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# Nutritional and environmental losses embedded in global food waste

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ABSTRACT

Reducing food waste can contribute positively towards multiple sustainable development goals (SDGs) but the differences in the food waste across countries in terms of embedded nutrients and environmental impacts is not well-known. Here we assess the value of daily per capita food waste of 151 countries using two recent indicators for embedded nutrition losses (wasted nutrient days and wasted daily diets) and five indicators for environmental impacts. Globally, on average, 65 kg of food is wasted per year by one person of which 25% is through wasted vegetables, 24% through cereals and 12% through fruits. Daily wasted amounts of vitamin C, K, Zinc, Copper, Manganese and Selenium are especially high representing 25-50% of their daily dietary recommended intake (DRI) value. Cereals, fruits and vegetables are the three major food groups contributing the most to wasted nutrients followed by meat, dairy and eggs that contribute substantially to the wasted calcium, choline, riboflavin, zinc, and vitamin $B_{12}$. Global average amount of food waste per capita per year contains 18 healthy diets meaning it can fulfil the DRIs of 25 nutrients for one person for 18 days. The embedded environmental footprints in average person's daily food waste are: 124 g $CO_2$ eq., 58 Litre freshwater use, 0.36 $m^2$ cropland use, 2.90 g nitrogen and 0.48 g phosphorus use. Cereals, meat, and sugar are major food groups contributing to environmental impacts. Our results show that different countries have widely varying nutrients and environmental footprints embedded in their food waste entailing country-specific waste reduction interventions.

## 1. Introduction

Two billion people globally have nutritional deficiencies and about 800 million still suffer from hunger due to poverty and poorly developed food systems (FAO et al., 2018; Swinburn et al., 2019). Food production is one of the major drivers of global global greenhouse gas emissions, freshwater withdrawals, and land use. Yet, one third of the food produced globally is lost (at post-harvest and pre-consumption stage) or wasted (at post-consumption stage) along the food supply chain from production to consumption (Gustavsson et al., 2011). Losses throughout the food system not only increase the demands on food production but also induce the consequent production-related environmental impacts that could be avoided in absence of food waste.

It is now well documented that reducing global food waste can create a 'win-win' situation for nutrition security and environmental sustainability and thus reducing per capita food waste by half by 2030 has been declared as one of sustainable development goals target 12.3 of the United Nations (United Nation, 2015). The recently published report of the EAT-Lancet commission on healthy diets from sustainable food systems showed that reducing food loss and waste by 50% can go a long way in ensuring healthy food availability globally and that the Earth's environmental planetary boundaries (Steffen et al., 2015) do not get transgressed (Willett et al., 2019).

Many regional and global studies have quantified the resources wasted and environmental consequences due to food loss and food waste at a national (Birney et al., 2017; Blas et al., 2018; Kashyap and Agarwal, 2019; Ma et al., 2019; Tonini et al., 2018), regional (Porter et al., 2018; Scherhaufer et al., 2018; Vanham et al., 2015), or global levels (Kummu et al., 2012; Porter et al., 2016). For example, Porter et al. (2016) estimated the global average per capita greenhouse gas (GHG) emission of food loss and waste to be 323 kg $CO_2$eq. in 2011 and identified that developing economies have the largest increases in associated emission primarily due to the increasing losses in fruits and vegetables. Others found that food loss and waste embeds 23–24% of the total global use of cropland, freshwater resource, and fertilizers for food production (Kummu et al., 2012). Scherhaufer et al. (2018) found that 15-16% of the total environmental impact of the food supply chain in Europe can be attributed to food waste. The freshwater footprint of food waste in Europe is approximately 27 litres capita$^{-1}$ day$^{-1}$, which is almost the same in its magnitude to the per capita municipal

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freshwater consumption in Europe (Vanham et al., 2015). Even excluding land use-based emissions, the amount of GHG emission associated with global food waste is more than the national carbon footprint of most countries except USA and China (FAO, 2013). The estimation of EAT-Lancet commission suggests halving global food loss and waste could reduce agricultural GHG by 5%, lower water use by about 13%, decrease use of each nutrient (nitrogen, phosphorus) by up to 15%, and reduce projected biodiversity loss by up to 33% relative to the business-as-usual scenario (Willett et al., 2019). Cropland use for food production also causes habitat degradation leading to decline in biodiversity (Chaudhary and Kastner, 2016; Chaudhary and Brooks, 2019).

On the nutrition and food availability consequences side, Buzby et al. (2014) estimated that 31% of available food in the US remains uneaten due to the losses at the retail and consumer levels, which equals to 1249 calories capita$^{-1}$ day$^{-1}$. All the world's 815 million hungry people (FAO et al., 2018) could be lifted out of energy or protein malnourishment on less than a quarter of the wasted food in the USA, UK, and Europe or by the approximately 40 million tonnes of food wasted by USA households, retailers, and food services each year (Stuart, 2009). Halving food loss and waste would also potentially increase food availability by 1,300 trillion kcal per year by 2050, corresponding to 22% of the estimated crop production increase required to meet demand in 2050 (Lipinski et al., 2013). By analysing different losses of available calories across different food commodities, West et al. (2014) found that curbing consumer waste of crops (i.e., wheat, rice, and vegetables) and meats (i.e., beef, pork, and poultry) in US, China, and India alone could feed ~413 million people per year if the feed calories embodied in meat production are included.

However, food security is more than meeting just the daily energy (caloric) requirement. The needs of essential macro and micronutrients for healthy functioning of body should also be considered. Since different food items differ widely in their nutritional content and environmental footprint (Chen et al. 2019; Chaudhary and Krishna, 2019; Willett et al., 2019; Chaudhary et al. 2018a, b), quantifying the food waste in simple mass or caloric terms (as is practised most often) does not provide the true extent of damage done. It is particularly important that the wastage of commodities with high production stage environmental impact and nutritional content be avoided to minimize the impact on food security and planetary boundaries (West et al., 2014).

For example, fruits and vegetables are high in essential micronutrients and their low consumption has been found to be a major obstacle to achieving healthy diets globally (Afshin et al., 2019; Lock et al., 2005; Mason-D'Croz et al., 2019). The EAT-Lancet commission designed a healthy reference diet, advocating the daily per capita fruit, vegetable, and pulses (dry beans, lentils, and peas, which are grains or seeds of leguminous crops) intakes of 200 g, 300 g, and 50 g per person respectively (Willett et al., 2019). However, the global fruit and vegetable availability has consistently been insufficient to supply these recommended intake levels and only 55% of the global population had average fruit and vegetable availability above WHO's minimum target (Mason-D'Croz et al., 2019). It is clear that, in order to achieve sustainable diets that meet nutritional and environmental targets, a significant increase in the consumption of fruits, vegetables, and legumes from their current intake levels is required in almost all the countries (Chaudhary and Krishna, 2019; Willett et al., 2019). Ironically, due to their perishable nature, large amounts of fruits & vegetables are either lost due to inadequate storage and refrigeration facilities post-production in low-income countries or are simply wasted at the household level in high-income countries (Gustavsson et al., 2011).

A major research gap is that most studies present the food waste consequences on a limited number of environmental or nutritional indicators (e.g. GHG emissions for environment and calories or protein for food security). Studies assessing both the environmental and nutritional implications of food waste are rare (Hayashi et al., 2018; Hiç et al., 2016; Kummu et al., 2012; West et al., 2014). A few studies assessing the nutritional losses of uneaten foods that have employed multiple indicators are restricted to a particular country (Garcia-Herrero et al., 2019, 2018; Khalid et al., 2019; Spiker et al., 2017) or food group (Love et al., 2015; Wesana et al., 2019).

For example, Cooper et al. (2018) recently presented one of the most comprehensive assessment of the household food wasted in the U.K., employing five environmental impact indicators and 21 essential nutrients. In addition, they presented novel indicators "nutrient days" wasted per capita per year, and "daily diets" wasted per capita per year. The wasted nutrient days (WND) for a particular nutrient is calculated by simply normalizing (i.e. dividing) the nutrient amount wasted per capita per year with their respective daily Dietary Reference Intake (DRI) level. Wasted daily diets (WDD) per capita per year is the lowest WND value among all the 21 nutrients considered (see method section for details).

They found that approximately 42 daily diets were embedded in the typical food wasted by each person in a year. In other words, the annual food wasted by a person in the UK can provide a healthy diet (meeting recommended levels for 21 nutrients plus energy) to a single person for 42 days. By individual nutrient, the highest losses were vitamin $B_{12}$, vitamin C, and thiamine (160, 140, and 130 nutrient days/capita/year, respectively). Substantial amounts of currently under-consumed nutrients in the UK such as calcium, fiber and folate were mostly lost via vegetables/salads and bakery. Wasted meat and fish contributed the most towards total embodied environmental impacts.

To our knowledge, no study to date has assessed national food waste through multiple environmental indicators and multiple nutrients at a global scale. The goal of this study is to calculate the wasted nutrition days (for 25 nutrients) and wasted diet days embedded in the daily per capita food waste of 151 countries along with the embodied environmental impacts.

## 2. Materials and methods

### 2.1. Food waste and consumption data

We first estimated the wasted amounts of 225 food items (i.e., loss at consumption level in g capita$^{-1}$ day$^{-1}$) for 151 countries by combining their edible amounts reported by GENuS dataset for the year 2011 (Smith et al., 2016) with the region-specific food waste ratio for major food categories reported by FAO (Gustavsson et al., 2011). The GENuS database was created by expanding the 94 aggregated food categories of FAO's food balance sheet data (Smith et al., 2016).

### 2.2. Nutritional content and requirement

To estimate the amounts of calories and nutrients embedded in national food waste, we multiplied the individual food item waste values (g capita$^{-1}$ day$^{-1}$) with their nutrient densities (e.g., g protein per 100 g of wheat) obtained from region-specific food composition tables provided by the GENuS database (Smith et al., 2016). These tables provide content of 19 nutrients and calories for each of the 225 food items. For other essential nutrients, vitamin E, vitamin $B_{12}$, vitamin K, selenium, and pantothenic acid, we complement the GENuS food composition tables with the nutrient density values from the USDA SR 28 food composition tables (United States Department of Agriculture (USDA), 2016).

We then compared the amounts of wasted nutrients with the average country-specific nutrient requirements reported by Beal et al. (2017). For the 10 nutrients for which Beal et al. do not provide the requirements, we calculated the population-weighted average required intakes by combining the age- and sex-specific nutrient recommendations from Institute of Medicine (Institute of Medicine, 2019, 2005, 2001, 2000, 1998a, b) and the age and sex subgroup data from Population Division of United Nations (United Nations Department of Economic and Social Affairs., 2017).

To estimate the requirements of protein intake (g per capita per day), we matched the recommended amount per unit of human body weight (g protein per kg) (Institute of Medicine, 2005) with the national average body weight calculated from data reported by NCD Risk Factor Collaboration (NCD Risk Factor Collaboration (NCD-RisC), 2017, 2016).

For energy requirements, we adopted country-specific Minimum Dietary Energy Requirement (MDER) from FAO food security statistics (FAO, 2014). MDER (expressed as kilocalories per person per day) is the amount of energy needed for light activity and minimum acceptable weight for attained-height. The national MDER was calculated on three-year population-weighted average which depends on the gender and age structure of national population (FAO, 2014). We adopted the MDER values for year 2011-2013 in our analysis.

### 2.3. Wasted nutrient days, wasted daily diets and wasted healthy foods

Following Cooper et al. (2018), we normalized (i.e. divided) the nutrient amount wasted per capita per year in each country with their respective daily Dietary Reference Intake (DRI) level and calculated the Wasted Nutrient Days (WND) per year for each nutrient-country combination (a total of $25 \times 151 = 3775$ combinations). For example, a WND of 90 for protein signifies that the food wasted by one person in a year can meet the daily protein requirements of one person from the same country for 90 days. This provides much more intuitive and useful information than simply saying that 500 g of protein is embedded in the food waste by one person in a year.

Once the WND for all 25 nutrients were calculated, the lowest WND value among these 25 values provide the "wasted daily diets (WDD)" per capita per year. The nutrient with the lowest WND is called the limiting nutrient (see Cooper et al. 2018 for details). For example, if the lowest WND among 25 nutrients is for fiber and is equal to 40, it tells that the total food wasted by one person in a year can provide a healthy diet (i.e. meeting recommended levels for 25 nutrients) to a single person for 40 days. In other words, the annual per capita food wasted can provide a healthy diet to 40 people for one day.

In addition, we compared the wasted amounts of fruits and vegetables per capita per year in each country with the levels recommended by EAT-Lancet commission on healthy diets (Willett et al., 2019), where an intake of 200 g of fruit and 300 g of vegetables per person per day (about five servings of fruit and vegetables) are suggested respectively. We included these food groups in our analysis because of their health benefits as well as their prevalent insufficient intakes at the global level (Afshin et al., 2014; Aune et al., 2017; Bernstein et al., 2010; Mason-D'Croz et al., 2019; Muraki et al., 2013; Wang et al., 2014).

### 2.4. Embedded environmental impacts in food waste

In order to calculate the embedded environmental footprints of national daily food waste, we matched the recently available characterization factors (i.e., environmental impacts per gram of food) to our product resolution (225 items). The original characterization factors from Springmann et al. (2018a) are available for 28 broad food groups. Each of the 225 food items of GENuS database were assigned to one of these 28 food groups (see Table S1 in supporting information for matching). These global average characterization factors per food group are available for five environmental domains (Springmann et al., 2018a): greenhouse gas emissions (g $CO_2$eq/g), freshwater use (liters/g), cropland use ($m^2$/g), nitrogen application (gN/g) and phosphorus application (g P/g).

We multiplied characterization factor of individual food item with its wasted amount per capita per day and sum up the amount of all food items to calculate national per capita per day food waste footprint for each of the five environmental domains.

### 2.5. Environmental impacts in relation to planetary boundaries

In addition, to get an idea on how much the food waste reduction can contribute towards meeting the global environmental planetary boundaries (or environmental limits), we normalized (divided) the total per capita national food waste environmental footprints with their respective per capita food-related planetary boundaries (Chaudhary and Krishna, 2019; Steffen et al., 2015; Willett et al., 2019). The per capita food-related planetary boundaries were obtained by simply dividing the mean planetary boundaries reported by Springmann et al. (2018a) with the global population for the year 2011. The calculated per capita per day planetary boundaries for the greenhouse gas (GHG) emissions, cropland use, freshwater use, nitrogen application and phosphorus application are: 1867 g$CO_2$eq., 5.01 $m^2$, 786 L, 27.4 gN and 6.4 gP, respectively (see also Chaudhary and Krishna 2019).

These per capita planetary boundaries signify that as long as an individual's food consumption related environmental footprint remains below these values, the Earth's ecosystem integrity will not be jeopardized. For the GHG boundary, Springmann et al. (2018a) adopted a non-CO2 emission (methane and nitrous oxide) budget related to agriculture in line with limiting global warming to below 2°C (Representative Concentration Pathway (RCP) 2.6) with a 66% probability. This budget was derived from a model comparison of three integrated assessment models (Wollenberg et al. 2016). The food-related land boundary was derived in line with not reducing current forest cover and keeping current cropland use extent (Robinson et al. 2015). For the bluewater boundary, they adopted value from a basin-level assessment of the flow requirements of river systems (Gerten et al. 2013) along with the consumptive bluewater used in agriculture (Robinson et al. 2015). The nitrogen boundary value was informed by estimates of global risk values for eutrophication (de Vries et al. 2013) and nitrogen application rates from fertilizers (Mueller et al. 2012). Finally, the phosphorus boundary was based on the phosphorus-flow model by de Vries et al. (2013) in line with keeping phosphorus concentrations below critical levels of 50–100 mg per litre to prevent eutrophication and current phosphorus application rates (Mueller et al. 2012).

Similar to the normalization of wasted nutrients with their daily recommended levels to get 'wasted nutrient days', the normalization of environmental footprints presents a much more intuitive indicator than simply reporting litres of water or grams of carbon wasted due to food wasted per capita per day.

## 3. Results

### 3.1. Food waste amounts per country

We found that a total of 1.13 million tons of edible food products are wasted per day throughout the world with the global average food waste being 178 g per capita per day (or 65 kg per year). The wasted amounts vary widely depending upon the country. The mean food waste in high-income countries is approximately 307 g per capita per day, which is almost two times to that in upper-middle-income countries (163 g) and four to six times higher than that in low-middle income (81 g) and low-income (43 g) countries. Food waste in certain high-income countries like New Zealand, Ireland, United States, and Australia even exceeds 500 g per capita per day. China's per capita food waste is around 276 g per day, ranking 46 out of 151 countries in our analysis. The estimates for Brazil and India are 133 g and 40 g per capita per day, respectively (see Table S1 and Table S2 of supporting information for wasted food amounts per country).

Results shows that an average North American consumer throws out 23% of the total weight of food entering the household. The corresponding figures for Europe, East Asia & Pacific and China are 17%, 15% and 15% respectively. This is in stark contrast with South Asia and Africa where the post-consumption food waste is $<5\%$. Middle East and Latin America lie

**Table 1**
Contribution (%) of major food categories to the total food waste (by weight) in different world regions. See Table S2 in supporting information for results per country.

| Region | Cereals | Roots & Tubers | Vegetables | Fruits | Dairy | Legumes | Meat & Fish | Other |
|---|---|---|---|---|---|---|---|---|
| High income | 17 | 7 | 15 | 12 | 17 | 0.1 | 6 | 26 |
| Upper middle income | 27 | 5 | 33 | 11 | 4 | 0.2 | 5 | 15 |
| Lower middle income | 31 | 8 | 26 | 16 | 5 | 0.6 | 3 | 10 |
| Low income | 27 | 13 | 22 | 16 | 3 | 1.2 | 4 | 14 |
| East Asia & Pacific | 27 | 5 | 37 | 11 | 2 | 0.2 | 5 | 13 |
| Europe & Central Asia | 21 | 8 | 17 | 11 | 12 | 0.1 | 5 | 26 |
| Latin America | 25 | 4 | 10 | 18 | 11 | 0.6 | 7 | 25 |
| Middle East & N. Africa | 35 | 3 | 28 | 17 | 3 | 0.3 | 4 | 10 |
| North America | 13 | 8 | 14 | 12 | 22 | 0.1 | 6 | 25 |
| South Asia | 33 | 5 | 28 | 17 | 6 | 0.9 | 1 | 8 |
| Sub-Saharan Africa | 14 | 28 | 20 | 23 | 0.5 | 1.4 | 4 | 9 |
| China | 27 | 5 | 40 | 10 | 1 | 0.2 | 4 | 12 |
| India | 31 | 5 | 31 | 18 | 6 | 1.0 | 1 | 8 |
| World | 24 | 6 | 25 | 12 | 9 | 0.2 | 5 | 19 |

somewhere in middle with around 8-10% by weight of the total food entering the household is wasted (Gustavsson et al. 2011).

Food waste comes from almost every food category but in varying degrees (Table 1). On average, the food groups contributing the most to the total weight of food waste are vegetables (25%), cereals (24%), and fruits (12%).

The contribution of other food groups are: roots & tubers (9%), dairy/ eggs (7%), meat/fish (6%), and other foods (18%). Table 1 shows that the contributions of different food groups towards total food waste weight is almost similar across low- and high-income nations except for dairy products and roots & tubers categories. Almost 17% of food waste in high income nations is constituted of dairy products and just 7% of roots & tubers whereas in low-income nations it is reverse with 13% of waste coming from wasted roots & tubers and just 3% from discarded dairy products. Differences are much more evident across major geographic regions. North America has low cereals and roots & tubers waste (8%) but high dairy waste (22%) and the opposite is true for South Asia and Sub-Saharan Africa (Table 1).

### 3.2. Embedded nutrient loss per country and their sources

By linking the country and food item-specific waste amounts (Table S1) with their nutrient composition from GENuS database (Smith et al. 2016), we obtained the the amount of 25 nutrients (24 essential nutrients plus calories) embedded in national food waste in 2011 (see Table S3a in supporting information for wasted nutrient amounts per country). Out of these 25 nutrients, at the global stage, recent studies indicate concern on inadequate intake of eight of them. This includes macronutrients such as fiber, minerals such as iron, and potassium, and vitamins such as vitamin A, folate (vitamin $B_9$), vitamin E, vitamin K and riboflavin in a number of countries (Chaudhary and Krishna, 2019; Springmann et al., 2018b; Muthayya et al., 2013).

Table 2 shows that worldwide on average, 273 kcal of energy (calories) is embedded in food waste generated by per person per day which represents ~15% of its global median daily dietary recommended intake (DRI) value. Results for other nutrients indicate that 3.5 g of fiber (~ 12% of the DRI), 2.2 mg of iron (24% of the DRI), and 323 mg of potassium (12% of the DRI) are embedded in food waste. For some micronutrients such as vitamin C, vitamin K, vitamin B6, Iron, Zinc, Copper, Manganese and Selenium, the wasted amount is as high as 25-50% of their daily requirements (Table 2). The corresponding embedded amounts of other vitamins is around 10 – 20% of their DRI.

We found considerable variation in the Dietary Reference Intake (DRIs) across countries underscoring the need to employ country-specific DRIs for different nutrients rather than generic global DRIs. For example, the caloric requirements varied from 1667 kcal capita$^{-1}$ day$^{-1}$ for Angola to 1996 kcal capita$^{-1}$ day$^{-1}$ for UAE. The DRI for protein varied from 38 to 61 g capita$^{-1}$ day$^{-1}$ across 151 countries (lowest for Madagascar and highest for French Polynesia). These variations arise from differences in age and gender structure of national populations. Countries with larger portion of females and people under the age of 14 would have lower population-weighted average DRI for most nutrients. For protein requirements, the national average DRI would be higher if people have larger body weight. The coefficient of variation (CV) of DRI values across 151 countries ranged from 1.8% for phosphorus to 9.9 % for protein (see Table S3b in supporting information).

**Table. 2**
Global average nutrient losses (mass capita$^{-1}$ day$^{-1}$) embedded in food waste, nutrient loss as % of their global median daily dietary recommended intake (DRI) levels and Wasted Nutrient Days (WND). Both the global median and population-weighted global average WND is presented. See Table S3 in supporting information for nutrient losses per country.

| Essential nutrient | Wasted amount | % of DRI | Median WND | Average WND |
|---|---|---|---|---|
| Calories (kcal) | 273 | 15 | 43 | 53 |
| Macronutrients | | | | |
| Protein (g) | 7.3 | 14 | 43 | 55 |
| Fiber (g) | 3.4 | 12 | 35 | 44 |
| Polyunsaturated fatty acids (g) | 0.9 | 6 | 22 | 24 |
| Vitamins | | | | |
| Vitamin A (µg RAE) | 88 | 15 | 32 | 52 |
| Vitamin B6 (mg) | 0.3 | 24 | 52 | 73 |
| Vitamin B12 (µg) | 0.3 | 14 | 33 | 45 |
| Folate (µg) | 34.7 | 10 | 24 | 36 |
| Niacin (mg) | 2.0 | 16 | 54 | 59 |
| Pantothenic Acid (mg) | 0.6 | 13 | 35 | 48 |
| Riboflavin (mg) | 0.1 | 9 | 41 | 43 |
| Thiamine (mg) | 0.1 | 10 | 55 | 52 |
| Vitamin C (mg) | 17.1 | 25 | 69 | 88 |
| Vitamin E (mg) | 0.5 | 5 | 14 | 18 |
| Vitamin K (µg) | 26.7 | 30 | 35 | 106 |
| Choline (mg) | 25.6 | 6 | 13 | 21 |
| Minerals | | | | |
| Iron (mg) | 2.2 | 24 | 79 | 85 |
| Potassium (mg) | 323 | 12 | 38 | 42 |
| Calcium (mg) | 60.2 | 6 | 15 | 21 |
| Zinc (mg) | 1.2 | 51 | 149 | 178 |
| Copper (mg) | 0.2 | 27 | 74 | 93 |
| Phosphorus (mg) | 123 | 16 | 54 | 60 |
| Magnesium (mg) | 40.1 | 13 | 35 | 46 |
| Manganese (mg) | 0.7 | 37 | 84 | 133 |
| Selenium (µg) | 14.7 | 30 | 82 | 108 |

We also assessed how much of each nutrient is embedded in each wasted food item in each country. Table S4 in supporting information shows the % contribution of different food groups to the total amount of each nutrient wasted per capita per day. It is clear that the majority of nutrients are wasted through unused cereals, fruits & vegetables and meat products. Dairy and eggs contribute substantially to the waste of calcium, choline, riboflavin, and vitamin $B_{12}$. Wasted meat products are responsible for a substantial fraction of wasted vitamin $B_{12}$, polyunsaturated fatty acids, zinc, protein, niacin and choline.

Note that this analysis revealed a new level of information because for example, although meat and fish product losses accounted for just 5% of total food loss by weight (Table 1), they account for 72% of the losses of vitamin $B_{12}$ (Table S4). Similarly, wasted dairy products constitute just 7% of the total wasted food by weight but they contribute to 30% of wasted calcium per capita per day.

Results for fiber indicate that a total of 3.4 g of fiber is embedded in daily per capita global average food waste (Table 2), 46% of which is from wasted cereals and 41% of which is from discarded fruits & vegetables (Table S4). The major sources of wasted iron are cereals (49% of the total), vegetables (22%), and meat (9%) while for potassium are vegetables (36%), cereals (17%), roots & tubers (14%) and fruits (13%). Almost all of the vitamin C and vitamin K is wasted through discarded fruits & vegetables alone.

### 3.3. Wasted Nutrient Days (WND)

By dividing the total weight of each of 25 nutrients wasted per capita per year in each of 151 countries with their respective daily dietary recommended intake (DRI) values, we obtained the wasted nutrient days (WND) (for $151 \times 25$ combinations, see Table S5 in supporting information for all values per country). As shown in Table 2, for the global average annual per capita food waste, highest WND were found for zinc (global median WND = 149), followed by manganese (84), selenium (82), iron (79), copper (74) and vitamin C (69). In other words, the wasted food per capita per year contains enough zinc to meet the daily zinc requirement of one person for 149 days (i.e. for 41% of the year). On the other hand, the lowest WND are for choline (global median WND = 13), vitamin E (14), calcium (15), polyunsaturated fatty acid (22) and folate (24).

Fig. 1 presents the embedded WND per country for eight selected nutrients whose inadequate intake is a concern globally (Springmann et al. 2018b; Chaudhary & Krishna, 2019).

The nutritional value of wasted food varied widely across countries. Central Asian countries such as Azerbaijan, Armenia, and Georgia along with USA, Canada, Ireland, New Zealand, Austria, Denmark and China had consistently high wasted amounts (and hence WNDs) for most of the nutrients (Table S5). Across income groups, the wasted nutrient amounts decreased as incomes decreased with the average WNDs for high-income countries being around six times higher than low or lower-middle income countries.

In particular, we found that the losses of vitamin $B_{12}$ has the most significant differences across different income groups, where the wasted amount by a person in a high-income country (WND = 125) is almost three times as much as the wasted vitamin $B_{12}$ (WND = 51) for a person in an upper-middle-income country. It could be attributed to the high consumption and waste level of animal products, which are the main vitamin $B_{12}$ resources, in high-income countries comparing to the rest ones.

### 3.4. Wasted daily diets (WDD)

According to our estimation, 18 daily diets are embodied in the global average amount of food waste per capita per year and thus it can fulfil the daily requirements (DRIs) of 25 nutrients for one person for 18 days (i.e. Wasted daily diets, WDD = 18). In other words, the nutrients embedded in the typical food wasted by a person in a year could provide one person 18 days of nutritious diet or feed a nutritious diet to 18 persons for one day. Fig. 2 shows the WDD values for all countries (see Table S6 in supporting information for all values).

The average WDD for high income countries was around 5 – 9 times higher than low or lower-middle income countries. The annually wasted nutrients in 21 countries (15 of which are high-income), are estimated to fulfil the daily requirements (of the 24 nutrients & calories) of one person for more than a month (i.e. their WDD $\geq$ 30). North American countries (USA & Canada) had highest WDD (41) followed by Europe and Central Asian countries (32) and China (27). On the other extreme, the average WDD for India along with South Asian and Sub-Saharan African countries was less than three. The WDD of Zimbabwe and Sri Lanka is lowest (< 1).

We found that Vitamin E, Calcium, and Riboflavin were the most frequent limiting nutrients (i.e. the nutrients that are wasted in very less amounts and thus with the lowest WNDs among the 25 nutrients considered) in deciding the wasted daily diets (WDD) number for the countries. As these limiting nutrients are sourced from all major food categories, the “diet” estimated with WDD would have a comparable composition as shown in Table 1.

### 3.5. Embedded environmental impacts

We found that environmental footprints associated with global average per capita per day food waste are 124 g $CO_2$ eq., 58 Litre freshwater use, 0.36 $m^2$ cropland use, 2.90 g nitrogen and 0.48 g phosphorus use (Table 3). Consistent with the wasted food amounts and embedded nutrients, the highest environmental impacts are embedded in food waste of North America, followed by EU, East Asia and pacific (Australia, New Zealand, Japan, South Korea, China), while sub-Saharan Africa, south and southeast Asia are the regions with the lowest

**Table. 3**
Environmental footprints embedded in average per capita per day food waste of different World Bank regions. Footprint magnitude as % of respective food-related environmental planetary boundary is shown in parenthesis (see section 2.5). See Table S7 in supporting information for all values per country.

| Region | GHG emissions (gCO2 eq.) | Freshwater use (Litres) | Cropland use ($m^2$) | Nitrogen use (gN) | Phosphorus use (gP) |
|---|---|---|---|---|---|
| High income | 315 (17%) | 118 (15%) | 0.81 (16%) | 5.88 (21%) | 1.00 (16%) |
| Upper middle income | 144 (7.7%) | 77 (9.8%) | 0.45 (9.0%) | 3.94 (14%) | 0.64 (10%) |
| Lower middle income | 33 (1.8%) | 19 (2.4%) | 0.10 (2.0%) | 0.89 (3.2%) | 0.14 (2.3%) |
| Low income | 32 (1.7%) | 12 (1.5%) | 0.08 (1.7%) | 0.61 (2.2%) | 0.10 (1.6%) |
| E. Asia & Pacific | 130 (6.9%) | 79 (8.7%) | 0.44 (8.7%) | 3.99 (15%) | 0.64 (10%) |
| EU & Central Asia | 254 (14%) | 106 (15%) | 0.76 (15%) | 5.50 (20%) | 0.92 (15%) |
| Latin America | 143 (7.7%) | 45 (5.5%) | 0.28 (5.5%) | 2.17 (7.9%) | 0.36 (5.7%) |
| MENA | 96 (5.1%) | 51 (5.7%) | 0.29 (5.7%) | 2.58 (9.4%) | 0.42 (6.6%) |
| North America | 450 (24%) | 149 (20%) | 1.03 (20%) | 7.40 (27%) | 1.29 (20%) |
| South Asia | 22 (1.2%) | 15 (1.5%) | 0.07 (1.5%) | 0.66 (2.4%) | 0.10 (1.7%) |
| S.S. Africa | 18 (0.9%) | 5 (0.8%) | 0.04 (0.8%) | 0.27 (1.0%) | 0.05 (0.7%) |
| China | 152 (8.1%) | 96 (11%) | 0.54 (11%) | 4.97 (18%) | 0.79 (13%) |
| India | 19 (1.0%) | 15 (1.5%) | 0.08 (1.1%) | 0.66 (2.4%) | 0.11 (1.7%) |
| World average | 124 (6.6%) | 58 (7.1%) | 0.36 (7.3%) | 2.90 (11%) | 0.48 (7.5%) |

corresponding food waste related environmental burden (supporting information Table S7).

By normalizing (dividing) the embedded environmental footprints with respective planetary boundaries (section 2.5 above), we obtained the footprints relative to their environmental limits (Springmann et al. 2018a; Chaudhary and Krishna, 2019). As shown in Table 3, on average globally, environmental footprints embedded in current daily per capita food waste account for 6.6%, 7.3%, 7.1%, 11%, and 7.5% of daily per capita food-related planetary boundaries of GHG emission, cropland use, freshwater use, nitrogen use, and phosphorus use respectively.

The environmental impacts linked with edible food waste in each of the 151 countries are shown in Fig. 3. For countries, the greenhouse gas emissions associated wasted edible food is the highest in New Zealand, estimated to be 759 g $CO_2$ eq. emission per capita per day and equals to 40% of the GHG planetary boundary for food production (Willett et al., 2019; Springmann et al. 2018a). According to our analysis, New Zealand has largest amount of ruminant animal product waste (bovine, mutton and goat; 14.3 g per capita per day) and dairy product waste (152.3 g per capita per day) in the world. In contrast, food waste of Mozambique in sub-Saharan African has embedded emission of 6 g $CO_2$ eq. per capita per day (lowest value across countries) and its waste amount of all types of animal products is 0.54 g per capita per day.

United States has the highest freshwater (150.45 L per capita per day), nitrogen (7.45 gN) and phosphorus (1.31 gP) footprints embedded in their food waste. Ireland is the country with the top food-waste-linked cropland use, which is estimated to be 1.13 $m^2$ for food waste per capita per day.

Accounting for one quarter of total food waste on global average by weight, wasted cereal (e.g. wheat, rice) is the food group with the most embedded environmental impact accounting for 40–45% of total cropland, freshwater, nitrogen and phosphorus use. Comparing to other regions, wasted cereal products in East Asia & Pacific, South Asia, and Middle East & North Africa contribute more to their environmental footprints, being responsible for half of food waste footprints on average. China's cereal waste contribute to almost two thirds of freshwater footprints of national food waste. Following cereals, wasted fruits and vegetables are also important environmental impact contributors of fertilizer use and their contribution is highest in Sub-Saharan Africa accounting for more than 35% of total food waste related nitrogen and phosphorus footprints.

GHG emissions associated with per capita wasted meat products (i.e. pork, beef, and poultry) in high-income countries even exceeds the total emissions embedded in global average per capita total food waste (i.e. 124 $gCO_2$ eq.) and the level for North American countries is especially high with daily wasted meat products accounting for more than 230 $gCO_2$ eq. per capita. Wasted sugar is linked with remarkable freshwater footprint embedded in national food waste accounting for approximately 30% in North American, European, Latin American & Caribbean, and high-income countries (Table S8).

### 3.6. Wasted amounts of fruits, vegetables and pulses

Global average per capita per day fruits and vegetables waste are estimated to be 21 g and 44 g, respectively (Table 4). On an annual basis, this translates to a wastage of 7.65 kg of fruits and 16 kg of vegetables wasted per person per year. Similar to the concept of wasted nutrient days (WND, Section 2.4), dividing these annual wasted amounts with their respective daily recommended intake values (200 g for fruits and 300 g for vegetables; Willett et al. 2019), we calculated wasted fruits days and wasted vegetable days for each country's average daily per capita fruits and vegetable waste. We found that on average, annually wasted fruits and vegetables could meet one person's daily fruit and vegetable requirements for 38 and 54 days respectively (Table 4). In other words, these annual wasted amounts can meet the fruit and vegetable requirements of 38 and 54 persons for one day respectively.

**Table. 4**
Average wasted amounts of fruits and vegetables in grams per capita per day in different World Bank regions. Wasted fruits and vegetable days, i.e. their per capita annual wasted amounts divided by their EAT-Lancet commission (Willett et al. 2019) recommended daily intake values of 200g and 300g respectively are shown in parenthesis. See Table S9 in supporting information for values per country.

| Region | Fruits | Vegetables |
|---|---|---|
| High income | 44 (80 days) | 57 (69 days) |
| Upper middle income | 25 (46 days) | 73 (89 days) |
| Lower middle income | 9 (16 days) | 14 (17 days) |
| Low income | 6 (11 days) | 9 (11 days) |
| East Asia & Pacific | 24 (44 days) | 83 (101 days) |
| EU & Central Asia | 37 (68 days) | 57 (69 days) |
| Latin America & Caribbean | 22 (40 days) | 12 (15 days) |
| Middle East & North Africa | 24 (44 days) | 40 (49 days) |
| North America | 60 (110 days) | 72 (88 days) |
| South Asia | 6 (11 days) | 11 (13 days) |
| Sub-Saharan Africa | 6 (11 days) | 5 (6 days) |
| China | 28 (50 days) | 112 (136 days) |
| India | 7 (13 days) | 12 (15 days) |
| World average | 21 (38 days) | 44 (54 days) |

Wasted fruits and vegetables contribute the most to food waste accounting for approximately 38% of global food waste by mass (Table 1). Upper- and lower-middle income countries have higher proportion of food waste attributed to these two food groups (44% and 42% respectively of total food waste) than countries in lower income groups (Table 1). According to our estimation, an average person in high and upper-middle income countries generates ~100 g of fruits and vegetables waste per day while the amount for low and lower-middle income countries is 15 – 20 g on average (Table 4).

Interestingly, in contrast to overall food waste amounts (Table 1), Table 4 shows that the average per capita vegetable waste in East Asia and pacific including China (83 – 112 g) is even higher than North America and EU (57–72 g). North America has the largest amount of fruit waste per capita (60 g/day) followed by EU (37 g), China (28 g), East Asia and Pacific (24 g) and Middle-East and North Africa region (24 g).

## 4. Discussion

In a world with limited resources and increasing population, food security can only be achieved by a more sustainable use of resources along with adaptations to our consumption behavior, including the reduction or, ideally, the eradication of food waste. Our national results for 151 countries identify the global hotspots and picture the heterogeneity of the food waste and the associated impact (Figs. 1-3). Not surprisingly, the food waste of high-income countries of North America and EU embed many times higher nutrient losses and environmental footprints on a per capita level than low-income countries. However, there were some surprises, such as the fact that amount of wasted vegetables are higher in China, East Asia and Pacific than even North America and Europe (Table 4). This means that in such regions, interventions or education campaigns should focus relatively more on vegetable waste reduction rather than other food groups. In contrast, in Sub-Saharan Africa, interventions targeting waste reduction in roots & tubers are needed (Table 1).

This study also highlighted the priorities across countries and food groups in terms of food waste related nutritional and environmental sustainability concerns. For example, from our food contribution results (Table 1, Table S4, Table S8), one can infer that national interventions targeting reduction in cereal wastage could result in a high saving in micronutrients with high deficiency prevalence like iron, as well as a

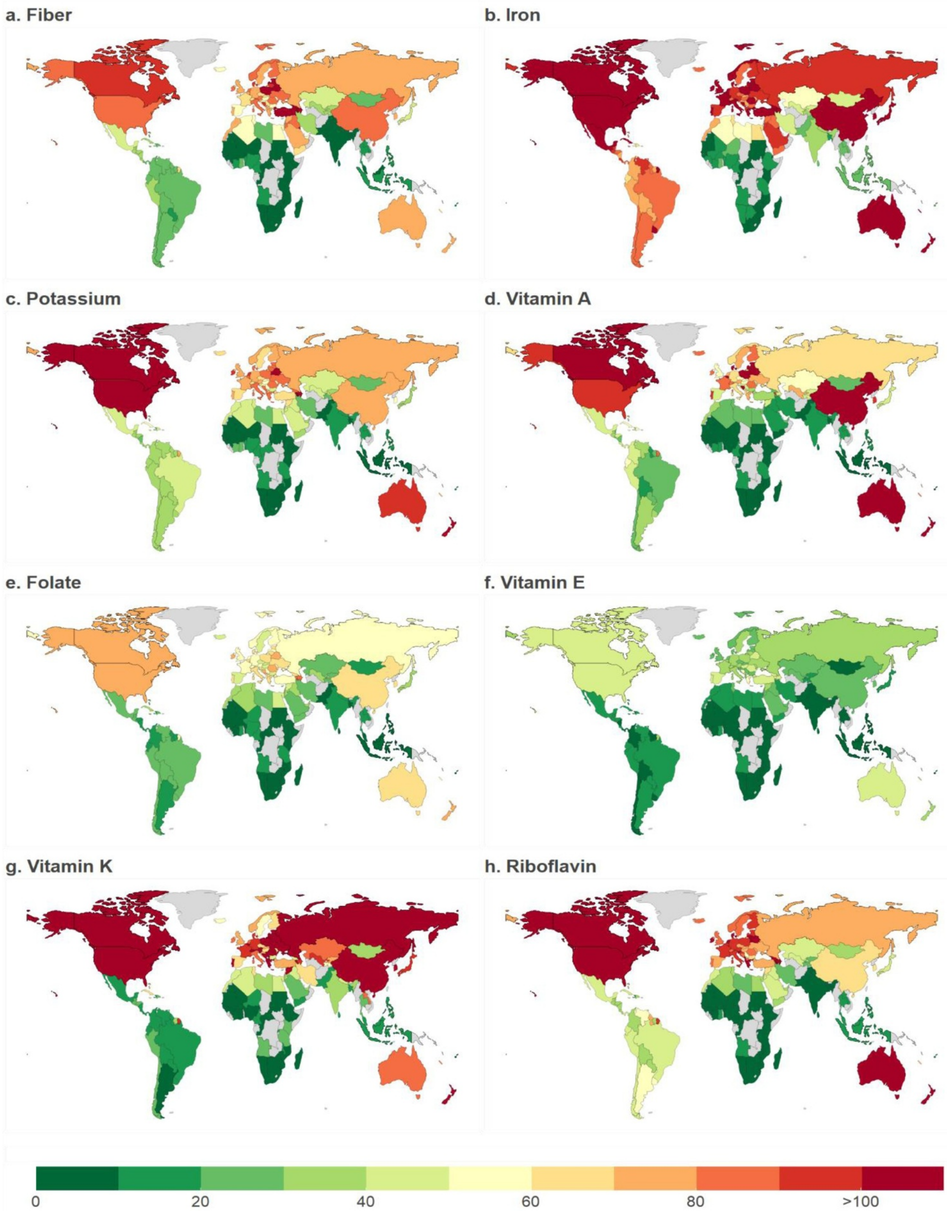


**Fig. 1.** Country-specific Wasted Nutrition Days (WND) for eight selected nutrients. The darker red color shows the higher nutrients losses embedded in their per capita food waste while the green shows lesser nutrient losses. For example, WND value for folate in USA is 72 meaning its wasted food per capita per year can meet daily recommended folate intake requirement (DRI) of one person for 72 days. See Table S5 in supporting information for all values per country.

substantial reduction in global environmental resources demand (cropland, freshwater, nitrogen, and phosphorus). The positive effect would be especially higher in South and East Asia along with Middle East & North Africa.

Our analysis underscored the importance of identifying the composition of food waste rather than simply using total food waste weight as an indicator. For example, we found that although meat products on average account for only 6% of the total daily per capita food waste by weight, they contribute 57% to GHG emission and ~10% to other environmental impacts associated with food waste (see Table S8 in supporting information). Meat waste reduction actions are particularly needed for countries with high food waste related GHG emission footprints (e.g. for New Zealand with 759 g of GHG emissions per capita per day associated with its food waste).

We calculated the recently proposed novel nutritional indicator (Wasted Nutrient Day or WND; Cooper et al. 2018) for all countries that enables the juxtaposition of essential macro and micro-nutrient losses embedded in wasted food with their daily recommended levels (Fig. 1, Table 2) and thus provide a more intuitive measure of appreciating the value of food wasted. Along the similar lines, we also juxtaposed the embedded environmental footprints with their downscaled daily per capita food-related planetary boundaries (Springmann et al. 2018a; Steffen et al. 2015). The embedded environmental footprints in North American food waste represent >20% of their daily food-related planetary boundaries meaning that cutting down on food waste is an effective strategy that can contribute substantially towards remaining below or not transgressing the global environmental planetary boundaries. We acknowledge that the planetary boundary framework is not without uncertainties and limitations because of their underlying modelling assumptions (Springmann et al. 2018a) and can only provide a very broad measure of the food system sustainability status. We allocated global planetary boundaries to individuals based on a top-down approach by simply dividing them by world population although it may not be an appropriate way for environmental domains with huge

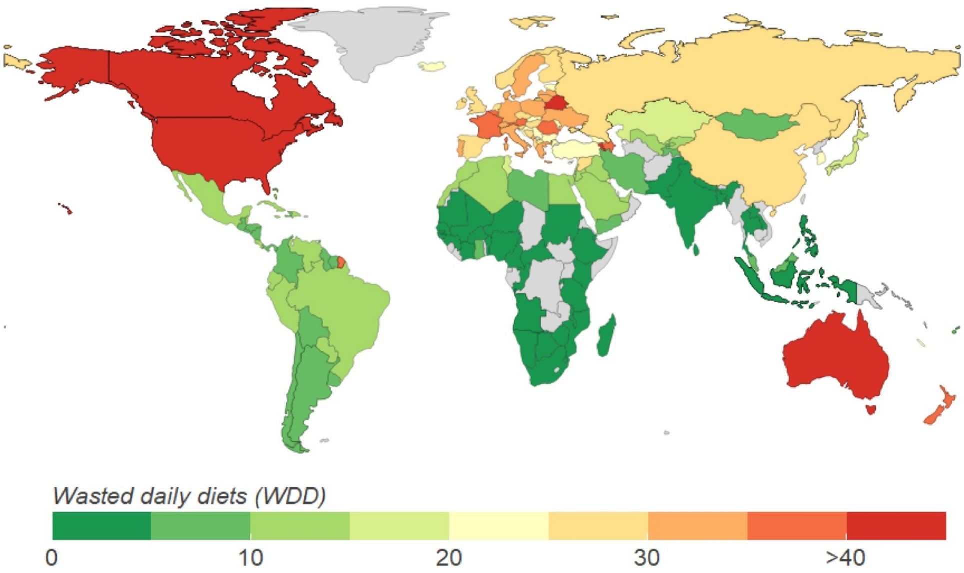


**Fig. 2.** Country-specific Wasted Diet Days (WDD) embedded in national per capita per year food waste. The WDD indicator for a country is calculated as the minimum of the WND values of 25 nutrients in that country. It represents number of daily nutritious diets embedded in national per capita per year food waste, i.e. number of days for which a person can be fed a healthy diet meeting the daily required nutrient intake of all 24 essential nutrients and calories. See Table S6 in supporting information for all values per country.

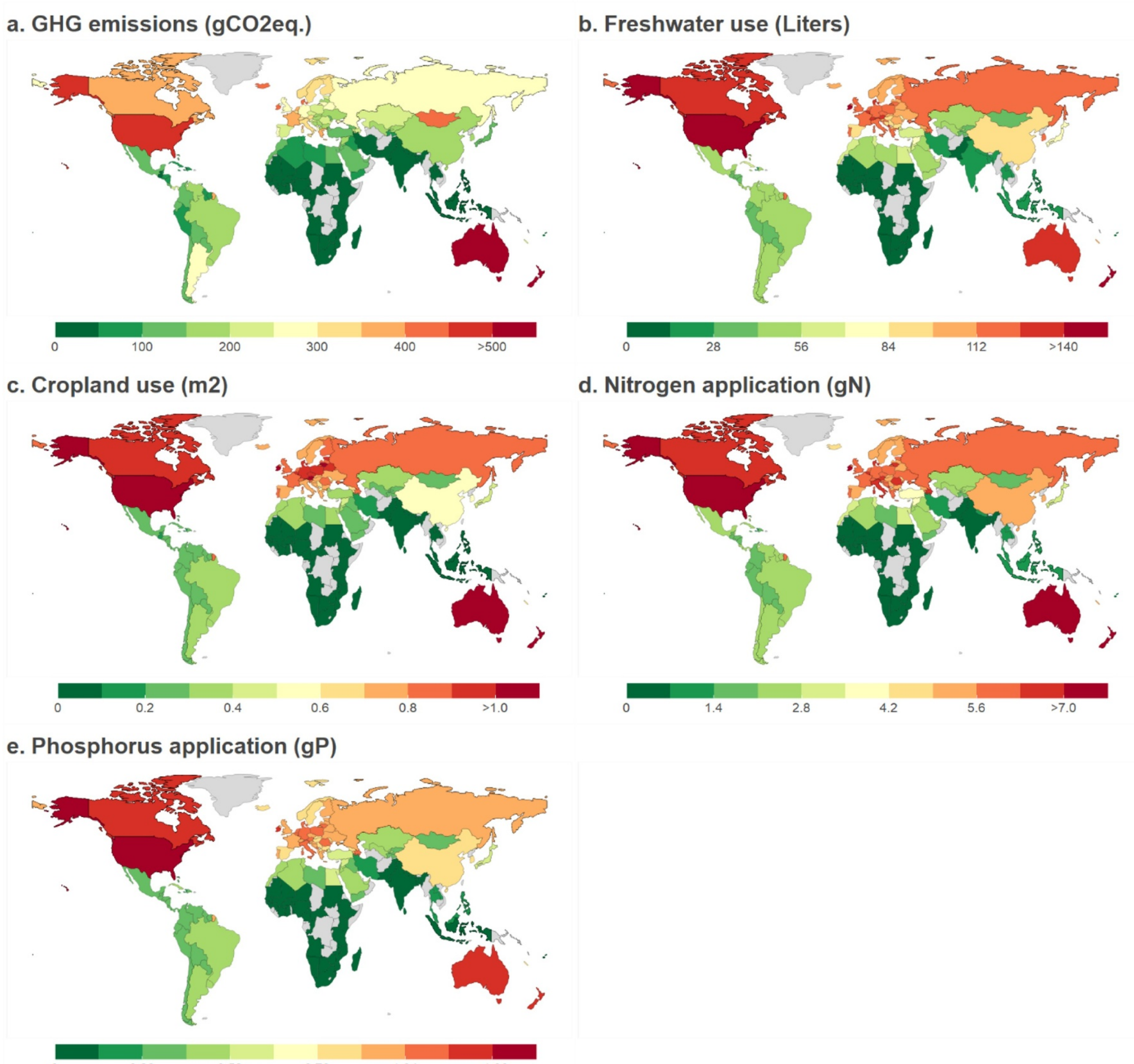


**Fig. 3.** Environmental footprints embedded in per capita per day food waste of each country: (a) GHG emission in g $CO_2$ eq., (b) cropland use in $m^2$, (c) freshwater use in litres, (d) nitrogen use in gN, and (e) phosphorus use in gP. Analysis was based on data for year 2011. The darker red color shows the higher environmental impacts embedded in their per capita food waste. See Table S7 in supporting information for all values per country.

geographical and temporal variations such as freshwater or fertilizer use (see O'Neill et al. 2018 for planetary boundary allocation discussion). Nevertheless, our analysis highlights that food waste reduction can simultaneously increase nutrition security and lower food-related environmental burden.

Despite using the latest available input data for a global analysis, our results come with several uncertainties and limitations that need to be overcome in future. First, the waste percentages employed in our analysis come from a United Nations' report (Gustavsson et al., 2011) and are limited to seven world regions and seven broad food groups. Therefore, there is a mismatch in data granularity because our analysis considers 151 countries and 225 food items in contrast with seven world regions and seven food groups of Gustavsson et al. (2011). The differences between countries within the same region and the variation in waste percentage among individual food items within a food group can be substantial. This might lead to under or overestimation of embedded nutrition and environmental impacts in a country's food waste depending upon whether the wasted amount in a particular country or a food item is lower or higher compared to the aggregated average available from Gustavsson et al. (2011). For example, Gustavsson et al. (2011) provides a single value of 19% waste for all fruits and vegetable across all countries in Europe. However, a review compared the waste percentages (ratio of avoidable waste and purchased amount per person) in different countries within Europe and found that the percentage of fruits and vegetable waste ranges from 7% to 15% and 4% to 21%, respectively across Germany, Spain, Denmark, Netherlands, Finland, and UK (De Laurentiis et al., 2018). However, the above data source available from UN FAO (Gustavsson et al., 2011) that we used is the most up-to-date and publicly available dataset for the purpose of global-scale calculations and comparison. As the global efforts in waste accounting methodology improvements and data collection increase (Corrado et al., 2019), our methodology can be used to calculate more accurate estimates of embedded nutrients and environmental losses per country.

Second, we used the GENuS database that provides the edible food supply and nutrient composition for 225 food items per country (Smith et al., 2016), which is a higher-resolution global dataset for nutrient waste analysis than the 94 aggregated food items in FAO's food balance sheets (FBS). For example, the GENuS database provides intake amounts and nutrient composition separately for milk, cheese, ice cream as well as for grains and their flours or raw fruits and their juices. Despite that, the data on many other processed food products (e.g., pizza, burger, pasta, etc.) is not available yet. Therefore, the nutrition changes during processing and cooking could not be taken into account in our analysis. Future work should incorporate more food products to obtain more accurate estimates of national food waste composition. More detailed dataset is expected to provide information on sex, age, or socioeconomic disparities in access to food and food wasting behaviour, thereby giving greater insights into intra-country's intervention priorities on food waste reduction, vulnerability to malnutrition and dietary gaps from the recommended intake levels (e.g. sufficient vegetables).

Third, we use the available global average values of environmental emission factors for different food items and could not employ country-specific values that account for variability in the production methods due to the data unavailability (Springmann et al., 2018a). In addition, we could not include other food-related environmental impacts such as ecosystem services loss (Chaudhary et al. 2017), industrial pollution, disease risk and species extinction (Chaudhary and Brooks, 2018) and evolutionary history loss (Chaudhary and Mooers, 2018; Chaudhary et al. 2018c; Steel et al. 2018) that occur during the production of food that is being wasted. We could not calculate the uncertainty around our results because the input data on intake amounts, nutrition composition, and environmental emission factors (Smith et al., 2016; Springmann et al., 2018a) that we use do not provide the 95% confidence intervals.

Our results on embedded losses in global food waste are in line with previous global studies (Kummu et al., 2012; Porter et al., 2016; Hic et al., 2016). For example, our estimate of 0.205 $m^2$/capita/day cropland use and 191 kcal/capita/day embodied in wasted cereals, fruits & vegetables, oils, pulses and roots is very close to the 0.211 $m^2$/capita/day and 213 kcal/capita/day respectively estimated by Kummu et al. (2012). Our estimate of carbon footprint of food waste (124 g $CO_2$ eq./capita/day) is slightly on the lower side than 170-200 g $CO_2$ eq./capita/day estimated by Porter et al. (2016) and Hic et al. (2016).

Differences in absolute values of the footprint between our and previous studies might occur due to a number of factors such as different food product environmental emission factors (we used factors from Springmann et al., 2018a), different year of the analysis (2005-07 for Kummu et al. vs. 2011 here), different resolution of food items (e.g. 26 food groups in Porter et al. vs. 225 food items here), scope of food waste accounted (e.g. food loss and waste in Kummu et al. vs. food waste only here) etc.

To reduce the waste in foods at the consumption stage, many interventions have been suggested. Leverenz et al. (2019) found that a reduction in fresh food waste by more than 50% by weight is possible through coaching and simple interventions such as encouraging the households to keep a diary for self-reporting the amount of different food items they are wasting. Reynolds et al. (2019) provide a review of 17 interventions and their effectiveness in reducing food waste at consumption stage. They found that using appropriate size of package and plate, improving nutritional guidelines in schools, and running information campaigns are very effective in achieving food waste reductions.

Apart from consumers themselves, food business actors can play a huge role in reduction of food waste by adopting conscious strategies on packaging, date-labelling, and retail marketing (Newsome et al., 2014; Verghese et al., 2015; Williams et al., 2012; Yokokawa et al., 2018). For example, a Swedish household study looked at the influence of food packaging on the quantity and type of food wasted. It appeared that 20–25% of food was wasted due to packaging factors, such as packages being too large, packages being difficult to empty and best-before dates having passed (Williams et al., 2012). Strategies such as improved prediction of consumer demand by retail stores or restaurants and designing food packages and portion sizes targeted to consumption patterns and nutrition are need of the hour.

Institutions, private businesses and NGOs can play their part by creating awareness in society. An in-restaurant information campaign in Netherland nudged consumers for smaller portion sizes resulting in less food left on plate (Jagau and Vyrastekova, 2017). Young et al. (2017) found online and social media information as effective as traditional information dissemination for reducing food waste behaviour among UK households. Studies in Germany, France, USA, and Thailand also found that raising awareness or coaching practical skills is effective for waste prevention (Dyen and Sirieix, 2016; Leverenz et al., 2019; Manomaivibool et al., 2016; Schmidt, 2016; Whitehair et al., 2013).

In addition to information-oriented intervention, legislation and economic incentives (fees, taxes, and subsidies) and policy tools can be employed for food waste reduction (FUSIONS, 2016; UNEP, 2014). By examining data across 44 countries with different income levels, Chalak et al. (2016) found that well-defined regulations were more effective at combating household food waste generation than fiscal and economic incentives.

The main novelty of our analysis is the use of smart nutritional (WND, WDD) and environmental indicators at a global scale that can increase the perceived value of wasted food. Presenting true value of wasted food is a first step towards inducing consumers, businesses and government to take mitigation actions. Increased perceived value of wasted food could contribute to the food waste prevention because the value of food is negatively linked with the tendency of wasting it. The total value of food in addition to its monetary value (i.e. food price) can be attributed to the values related to quality, taste, social interaction, caring and use-occasions to food products (Hebrok and Heidenstrøm, 2019). Our study links the wasted amounts of different food items by individuals of different countries with both the nutritional security and environment-related social responsibility. It is reported that communicating health (nutritional) benefits increases the chances of adopting environmental mitigation actions by people in high-income countries (Amelung et al., 2019). Rather than only presenting environmental burden of wasted food, our nutrition combined environmental analysis results can thus be useful for interventions targeting reduction in food waste in high-income countries.

Another main contribution of our paper to food sustainability discussions is that our analysis provides a template for future studies to quantitatively assess the embedded nutrition and environmental value of wasted food in a comprehensive manner. Note that past studies either focused on a single environmental domain (e.g. water or GHG) or limited nutrition aspect (e.g. calories, protein) only. Whereas we not only present results for 25 nutrients and five environmental domains but also normalize them with dietary reference intakes and planetary boundaries respectively to get a more intuitive understanding of value of wasted food.

Overall, our results contribute to the existing scientific efforts on investigating the food waste behaviours across globe and generating quantitative results that can potentially be used by policy makers to design effective interventions to achieve the Sustainable Development goal 12.3 on halving per capita global food waste at the retail and consumer levels (Willet et al. 2019; Aschemann-Witzel et al., 2017; Hebrok and Boks, 2017; Schanes et al., 2018; Thyberg and Tonjes, 2016; Chaboud, 2017). The numbers presented here can serve as a baseline for tracking the influence of interventions, promoting the efficiency of policies or investments, and engaging various stakeholders with different interests (food security, nutrition, public health, natural resources, environmental sustainability, etc.).

## Appendix A Supplementary data

Supplementary material related to this article containing Tables S1-S9 can be found, in the online version.

## CRediT authorship contribution statement

**Canxi Chen:** Methodology, Software, Validation, Formal analysis, Investigation, Resources, Data curation, Writing - original draft, Writing - review & editing, Visualization, Supervision, Project administration, Funding acquisition. **Abhishek Chaudhary:** Methodology, Validation, Formal analysis, Investigation, Resources, Writing - original draft, Writing - review & editing, Supervision, Project administration, Funding acquisition. **Alexander Mathys:** Writing - review & editing, Supervision, Project administration, Funding acquisition.

## Declaration of Competing Interest

We have no conflicts of interest to disclose.

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## Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.resconrec.2020.104912.

## References

Afshin, A., Micha, R., Khatibzadeh, S., Mozaffarian, D., 2014. Consumption of nuts and legumes and risk of incident ischemic heart disease, stroke, and diabetes : a systematic review and. Am. J. Clin. Nutr. 278–288. https://doi.org/10.3945/ajcn.113.076901.

Afshin, A., et al., 2019. Health effects of dietary risks in 195 countries, 1990–2017: a systematic analysis for the Global Burden of Disease Study 2017. Lancet 393, 1958–1972. https://doi.org/10.1016/S0140-6736(19)30041-8.

Amelung, D., Fischer, H., Herrmann, A., Aall, C., Louis, V.R., Becher, H., Wilkinson, P., Sauerborn, R., 2019. Human health as a motivator for climate change mitigation: results from four European high-income countries. Glob. Environ. Change 57. https://doi.org/10.1016/j.gloenvcha.2019.05.002.

Aschemann-Witzel, J., Jensen, J.H., Jensen, M.H., Kulikovskaja, V., 2017. Consumer behaviour towards price-reduced suboptimal foods in the supermarket and the relation to food waste in households. Appetite 116, 246–258. https://doi.org/10.1016/J.APPET.2017.05.013.

Aune, D., Giovannucci, E., Boffetta, P., Fadnes, L.T., Keum, N.N., Norat, T., Greenwood, D.C., Riboli, E., Vatten, L.J., Tonstad, S., 2017. Fruit and vegetable intake and the risk of cardiovascular disease, total cancer and all-cause mortality-A systematic review and dose-response meta-analysis of prospective studies. Int. J. Epidemiol. 46, 1029–1056. https://doi.org/10.1093/ije/dyw319.

Beal, T., Massiot, E., Arsenault, J.E., Smith, M.R., Hijmans, R.J., 2017. Global trends in dietary micronutrient supplies and estimated prevalence of inadequate intakes. PLoS ONE. https://doi.org/10.1371/journal.pone.0175554.

Bernstein, A.M., Sun, Q., Hu, F.B., Stampfer, M.J., Manson, J.E., Willett, W.C., 2010. Major dietary protein sources and risk of coronary heart disease in women. Circulation 122, 876–883. https://doi.org/10.1161/CIRCULATIONAHA.109.915165.

Birney, C.I., Franklin, K.F., Davidson, F.T., Webber, M.E., 2017. An assessment of individual foodprints attributed to diets and food waste in the United States. Environ. Res. Lett. 12, 105008. https://doi.org/10.1088/1748-9326/aa8494.

Blas, A., Garrido, A., Willaarts, B., 2018. Food consumption and waste in Spanish households: Water implications within and beyond national borders. Ecol. Indic. 89, 290–300. https://doi.org/10.1016/J.ECOLIND.2018.01.057.

Buzby, J.C., Wells, H.F., Hyman, J., 2014. The Estimated Amount, Value, and Calories of Postharvest Food Losses at the Retail and Consumer Levels in the United States.

Chaboud, G., 2017. Assessing food losses and waste with a methodological framework: insights from a case study. Resour. Conserv. Recycl. 125, 188–197.

Chalak, A., Abou-Daher, C., Chaaban, J., Abiad, M.G., 2016. The global economic and regulatory determinants of household food waste generation: a cross-country analysis. Waste Manag. 48, 418–422. https://doi.org/10.1016/j.wasman.2015.11.040.

Chaudhary, A., Kastner, T., 2016. Land use biodiversity impacts embodied in international food trade. Glob. Environ. Change 38, 195–204. https://doi.org/10.1016/j.gloenvcha.2016.03.013.

Chaudhary, A., Carrasco, L.R., Kastner, T., 2017. Linking national wood consumption with global biodiversity and ecosystem service losses. Sci. Total Environ. 586, 985–994.

Chaudhary, A., Brooks, T.M., 2018. Land use intensity-specific global characterization factors to assess product biodiversity footprints. Environ. Sci. Technol. 52, 5094–5104. https://doi.org/10.1021/acs.est.7b05570.

Chaudhary, A., Mooers, A., 2018. Terrestrial vertebrate biodiversity loss under future global land use change scenarios. Sustainability 10 (8), 2764.

Chaudhary, A., Gustafson, D., Mathys, A., 2018a. Multi-indicator sustainability assessment of global food systems. Nat. Commun. 9 (1), 848.

Chaudhary, A., Marinangeli, C.P., Tremorin, D., Mathys, A., 2018b. Nutritional combined greenhouse gas life cycle analysis for incorporating canadian yellow pea into cereal-based food products. Nutrients 10 (4), 490.

Chaudhary, A., Pourfaraj, V., Mooers, A.O., 2018c. Projecting global land use-driven evolutionary history loss. Divers. Distrib. 24 (2), 158–167.

Chaudhary, A., Krishna, V., 2019. Country-specific sustainable diets using optimization algorithm. Environ. Sci. Technol. 53 (13), 7694–7703. https://doi.org/10.1021/acs.est.8b06923.

Chaudhary, A., Brooks, T.M., 2019. National consumption and global trade impacts on biodiversity. World Dev. 121, 178–187.

Chen, C., Chaudhary, A., Mathys, A., 2019. Dietary change scenarios and implications for environmental, nutrition, humsan health and economic dimensions of food sustainability. Nutrients 11 (4), 856.

Cooper, K.A., Quested, T.E., Lanctuit, H., Zimmermann, D., Espinoza-Orias, N., Roulin, A., 2018. Nutrition in the bin: a nutritional and environmental assessment of food wasted in the UK. Front. Nutr. 5, 19. https://doi.org/10.3389/fnut.2018.00019.

Corrado, S., Caldeira, C., Eriksson, M., Hanssen, O.J., Hauser, H.-E., van Holsteijn, F., Liu, G., Östergren, K., Parry, A., Secondi, L., Stenmarck, Å., Sala, S., 2019. Food waste accounting methodologies: challenges, opportunities, and further advancements. Glob. Food Sec. 20, 93–100. https://doi.org/10.1016/J.GFS.2019.01.002.

De Laurentiis, V., Corrado, S., Sala, S., 2018. Quantifying household waste of fresh fruit and vegetables in the EU. Waste Manage. 77, 238–251. https://doi.org/10.1016/J.WASMAN.2018.04.001.

De Vries, W., Kros, J., Kroeze, C., Seitzinger, S.P., 2013. Assessing planetary and regional nitrogen boundaries related to food security and adverse environmental impacts. Curr. Opin. Environ. Sustain. 5, 392–402.

Dyen, M., Sirieix, L., 2016. How does a local initiative contribute to social inclusion and promote sustainable food practices? Focus on the example of social cooking workshops. Int. J. Consum. Stud. 40, 685–694. https://doi.org/10.1111/ijcs.12281.

FAO, 2013. Food Wastage Footprint: Impacts on Natural Resources.

FAO, 2014. Food Security Indicators. http://web.archive.org/web/20141108183923/http://www.fao.org:80/economic/ess/ess-fs/fs-data/en/ Accessed October 27, 2019.
FUSIONS, 2016. In: Market-Based Instruments and Other Socio-Economic Incentives Enhancing Food Waste Prevention and Reduction, Wageningen.
Garcia-Herrero, I., Hoehn, D., Margallo, M., Laso, J., Bala, A., Batlle-Bayer, L., Fullana, P., Vazquez-Rowe, I., Gonzalez, M.J., Durá, M.J., Sarabia, C., Abajas, R., Amo-Setien, F.J., Quiñones, A., Irabien, A., Aldaco, R., 2018. On the estimation of potential food waste reduction to support sustainable production and consumption policies. Food Policy 80, 24–38. https://doi.org/10.1016/J.FOODPOL.2018.08.007.
Garcia-Herrero, I., Margallo, M., Laso, J., Batlle-Bayer, L., Bala, A., Fullana-i-Palmer, P., Vazquez-Rowe, I., Gonzalez, M.J., Amo-Setien, F., Durá, M.J., Sarabia, C., Abajas, R., Quiñones, A., Irabien, A., Aldaco, R., 2019. Nutritional data management of food losses and waste under a life cycle approach: case study of the Spanish agri-food system. J. Food Compos. Anal. 82, 103223. https://doi.org/10.1016/J.JFCA.2019.05.006.
Gerten, D., 2013. . Towards a revised planetary boundary for consumptive freshwater use: role of environmental flow requirements. Curr. Opin. Environ. Sustain. 5, 551–558.
Gustavsson, J., Cederberg, C., Sonesson, U., Van Otterdijk, R., Meybeck, A., 2011. Global Food Losses and Food Waste - Extent, Causes and Prevention. Food and Agriculture Organization of the United Nations, Rome.
Hayashi, K., Oita, A., Lassaletta, L., Shindo, J., Shibata, H., Sakurai, G., Eguchi, S., 2018. Reducing nitrogen footprints of consumer-level food loss and protein over-consumption in Japan, considering gender and age differences. Environ. Res. Lett. 13, 124027. https://doi.org/10.1088/1748-9326/aaec63.
Hebrok, M., Boks, C., 2017. Household food waste: Drivers and potential intervention points for design – an extensive review. J. Clean. Prod. https://doi.org/10.1016/j.jclepro.2017.03.069.
Hebrok, M., Heidenstrøm, N., 2019. Contextualising food waste prevention - decisive moments within everyday practices. J. Clean. Prod. 210, 1435–1448. https://doi.org/10.1016/J.JCLEPRO.2018.11.141.
Hiç, C., Pradhan, P., Rybski, D., Kropp, J.P., 2016. Food surplus and its climate burdens. Environ. Sci. Technol. 50, 4269–4277. https://doi.org/10.1021/acs.est.5b05088.
Institute of Medicine, 2019. Dietary Reference Intakes for Sodium and Potassium. National Academies Press, Washington, DC.
Institute of Medicine, 2005. Dietary Reference Intakes for Energy, Carbohydrate, Fiber, Fat, Fatty Acids, Cholesterol, Protein, and Amino Acids (Macronutrients). National Academies Press, Washington, DC.
Institute of Medicine, 2001. Dietary Reference Intakes for Vitamin A, Vitamin K, Arsenic, Boron, Chromium, Copper, Iodine, Iron, Manganese, Molybdenum, Nickel, Silicon, Vanadium, and Zinc. National Academies Press, Washington, DC.
Institute of Medicine, 2000. Dietary Reference Intakes for Vitamin C, Vitamin E, Selenium, and Carotenoids. National Academies Press, Washington, DC.
Institute of Medicine, 1998a. Dietary Reference Intakes for Thiamin, Riboflavin, Niacin, Vitamin B6, Folate, Vitamin B12, Pantothenic Acid, Biotin, and Choline. National Academies Press, Washington, DC.
Institute of Medicine, 1998b. Dietary Reference Intakes: A Risk Assessment Model for Establishing Upper Intake Levels for Nutrients. National Academies Press, Washington, DC.
Jagau, H.L., Vyrastekova, J., 2017. Behavioral approach to food waste: an experiment. Br. Food J. 119, 882–894. https://doi.org/10.1108/BFJ-05-2016-0213.
Kashyap, D., Agarwal, T., 2019. Food loss in India: water footprint, land footprint and GHG emissions. Environ. Dev. Sustain 1–14. https://doi.org/10.1007/s10668-019-00325-4.
Khalid, S., Naseer, A., Shahid, M., Shah, G.M., Ullah, M.I., Waqar, A., Abbas, T., Imran, M., Rehman, F., 2019. Assessment of nutritional loss with food waste and factors governing this waste at household level in Pakistan. J. Clean. Prod. 206, 1015–1024. https://doi.org/10.1016/J.JCLEPRO.2018.09.138.
Kummu, M., de Moel, H., Porkka, M., Siebert, S., Varis, O., Ward, P.J., 2012. Lost food, wasted resources: global food supply chain losses and their impacts on freshwater, cropland, and fertiliser use. Sci. Total Environ. 438, 477–489. https://doi.org/10.1016/J.SCITOTENV.2012.08.092.
Leverenz, D., Moussawel, S., Maurer, C., Hafner, G., Schneider, F., Schmidt, T., Kranert, M., 2019. Quantifying the prevention potential of avoidable food waste in households using a self-reporting approach. Resour. Conserv. Recycl. 150, 104417. https://doi.org/10.1016/j.resconrec.2019.104417.
Lipinski, B., Hanson, C., Lomax, J., Kitinoja, L., Waite, R., Searchinger, T., 2013. Reducing Food Loss and Waste, Installment 2 of Creating a Sustainable Food Future. Washington, DC.
Lock, K., Pomerleau, J., Causer, L., Altmann, D.R., McKee, M., 2005. The global burden of disease attributable to low consumption of fruit and vegetables: implications for the global strategy on diet. Bull. World Health Organ. 83, 100–108. https://doi.org/10.1590/S0042-96862005000200010.
Love, D.C., Fry, J.P., Milli, M.C., Neff, R.A., 2015. Wasted seafood in the United States: quantifying loss from production to consumption and moving toward solutions. Glob. Environ. Change 35, 116–124. https://doi.org/10.1016/J.GLOENVCHA.2015.08.013.
Ma, L., Bai, Z., Ma, W., Guo, M., Jiang, R., Liu, J., Oenema, O., Velthof, G.L., Whitmore, A.P., Crawford, J., Dobermann, A., Schwoob, M., Zhang, F., 2019. Exploring future food provision scenarios for China. Environ. Sci. Technol. 53, 1385–1393. https://doi.org/10.1021/acs.est.8b04375.
Manomaivibool, P., Chart-asa, C., Unroj, P., 2016. Measuring the impacts of a save food campaign to reduce food waste on campus in Thailand. Appl. Environ. Res 13–22. https://doi.org/10.35762/aer.2016.38.2.2.
Mason-D'Croz, D., Bogard, J.R., Sulser, T.B., Cenacchi, N., Dunston, S., Herrero, M., Wiebe, K., 2019. Gaps between fruit and vegetable production, demand, and recommended consumption at global and national levels: an integrated modelling study. Lancet Planet. Heal. 3, e318–e329. https://doi.org/10.1016/S2542-5196(19)30095-6.
Mueller, N.D., 2012. Closing yield gaps through nutrient and water management. Nature 490, 254–257.
Muraki, I., Imamura, F., Manson, J.E., Hu, F.B., Willett, W.C., Van Dam, R.M., Sun, Q., 2013. Fruit consumption and risk of type 2 diabetes: results from three prospective longitudinal cohort studies. BMJ 347. https://doi.org/10.1136/bmj.f5001.
Muthayya, S., Rah, J.H., Sugimoto, J.D., Roos, F.F., Kraemer, K., Black, R.E., 2013. The global hidden hunger indices and maps: an advocacy tool for action. PLoS ONE 8. https://doi.org/10.1371/journal.pone.0067860.
NCD Risk Factor Collaboration (NCD-RisC), 2017. Worldwide trends in body-mass index, underweight, overweight, and obesity from 1975 to 2016: a pooled analysis of 2416 population-based measurement studies in 128•9 million children, adolescents, and adults. Lancet 390, 2627–2642. https://doi.org/10.1016/S0140-6736(17)32129-3.
NCD Risk Factor Collaboration (NCD-RisC), 2016. A century of trends in adult human height. Elife 5, e13410. https://doi.org/10.7554/eLife.13410.
Newsome, R., Balestrini, C.G., Baum, M.D., Corby, J., Fisher, W., Goodburn, K., Labuza, T.P., Prince, G., Thesmar, H.S., Yiannas, F., 2014. Applications and perceptions of date labeling of food. Compr. Rev. Food Sci. Food Saf. 13, 745–769. https://doi.org/10.1111/1541-4337.12086.
O'Neill, D.W., Fanning, A.L., Lamb, W.F., Steinberger, J.K., 2018. A good life for all within planetary boundaries. Nat. Sustain. 1, 88.
Porter, S.D., Reay, D.S., Bomberg, E., Higgins, P., 2018. Production-phase greenhouse gas emissions arising from deliberate withdrawal and destruction of fresh fruit and vegetables under the EU's Common Agricultural Policy. Sci. Total Environ. 631–632, 1544–1552. https://doi.org/10.1016/J.SCITOTENV.2018.03.089.
Porter, S.D., Reay, D.S., Higgins, P., Bomberg, E., 2016. A half-century of production-phase greenhouse gas emissions from food loss & waste in the global food supply chain. Sci. Total Environ. 571, 721–729. https://doi.org/10.1016/J.SCITOTENV.2016.07.041.
Reynolds, C., Goucher, L., Quested, T., Bromley, S., Gillick, S., Wells, V.K., Evans, D., Koh, L., Kanyama, Carlsson, A., Katzeff, C., Svenfelt, Å., Jackson, 2019. Review: Consumption-stage food waste reduction interventions – what works and how to design better interventions. Food Policy 83, 7–27. https://doi.org/10.1016/J.FOODPOL.2019.01.009.
Robinson, S., et al., 2015. The International Model for Policy Analysis of Agricultural Commodities and Trade (IMPACT)—Model Description for Version 3. IFPRI Discussion Paper 1483 (IFPRI, 2015).
Schanes, K., Dobernig, K., Gözet, B., 2018. Food waste matters - a systematic review of household food waste practices and their policy implications. J. Clean. Prod. 182, 978–991. https://doi.org/10.1016/J.JCLEPRO.2018.02.030.
Scherhaufer, S., Moates, G., Hartikainen, H., Waldron, K., Obersteiner, G., 2018. Environmental impacts of food waste in Europe. Waste Manag 77, 98–113. https://doi.org/10.1016/J.WASMAN.2018.04.038.
Schmidt, K., 2016. Explaining and promoting household food waste-prevention by an environmental psychological based intervention study. Resour. Conserv. Recycl. 111, 53–66. https://doi.org/10.1016/j.resconrec.2016.04.006.
Smith, M.R., Micha, R., Golden, C.D., Mozaffarian, D., Myers, S.S., 2016. Global expanded nutrient supply (GENuS) model: a new method for estimating the global dietary supply of nutrients. PLoS ONE 11https://doi.org/10.1371/journal.pone.0146976.e0146976.
Spiker, M.L., Hiza, H.A.B., Siddiqi, S.M., Neff, R.A., 2017. Wasted food, wasted nutrients: nutrient loss from wasted food in the united states and comparison to gaps in dietary intake. J. Acad. Nutr. Diet 117, 1031–1040. https://doi.org/10.1016/J.JAND.2017.03.015. e22.
Springmann, M., 2018a. Options for keeping the food system within environmental limits. Nature 562, 519–525. https://doi.org/10.1038/s41586-018-0594-0.
Springmann, M., Wiebe, K., Mason-D'Croz, D., Sulser, T.B., Rayner, M., Scarborough, P., 2018b. Health and nutritional aspects of sustainable diet strategies and their association with environmental impacts: a global modelling analysis with country-level detail. Lancet Planet. Heal. 2, e451–e461. https://doi.org/10.1016/S2542-5196(18)30206-7.
Steel, M., Pourfaraj, V., Chaudhary, A., Mooers, A., 2018. Evolutionary isolation and phylogenetic diversity loss under random extinction events. J. Theor. Biol. 438, 151–155.
Steffen, W., et al., 2015. Planetary boundaries: guiding human development on a changing planet. Science 347, 1259855. https://doi.org/10.1126/science.1205106.
Stuart, T., 2009. Waste - Uncovering the Global Food Scandal. Penguin Books, London.
Swinburn, B.A., et al., 2019. The global syndemic of obesity, undernutrition, and climate change: the lancet commission report. Lancet 393, 791–846. https://doi.org/10.1016/S0140-6736(18)32822-8.
Thyberg, K.L., Tonjes, D.J., 2016. Drivers of food waste and their implications for sustainable policy development. Resour. Conserv. Recycl. 106, 110–123. https://doi.org/10.1016/J.RESCONREC.2015.11.016.
Tonini, D., Albizzati, P.F., Astrup, T.F., 2018. Environmental impacts of food waste: learnings and challenges from a case study on UK. Waste Manage 76, 744–766. https://doi.org/10.1016/J.WASMAN.2018.03.032.
UNEP, 2014. Prevention and Reduction of Food and Drink Waste in Businesses and Households - Guidance for Governments, Local Authorities, Businesses and other Organisations, Version 1.0.
United Nation, 2015. Transforming Our World: the 2030 Agenda for Sustainable Development [WWW Document]. http://www.un.org/ga/search/view_doc.asp?symbol = A/RES/70/1&Lang = E (accessed 12.21.18).
United Nations Department of Economic and Social Affairs, 2017. World Population Prospects: The 2017 Revision. [WWW Document]. https://population.un.org/wpp (accessed 1.15.18).

United States Department of Agriculture (USDA), 2016. National Nutrient Database for Standard References. Release 28. [WWW Document]. USDA Agric. Res. Serv. http://ndb.nal.usda.gov/ndb/search/list accessed 3.20.18.
Vanham, D., Bouraoui, F., Leip, A., Grizzetti, B., Bidoglio, G., 2015. Lost water and nitrogen resources due to EU consumer food waste. Environ. Res. Lett. 10, 084008. https://doi.org/10.1088/1748-9326/10/8/084008.
Verghese, K., Lewis, H., Lockrey, S., Williams, H., 2015. Packaging's role in minimizing food loss and waste across the supply chain. Packag. Technol. Sci. 28, 603–620. https://doi.org/10.1002/pts.2127.
Wang, X., Ouyang, Y., Liu, J., Zhu, M., Zhao, G., Bao, W., Hu, F.B., 2014. Fruit and vegetable consumption and mortality from all causes, cardiovascular disease, and cancer: Systematic review and dose-response meta-analysis of prospective cohort studies. BMJ 349. https://doi.org/10.1136/bmj.g4490.
Wesana, J., Gellynck, X., Dora, M.K., Pearce, D., De Steur, H., 2019. Measuring food and nutritional losses through value stream mapping along the dairy value chain in Uganda. Resour. Conserv. Recycl. 150, 104416. https://doi.org/10.1016/J.RESCONREC.2019.104416.
West, P.C., Gerber, J.S., Engstrom, P.M., Mueller, N.D., Brauman, K.A., Carlson, K.M., Cassidy, E.S., Johnston, M., MacDonald, G.K., Ray, D.K., Siebert, S., 2014. Leverage points for improving global food security and the environment. Science 345, 325–328. https://doi.org/10.1126/science.1246067.
Whitehair, K.J., Shanklin, C.W., Brannon, L.A., 2013. Written messages improve edible food waste behaviors in a university dining facility. J. Acad. Nutr. Diet. 113, 63–69. https://doi.org/10.1016/j.jand.2012.09.015.
Willett, W., 2019. Food in the anthropocene: the EAT–lancet commission on healthy diets from sustainable food systems. Lancet 393, 447–492. https://doi.org/10.1016/S0140-6736(18)31788-4.
Williams, H., Wikström, F., Otterbring, T., Löfgren, M., Gustafsson, A., 2012. Reasons for household food waste with special attention to packaging. J. Clean. Prod. 24, 141–148. https://doi.org/10.1016/j.jclepro.2011.11.044.
Wollenberg, E., 2016. Reducing emissions from agriculture to meet the 2°C target. Glob. Change Biol. 22, 3859–3864.
Yokokawa, N., Kikuchi-Uehara, E., Sugiyama, H., Hirao, M., 2018. Framework for analyzing the effects of packaging on food loss reduction by considering consumer behavior. J. Clean. Prod. 174, 26–34. https://doi.org/10.1016/J.JCLEPRO.2017.10.242.
Young, W., Russell, S.V, Robinson, C.A., Barkemeyer, R., 2017. Can social media be a tool for reducing consumers' food waste? A behaviour change experiment by a UK retailer. Resour. Conserv. Recycl. 117, 195–203. https://doi.org/10.1016/j.resconrec.2016.10.016.