Global water and energy losses from consumer avoidable food waste

Coudard, A.; Corbin, E; de Koning, J.I.J.C.; Tukker, Arnold; Mogollón, José

DOI
10.1016/j.jclepro.2021.129342

Publication date
2021

Document Version
Final published version

Published in
Journal of Cleaner Production

Journal of Cleaner Production 326 (2021) 129342

Contents lists available at ScienceDirect

Journal of Cleaner Production

journal homepage: www.elsevier.com/locate/jclepro

Global water and energy losses from consumer avoidable food waste

A. Coudard [a,b,*], E. Corbin [b], J. de Koning [c], A. Tukker [a], J.M. Mogollón [a]

[a] Institute of Environmental Sciences (CML), Leiden University, PO Box 9518, 2300 RA, Leiden, the Netherlands
[b] Metabolic Institute, Klimopweg 150, 2032HX, Amsterdam, the Netherlands
[c] Delft University of Technology, Department of Design Engineering, Design for Sustainability, Landbergstraat 15, 2828CE, Delft, the Netherlands

ARTICLE INFO

Handling editor: Yutao Wang

Keywords:
Consumer food waste
Food-energy-water nexus
Water footprint
Embodied energy
Resource-efficiency
Sustainable food system

ABSTRACT

Food products require significant amounts of energy and water throughout their lifecycle, yet humanity wastes 1.3e9 tons of food on a yearly basis. A large part of this waste occurs during the consumption (post-retail) phase of the food system as avoidable food waste, the discarded edible (parts of) food products. In this study, we explore the effects of avoidable food waste on the Food-Energy-Water nexus. We show that the 344 million tonnes of global avoidable food waste is responsible for squandering 4e18 J of energy and 82e9 m^3 of water. While there are important regional differences in terms of avoidable food waste due to varying diets and waste incidences, these energy and water losses are rivaling the electricity and the blue water use of populous nations, and adding to needless pressures on the environment.

1. Introduction

Each year, a third of global food production (around 1.3e9 tons) exits the food supply chain as waste (FAO, 2019). 27% of these losses happen at the consumption phase (post-retail) as avoidable food waste (AFW), the discarded edible (parts of) food products. Unlike unavoidable food waste (UFW, the expected, non-consumable waste streams), AFW is never used for their intended purpose, namely human consumption. Food production requires resources, energy, and water, thus, AFW is linked with unavailing energy and water use, compounding to the detrimental environmental impacts of the food system (Springmann et al., 2018) (Melo et al., 2020).

Energy efficiency is key to mitigate climate impacts and meet energy targets (Patt et al., 2019). The energy footprint of the global food system was estimated to be slightly above 70 Exajoules (10^{18}J, EJ) (Usubiaga-Liaño et al., 2020a). Food production requires energy for tilling, seeding, harvesting, and the production of fertilizers and pesticides (Daher et al., 2017a). This represents between 15 and 20% of the overall global energy footprint of food. Food processing requires energy for milling, grinding, fermentation, drying, cooking, canning and packaging, and can represent up to 25% of the total energy footprint (Usubiaga-Liaño et al., 2020b). Food transportation may require significant amounts of energy depending on the transportation mode and distances travelled (Sim et al., 2007). Refrigeration is often required during transportation and storage at wholesalers, retail stores, and in private households. Energy is also required to prepare food (e.g., boiling, frying, baking, grilling, grinding) before its final consumption in food services, restaurants, and households. Depending on the cooking medium used throughout the world's regions, household cooking can represent between 15% in high-income countries to above 55% in developing countries of the total energy footprint of food (Usubiaga-Liaño et al., 2020c).

Freshwater resources worldwide are scarce, unevenly distributed, and overexploited (Ridoutt and Pfister, 2010). Agriculture represents 70% of the global freshwater use, with about a quarter of global arable land being artificially irrigated, where 40% of global food is produced (Mannan et al., 2018a). Water is also used during food processing as an ingredient or as a cooking medium (Daher et al., 2017b) (Munasinghe et al., 2017).

AFW is therefore inherently connected to the Food-Energy-Water (FEW) nexus. This nexus perspective sees the water, food, and energy systems as highly connected and mutually dependent, and was established as a novel way to deal with global challenges, such as urbanization, degradation of resources, and globalization (Hoff, 2011). FEW nexus studies have been characterized by a wide diversity of methodologies and scales, both quantitative and qualitative (Albrecht et al., 2018) (Mannan et al., 2018b). Global reviews of food, energy, water nexus interactions have been performed in recent years, providing the conceptual basis of these systemic connections (D'Odorico et al., 2018). More scarcely, the nexus perspective has also been applied

* Corresponding author. Metabolic Institute, Klimopweg 150, 2032HX, Amsterdam, the Netherlands.
E-mail address: antoine@metabolic.nl (A. Coudard).

https://doi.org/10.1016/j.jclepro.2021.129342
Received 23 February 2021; Received in revised form 20 September 2021; Accepted 10 October 2021
Available online 11 October 2021

quantitatively to analyze countries, cities, and even households, and uncover synergies and trade-offs arising between the different sub-systems. These studies use a wide variety of methods, ranging from substance flow analysis, system-dynamic modelling, and resource final demand models (Karnib, 2017) (Villarroel Walker et al., 2014) (Hussien et al., 2017).

On the topic of FW, only few studies, mostly at a conceptual level, have used the nexus approach to assess FW and its water and energy impacts (Kibler et al., 2018), with most studies not differentiating between AFW and UFW during their impact assessment. Quantified impacts of FW have been also applied, albeit to restricted geographies and only analyzing either energy or water impacts (Vittuari et al., 2020a). Thus, this paper aims to expand the literature of FW and the FEW nexus, providing a first quantitative assessment of consumer AFW's impact on the FEW nexus, at global and regional scales. At a practical level, we quantify the global consumer AFW generated in 2017 by using regional food waste fraction, specific to each food product type, and then removing the unavoidable components (UFW). While UFW is also an important waste stream that should be valorized as a promising feedstock for biomass technologies (Nayak and Bhushan, 2019), here we focus solely on the unnecessary losses related to AFW by collecting data on the amounts of cumulative energy demand and (blue) water used throughout food products' lifecycles to quantify the wasted energy and water for the different AFWs of each food product type for every country.

This study provides a new granular understanding of the different food types' nexus impacts, and illustrates how national dietary choices affect the total energy and water losses stemming from national consumer AFW. We stress that solutions toward increasing the sustainability of the food system (i.e., shifting towards more plant-based diets) remain incomplete without proper reduction of AFW, and finalize by assessing some solutions that can help minimize AFW.

2. Material and methods

AFW generated at the consumption-level (households and food services), is quantified by using regional food waste fraction (AFW+UFW), specific to each food product type, and then removing the UFW components. Subsequently, data on the amounts of energy and water that were used throughout food products' life-cycles are collected and the total amounts of energy and water wasted are quantified for the different AFW amounts of each food product type for every country.

2.1. Quantifying food availability at the household and food services level

The first step is to quantify the amounts of available food at the consumption-stage (households and food services). This study uses FAOSTAT Food Balance Sheets (FBSs) that compile the food available at the distribution stage in a given country, after accounting for losses upstream in the supply chain and the use of food products for non-human consumption (seeds, feed, etc), and exports (FAO, 2017). The FBSs therefore provides the average food supply at the national-level for a given entire country in kg per capita per annum for about 90 food product types or 18 aggregated food groups. FAOSTAT reports food availability in primary equivalent - therefore for processed products, the amounts compiled are in primary equivalent. For example, pasta or bread products are quantified as wheat-equivalent (Vanham et al., 2016a). The conversion from raw equivalent to product-weight is necessary to calculate more precisely the amount of avoidable food waste at the consumption stage, and avoid overestimation, since the raw-equivalent of some food product may have a higher volume than the actual amount that reaches end-consumers. Taking again the example of pasta, it takes 1 kg of (raw) wheat to make 0.8 kg of pasta. The latter number is therefore the one used to calculate the AFW and UFW estimation for this food type. Therefore, to quantify the actual amounts of food available, the FBSs sheets must be corrected for every country by using technical conversation factors (TCFs), following the approach of Vanham et al. (2015) (Vanham et al., 2016b) and Chapagain & Mekonnen (Chapagain and Hoekstra, 2004). Here we use the TCFs originally developed by FAO and compiled by Bruckner et al. (2019) The TCFs provided by FAO are specific to the most disaggregated food items recorded by FAO. The food items in the FBSs are presented as one level higher of aggregation. As a result, each TCF was classified in its respective FBSs' food items and a median TCFs values were calculated to determine the TCFs of the FBSs food items. The new TCFs were then used to calculate the product-equivalent from the raw equivalent data of the FBSs (Eq. (1)).

$$\boldsymbol{FA}_{f} = \boldsymbol{FA}_{f\ PE} * \boldsymbol{TCF}_{f} \tag{1}$$

Where:

$\boldsymbol{FA}_{f}$ is the corrected, actual quantity of a food item f available at the Distribution stage, in kg

$\boldsymbol{FA}_{f\ PE}$ is the primary-equivalent quantity of food item f, compiled in the FBS, in kg

$\boldsymbol{TCF}_{f}$ is the Technical Conversion Factor of food item f, as a percentage.

Additionally, prior to calculating losses at the Distribution stage, the nature of food products (processed or fresh) must be taken into consideration as they have different food waste incidence rates. As a result, FAO provides different waste estimates, for when a food type is consumed, processed or fresh (Appendix B, Table S7). This differentiation in the nature of products is available for the following aggregated food groups: Vegetables, Fruits, Starchy Roots, and Fish and Seafood, with estimates for each region of the world. Processed food products are generally less wasted than fresh ones (FAO, 2011). Once these food groups are further allocated to processed or fresh subgroups, the losses at the retail-level are computed using the FAO *Global Food Losses and Waste* landmark report. This report provides the incidence of food waste at an aggregated level for the different regions of the world at the Distribution stage (retail-level) for different food types (whether processed or fresh) (Appendix B, Table S7). A harmonization of food items classification is required to match the food categories used in the *Global Food Losses and Waste* estimates (more aggregated) to the 18 aggregated food groups (less aggregated) of the FBSs, and further applied to the 90 disaggregated food items (Appendix B). This final step yields the actual amounts of food that reach households and food services in each country. Equation (2) presents this calculation step for fresh food products, see Appendix A for intermediate calculation steps, and additional methodological details.

$$\boldsymbol{FAC}_{f\ FRESH} = \mathbf{FA}_{f} * \boldsymbol{CT\ share}_{\boldsymbol{FRESH}} - \boldsymbol{FWD}_{f\ FRESH} \tag{2}$$

Where:

- $\boldsymbol{FAC}_{f\ FRESH}$ is the quantity of a food item f, fresh, available at the Consumption stage (food services and households), in kg
- $\boldsymbol{FA}_{f}$ is the corrected, actual quantity of a food item f available at the Distribution stage, in kg
- $\boldsymbol{CT\ share}$ is the consumption type share of food item f considered to be consumed, whether fresh or processed, as a percentage.
- $\boldsymbol{FWD}_{f}$ is the quantity of a food item f, consumed fresh or processed, wasted at the Distribution stage, in kg.

2.2. Quantifying avoidable food waste at the consumption-level

Avoidable Food Waste (AFW) is calculated by using the regional food waste factors of FAO *Global Food Losses and Waste* report at the household-level for every country, (Appendix B, Table S7). These FAO food waste estimates take into account both AFW and UFW. Therefore, the UFW fraction is removed from the calculated total food waste, using the "waste floor" approach. The "waste floor" approach aims to quantify the total "minimal" amounts of UFW linked to the final consumption of food in households and food services, in each country. We use data from Laurentiis et al. (De Laurentiis et al., 2018)., for vegetables, fruits, and starchy roots, and data from WRAP (WRAP, 2014a) for estimates for the meat food types and its subtypes (bovine, pork, poultry, sheep). Additionally, it is assumed that stimulants (coffee and tea grounds) constitute 100% of UFW. An inedible fraction estimate is also provided for fish and seafood (WRAP, 2014b), and egg (shell) (John-Jaja et al., 2016). A core assumption in the approach developed in this study is to consider processed food products (cans, jars, frozen, juice, dried) as entirely edible, and therefore not generating any UFW, as the inedible portions were removed at the processing stage. This is coherent with the "waste floor" approach aiming to quantify the *minimal* amounts of UFW. As a result, the inedible fractions of the relevant food products are matched with their respective food groups, and the total amount of UFW is quantified for each country by multiplying the fraction with the total available amounts (post-distribution) of (fresh) food products.

$$\boldsymbol{UFW}_{f\ FRESH} = \boldsymbol{FAC}_{f\ FRESH} * \boldsymbol{IF}_{f\ FRESH}$$

$$\boldsymbol{UFW}_{f\ PROCESSED} = 0$$

Eqs. (3) and (3).bis.Where:

- $\boldsymbol{UFW}_f$ is the inedible quantity of a food item f, consumed fresh, that is generated at the Consumption stage, in kg
- $\boldsymbol{FAC}_{f\ FRESH}$ is the quantity of a food item f, fresh, available at the Consumption stage (food services and households), in kg
- $\boldsymbol{IF}_{f\ FRESH}$ is the inedible fraction of food item f, consumed fresh, as a percentage.
- $\boldsymbol{UFW}_{f\ PROCESSED}$ is considered to be 0 as the processed food item f is considered to have been stripped of the inedible, or unavoidable waste elements

This step results in the final amounts of UFW for each country that constitute an available biomass feedstock if collected properly. This inedible fraction is subtracted from the FW values calculated via the FAO *Global Food Losses and Waste* estimates, which yields the total amounts of AFW for each food group for every country. See Appendix A for intermediate calculation steps.

$$\boldsymbol{AFW}_{f\ FRESH} = \boldsymbol{FWC}_{f\ FRESH} * (1 - \boldsymbol{IF}_{f\ FRESH}) \quad (4)$$

Where:

- $\boldsymbol{AFW}_{f\ FRESH}$ is the edible quantity of a food item f, consumed fresh, that is wasted at the Consumption stage, in kg
- $\boldsymbol{FWC}_{f\ FRESH}$ is the quantity of a food item f, consumed fresh, wasted at the Consumption stage, in kg.
- $\boldsymbol{IF}_{f\ FRESH}$ is the inedible fraction of food item f, consumed fresh, as a percentage.

2.2.1. Disaggregation of the milk, excluding butter food items

The food item *Milk, excluding Butter* has been disaggregated further to assess more precisely the energy and water impacts of this food item. This category includes fresh milk, cheese, yogurt, and other dairy products. This food category is expressed in milk-equivalent. The energy and water profile of milk, cheese, and other dairy like yoghurt are significantly different and therefore will impact the results significantly. The consumption of fresh milk in comparison to cheese varies a lot across countries, developing countries consuming far less cheese products than developed countries located in Europe or North-America (FAO-OECD, 2019). To account for the difference in diet (and ultimately gain a more precise energy and water profile of these food items), we use OECD-FAO datasets from 2017 that present the milk, cheese, and other dairy products consumption in kg per capita for the OECD countries and regions of the world. To calculate the adequate shares of cheese and other dairy products (excluding fluid milk) within *Milk, excluding Butter*, the value (kg of cheese or other dairy products) is converted in fresh milk-equivalent with the corresponding FAO's TCFs. The share of the cheese, milk, and other dairy products are computed based on their 2017 consumption for the distinct countries available in the OECD-FAO datasets and regional weighted averages are determined to complete the coverage. Using these newly computed shares, the *Milk, excluding Butter* category in each country's FBS is disaggregated in three food subtypes: *Fresh dairy products; Cheese and Other dairy products.* See Appendix A for detailed calculations.

2.3. Quantifying the energy and water footprints of food products

The cumulated energy and water footprint profiles are estimated in order to calculate the amounts of energy and water resources wasted through AFW incidence. In this study we use a global average for energy and water consumption throughout the production and supply chain of each food product to quantify the water and energy losses due to avoidable food waste.

The cumulative energy use is selected for each of the 90 food items of the FBSs (Appendix B) from a meta-analysis study that compiled the total life-cycle energy use (up to the consumption stage) for a wide variety of food products (Tom et al., 2016). The food product energy data classification is harmonized to match the FAO FBS food items used throughout this study (Appendix B).

The blue water footprint of food products, that is the direct amounts of water resource used by food products in their life-cycle, was selected from the work of Mekonnen and Hoekstra and their global-weighted average datasets (Mekonnen and Hoekstra, 2011) (Mekonnen and Hoekstra, 2012). A superficial harmonization is also required to match the animal product food categories of the water footprint data to the FAO FBS food items used throughout this study (Appendix B). Water footprint datasets for vegetal products (crops, vegetables, fruits) used the same classification systems as FAO's FBS.

It should be highlighted that while the water footprint of food products has been well-researched and documented across regions, the energy footprint of food products is less cohesive and complete (Vittuari et al., 2020b), with a disproportionate share of studies coming from European countries. Therefore, the cumulative energy use dataset has a tendency to be skewed towards the European context. As more data is collected across countries and regions, it will be possible to refine the model developed in this study and gain further granularity on the impacts of AFW on the FEW-nexus. Preliminary uncertainties calculations have been included in Appendix A to account for the uncertainties surrounding the energy data of food products. Finally, for each country, the wasted energy and water amounts are computed by multiplying the amounts of the cumulated energy demand and blue water footprint by the total amounts of AFW of their respective food groups. (Eq5 and 5.bis). This final step yields the amount of energy (MJ) and water (m3) resources that have been wasted through AFW.

$$\boldsymbol{WE}_f = \boldsymbol{AFW}_f * \boldsymbol{CED}_f \quad (5)$$

$$\boldsymbol{WW}_f = \boldsymbol{AFW}_f * \boldsymbol{WF}_f \quad \text{5.bis}$$

Where:

- $\boldsymbol{WE}_f$ is the amount of energy wasted through the generation of avoidable food waste of food item f, in MJ
- $\boldsymbol{AFW}_f$ is the edible quantity of a food item f, that is wasted at the Consumption stage, in kg
  $\boldsymbol{CED}_f$ is the cumulated energy demand, representing the amount of energy used throughout the life-cycle of food item f up to the consumption stage, in MJ/kg.

- WW_f is the amount of water wasted through the generation of avoidable food waste of food item f, in m3.
- WF_f is the water footprint, representing the amount of blue water used throughout the life-cycle of food item f, in m3/kg.

2.4. Considering uncertainty around food waste estimates

This study uses the most widely-cited global food waste estimates report published by FAO in 2011 to quantify the amounts of avoidable food waste generated at the consumption stage in 2017. Food waste estimates, whether at local, national, or regional do not benefit from a consistent temporal coverage in the vast majority of cases (Xue et al., 2017). As a result, it is difficult to quantify precise uncertainties ranges due to the vast variety of methods and scope of food waste studies (Dou and Toth, 2020). Nonetheless, a preliminary uncertainty analysis was performed to consider uncertainties surrounding food waste estimates, food energy demand and water footprint estimates. To account for the temporal variations in food waste estimates, food waste statistics were collected for several countries, such as the United States and Australia or regions, such as Europe that offer insights on food waste incidence change over similar time intervals. Minimum and maximum food waste estimate change over the 2011–2017 period were calculated across the selected regions. Regarding the water footprint data, Zhuo et al. provide uncertainties ranges for the different variables used during the calculation of the water footprint for a selection of crops (Zhuo et al., 2014). These uncertainties ranges are included in the preliminary uncertainty calculations surrounding global water loss due to global consumer AFW (Appendix A). For the energy data, we used the dataset built by Carlsson-Kanyama et al. (2003) to calculate the relative standard deviations of the energy data, and applied them to calculate the uncertainty ranges of the global energy loss from consumer AFW (Appendix A). The results of this analysis are visible with the error bars included in Fig. 2 for the wasted CED and blue water footprint of global AFW. The uncertainties calculations are compiled in Appendix A.

3. Results and discussion

3.1. Avoidable food waste and the FEW nexus

In 2017, global post-retail AFW amounted to 345 million tons, or roughly 47 kg/capita/year. Globally, more affluent regions tend to produce more AFW than UFW (Table 1) as: 1) Affluence tends to produce more waste, as attested by the positive correlation between waste production per capita and GDP growth (Kaza et al., 2018) (Lopez Barrera and Hertel, 2020). 2) With increasing wealth, food has a lower impact on household budgets, and thus the share of expenditures devoted to food decreases, as established by the so-called Engels' Law (Clements et al., 2017). 3) Wealthier regions tend to consume more processed food items (FAO, 2011), which have been stripped of the inedible, or unavoidable waste elements.

Globally, this study shows that *Japan, China and South Korea* were responsible for 46% of the total incidence of AFW at consumption stage in 2017, followed by *Europe* (18%), and *USA, Canada, Oceania* (11%) (Table 1). On a per-capita basis, *USA, Canada, Oceania, Japan, China and South Korea* had similar volumes with circa 97 kg/cap/yr. European consumers produced about 83 kg of AFW. *Northern Africa and Central and West Asia* consumers produced annually slightly below the global average, with 41 kg/capita/year of AFW. *Latin America* consumers generated 29 kg/cap/yr. *South and South-East Asia* and *Sub-Saharan Africa* consumers produced by far the least amount of AFW, with 16 and 8 kg/cap/year, respectively.

By assessing each individual food product's energy footprint, for 2017 the global, cumulative energy use of AFW amounts to 4 Exajoules (10^{18}J, EJ) (Fig. 2a), which represents a number comparable to both the electricity and primary energy usage of large nations. For instance, it would represent roughly a fourth and a sixth of the USA's and China's 2017 electrical consumption (about 15 EJ and 23 EJ, respectively) (IEA, 2018). On the other hand, it is on par with India's 2017 consumption of almost 4.5 EJ of electricity. In Europe, France and Germany consumed, respectively, 1.7 and 2 EJ of electricity (14 and 10 EJ of primary energy, respectively). Therefore, global annual post-retail AFW generation is responsible for wasting slightly more than the equivalent of the annual electricity consumption of France and Germany combined (raking 4th on a country-use basis, Fig. 2a) and about half to a third of the primary energy consumption of a large European country.

The global blue water footprint of AFW amounts to 82e9 m3 (Fig. 2b). These water losses compare to the blue water footprints of Mexico and Vietnam (FAO, 2017) and AFW would rank as the ninth largest consumer of blue water from a country perspective. India, China and the USA are the top (blue) water-consuming countries (FAO, 2016) (Fig. 2b).

These significant numbers may hinder national efforts to reach energy-efficiency targets (Rosenow et al., 2017) and to tackle rising water scarcity (Yannopoulos et al., 2019), and vary greatly at the regional and country levels due to different regional diets and waste incidence of each food type.

3.2. Avoidable food waste at the product level

The leading food groups of global AFW are *Cereals, Vegetables, Fruits, Milk* (dairy products, except butter), *Starchy Roots*, and *Meat* (Fig. 1). *Cereals* amount to 36%, mainly driven by AFW incidence in the *Wheat* and *Rice* types (both around 16%- Appendix A). *Vegetables* waste is driven by a wide range of vegetable products. For *Fruits*, *Apple, Orange,* and *Banana* products can be noted as substantial contributors (See Appendix. A). Dairy products are also substantial contributors to AFW, with 6% of the global tonnage in 2017. This is mainly driven by *Fresh dairy products*, and *Cheese*. *Starchy Roots* contribute also significantly with about 6% of global AFW. Finally, *Meat* products amount together to 6% of AFW waste, with in decreasing order, pork (2%), poultry (2%), and beef (1%) (Fig. 1).

Global energy loss from consumer AFW is also dominated by these

Table 1
Regional Contribution to global UFW and AFW Production and associated AFW energy and water footprints (consumption stage).

Region	AFW share	UFW share	AFW -*(kg/cap)*	UFW -*(kg/cap)*	Wasted Cumulative energy (MJ/cap)	Wasted water footprint (m3/cap)	Income -Level
Japan, China, and South Korea	46%	49%	97	98	1122	22	High-income/Upper middle
USA, Canada, Oceania	11%	4%	96	34	1354	23	High-income
Europe	18%	6%	83	28	1009	20	High-income
Northern Africa and Central and West Asia	6%	4%	41	30	401	11	Lower Middle/Low income
Latin America	5%	6%	29	30	353	8	Lower Middle/Low income
South and Southeast Asia	11%	24%	16	31	163	4	Lower Middle/Low income
Sub-Sahara Africa	2%	7%	8	24	87	1	Low income

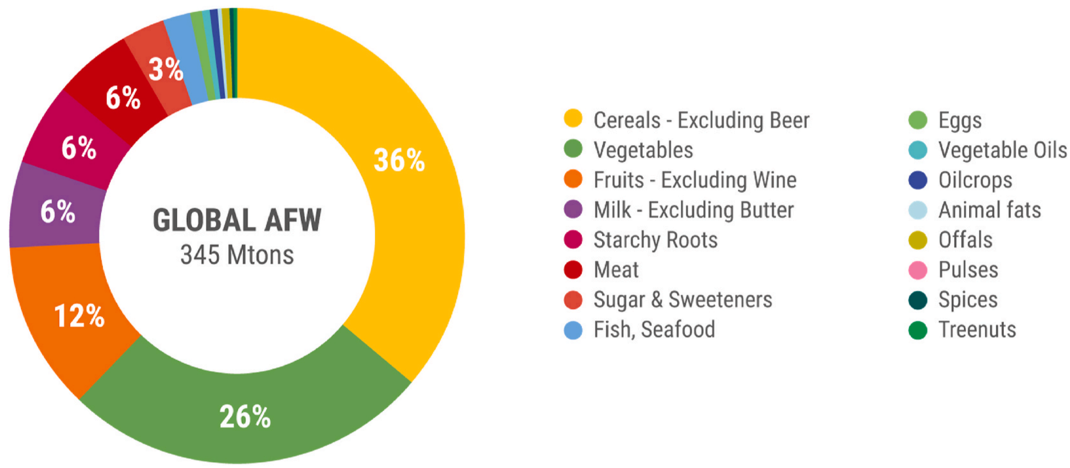

Fig. 1. Global Avoidable Food Waste in 2017- Contribution by weight by food type based on this study' results.

few food types. *Vegetables* are responsible for more than a quarter (27%), while *Cereal* products, especially rice and wheat products are responsible for an additional 22% (Fig. 3a). Globally, *Meat* products contribute about 17% of the energy loss, while only contributing 6% to the global AFW mass (Fig. 1). *Milk* (dairy products, except butter) contributes 7% to the global AFW energy loss. *Cheese*, which only contributes 0.6% of AFW mass, contributes 3% of global AFW energy loss (Appendix A). Additionally, *Fish,* and *Seafood*, which amount to only 2% of global AFW, disproportionately contribute to 10% of the AFW energy loss (Fig. 3a).

These same food types drive global AFW water loss, albeit in a different order. *Cereals* are the main contributors with a 55% share, mostly due to significant wasted quantities of rice and wheat products (Fig. 3b). Meat products contribute disproportionately, as *Meat* represents less than 6% of global AFW, yet 10% of the blue water footprint (Fig. 3b). Pork, beef, and poultry are responsible for contributions of about 4%, 2.5% and 2.5%, respectively (Appendix A). Conversely, while more than a quarter of all AFW is composed of vegetables, it only amounts to 7.5% of the total water footprint of AFW (Fig. 3b). This is due to the generally lower water footprints of vegetables compared to meat and cereal products. Similar conclusions can be derived for *Fruits*, they also contribute a little less to the AFW water footprint relative to their contribution to the total volume of AFW.

Different food consumption patterns drive the regional differences in wasted energy (Fig. 2). While *Japan, China, and South Korea* have the leading per capita generation of AFW, their wasted annual cumulative energy use per capita comes second, behind the *US, Canada, Oceania* (1354 MJ/capita/year) and just above *Europe*'s AFW cumulative energy use (1009 MJ/capita/year). This is mainly due to the higher consumption of both meat and dairy products (especially cheese) in the two latter regions. While the *US, Canada, Oceania* have similar water footprints per capita as *Japan, China, and South Korea*, with 23 and 22 m3/capita respectively, the composition of the AFW water footprints across these regions is very different. The *US, Canada, Oceania* AFW water footprint per capita is driven by wheat, and meat and dairy products, which are consumed in high quantities in this region. *Japan, China, and South Korea's* per capita AFW water footprint is overwhelmingly driven by rice, which has a relatively high water footprint (Chapagain and Hoekstra, 2011), and to a lesser extent by wheat products. Similarly, *Europe* has a lower AFW generated per capita (83kg/capita) than *Japan, China, South Korea* (97 kg/capita), but its AFW water footprint, is very similar with 20 m3/capita/year. Europe's higher water footprint per capita relative to its AFW volumes is due to its higher consumption of meat and dairy products, especially cheese.

3.3. From global to local energy and water impacts

The food system is part of a complex trade network, and energy and water resources are unevenly distributed across the planet. Recent studies have highlighted the connection between domestic consumption of products and their embedded water and energy resources, that is the sum of water and energy cumulatively used in the entire product's lifecycle (Mekonnen and Hoekstra, 2020) across the different supplying countries (Owen et al., 2018) (Lan et al., 2016). For example, Owen et al. (2018) used input-output analysis to show that only 21% and 52% of the water and energy impacts of the UK Food and Beverage Industry occur domestically. The remainder of the energy impacts were borne by China, Germany, France and other European countries. For water, the bulk of the impacts were especially felt in France and non-OECD countries. Likewise, Lenzen et al. (2013) highlighted that Indonesia and New Zealand consumed cattle produced in water-scarce regions of Australia (Lenzen et al., 2013). More broadly, large food producing countries, such as China, India, the USA or Spain, all top food-exporting countries are all experiencing increasing water scarcity (Greve et al., 2018), while other food-producing regions, such as North-Eastern Africa, Central and East Asia, and the South-West of the USA often experience severe water stress (Qin et al., 2019). Furthermore, non-irrigation water demand (municipal, industrial, and livestock) is forecasted to more than double in Africa and Asia by 2050 (Schlosser et al., 2014), directly competing with food production. By and large, each system of the Food-Energy-Water nexus is expected to significantly increase their output by the middle of the century due to increased demand (Van Vuuren et al., 2019) (Pastor et al., 2019). Further analysis using Multi-Regional Input-Output models on detailed food products can specifically localize the use of water throughout the global supply chain and help pinpoint how dietary shifts (Behrens et al., 2017) together with AFW reduction can alleviate the pressure on the FEW nexus in food-producing regions.

3.4. AFW and sustainable food systems

In 2019, the EAT-*Lancet Commission* published the first benchmark for a nutritive and sustainable global diet, stressing the necessity to shift diets away from meat and dairy as they contribute disproportionately to the global food system's current environmental burden (Poore and Nemecek, 2018) (Willett et al., 2019a), and towards those largely based on vegetables, fruits, and whole grains (Willett et al., 2019b). Nevertheless, these latter groups' high waste incidence, as highlighted in our study, represents a barrier that must be overcome to reach these targets sustainably. Additionally, compounding plant-based diets growth in popularity (Gehring et al., 2020) in affluent regions with these region's

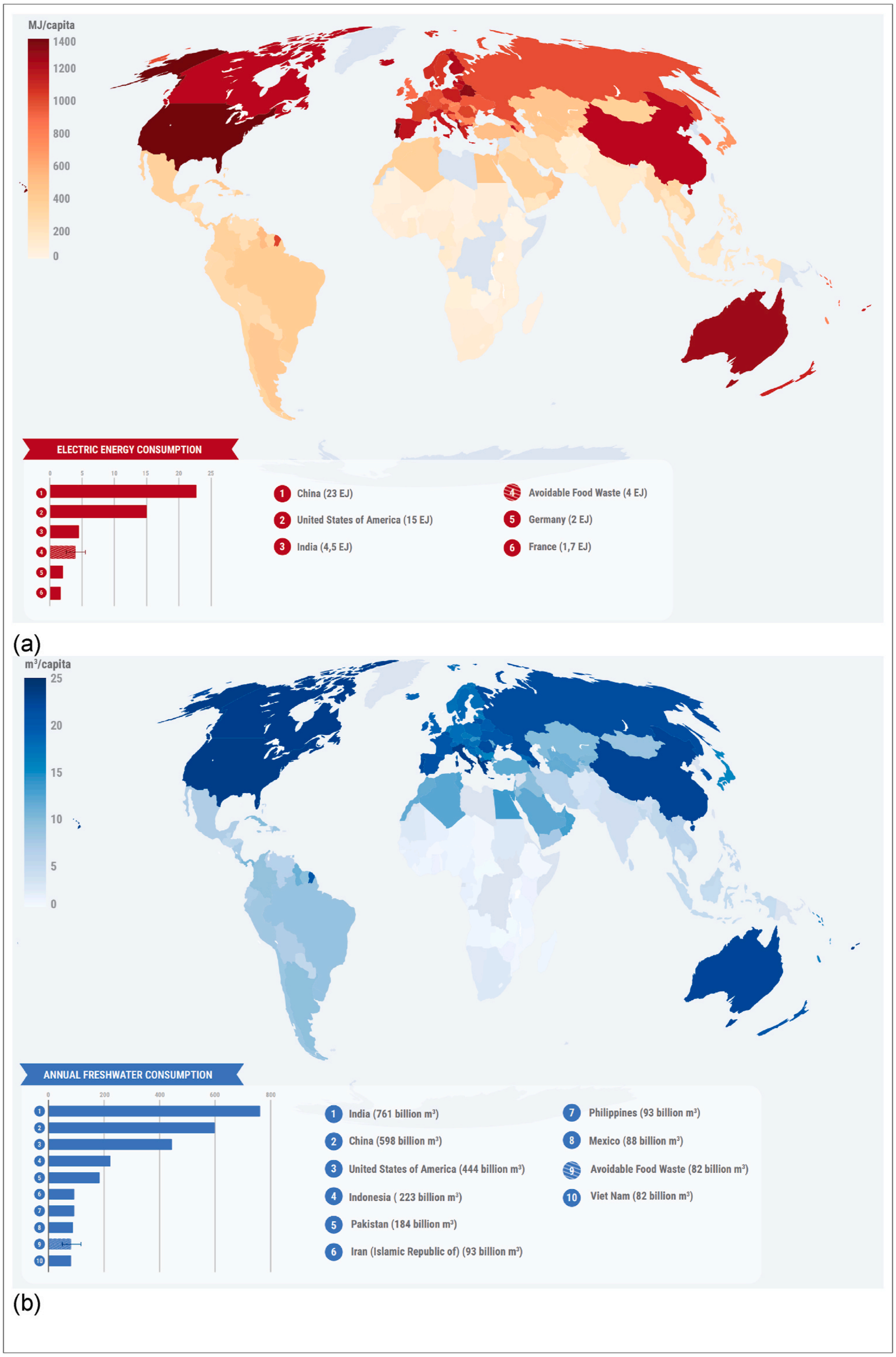

Fig. 2. (a) AFW's wasted cumulative energy use per capita (MJ/capita) for each country in 2017 (b) AFW's water footprint per capita for each country (m3/capita) in 2017 – according to study's results. (a) The electric energy consumption (expressed in EJ) of China, US, India, France and Germany derived from IEA's country energy profiles, is compared to the total wasted cumulative energy of global AFW in 2017 quantified by this study. (b) The water consumption of the top 10 most-water consuming countries (expressed in billion m3), derived from AQUASTAT, is compared to the water footprint of global AFW in 2017, quantified by this study. The AQUASTAT data time coverage varies per country – the most recent assessment year per country was selected and range between 2010 and 2017 among the top consuming countries.

more wasteful consumption behaviours may lead to much energy and water loss. *Vegetables* and *Fruits* are responsible for more than a third of the total cumulative energy use of AFW as their waste incidence is very high (Fig. 3a). In an *EAT-Lancet Commission* vegetarian scenario, pulses, legumes, and nuts replace two-thirds of the calories now consumed through meat and fish products; and vegetables and fruits replace the remaining third (Willett et al., 2019c). This global vegetarian diet would still waste 3.8 EJ of energy, unless the waste factors and/or cumulative energy uses vary across food types and regions. This illustrates that shifting diets without significantly reducing avoidable food waste at the consumption stage will only have limited impacts on the food system's energy footprint.

A shift to more plant-based diets may also have limited impacts on the global AFW blue water footprint due to high water demand of rice and wheat products, and their high global waste incidence. Furthermore, although the blue water footprints of *Meat* and *Dairy* products are higher than of *Vegetables* and *Fruits*, the increase in the consumption of vegetables and fruits, together with their high AFW incidence, will dampen the benefits of such a shift. Considering the same dietary scenario, a global vegetarian diet would waste about 80e9 m3 of blue

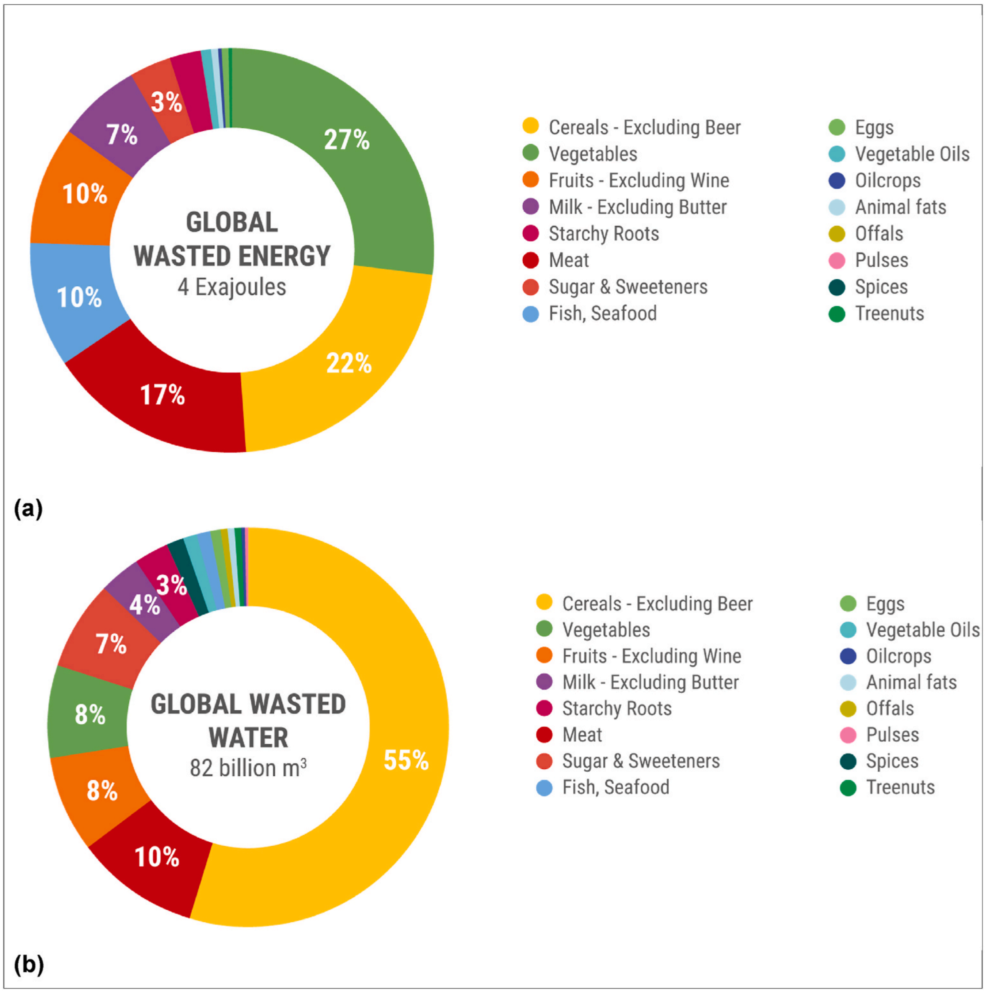

Fig. 3. Food type contribution to the global (a) wasted cumulative energy demand and (b) water footprint of global AFW in 2017 - based on this study' results.

water. This is only a 3% decrease compared to the current global diet. Therefore, incrementally shifting to plant-based diets, while not significantly reducing waste in the cereal (especially rice and wheat), vegetables, and fruits groups will only tacitly alleviate stress on global blue water resources.

3.5. Strategies to minimize AFW at the consumption stage

In order to reduce the more than 340 million tonnes of AFW, several prevention and rescue or avoidance strategies must be implemented. In affluent and middle-income countries, different solutions should be developed, scaled, and integrated into holistic national strategies, including awareness raising campaigns, education, better labelling schemes, dietary guidelines, and policies to encourage food sharing through food banks. In the hospitality industry, studies have shown that a reduction in plate size can reduce up to 57% the amount of food wasted (Wansink and van Ittersum, 2013). Changes in dietary guidelines in schools, promoting healthy food, have shown a waste decrease of up to 28% for vegetables (Schwartz et al., 2015). Informational campaigns about food waste in both households and hotels, have reportedly reduced waste by 28% and 20% (Reynolds, 2019a). The rise of online food sharing platforms (e.g., Too Good to Go, Olio) constitutes a promising new path to *rescue* avoidable food waste at a large scale (Harvey et al., 2020), but their potential needs further assessing (Reynolds, 2019b). In low-income countries, on top of education, improving packaging and the incremental deployment of cold chain technologies in food services and households will enable a prolonged shelf-life of food products. For example, the rise of refrigeration availability in Chinese households between 1991 and 2009 correlates with a reduction in food waste (Qi et al., 2020). The scale and depth of the issue of post-retail AFW requires a combination of the above-mentioned strategies, applied simultaneously, that considers the local context (economic, social, dietary, and urbanization level). As the global GDP-per capita increases, it is key to implement these strategies to curtail a future increase in AFW and its associated energy and water losses.

4. Conclusions

The present study analyses through the Food-Energy-Water nexus perspective the impacts of consumer avoidable food waste on the global energy and water systems. Significant amounts of water and energy are used along the global food chain, resulting in large amounts of energy and water resources being wasted whenever edible food that reach its final consumers is not consumed.

The nexus impacts of consumer avoidable food waste has been explored with a comprehensive analytical model for the quantification of avoidable food waste and its related wasted water and energy impacts. In terms of energy, the 344 million tons of consumer avoidable food are responsible for about 4 EJ of wasted energy globally. This burden is equivalent to the electricity consumption of Germany and France, combined. In terms of water, the blue water footprint of global consumer AFW is 82 billion cubic meters, representing amounts similar to Vietnam or Mexico's annual water consumption.

The main innovation in the model is the possibility to understand the contribution of different food types on the energy and water impacts of global consumer AFW and the roles of regional and national diets and waste patterns in shaping these impacts. This will help establish a prioritization on regional AFW reduction strategies per food type to achieve a sustainable and resilient food system. Another key aspect is that the model presented in this paper enables us to refine our understanding on how projected shift in diets at the regional and national levels will impact the environment, and specifically the energy and water systems by considering current waste patterns per food type.

In addition to the need for improved and more detailed energy and food waste statistics, further research is needed to spatialize the energy and water impacts of global consumer AFW. The model developed in this study could be integrated further into Multi-Regional Input Output models to understand the ramification of food-type specific avoidable food waste reduction strategies on the local energy and water systems of food producing regions.

As countries become wealthier, it is urgently needed to curb global consumer avoidable food waste by deploying rapidly a combination of food waste reduction strategies that takes into account local contexts and diets.

Data availability

The datasets generated during and/or analysed during the current study are available from the corresponding author upon request.

Funding source

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

CRediT authorship contribution statement

A. Coudard: Conceptualization, Methodology, Software, Formal analysis, Data curation, Writing – original draft, Visualization, Writing – review & editing. **E. Corbin:** Conceptualization, Methodology, Writing – review & editing. **J. de Koning:** Conceptualization, Writing – review & editing. **A. Tukker:** Conceptualization, Methodology, Writing – review & editing. **J.M. Mogollón:** Conceptualization, Methodology, Writing – review & editing, Validation, Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A & B. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jclepro.2021.129342.

References

Albrecht, T.R., Crootof, A., Scott, C.A., 2018. The Water-Energy-Food Nexus: a systematic review of methods for nexus assessment. Environ. Res. Lett. 13 (4), 043002 https://doi.org/10.1088/1748-9326/aaa9c6.

Behrens, P., Kiefte-de Jong, J.C., Bosker, T., Rodrigues, J., de Koning, A., Tukker, A., 2017. Environmental impacts of dietary recommendations. Proc. Natl. Acad. Sci. Unit. States Am. 114 (51), 13412–13417. https://doi.org/10.1073/pnas.1711889114.

Bruckner, M., Wood, R., Moran, D., Kuschnig, N., Wieland, H., Maus, V., Börner, J., 2019. FABIO—the construction of the food and agriculture biomass input–output model. Environ. Sci. Technol. 53 (19), 11302–11312. https://doi.org/10.1021/acs.est.9b03554, 2019.

Carlsson-Kanyama, A., Ekström, M.P., Shanahan, H., 2003. Food and life cycle energy inputs: consequences of diet and ways to increase efficiency. Ecol. Econ. 44 (2–3), 293–307. https://doi.org/10.1016/s0921-8009(02)00261-6.

Chapagain, A.K., Hoekstra, A.Y., 2004. Water footprints of nations. Value of Water Research Report Series No. 16. UNESCO-IHE, Delft, the Netherlands. Available online: www.waterfootprint.org/Reports/Report16Vol1.pdf.

Chapagain, A.K., Hoekstra, A.Y., 2011. The blue, green and grey water footprint of rice from production and consumption perspectives. Ecol. Econ. 70 (4), 749–758. https://doi.org/10.1016/j.ecolecon.2010.11.012.

Clements, K.W., Si, J., 2017. Engel's Law, diet diversity, and the quality of food consumption. Am. J. Agric. Econ. 100 (1), 1–22. https://doi.org/10.1093/ajae/aax053.

Daher, B., Mohtar, R.H., Lee, S.-H., Assi, A., 2017a. Modeling the water-energy-food nexus. Geophys. Monogr. 55–66. https://doi.org/10.1002/9781119243175.ch6.

Daher, B., Mohtar, R.H., Lee, S.-H., Assi, A., 2017b. Modeling the water-energy-food nexus. Geophys. Monogr. 55–66. https://doi.org/10.1002/9781119243175.ch6.

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

Dou, Z., Toth, J.D., 2020. Global primary data on consumer food waste: rate and characteristics – a review. Resour. Conserv. Recycl., 105332 https://doi.org/10.1016/j.resconrec.2020.105332.

D'Odorico, P., Davis, K.F., Rosa, L., Carr, J.A., Chiarelli, D., Dell'Angelo, J., Gephart, J., MacDonald, G., Seekell, D., Suweis, S., Rulli, M.C., 2018. The global food-energy-water nexus. Rev. Geophys. https://doi.org/10.1029/2017rg000591.

FAO, 2011. Global Food Losses and Food Waste - Extent, Causes, and Prevention. Rome. FAO.

FAO, 2016. AQUASTAT Country Fact Sheet.

FAO, 2017. AQUASTAT Country Fact Sheet.

FAO, 2017. Food Balance Sheets. FAO. https://www.fao.org/faostat/en/#data/FBS.

FAO-OECD, 2019. OECD/FAO Agricultural Outlook 2020-2029 - Agricultural Statistics. FAO-OECD.

FAO, 2019. The State of Food and Agriculture 2019. Moving Forward on Food Loss and Waste Reduction. FAO, Rome.

Gehring, J., Touvier, M., Baudry, J., Julia, C., Buscail, C., Srour, B., Hercberg, S., Péneau, S., Kesse-Guyot, E., Allès, B., 2020. Consumption of ultra-processed foods by pesco-vegetarians, vegetarians, and vegans: associations with duration and age at diet initiation. J. Nutr. https://doi.org/10.1093/jn/nxaa196, 2020 Jul 21:nxaa196, Epub ahead of print. PMID: 32692345.

Greve, P., Kahil, T., Mochizuki, J., Schinko, T., Satoh, Y., Burek, P., Fischer, G., Tramberend, S., Burtscher, R., Langan, S., Wada, Y., 2018. Global assessment of water challenges under uncertainty in water scarcity projections. Nature Sustain. 1 (9), 486–494. https://doi.org/10.1038/s41893-018-0134-9.

Harvey, J., Smith, A., Goulding, J., Branco Illodo, I., 2020. Food sharing, redistribution, and waste reduction via mobile applications: a social network analysis. Ind. Market. Manag. https://doi.org/10.1016/j.indmarman.2019.02.019.

Hoff, H., 2011. Background paper for the bonn 2011 nexus conference: the water, energy and food security nexus. Retrieved from. http://wef-conference.gwsp.org/fileadmin/documents_news/understanding_the_nexus.pdf.

Hussien, W.A., Memon, F.A., Savic, D.A., 2017. An integrated model to evaluate water-energy-food nexus at a household scale. Environ. Model. Software 93, 366–380. https://doi.org/10.1016/J.ENVSOFT.2017.03.034.

IEA, 2018. Key Energy Statistics. IEA, 2019. https://www.iea.org/countries/.

John-Jaja, S.A., Udoh, U.H., Nwokolo, S.C., 2016. Repeatability Estimates of Egg Weight and Egg-Shell Weight under Various Production Periods for Bovan Nera Black Laying Chicken. Beni-Suef University Journal of Basic and Applied Sciences. https://doi.org/10.1016/j.bjbas.2016.11.001.

Karnib, A.A., 2017. Quantitative assessment framework for water, energy and food nexus, 01 Comput. Water Energy Environ. Eng. 6, 11–23, 10.4236/cweee.2017.61002.

Kibler, K.M., Reinhart, D., Hawkins, C., Motlagh, A.M., Wright, J., 2018. Food waste and the food-energy-water nexus: a review of food waste management alternatives. Waste Manag. 74, 52–62. https://doi.org/10.1016/j.wasman.2018.01.014.

Lan, J., Malik, A., Lenzen, M., McBain, D., Kanemoto, K., 2016. A structural decomposition analysis of global energy footprints. Appl. Energy 163, 436–451. https://doi.org/10.1016/J.APENERGY.2015.10.178.

Lenzen, M., Moran, D., Bhaduri, A., Kanemoto, K., Bekchanov, M., Geschke, A., Foran, B., 2013. International trade of scarce water. Ecol. Econ. 94, 78–85. https://doi.org/10.1016/J.ECOLECON.2013.06.018.

Lopez Barrera, E., Hertel, T., 2020. Global food waste across the income spectrum: implications for food prices, production and resource use. Food Pol. https://doi.org/10.1016/j.foodpol.2020.101874.

Mannan, M., Al-Ansari, T., Mackey, H.R., Al-Ghamdi, S.G., 2018a. Quantifying the energy, water and food nexus: a review of the latest developments based on life-cycle assessment. J. Clean. Prod. 193, 300–314. https://doi.org/10.1016/J.JCLEPRO.2018.05.050.

Mannan, M., Al-Ansari, T., Mackey, H.R., Al-Ghamdi, S.G., 2018b. Quantifying the energy, water and food nexus: a review of the latest developments based on life-cycle assessment. J. Clean. Prod. 193, 300–314. https://doi.org/10.1016/J.JCLEPRO.2018.05.050.

Mekonnen, M.M., Hoekstra, A.Y., 2011. Hydrology and Earth System Sciences the green, blue and grey water footprint of crops and derived crop products. Hydrol. Earth Syst. Sci. 15, 1577–1600. https://doi.org/10.5194/hess-15-1577-2011.

Mekonnen, M.M., Hoekstra, A.Y., 2012. A Global Assessment of the Water Footprint of Farm Animal Products. https://doi.org/10.1007/s10021-011-9517-8.

Mekonnen, M.M., Hoekstra, A.Y., 2020. Blue water footprint linked to national consumption and international trade is unsustainable. Nat Food 1, 792–800. https://doi.org/10.1038/s43016-020-00198-1.

Melo, F.P.L., Parry, L., Brancalion, P.H.S., et al., 2020. Adding forests to the water–energy–food nexus. Nat Sustain. https://doi.org/10.1038/s41893-020-00608-z.
Munasinghe, M., Deraniyagala, Y., Dassanayake, N., Karunarathna, H., 2017. Economic, social and environmental impacts and overall sustainability of the tea sector in Sri Lanka. Sustain. Prod. Consum. 12, 155–169. https://doi.org/10.1016/j.spc.2017.07.003.
Nayak, A., Bhushan, B., 2019. An overview of the recent trends on the waste valorization techniques for food wastes. J. Environ. Manag. 233, 352–370. https://doi.org/10.1016/J.JENVMAN.2018.12.041.
Owen, A., Scott, K., Barrett, J., 2018. Identifying critical supply chains and final products: an input-output approach to exploring the energy-water-food nexus. Appl. Energy 210, 632–642. https://doi.org/10.1016/J.APENERGY.2017.09.069.
Pastor, A.V., Palazzo, A., Havlik, P., et al., 2019. The global nexus of food–trade–water sustaining environmental flows by 2050. Nat Sustain 2, 499–507. https://doi.org/10.1038/s41893-019-0287-1.
Patt, A., Van Vliet, O., Lilliestam, J., Pfenninger, S., 2019. Will policies to promote energy efficiency help or hinder achieving a 1.5 °C climate target? Energy Eff. 12, 551–565. https://doi.org/10.1007/s12053-018-9715-8.
Poore, J., Nemecek, T., 2018. Reducing food's environmental impacts through producers and consumers. Science 360 (6392), 987–992. https://doi.org/10.1126/science.aaq0216.
Qi, D., Apolzan, J.W., Li, R., Roe, B.E., 2020. Unpacking the decline in food waste measured in Chinese households from 1991 to 2009. Resour. Conserv. Recycl. 160, 104893 https://doi.org/10.1016/j.resconrec.2020.104893.
Qin, Y., Mueller, N.D., Siebert, S., Jackson, R.B., AghaKouchak, A., Zimmerman, J.B., Tong, D., Hong, C., Davis, S.J., 2019. Flexibility and intensity of global water use. Nature Sustain. https://doi.org/10.1038/s41893-019-0294-2.
Reynolds, C., 2019a. Review: consumption-stage food waste reduction interventions – what works and how to design better interventions. Food Pol. 83, 7–27. https://doi.org/10.1016/j.foodpol.2019.01.009.
Reynolds, C., 2019b. Review: consumption-stage food waste reduction interventions – what works and how to design better interventions. Food Pol. 83, 7–27. https://doi.org/10.1016/j.foodpol.2019.01.009.
Ridoutt, B.G., Pfister, S., 2010. A revised approach to water footprinting to make transparent the impacts of consumption and production on global freshwater scarcity. Global Environ. Change 20 (1), 113–120. https://doi.org/10.1016/j.gloenvcha.2009.08.003.
Rosenow, J., Cowart, R., Bayer, E., Fabbri, M., 2017. Assessing the European Union's energy efficiency policy: will the winter package deliver on "Efficiency First". Energy Res. Social Sci. 26, 72–79. https://doi.org/10.1016/j.erss.2017.01.022.
Schlosser, C.A., Kenneth, S., Goa, X., Fant, C., Blanc, E., Paltselv, S., Jacoby, H., Reilly, J., Gueneau, A., 2014. The future of global water stress: an integrated assessment. Earth's Future 2, 341–361. https://doi.org/10.1002/2014EF000238.
Schwartz, M.B., Henderson, K.E., Read, M., Danna, N., Ickovics, J.R., 2015. New school meal regulations increase fruit consumption and do not increase total plate waste Child. Obesity 11, 242–247. https://doi.org/10.1089/chi.2015.0019.
Sim, S., Barry, M., Clift, R., Cowell, S.J., 2007. The relative importance of transport in determining an appropriate sustainability strategy for food sourcing. Int. J. Life Cycle Assess. 12, 422–431. https://doi.org/10.1065/lca2006.07.259.
Springmann, M., Clark, M., Mason-D'Croz, D., Wiebe, K., Bodirsky, B.L., Wim de Vries, Lassaletta L., Vermeulen, S., Herrero, M., Carlson, K., Jonell, M., Troell, M., DeClerck, F., Gordon, L., Zurayk, R., Scarborough, P., Rayner, M., Loken, B., Franzo, J., Godfray, C., Tilman, D., Rockström, J., Willett, W., 2018. Options for keeping the food system within environmental limits. Nature. https://doi.org/10.1038/s41586-018-0594-0.
Tom, M.S., Fischbeck, P.S., Hendrickson, C.T., 2016. Energy use, blue water footprint, and greenhouse gas emissions for current food consumption patterns and dietary 165 recommendations in the US. Environ. Syst. Dec. 36 (1), 92–103. https://doi.org/10.1007/s10669-015-9577-y.
Usubiaga-Liaño, A., Behrens, P., Daioglou, V., 2020a. Energy use in the global food system. J. Ind. Ecol. https://doi.org/10.1111/jiec.12982.
Usubiaga-Liaño, A., Behrens, P., Daioglou, V., 2020b. Energy use in the global food system. J. Ind. Ecol. https://doi.org/10.1111/jiec.12982.
Usubiaga-Liaño, A., Behrens, P., Daioglou, V., 2020c. Energy use in the global food system. J. Ind. Ecol. https://doi.org/10.1111/jiec.12982.
Van Vuuren, D.P., Bijl, D.L., Bogaart, P., et al., 2019. Integrated scenarios to support analysis of the food–energy–water nexus. Nat Sustain 2, 1132–1141. https://doi.org/10.1038/s41893-019-0418-8.
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 (8), 084008 https://doi.org/10.1088/1748-9326/10/8/084008.
Vanham, D., Mak, T.N., Gawlik, B.M., 2016a. Urban food consumption and associated water resources: the example of Dutch cities. Sci. Total Environ. 565, 232–239. https://doi.org/10.1016/J.SCITOTENV.2016.04.172.
Vanham, D., Mak, T.N., Gawlik, B.M., 2016b. Urban food consumption and associated water resources: the example of Dutch cities. Sci. Total Environ. 565, 232–239. https://doi.org/10.1016/J.SCITOTENV.2016.04.172.
Villarroel Walker, R., Beck, M.B., Hall, J.W., Dawson, R.J., Heidrich, O., 2014. The energy-water-food nexus: strategic analysis of technologies for transforming the urban metabolism. J. Environ. Manag. 141, 104–115. https://doi.org/10.1016/J.JENVMAN.2014.01.054.
Vittuari, M., Pagani, M., Johnson, T.G., De Menna, F., 2020a. Impacts and costs of embodied and nutritional energy of food waste in the US food system: distribution and consumption (Part A). J. Clean. Prod. 252 https://doi.org/10.1016/j.jclepro.2019.119857.
Vittuari, M., Pagani, M., Johnson, G.T., Menna, F., 2020b. Impacts and costs of embodied and nutritional energy of food waste in the US food system: distribution and consumption (Part B). J. Clean. Prod. 182 https://doi.org/10.1016/j.jclepro.2019.119857, 119857.
Wansink, B., van Ittersum, K., 2013. Portion size me: plate-size induced consumption norms and win-win solutions for reducing food intake and waste. J. Exp. Psychol. Appl. 19 (4), 320–332. https://doi.org/10.1037/a0035053.
Willett, W., et al., 2019a. 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.
Willett, W., et al., 2019b. 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.
Willett, W., et al., 2019c. 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.
WRAP, 2014a. Household Food and Drink Waste: A Product Focus – Final Report, 978-1-84405-469-5.
WRAP, 2014b. Household Food and Drink Waste: A Product Focus – Final Report, 978-1-84405-469-5.
Xue, L., Liu, G., Parfitt, J., Liu, X., Van Herpen, E., Stenmarck, Å., Cheng, S., 2017. Missing food, missing data? A critical review of global food losses and food waste data. Environ. Sci. Technol. 51 (12), 6618–6633. https://doi.org/10.1021/acs.est.7b00401.
Yannopoulos, S., Giannopoulou, I., Kaiafa-Saropoulou, M., 2019. Investigation of the current situation and prospects for the development of rainwater harvesting as a tool to confront water scarcity worldwide. Water 11, 2168. https://doi.org/10.3390/w11102168.
Zhuo, L., Mekonnen, M.M., Hoekstra, A.Y., 2014. Sensitivity and uncertainty in crop water footprint accounting: a case study for the Yellow River basin. Hydrol. Earth Syst. Sci. 18, 2219–2234. https://doi.org/10.5194/hess-18-2219-2014.
Kaza, Silpa, Yao, Lisa, Bhada-Tata, Perinaz, Van Woerden, Frank, 2018. What a Waste 2.0: A Global Snapshot of Solid Waste Management to 2050. Urban Development Series. World Bank, Washington, DC. https://doi.org/10.1596/978-1-4648-1329-0. License: Creative Commons Attribution CC BY 3.0 IGO.