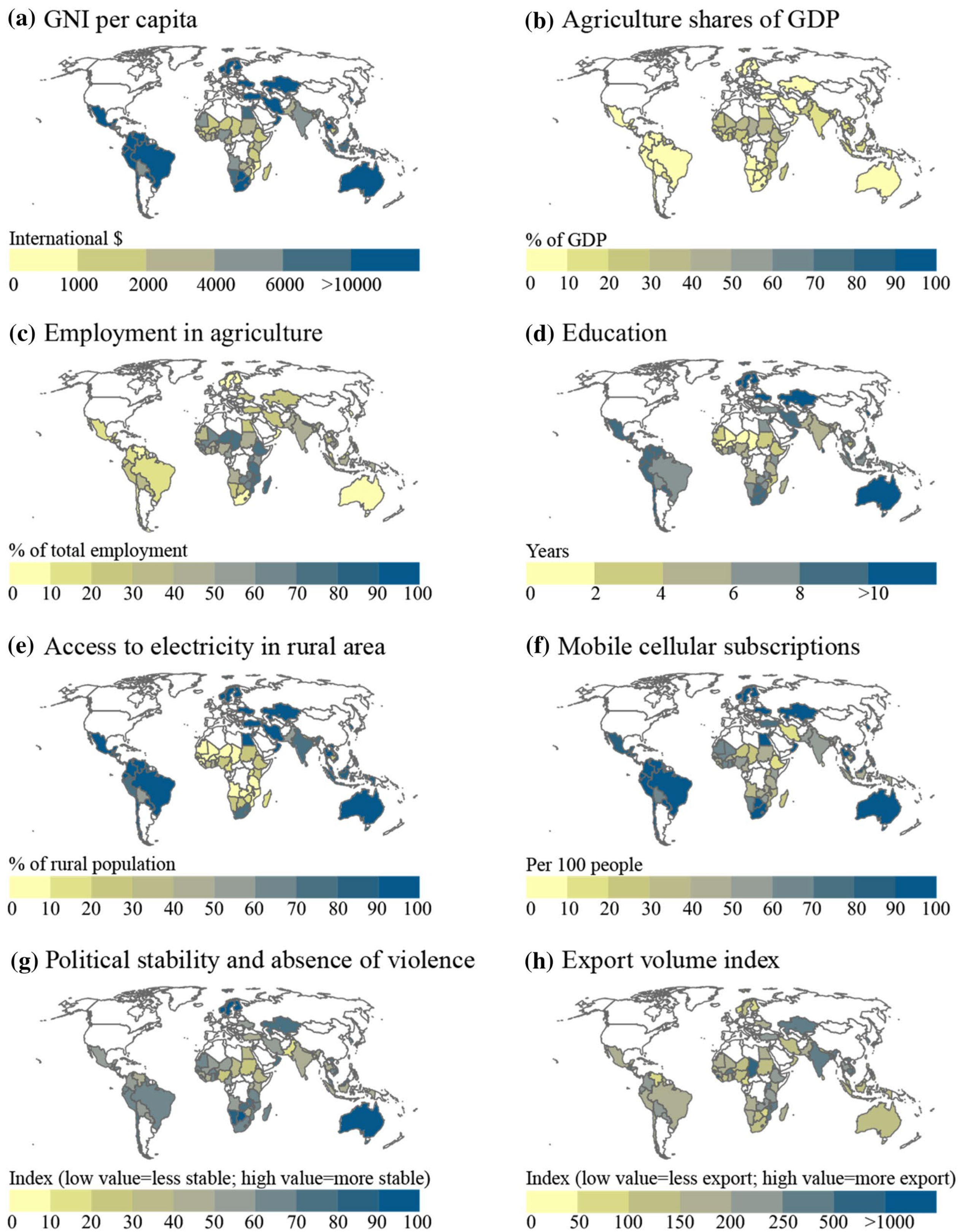

Fig. 3 (See legend on previous page.)

Low political stability is prone to conflict and social unrest. Some studies have shown how food loss escalates during conflicts, especially armed ones [59, 63]. In extreme cases, armed groups interrupt food production and distribution by attacking, stealing, and destroying edible food [35]. Unstable political conditions can force farmers to abandon their ready-to-be-harvested crops or prevent them from transporting their outputs to the market, increasing food losses. Conflict may also interrupt export flows. We use the export volume index as an independent variable that represents an openness of a country in trading with other countries. Many countries are specialized in certain crops and major suppliers of global food demand, for example, Ukraine and Russia supply 30% of global wheat, 20% of maize, and almost 80% of sunflower seeds. Export disturbance because of the Russian attack on Ukraine in the spring of 2022 increases losses on those crops [22].

Filling missing data in socio-economic dataset

Some countries had missing data for various numbers of years in the socioeconomic dataset. To fill in the missing data points, we first used linear interpolation to fill the gaps between reported values. This was done with na.approx -function in R (under zoo package; Zeleis & Grothendieck [62]). In general, there were not many 'holes' in the data that we needed to interpolate. However, a larger issue was missing values at the beginning or at the end of the time series of a country. We thus developed a multi-step extrapolation method to fill in these missing values:

1. We first divided the countries into the following groups, based on the data coverage over the study period 2000–2020: (a) full data extent, (b) nearly full data extent (max 3 years missing from beginning or end), (c) limited data extent (more than 3 years missing from either end but more than 5 data points), (d) very limited data extent (less than 5 data points).
2. We went through the nearly full data extent data country by country and extrapolated those using the full data extent countries. This was done by constructing a linear model (lm) between a country with missing values (targetCountry) and each country with a full extent. Then we filtered out seven countries with the best fits based on R2 and chose the closest country (bestClosestCountry) to the targeCountry from those. The lm was then used to estimate the full-time series (lmTimeseries) for a targetCountry, using the data from bestClosestCountry as an input. Finally, we used the first and last reported value of the targetCountry and the corresponding values from lmTimeseries to calculate the ratio. We used these ratios to scale the lmTimeseries to fill in the missing values from the beginning (ratio over the first non-missing value) and end (ratio over the last non-missing value) of the study period.
3. We combined the full data set with the filled near full data set to a combined full_nearlyFull dataset.
4. We then filled in the missing data points for the limited data extent, using full_nearlyFull dataset and the same method as in step 2.
5. We filled the countries with less than 5 data points by first identifying the closest country within *full_nearlyFull* dataset for each country in this group (*closestCountry*). We then scaled the leading and trailing missing values based on the trajectory of the *closestCountry* in a similar way to in point step 2, i.e., we calculated the ratio between the first non-missing value and the corresponding *closestCountry* value. We used this to estimate the leading missing values and the ratio between the last non-missing value and the corresponding *closestCountry* value. These ratios were then used together with full data series from the *closestCountry* to estimate the missing values.
6. Finally, we combined the full and filled datasets to create a complete dataset.

These steps were repeated for each socio-economic variable (see independent variables in Table 1).

Regression approach

To test our hypotheses that various socioeconomic variables are associated with food loss, we used fixed effects models of the following type:

$$FL = \alpha + \beta SE + \gamma WR + \delta T + \varepsilon \quad (1)$$

where FL is the loss of food measured in percentage and SE is a vector of socioeconomic variables of interest. We are particularly interested in the coefficient estimate β. A positive and significant estimate of β would indicate that the socioeconomic variables are positively associated with high food loss, while a negative estimate proves otherwise. In order to get the net association between food loss and socioeconomic variables, we also included world region fixed effects WR to control for unobserved regional differences such as agroecological, general infrastructure, and socioeconomic conditions. T is a vector of time-fixed effects. Finally, ε is a clustered standard error at the world region level. The database reports losses from countries in seven world regions: Europe and North America, Latin America & the Caribbean, the Middle East & North Africa, Sub-Saharan Africa, Central & South Asia, East & Southeast Asia, and Australia & Oceania. We ran a regression model combining all data

Table 2 Food loss and socioeconomic factors based on countries' income levels

Variables	Low-income			Middle- & high-income		
	Mean	Standard error	N	Mean	Standard error	N
Losses (%)						
Wheat–farm	8.945	0.223	243	7.890	0.368	113
Wheat–harvest	4.908	0.360	243	4.316	0.290	107
Wheat–storage	2.722	0.203	116	2.402	0.512	67
Wheat–transport	1.080	0.057	114	1.212	0.238	59
Maize–farm	12.829	0.140	482	12.069	0.177	223
Maize–harvest	6.997	0.119	483	6.296	0.106	218
Maize–storage	3.692	0.273	241	3.280	0.287	160
Maize–transport	1.600	0.054	235	1.529	0.109	152
Rice–farm	7.669	0.073	479	7.796	0.253	124
Rice–harvest	5.183	0.175	480	4.656	0.147	115
Rice–storage	2.972	0.201	209	3.864	0.685	68
Rice–transport	1.135	0.094	210	1.139	0.172	53
Other cereals & pulses–farm	7.625	0.038	1122	7.289	0.113	361
Other cereals & pulses–harvest	4.165	0.052	1152	3.710	0.073	420
Other cereals & pulses–storage	2.578	0.103	462	1.950	0.087	265
Other cereals & pulses–transport	1.006	0.008	436	1.071	0.061	254
Fruits & vegetables–farm	16.553	1.987	65	12.930	1.001	126
Fruits & vegetables—harvest	2.941	0.731	19	9.747	1.230	91
Fruits & vegetables–storage	10.354	1.735	24	6.356	0.692	72
Fruits & vegetables–transport	13.198	2.647	26	8.928	2.137	38
Roots, tubers, & oil crops–farm	16.553	2.057	17	12.930	1.406	37
Roots, tubers, & oil crops–harvest	2.941	2.318	18	9.747	1.047	28
Roots, tubers, & oil crops–storage	10.354	2.864	19	6.356	1.699	25
Roots, tubers, & oil crops–transport	13.198	1.288	12	8.928	0.474	17
Socioeconomic factors						
GNI per capita (International $)	1724.357	8.482	6907	8038.598	158.860	3193
Agriculture share of GDP (%)	27.592	0.127	6907	11.226	0.139	3193
Employment in agriculture (%)	63.204	0.184	6907	35.744	0.298	3193
Education (years)	3.574	0.020	6907	6.598	0.043	3193
Access to electricity in rural area (%)	11.475	0.145	6907	38.883	0.537	3193
Mobile cellular subscription (/100 people)	32.171	0.390	6907	79.500	0.693	3193
Political stability	0.559	0.002	6907	0.635	0.003	3193
Export volume index	291.229	7.221	6907	199.353	1.778	3193

points and separate models based on different income levels, commodities, and food supply stages.

Results and discussion

Magnitudes of food loss

Generally, the proportion of food loss is higher in low-income countries than in middle- & high-income countries, especially in wheat, other cereals & pulses, fruits & vegetables, and root, tubers, & oil crops in most stages (Table 2). This is plausible and coherent with existing research that shows that food loss mainly happens in lower-income countries [40, 48]. However, higher losses are observed in middle- & high-income countries, for example, rice in most stages. This inconsistency is most probably due to the small number of observations in middle- & high-income countries. There is also a possibility that losses rarely occur in higher-income countries so only significant, unusual losses are reported, which might skew the number. The socioeconomic factors of low-income and middle- & high-income countries are also different (Table 2). Low-income countries have notably lower GNI, education, access to electricity, and less political stability, among others. These socioeconomic factors might correlate with losses.

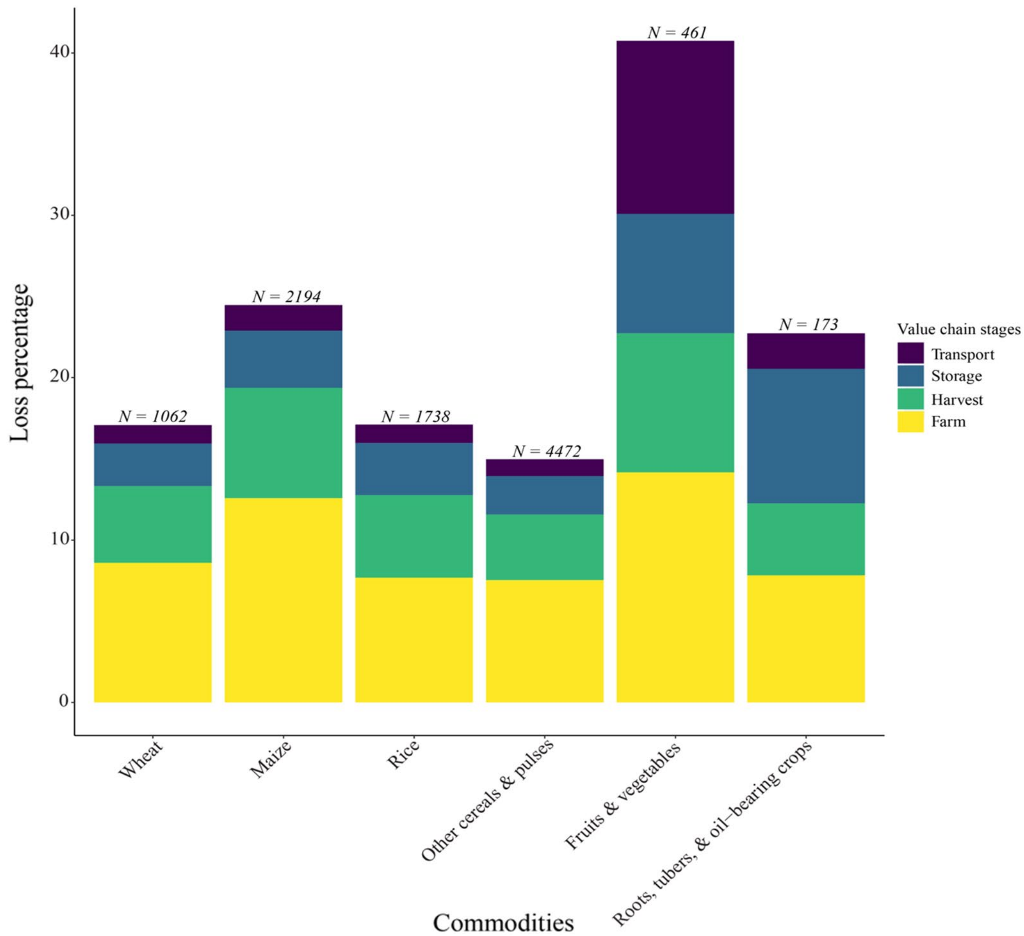

Fig. 4 Average loss percentage of different commodities in different food supply stages

We also found that, unsurprisingly, fruits and vegetables had the highest loss percentage (Fig. 4), as they are more perishable than other groups. In the studied countries, on average more than 40% of fruits and vegetables are lost before they reach the retailers or consumers, with around 15% occurring on the farm alone. It is commonly acknowledged that growing fruits and vegetables can often be more challenging than growing other types of crops. It demands certain high skills and techniques unique to specific fruits and vegetables. They are also more affected by climate change, pests, and diseases in terms of quality than other groups [6, 38, 46]. Furthermore, FAO [22] reveals that fruits and vegetables are the least supported commodities through policy in low- and middle-income countries. For example, farmers are sometimes penalized through farm-gate price reductions because governments want to protect poor consumers. This condition disincentivizes farmers from harvesting ripe fruits and vegetables, contributing to on-farm losses. On the contrary, staple foods are often supported through price incentives and input subsidies.

Maize also has a high percentage of food loss, which is 25% on average (Fig. 4). Around 13% of the losses occur on the farm, possibly due to poor farming techniques, food safety issues, and pest attacks prior to harvest [24, 49]. The particularly high loss values for maize are reported in Sub-Saharan Africa (Fig. 1), where the crop is also the most important cereal in the region [50]. Furthermore, around 15–23% of wheat, rice, other cereals & pulses, and roots, tubers, & oil crops are lost before they reach the retailer. Most losses occur on the farm level for all cereal and pulse crops. Meanwhile, for roots, tubers, & oil crops, which are more perishable, the losses mostly occur in storage.

Associations of socioeconomic factors and food loss

We linked the food loss database with various socioeconomic variables to understand the associations between various socioeconomic factors and food loss of different commodities and food supply stages (Table 1). The associations have variations in directions, magnitudes,

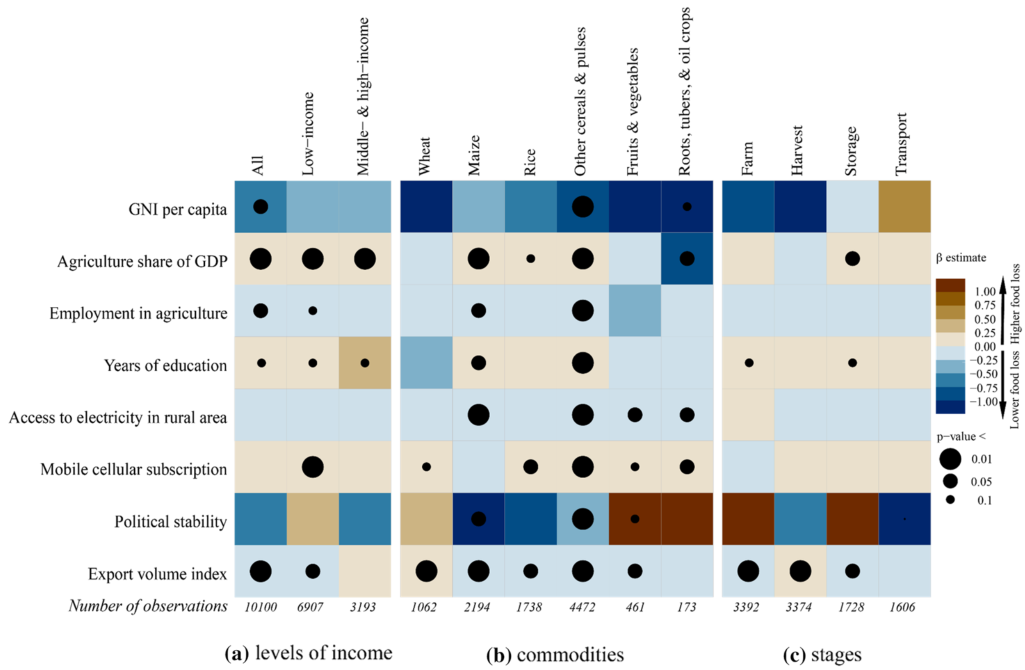

Fig. 5 Associations between socioeconomic factors and food loss based on countries' levels of income **a**, commodities **b**, and stages **c**. The Figure is a visualization of Table 3, as well as Tables 4 and 5 in the Appendix

Table 3 Associations between socioeconomic factors and food loss based on countries' level of income

	All(1)	**Low-income(2)**	**Middle- and high-income(3)**
GNI per capita (log)	− 0.733**	− 0.349	− 0.371
	(0.210)	(0.260)	(0.504)
Agriculture share of GDP	0.055***	0.047***	0.157***
	(0.004)	(0.004)	(0.025)
Employment in agriculture	− 0.025**	− 0.023*	− 0.003
	(0.009)	(0.008)	(0.040)
Years of education	0.167*	0.121*	0.367*
	(0.079)	(0.052)	(0.115)
Access to electricity in rural area	− 0.016	− 0.013	− 0.010
	(0.017)	(0.022)	(0.021)
Mobile cellular subscription	0.008	0.011***	0.004
	(0.005)	(2.040e-4)	(0.014)
Political stability	− 0.504	0.345	− 0.749
	(0.838)	(0.314)	(2.108)
Export volume index	− 3.157e-4***	− 2.960e-4**	0.001
	(6.503e-5)	(8.779e-5)	(0.003)
World region fixed effects included	Yes	Yes	Yes
Time fixed effects included	Yes	Yes	Yes
Number of observations	10100	6907	3193
Standard errors by:	World region	World region	World region

Coefficient estimates of fixed effects models are shown with standard errors in parentheses. ***, **, * are significant at 1%, 5%, and 10%, respectively.

and significance (Fig. 5 and Table 3).[1] From the regression results, some of the socioeconomic variables we employed significantly correlate with food loss in the full model (Fig. 5 and Table 3 Column 1). The directions of the correlations are quite similar in low-income and middle- & high-income countries, with low-income countries showing higher significance (i.e., in employment in agriculture and export volume index). The results have more variations when we look at them based on different commodities and stages (Fig. 5).

GNI per capita, employment in agriculture, access to electricity in rural areas, and export volume index correlate negatively with food loss (Fig. 5). Meanwhile, agriculture shares of GDP, education, and mobile cellular subscription correlate positively with food loss (Fig. 5). GNI per capita, expressed in logarithmic terms, representing a country's economy, correlates with low food loss significantly. For example, from the full model, when the GNI is 10 and 50 percentage points higher, the food loss is 3 and 13 percentage points lower, respectively (Table 6 Column 1).[2] The directions of effect are also the same in all food groups and supply stages, except transport, and are significant in other cereals & pulses and roots, tubers, & oil crops (Fig. 5). These results support our hypothesis that GNI denotes a country's financial ability to invest in technology and infrastructure to reduce food losses, such as harvesting machines and roads.

On the other hand, agriculture shares of GDP correlates positively with food loss (Fig. 5). With an increase of 1 percentage point in agriculture shares of GDP, a country faces a 5.5 percentage points increase in food loss (Table 3 Column 1). A high share of agriculture in the GDP is usually associated with low technology and farming inefficiency [2]. Furthermore, in a case where a country is technology-inferior, employment in agriculture that proxies manual labor is still important and negatively associated with food loss. It decreases food losses by 2.5 percentage points in the full model (Table 3 Column 1). It implies that a country can still invest in human capital to reduce food loss when technology is not yet present.

Education has ambiguous impacts on food loss. It correlates positively with food loss and is significant in all income levels, maize, other cereals & pulses, farm, and storage (Fig. 5). It thus seems that simply the longer people stay in school does not necessarily give incentives to reduce food loss.[3] One plausible explanation could be that people who have higher education do not necessarily work in agriculture [1, 32]. When they do, they tend to manage bigger farms, yield more outputs, and thus lose more [42]. Furthermore, losses have also reportedly happened when farmers have more knowledge and receive more information about market situations, which is important to analyze the benefit of harvesting crops. Some crops never leave the field or are unharvested simply because farmers understand the economic reality, for example, because the selling price is too low or the transport cost is too high that the revenue cannot compensate [30, 47]. It is also important to acknowledge that years of education in a formal institution might not be a perfect variable to explain traditional producers' knowledge and skills in farming since most of them can be acquired through informal training and intergenerational experience in the community [5, 10, 33, 54]. A study by IFPRI for FAO in Malawi, Nigeria, Tanzania, Ecuador, Ethiopia, Guatemala, Honduras, and Peru also shows ambiguous impacts of education on food loss [19].

In line with existing research, access to electricity in rural areas is negatively associated with food loss. It is even significant in maize, other cereals & pulses, fruits & vegetables, and roots, tubers, & oil crops. Access to electricity induces mechanization activities (e.g., mechanical harvesting) and the use of cooling facilities for storing, which reduces food loss.

Mobile cellular subscription is another variable that has an unexpected relationship with food loss. It associates significantly positively with food loss (Fig. 5) and contradicts existing research. One plausible explanation could be that farmers also receive information through mobile phones that prevent them from harvesting and selling their crops (e.g., low market price), or they use other means of communication to receive information. It is also possible that countries with better connectivity have better documentation of food losses, explaining the high food loss observance. However, the linkages between mobile cellular subscriptions and food loss are insignificant based on different food supply stages. Meanwhile, the export volume index is also negatively associated with food loss, except in wheat and harvest (Fig. 5). As food can be exported, the domestic market is not glutted by the food supply, especially when overproduction occurs. Therefore, losses can be avoided.

[1] We also ran regressions for different commodities (Table 4 in the Appendix), different food supply stages (Table 5 in the Appendix), different commodities and income levels (Table 6 in the Appendix), and different food supply stages and income levels (Table 7 in the Appendix). The directions of the relationships are similar, with few variations with the full model.

[2] A p percentage point increase in GNI per capita in the linear-log model is associated with β x log(100+p100) change in food loss.

[3] We have also tried other education-related variables such as education index and literacy rates. The magnitude and direction of the relationship are similar to years of education.

We conducted a sensitivity analysis for a robustness check where we ran multiple regressions by excluding one country at a time. In general, the results do not change. They are influenced only when a country with a large number of observations is excluded from the analysis, which is plausible and, at the same time, shows that our model is robust (Fig. 6 in the Appendix).

Conclusion and policy implications

Understanding socioeconomic factors of food loss is essential for intervention reduction strategy. This study examines associations between various socioeconomic factors and food losses on different commodities and supply stages. We found that higher GNI per capita, employment in agriculture, access to electricity, and export volume are associated with lower food loss (Fig. 5; Table 3). On the other hand, shares of agriculture in GDP, years of education, and mobile cellular subscriptions are associated with higher amounts of lost food, the latter contradicting existing studies.

Governments and policymakers can make some efforts by focusing on socioeconomic factors associated with low food loss. As some variables correlate more significantly in low-income countries, prioritizing actions in those countries could be advantageous. Our results show that GNI per capita is associated with lower food loss, suggesting that income is invested in equipment, technologies, or facilities that allow more efficient farming. Therefore, increasing a country's general economy could affect food loss reduction. Providing access to electricity in rural areas, especially in low-income countries, could also be a strategy, as electricity induces the use of electrified harvesting machines that could optimize the yield or storage that could prevent pests, fungi, and diseases. In countries where employment in agriculture is still essential, providing training for farmers (investing in human capital) on reducing food loss on their farms could be a good approach. Lastly, improving access to export could help distribute the food surplus from the national market to other countries that might need them.

Though we used the most comprehensive food loss data available, we observed that improving the data quality by implementing a standardized method of food loss measurement to reduce uncertainties is essential. Including other relevant socioeconomic variables in the analysis would also be meaningful, such as land tenure and gender variables. It is critical for food producers to have secure tenure on the land that they farm. Secure land ownership has various impacts on food losses across different contexts [19]. For example, in a country where land tenure is not respected, farmers face the risk of losing land, therefore minimizing their investment and efforts in cultivating the farm efficiently, contributing to food loss. Gender might also play an essential role in reducing food loss. On average, more than 40% of the agricultural workforce are women [16]. As we know that gender inequality is still a problem in most parts of the world, women's access to education or productive assets and their freedom of movement might affect food loss. If that is the case, policy or intervention to empower women might effectively reduce food loss. In this study, we tried to incorporate land tenure and gender-related variables in our analysis, but unfortunately, we were restricted by data availability.

We also acknowledge that food loss is strongly related to weather. For example, floods caused by heavy rain could leave crops unharvested on the farm, or humidity could trigger the presence of fungi that cause spoilage in the storage. However, we do not have a detailed location of the losses in the country, and in large countries, the weather varies considerably across locations. Therefore, weather-related factors are not included in our study as we could not link them with the food loss data. However, if the data allows, it should be incorporated in future studies.

Our study is conducted at a global level. There are heterogeneities that one should pay attention to among countries. Therefore, interpretation should be made carefully. Policymakers should always validate with national and local context whenever a relevant policy is being formed. We suggest performing a case study before downscaling our results. Policymakers should be aware that even though understanding food loss at each specific food supply stage is vital to formulating right-on-target policy and intervention, loss reduction in each stage is effective when other stages operate well. For example, farm-level improvements would be less effective in reducing the overall loss if there is still not enough adequate storage to store all yields. Therefore, assessing loss at each supply stage, at the aggregate level, and how all stages are connected are essential.

Appendix

See Tables 4, 5, 6, 7.

See Fig. 6.

Table 4 Associations between socioeconomic factors and loss of different commodities

	Wheat (1)	Maize (2)	Rice (3)	Other cereals & pulses (4)	Fruits & vegetables (5)	Roots, tubers, and oil crops (6)
GNI per capita (log)	− 1.870	− 0.427	− 0.569	− 0.964***	− 2.023	− 14.921*
	(1.585)	(0.241)	(0.598)	(0.014)	(7.046)	(6.983)
Agriculture share of GDP	− 0.011	0.075***	0.040*	0.043***	− 0.050	− 0.807**
	(0.012)	(0.006)	(0.013)	(0.001)	(0.161)	(0.274)
Employment in agriculture	− 0.057	− 0.028**	− 0.021	− 0.027***	− 0.284	− 0.198
	(0.050)	(0.008)	(0.016)	(0.001)	(0.379)	(0.121)
Years of education	− 0.336	0.134**	0.235	0.086***	− 0.027	− 0.077
	(0.222)	(0.030)	(0.111)	(0.003)	(1.098)	(1.340)
Access to electricity in rural area	− 0.022	− 0.020***	− 0.014	− 0.020***	− 0.246**	− 0.243**
	(0.022)	(0.001)	(0.027)	(0.001)	(0.093)	(0.069)
Mobile cellular subscription	0.013*	− 1.964e-4	0.018**	0.007***	0.120*	0.237**
	(0.005)	(0.003)	(0.005)	(0.001)	(0.056)	(0.062)
Political stability	0.259	− 2.009**	− 0.812	− 0.490***	13.256*	10.826
	(1.823)	(0.408)	(1.046)	(0.045)	(6.025)	(7.542)
Export volume index	0.002***	− 0.001***	− 1.966e-4**	− 0.001***	− 0.033**	− 0.007
	(2.182e-4)	(3.181e-5)	(5.210e-5)	(4.737e-5)	(0.011)	(0.010)
World region fixed effects included	Yes	Yes	Yes	Yes	Yes	Yes
Time fixed effects included	Yes	Yes	Yes	Yes	Yes	Yes
Number of observations	1062	2194	1738	4472	461	173
Standard errors by	World region	World region	World region	World region	World region	World region

Coefficient estimates of fixed effects models are shown with standard errors in parentheses. ***, **, * are significant at 1%, 5%, and 10%, respectively.

Table 5 Associations between socioeconomic factors and food loss at different food supply stages

	Farm (1)	Harvest (2)	Storage (3)	Transport (4)
GNI per capita (log)	− 0.792	− 1.031*	− 0.177	0.564
	(0.425)	(0.454)	(0.474)	(0.663)
Agriculture share of GDP	0.012	− 0.001	0.091**	0.057
	(0.006)	(0.009)	(0.028)	(0.046)
Employment in agriculture	− 0.011	− 0.034	− 0.012	− 0.008
	(0.011)	(0.017)	(0.011)	(0.015)
Years of education	0.201*	0.147	0.211*	0.087
	(0.099)	(0.096)	(0.090)	(0.098)
Access to electricity in rural area	0.007	− 0.021	− 0.019	− 0.029
	(0.017)	(0.021)	(0.021)	(0.030)
Mobile cellular subscription	− 0.001	0.006	0.007	0.011
	(0.006)	(0.004)	(0.015)	(0.017)
Political stability	1.242	− 0.718	1.153	− 1.399*
	(0.791)	(1.102)	(1.302)	(0.637)
Export volume index	− 1.579e-4***	0.001***	− 0.001**	− 3.653e-4
	(3.804e-5)	(1.279e-5)	(2.567e-4)	(3.216e-4)
World region fixed effects included	Yes	Yes	Yes	Yes
Time fixed effects included	Yes	Yes	Yes	Yes
Number of observations	3392	3374	1728	1606
Standard errors by	World region	World region	World region	World region

Coefficient estimates of fixed effects models are shown with standard errors in parentheses. ***, **, * are significant at 1%, 5%, and 10%, respectively

Table 6 Associations between socioeconomic factors and loss of different commodities based on countries' level of income

	Low-income						Middle- and high income					
	Wheat (1)	**Maize (2)**	**Rice (3)**	**Other cereals & pulses (4)**	**Fruits & vegetables (5)**	**Roots, tubers, and oil crops (6)**	**Wheat (7)**	**Maize (8)**	**Rice (9)**	**Other cereals & pulses (10)**	**Fruits & vegetables (11)**	**Roots, tubers, and oil crops (12)**
GNI per capita (log)	− 2.001	0.332	− 0.299	− 0.489***	− 35.381	52.812***	− 2.033	-0.579	0.947*	− 0.861***	− 9.096	− 11.191*
	(2.861)	(0.296)	(0.385)	(3.931e-4)	(15.632)	(5.079e-8)	(1.122)	(0.971)	(0.392)	(0.065)	(6.248)	(5.500)
Agriculture share of GDP	− 0.050**	0.057	0.034*	0.044***	− 0.647*	− 16.253***	0.116	0.190***	0.104***	0.090***	− 0.259	− 0.182
	(0.006)	(0.010)	(0.009)	(1.849e-4)	(0.247)	(2.495e-9)	(0.082)	(0.024)	(0.016)	(0.010)	(0.619)	(0.105)
Employment in agriculture	− 0.069	− 0.021	− 0.017	− 0.027***	− 1.270**	− 2.268***	− 0.053	− 0.041*	− 0.057***	− 0.004	− 0.528	0.502*
	(0.098)	(0.015)	(0.011)	(5.230e-5)	(0.313)	(1.055e-10)	(0.083)	(0.013)	(0.005)	(0.004)	(0.820)	(0.244)
Years of education	− 0.472	2.43e-4	0.143	0.094***	3.508**	− 9.748***	− 0.619	0.507***	0.599**	0.120***	0.841	7.488***
	(0.232)	(0.035)	(0.068)	(0.001)	(0.953)	(9.011e-9)	(0.345)	(0.082)	(0.176)	(0.017)	(2.387)	(1.058)
Access to electricity	− 0.079	0.001	− 0.005	− 0.004***	− 0.568***	− 0.381***	0.024	− 0.038***	− 0.014	− 0.028***	-0.481*	0.208**
	(0.061)	(0.013)	(0.019)	(1.645e-4)	(0.092)	(1.415e-10)	(0.018)	(0.004)	(0.024)	(0.002)	(0.204)	(0.077)
Mobile cellular subscription	0.007**	− 0.006	0.014***	0.008***	0.109	− 3.063***	− 0.003	0.002	0.021***	0.020***	0.115	− 0.023
	(0.001)	(0.004)	(8.10e-6)	(2.49e-7)	(0.102)	(9.046e-10)	(0.025)	(0.008)	(0.003)	(0.002)	(0.067)	(0.056)
Political stability	− 1.315	− 0.214	− 0.973	0.665***	− 5.011	363.458***	6.773	− 4.194***	2.706**	− 2.224***	21.713**	− 35.462*
	(0.460)	(0.820)	(0.536)	(0.005)	(13.169)	(1.613e-8)	(10.063)	(0.679)	(0.640)	(0.305)	(7.168)	(14.481)
Export volume index	0.002	− 0.001**	− 1.45e-4***	− 0.001***	− 0.103*	0.139***	− 0.003	− 0.001	− 0.001	0.002	− 0.007	− 0.031*
	(0.001)	(4.9e-5)	(4.04e-6)	(9.347e-6)	(0.041)	(3.560e-11)	(0.010)	(0.005)	(0.013)	(0.001)	(0.028)	(0.015)
World region fixed effects included	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Time fixed effects included	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Number of observations	716	1441	1378	3172	134	66	346	753	360	1300	327	107
Standard error by:	World region	World region	World region	World region	World region	World region	World region	World region	World region	World region	World region	World region

Coefficient estimates of fixed effects models are shown with standard errors in parentheses. ***, **, * are significant at 1%, 5%, and 10%, respectively.

Table 7 Associations between socioeconomic factors and food loss at different food supply stages based on countries' levels of income

	Low-income				Middle- and high income			
	Farm(1)	**Harvest(2)**	**Storage(3)**	**Transport(4)**	**Farm(5)**	**Harvest(6)**	**Storage(7)**	**Transport(8)**
GNI per capita (log)	− 0.986**	− 1.171	0.781	1.146	0.367	− 0.009	− 0.660	− 0.740**
	(0.263)	(0.527)	(1.111)	(2.240)	(0.580)	(0.689)	(0.927)	(0.214)
Agriculture share of GDP	− 8.9e-5	− 0.006	0.093	0.060	0.113***	− 0.015	0.266***	0.147***
	(0.003)	(0.008)	(0.032)	(0.065)	(0.025)	(0.050)	(0.060)	(0.025)
Employment in agriculture	− 0.016	− 0.035	4.42e-4	0.028	0.024	− 0.003	− 0.052	− 0.119**
	(0.010)	(0.021)	(0.035)	(0.062)	(0.026)	(0.026)	(0.050)	(0.039)
Years of education	0.188**	0.180	0.205	− 0.051	0.258	0.035	0.431	0.541**
	(0.055)	(0.099)	(0.187)	(0.333)	(0.137)	(0.156)	(0.236)	(0.178)
Access to electricity in rural area	− 0.012	− 0.024	0.006	− 0.031	0.031	− 0.018	− 0.032	− 0.075***
	(0.017)	(0.033)	(0.029)	(0.074)	(0.016)	(0.020)	(0.028)	(0.010)
Mobile cellular subscription	0.002*	0.005	0.017	0.028	− 0.017	0.012	0.008	− 0.006
	(0.001)	(0.002)	(0.023)	(0.039)	(0.023)	(0.019)	(0.016)	(0.016)
Political stability	1.093**	− 0.085	3.026	− 0.407	3.066	− 1.854	− 1.391	− 7.261***
	(0.337)	(0.836)	(1.074)	(1.963)	(1.921)	(1.782)	(4.074)	(0.543)
Export volume index	− 1.47e-4***	0.001***	− 0.001	− 3.90e-4	0.001	− 0.004	0.007	0.002
	(1.4e-5)	(2.4e-5)	(2.23e-4)	(4.54e-4)	(0.003)	(0.006)	(0.010)	(0.002)
World region fixed effects included	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Time fixed effects included	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Number of observations	2408	2395	1071	1033	984	979	657	573
Standard errors by:	World region	World region	World region	World region	World region	World region	World region	World region

Coefficient estimates of fixed effects models are shown with standard errors in parentheses. ***, **, * are significant at 1%, 5%, and 10%, respectively.

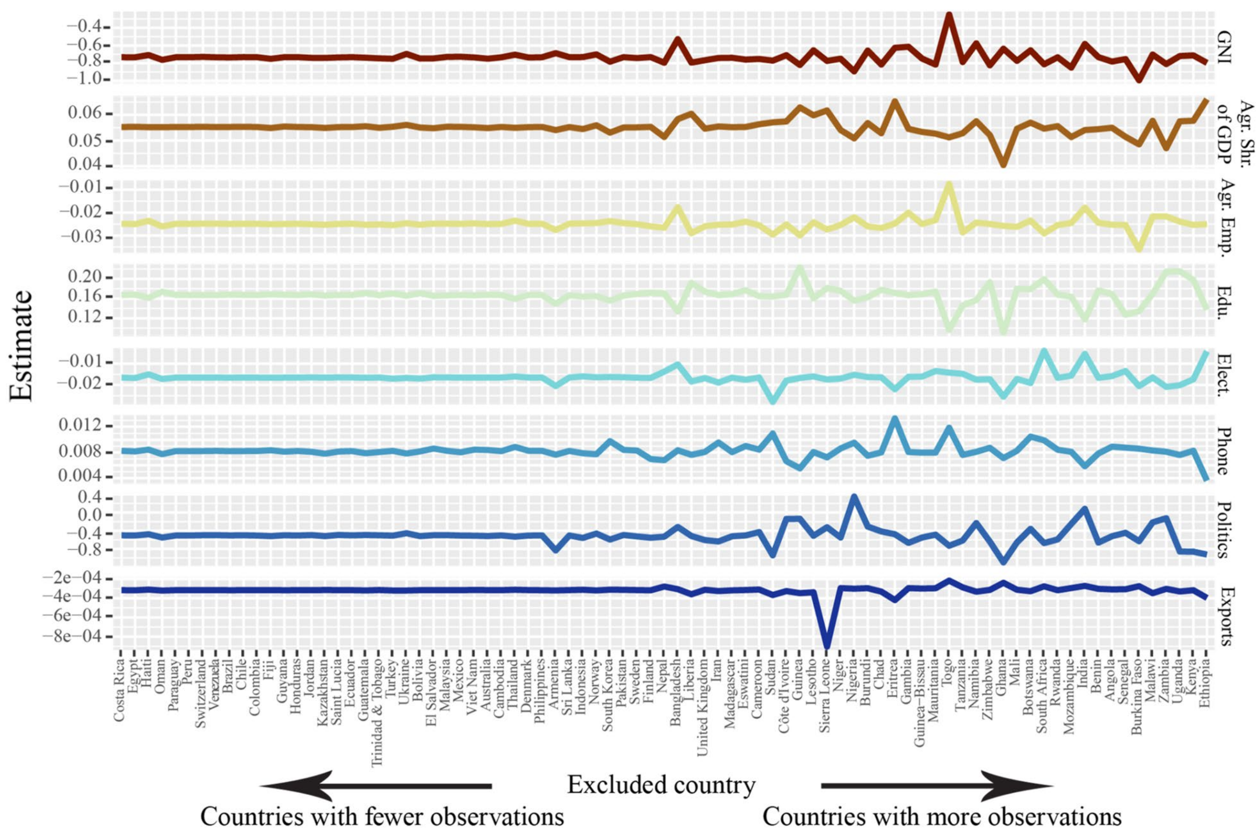

Fig. 6 Sensitivity plot illustrating the impact of excluding individual countries from the regression analysis on regression coefficients. The plot demonstrates how the estimates of each coefficient change when a single country is removed, showing the robustness of the model against the influence of individual countries

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Availability of data and materials
The data and code for creating the results are available at https://github.com/jpiippon/SocioeconomicFactorsOfGlobalFooLoss.

Declarations

Competing interests
The authors declared that they have no competing interests.

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