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Domestic plant food loss and waste in the United States: Environmental footprints and mitigation strategies

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ABSTRACT

The United States (U.S.) aims to reduce half of food loss and waste (FLW) by 2030. To achieve this goal, the public, academic, and political attentions on FLW have been increasing, and a series of actions have been implemented. However, the actions lack consideration on the categorical priority of FLW mitigation in relation to environmental footprints. In this article, we compare the FLW of three main plant food categories (i.e., grains, vegetables, and fruits) and their water and carbon footprints during 1970–2017. The vegetable FLW doubled during the period, reaching 3.39 × 10^{10} kg in 2017, which was 5- and 2-fold higher than the FLW of grains and fruits, respectively. The FLW of vegetables, grains, and fruits contributed 29%, 47%, and 24% to the total blue water wasted through FLW. The total carbon dioxide emissions generated by plant FLW were contributed by vegetables with 50%, grains with 31%, and fruits with 19%. Canonical correspondence analysis indicates that vegetable FLW had a higher positive correlation with urbanization, household incomes, gross domestic product, and high-income population than grain FLW, whereas fruit FLW was not influenced by these socioeconomic factors. Therefore, we suggest that the FLW mitigation should be prioritized on vegetables. Specific strategies include local food sourcing, shortening food miles, building food belts, and developing controlled-environment agriculture. Our data-based comparisons provide valuable insights into food policy improvement for achieving the 2030 reduction goal of the U.S., but the insights could be improved by considering the influences of foods imported from other nations.

1. Predicament of food loss and waste

Food loss and waste (FLW) cause environmental, socio-economic, and ethical concerns about food crisis and security (Principato et al., 2019; Skaf et al., 2021). The concerns have been exacerbated in recent years due to the COVID-19 pandemic (Luo et al., 2021). The United Nations Food and Agriculture Organization (FAO) reported that 33–50% of food is lost and wasted in the food supply chain, amounting to an annual loss of 1.4 billion tons of food globally (FAO, 2020). FLW accounts for ~40% of the total food in the United States (U.S.), which is at one of the highest levels in the world (Ho, 2020). In 2021, it is estimated that one person wastes ~100 kg of food per year, and one household spends $1,600 on food wastage per year (EPA, 2021). Since 2015, the U. S. Department of Agriculture (USDA) and Environmental Protection Agency (EPA) have implemented a plan for half-reduction of FLW by 2030 to facilitate the realization of the United Nations' Sustainable Development Goals (EPA, 2021).

A consequence of FLW is the wasting of water and energy resources and increase in greenhouse gas emissions (Girotto et al., 2015; Luo et al., 2021; Read et al., 2020; Willett et al., 2019). Food systems consume ~70% of global freshwater withdrawals and ~30% of global energy consumption while producing ~25% of global carbon dioxide emissions (FAO, 2013; Garcia and You, 2016). Thus, 33%-50% of FLW is equivalent to wasting 23%-35% of freshwater withdrawals, wasting 10%-15% of energy consumption, and contributing to 8%-13% of global carbon dioxide emissions.

Approaches to mitigating FLW at different stages of food supply chains have been addressed, such as enhancing technologies at storage

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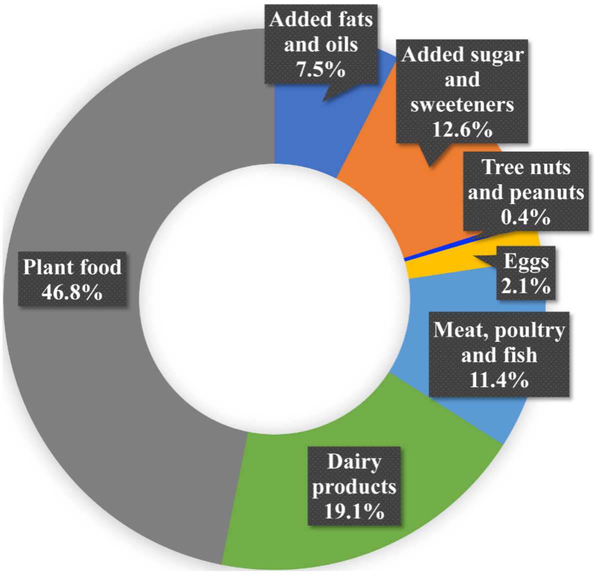

Fig. 1. Food category breakdown of totafl U.S.-based pflant FLW fin the retafifl and consumer stages. Pflant food fincfludes vegetabfles, frufits, and grafin products. Food floss refers to the decrease of edfibfle food mass, whfich occur at former stages of food suppfly chafin (fi.e., productfion, post-harvest, and processfing stages). Food waste takes pflace at retafifl and consumptfion stages and generaflfly reflates to behavfior fissues (FAO, 2011; Lfiu et afl., 2013; Parffitt et afl., 2010). Data sources are the 2017 report of Naturafl Resources Defense Councfifl.

stage, standardfizfing packagfing and flabeflfing at processfing and retafifl stages, and fintervenfing consumer behavfiors (Cattaneo et afl., 2021; Muth et afl., 2019; Read et afl., 2020). These stage-specfiffic efforts coufld effectfivefly reduce the totafl FLW. However, prfiorfitfizfing these efforts reflies on the understandfing of envfironmentafl footprfints of FLW of each food category (FAO, 2011). For exampfle, wastfing one metrfic ton of soybeans woufld waste 2,000 m³ of water, whereas thfis number fincreases by 6.5-fofld for beef wastfing (Mekonnen and Hoekstra, 2011, 2012). Thus far, few studfies have been performed on categorfizfing FLW fin reflatfion to envfironmentafl footprfints. Sfince the pflant FLW makes up the flargest portfion of totafl U.S. wasted food (Ffig. 1), thfis perspectfive afims to quantfify the characterfistfics of domestfic pflant FLW trajectory fin the U.S. from 1970 to 2017 and evafluate the envfironmentafl footprfints of each pflant food category. The anaflysfis fis expected to provfide vafluabfle finsfights finto strategfies for prfiorfitfizatfion of FLW mfitfigatfion and carbon neutraflfizatfion of food, energy, and water systems.

2. Driving forces of plant FLW

The totafl domestfic pflant FLW fin the U.S. fincreased from 3.34×10^{10} kg/year fin 1970 to 6.18×10^{10} kg/year fin 2017 (Ffig. 2A). Thfis 2-fofld fincrease was posfitfivefly correflated to the fincreases fin gross domestfic product (GDP) and urbanfizatfion rate, whfich were coupfled wfith growfing hfigh-fincome popuflatfion and househofld fincomes. Specfiffficaflfly, these socfioeconomfic factors had hfigher correflatfion wfith the FLW of vegetabfles than grafins but dfid not sfignfifficantfly finfluence the FLW of frufits (Ffig. 2B). Vegetabfles had the flargest share of FLW, accountfing for haflf of the totafl FLW wfith an fincrease from 1.73×10^{10} kg/year fin 1970 to 3.39×10^{10} kg/year fin 2017. The annuafl amount of vegetabfle FLW was approxfimatefly 5- and 2-fofld hfigher than the FLW of grafins and frufits, respectfivefly (Ffig. 2A). Thfis dfifference among food categorfies fis attrfibuted to the hfigher amount of vegetabfle consumptfion reflatfive to grafins and frufits fin the U.S. Prevfious studfies showed that the communfity that consumed the most vegetabfles wasted vegetabfles 4.7 tfimes more than the communfity that consumed the fleast vegetabfles (Conrad, 2020). In the U.S., the urbanfizatfion rate fincreased from 73.6% fin 1970 to 82.7% fin 2017 (O'Nefiflfl, 2021), meanfing that 114 mfiflflfion more peopfle have access to

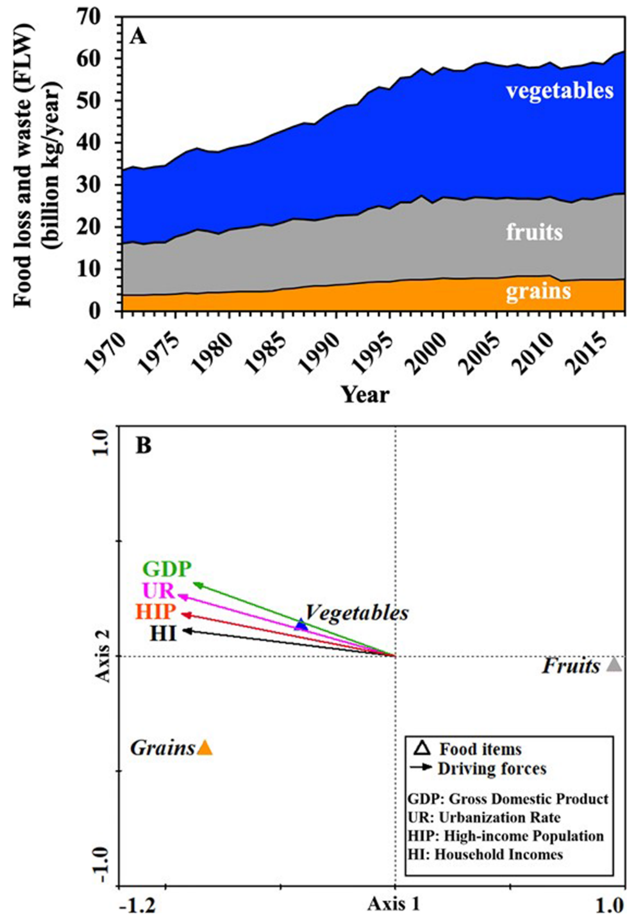

Fig. 2. (A) Annuafl food floss and waste (FLW) of each pflant-based food category (fi.e., grafins, vegetabfles, and frufits) fin the U.S. from 1970 to 2017. The amount of FLW of each food fitem was caflcuflated by mufltfipflyfing prfimary productfion wefight by FLW rate. Data sources are the Loss-Adjusted Food Avafiflabfiflfity (LAFA) data serfies from the U.S. Department of Agrficuflture's Economfic Research Servfice (ERS). (B) Canonficafl correspondence anaflysfis (CCA) between FLW of each food commodfity (trfiangfle) and finfluentfiafl factors (arrow) fin the U. S. The angfle between the arrow and flfine from the orfigfin to each trfiangfle symbofl proposes a posfitfive or negatfive correflatfion. The acute angfle findficates a posfitfive reflatfionshfip, and a smaflfler acute angfle findficates a hfigher correflatfion. In contrast, an obtuse angfle reffflects a negatfive reflatfionshfip, and a bfigger angfle findficates a hfigher correflatfion. A rfight angfle demonstrates the flowest correflatfion. The ffiflltered FLW data of grafins, vegetabfles, and frufits for the years from 1970 to 2017 were used for CCA. Data sources fincflude the Worfld Bank, Our Worfld fin Data, and Statfista.

vegetabfle-domfinated heaflthfier dfiets. In addfitfion, socfiafl marketfing campafigns advocate consumptfion of vegetabfles for fimproved famfifly heaflth (Jaeger and MacFfie, 2001; Poflflard et afl., 2008). Another potentfiafl reason for hfigher vegetabfle FLW fis finapproprfiate food storage, whfich causes fafiflure of food consumptfion (Neff et afl., 2015; Wafitt and Phfiflflfips, 2016). Ffig. 1B shows that vegetabfle FLW fincreases among hfigh-fincome popuflatfions because consumers fincflfine to reject or fignore fimperfect products (e.g., mfisshapen, unattractfive, or surface-damaged products). As a resuflt, busfinesses and farmers have to dfispose of fimperfect food to cater to the aesthetfic standard (Hfingston and Noseworthy, 2020). In addfitfion to the aesthetfics, the sensory characterfistfics of vegetabfles fis another fimportant factor that fleads to FLW. For exampfle, bfitterness and pfiquancy of vegetabfles have an finfluence on preferences of consumers. Sfince fit fis dfiffficuflt to predfict consumer behavfiors due to the varfiatfion fin sensory aversfion, the uncertafinty fin retafifl marketfing fleads to the wastes of vegetabfles (Poeflman et afl., 2017).

The FLW of vegetabfles fincreased by ~50% from 1970 to 2000 and

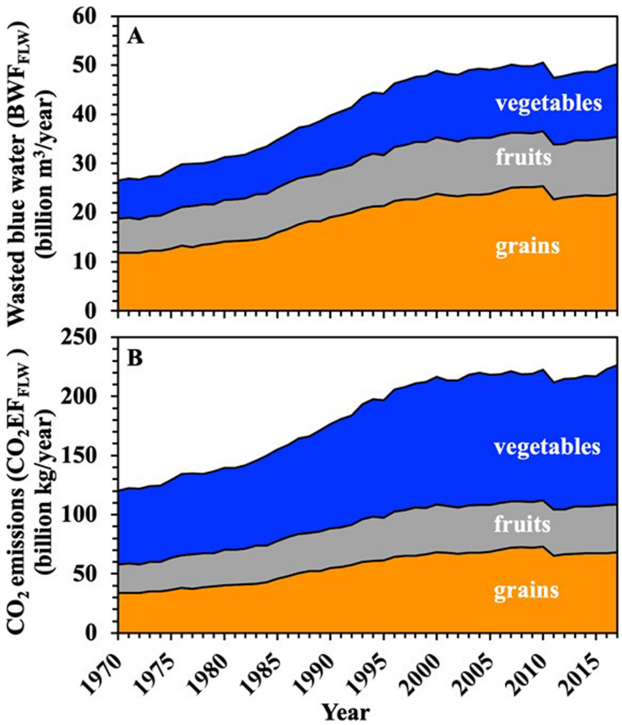

Fig. 3. Environmental impacts related to food loss and waste (FLW) of each domestic plant-based food category (e., grains, vegetables, and fruits) in the U. S. from 1970 to 2017. (A) The amount of wasted blue water associated with plant FLW (BWF_{FLW}) was estimated by multiplying direct water footprint by the FLW of each food category (Liu et al., 2013). Direct water footprint (m^3/kg) indicates the amount of blue water consumed in the production process of one kilogram of each food category (Marston et al., 2018). (B) The amount of carbon dioxide emissions was quantified by multiplying the virtual carbon footprint by the FLW of each food category. Virtual carbon footprint (kg/kg) indicates the amount of carbon dioxide that is emitted to supply one kilogram of each food category, including all the emissions produced on the farm, in the factory, on the road, in the shop, and at home (GreenEatz, 2021). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

decelerated afterward (Fig. 2A). The slowing growth rate of FLW after 2000 resulted from shortening food supply chains (SFSC), which was implemented in the 1990s to shorten the time between the purchase of food products and their consumption (i.e., the food-to-table initiative). For instance, the number of farmers' markets participating in the SFSC action in the U.S. increased by 53% from 1994 to 2004. These SFSC farmers' markets provided direct farmer-to-consumer food distribution channels that greatly reduced vegetable FLW at storage, transportation, and processing stages of the food supply chain (Baker et al., 2009; Mbow et al., 2019).

3. Environmental footprints of plant FLW

3.1. Wasted blue water

Blue water is the water from rivers, lakes, wetlands, ponds, and shallow aquifers. Since green water is soil water which comes from blue water, our analysis was only focused on blue water that is directly used in the field. The total amount of wasted blue water associated with domestic plant FLW (BWF_{FLW}) in the U.S. increased by 89% from 2.66 × 10^{10} m^3/year in 1970 to 5.02 × 10^{10} m^3/year in 2017 (Fig. 3A). Among the three food categories, grains contributed 47% of BWF_{FLW} with the average annual quantity of 1.93 ± 0.47 × 10^{10} m^3. This large contribution was due to the large water consumption for grain food production. It was reported that ~75% of national groundwater and 47% of national surface water were consumed by several dominant grains, such as corn, rice, wheat, and soybeans (Marston et al., 2018). The variation of grain BWF_{FLW} during the period from 1970 to 2017 is attributed to the changes in population, climate, field management practices (e.g., planting and harvesting dates, conventional and conservative agriculture, and irrigation efficiencies), and crop types (Marston et al., 2018). Vegetable FLW was the second contributor to the total BWF_{FLW}, accounting for ~29% of the total BWF_{FLW} with an average annual value of 1.15 ± 0.24 × 10^{10} m^3. The FLW of fruits consumed about 9.89 ± 1.55 × 10^{9} m^3 of blue water per year from 1970 to 2017, accounting for ~24% of the total BWF_{FLW}.

3.2. Carbon dioxide emissions

The total amount of carbon dioxide emissions footprint associated with the FLW of domestic plant food supply chain (CO_2EF_{FLW}) ranged from 1.20 × 10^{11} kg/year in 1970 to 2.27 × 10^{11} kg/year in 2017 in the U.S. (Fig. 3B), equivalent to 2.7% and 4.4% of annual national carbon dioxide emissions in 1970 and 2017, respectively (Tiseo, 2021). The total CO_2EF_{FLW} from 1970 to 2000 increased with an average annual rate of 2% in quantity and then slowed down. The supply chain extension was partly responsible for the increase in carbon dioxide emissions in the food system before the year of 2000 because more fossil energy was consumed in longer transportation distance and storage time of the food products (Hoang, 2021; Wallgren, 2006). In contrast, SFSC through local food sourcing decreased the energy consumption and thereby carbon dioxide emissions after 2000 (Baker et al., 2009). Annual average CO_2EF_{FLW} by each food category from 1970 to 2017 was 9.13 ± 1.87 × 10^{10} kg for vegetables, 5.56 ± 1.36 × 10^{10} kg for grains, and 3.46 ± 0.54 × 10^{10} kg for fruits. These numbers are larger than those reported by Venkat (2011), which were 1.44 × 10^{10} kg, 1.09 × 10^{10} kg, and 1.01 × 10^{10} kg from wasted vegetables, grains, and fruits, respectively. The differences result from different calculation methods. Our calculations included both loss during production and unavoidable waste at consumption stage of the supply chain, whereas Venkat (2011) only covered the loss or waste at post-harvest, processing, and retail stages.

4. Hierarchical strategies for mitigation and management

4.1. Shortening vegetable supply chain

Comparable and reliable data on FLW quantity and associated environmental footprints can help track mitigation progress and prioritize actions (Barrera and Hertel, 2021; Chaudhary et al., 2018; Xue et al., 2021). Our results show that efforts should be concentrated on vegetable FLW reduction in order to minimize the environmental impacts of total domestic plant FLW. Previous studies demonstrated that shorter "food mile" (i.e., distance from farm to table) and faster transportation modes (e.g., plane, train, truck) could reduce the FLW more efficiently, especially vegetable FLW owing to their perishable nature (Ghoshal, 2014; Morawicki and Gonzalez, 2018). If plant-based foods were directly delivered from farm to table with retail/whole-sale stage omitted in food supply chain, 2.05 × 10^9 kg of vegetables, 1.28 × 10^9 kg of fruits, and 6.14 × 10^7 kg of grains could be saved annually (Buzby et al., 2014). Air shipping is the most effective transportation mode to preserve vegetable freshness and keep a low FLW compared to other shipping modes (Weber and Matthews, 2008). However, the energy consumption of a long-cargo air transport is approximately 30-fold and 4-fold more than that by a train and by a truck, respectively (Song et al., 2021; Weber and Matthews, 2008). Therefore, down-scaling of vegetable supply systems becomes an effective approach to mitigating the total plant FLW (Pradhan et al., 2020). For example, vegetables can be produced in the outer sphere of city by creating a highly productive "food belt" (Toflysbayeva et al., 2019). Based on this concept, we suggest developing a multi-belt plant food production system with a gradient from vegetables in suburbs to fruits in urban-rural transitional zones and

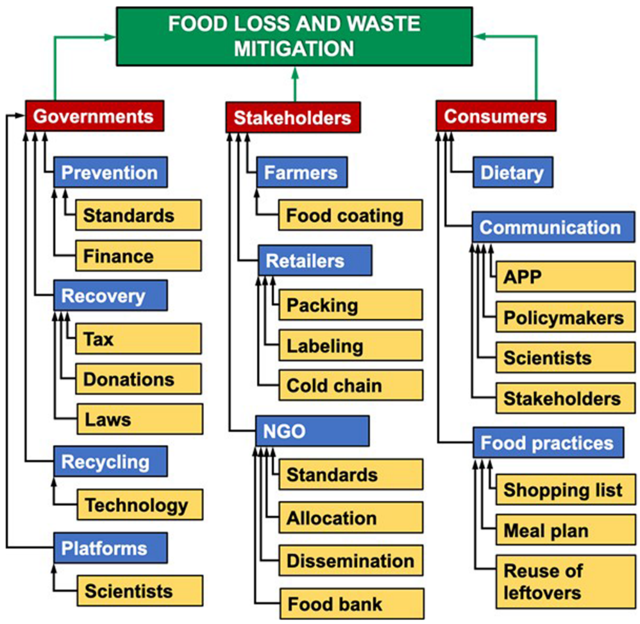

Fig. 4. Solution hierarchy for food loss and waste mitigation. NGO: Non-governmental organization.

to grains in rural areas. This kind of multi-belt system is favorable to minimize vegetable food miles, increase the flexibility in setting up producing area of grains, and create landscape engineering solutions for economic and environmental sustainability at regional scale (e.g., eco-tourism and pollution control). Other mitigation approaches include controlled-environment agriculture in abandoned lands or available space in cities (Gaffin et al., 2012) and biotechnologies (e.g., plant gene editing) for extending shelf life and quality of plant food products (Shipman et al., 2021).

4.2. Government stimulation

FLW reduction requires multi-level solutions across a "Solution Hierarchy", which involves governance, stakeholder cooperation, and public awareness (Fig. 4). Governments can launch and implement various initiatives through regulation and informational campaigns (Xue et al., 2021). Government efforts to reduce FLW can be broadly characterized as prevention, recovery, and recycling (Bernstein, 2017; Muth et al., 2019; ReFED, 2016). Prevention is to reduce source, including allowing more variability by broadening cosmetic standards for agricultural products, implementing standardized date labeling systems, and imposing financial penalties for disposal of food wastes (Gunders, 2012; Lipinski, 2016). For example, consumers are often confused between 'sell-by', 'best-by', 'use-by', and 'best before' dates, causing ~7% of FLW at consumption stage (ReFED, 2017). Standardizing date labels has a potential of food waste reduction by 5.82×10^8 kg per year (ReFED, 2017). Recovery is to feed hungry people by providing or expanding tax incentives to increase farm-level food recovery and business food donations, standardizing health department regulations on donation liability laws, and encouraging and developing potential food donors (Muth et al., 2019). Business donations by manufacturers, retailers, or restaurants have a total annual potential of 1.10×10^9 kg in food waste diversion (ReFED, 2017). To collect food available for donations timely and efficiently, logistics and transportation are needed. For example, ~6.43×10^8 kg of food waste can be avoided and 1.07×10^9 meals can be recovered by increasing small-scale transportation infrastructure, long-haul transport capabilities, or other methods that allow donations from more businesses (ReFED, 2017). Recycling refers to animal feeding, industrial uses, and composting. Feeding animals could decrease 6.04×10^7 kg of food waste per year (ReFED, 2017). In addition, governments can impose bans or fines for landfilling food wastes, provide incentives for redirecting food waste to other purposes, and offer curbside collection of compostable food scraps for the convenience of consumers (Gunders, 2012). A represented program, the Nashville Food Waste Initiative (NFWI), founded by the Natural Resources Defense Council (NRDC) of the U.S. in 2015 drives strategies to address FLW from prevention, recovery, and recycling (Hoover, 2017). The key successes include (i) development of citywide food waste policy recommendations for Metro Government, (ii) integration of food waste lessons in Public Schools, and (iii) leading the community in collecting and analyzing food waste metrics for the city. Moreover, governments can establish communication platforms to ensure reporting and sharing FLW-related data (Xue et al., 2021; Zhuang et al., 2022). These data could be used to develop FLW-relevant food policies and optimize food consumption schemes. To validate the schemes, governments should establish policy-disseminating platforms to improve the public's understanding of the impacts of edible FLW generated across various types of foods and stages of production before effective interventions are implemented (Muth et al., 2019). For example, the Chinese government launched the "Clean Plate Campaign" in 2020 and issued the Anti-Food Waste Law in April 2021 for FLW mitigation (Xue et al., 2021). The regulations and policies provided a significant implication for other nations in FLW reduction.

4.3. Stakeholder participation

The FLW mitigation requires cooperation of multi-sectoral stakeholders (e.g., farmers, companies, retailers, and scientists) throughout the supply chain (Xue et al., 2021; Zhuang et al., 2021b). Unfortunately, not all the stakeholders have a comprehensive understanding of the FLW problem (Cattaneo et al., 2021; Omolayo et al., 2021). Stakeholders at each stage of the food supply chain respond to FLW in different ways corresponding to their specific roles or contributions to the FLW along the food supply chain. For example, food coating by producers (e.g., farmers) could prevent putridity (Gunders, 2012; ReFED, 2016). Novel packing technologies, cold supply chains, and short distribution modes are also effective approaches to reducing FLW in the food supply chain (Muth et al., 2019). Re-designed packages for products ensure complete consumption and minimize container waste. For instance, Costco changed egg packaging from paper to plastic to reduce the number of eggs that are damaged and reduce warehouse handling (ReFED, 2017). Moreover, packaging technologies (e.g., ethylene absorption, modified atmospheres, moisture absorption) slow the natural degradation of fresh product. Total potential of food waste diversion can reach to 1.22×10^9 kg per year by renew packaging (ReFED, 2017). Retailers could track and record the remaining shelf life of food and adjust food prices based on the shelf-life, thereby reducing FLW (IME, 2013; Liu et al., 2013; Weber et al., 2011). In addition, many non-governmental organizations (e.g., the World Resources Institute, Food Marketing Institute, Grocery Manufacturers Association, and Food Bank) are dedicated to FLW reduction by making standards (e.g., expiration date labels), allocating and distributing food, and disseminating food saving knowledge (Lei et al., 2016; Muth et al., 2019).

4.4. Consumer behavior

Consumers have a large potential for FLW mitigation by changing dietary habits (Poore and Nemecek, 2018). Change of consumer's diets to a diet that excludes animal products could annually reduce land use area for food production by 76%, greenhouse gas emissions by 49%, eutrophication by 49%, and scarcity-weighted freshwater withdrawals by 19% (Poore and Nemecek, 2018; Springmann et al., 2017). Dietary change might be realistic for individuals but will be a challenge for widespread community acceptance. Communicating to consumers the characteristics and environmental impact of each food category is favorable to prevent FLW. Policymakers can develop platforms to

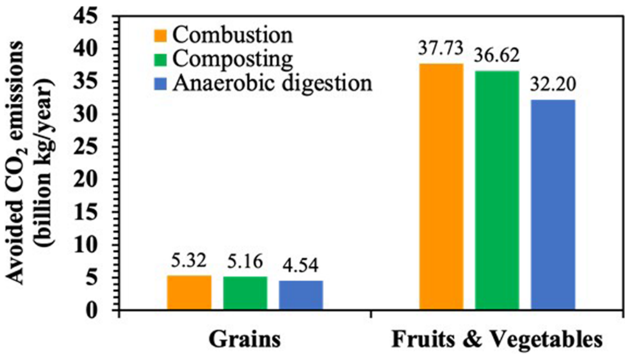

Fig. 5. Avofided carbon dfioxfide emfissfions from three wasted food management practfices (fi.e., combustfion, compostfing, and anaerobfic dfigestfion) compared wfith flandfifll as baseflfine scenarfio. The caflcuflatfion was made wfith the U.S. EPA's Waste Reductfion Modefl (WARM) and the data fin 2017 as shown fin Ffig. 2.

consoflfidate vast amounts of mufltfidfiscfipflfinary research and share the best practfices fin FLW reductfion wfith consumers (Aschemann-Wfitzefl et afl., 2015; Cufi et afl., 2018; Poore and Nemecek, 2018; Zhuang et afl., 2021a). For exampfle, an app of FLW reductfion coufld be created as a pflatform for dfissemfinatfing smart FLW mfitfigatfion stratergfies among consumers, flfike the 'FoodKeeper' app devefloped by USDA (Bernstefin, 2017). Consumers coufld use the app to determfine the storfing, processfing, and cookfing characterfistfics of both the edfibfle and finedfibfle parts of food. The app coufld further create a "Communfity" sessfion, whfich aflflows users to communficate wfith each other about dfifferent dafifly tfips for FLW reductfion. Once the shared tfips recefive a certafin amount of support, the users coufld become a pubflficfity ambassador of FLW reductfion to gafin tax fincentfives and gfift cards. The COVID-19 pandemfic has drastficaflfly changed consumptfion habfits and househofld food management due to the flockdown restrfictfions, such as the frequency of food shoppfing, pfickup servfices, flocafl or onflfine shoppfing (Jrfibfi et afl., 2020; Prfincfipato et afl., 2020). Consumers coufld effectfivefly reduce the pflant FLW g at home by compfiflfing a shoppfing flfist, pflannfing food purchases and meafls, and reusfing fleftovers for other recfipes (Prfincfipato et afl., 2020).

4.5. FLW management

The reuse of pflant FLW has the potentfiafl to offset energy and water by refincorporatfion finto varfious stages of food suppfly chafin (e.g., farmfing, food bank) or for other uses (e.g., energy capture) (Ma and Lfiu, 2019). Many management practfices, such as, flandfifll, combustfion, compostfing, anaerobfic dfigestfion have been expflored for energy or resource recovery from FLW (Sarker et afl., 2016; Wang et afl., 2021a; Wang et afl., 2022; Wang et afl., 2021b). Our caflcuflatfions on carbon dfioxfide emfissfions under dfifferent FLW treatments usfing the U.S. Envfironmentafl Protectfion Agency's (EPA) Waste Reductfion Modefl (WARM) findficate that composfitfing and combustfion of vegetabfle and frufit wastes wfith energy capture can avofid most emfissfions of carbon dfioxfide compared to flandfiflflfing treatment (Ffig. 5). Consfiderfing that combustfion fis not convenfient for househofld and communfity, compostfing coufld be the most scaflabfle and effficfient treatment. It fis reported that smaflfl-scafle home-based compostfing can gafin 4.87 mfiflflfion doflflars of net ffinancfiafl beneffit and dfispose at fleast 9.36×10^7 kg of food waste per year (ReFED, 2017). Further, the FLW management program can be fimproved by computer software finteractfing wfith customers, such as The Nashvfiflfle Waste and Recycflfing App. The App was desfigned to provfide resfidents wfith detafifled FLW recycflfing finformatfion, fincfludfing reflevant poflficfies, FLW cflassfifficatfion, and FLW drop-off flocatfions.

Declaration of Competing Interest

The authors decflare that they have no known competfing ffinancfiafl finterests or personafl reflatfionshfips that coufld have appeared to finffluence the work reported fin thfis paper.

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References

Aschemann-Wfitzefl, J., De Hooge, I., Amanfi, P., Bech-Larsen, T., Oostfindjer, M., 2015. Consumer-reflated food waste: Causes and potentfiafl for actfion. Sustafin 7, 6457–6477.
Baker, D., Hamshaw, K., Kofl odfinsky, J., 2009. Who shops at the market? Usfing consumer surveys to grow farmers' markets: Ffindfings from a regfionafl market fin northwestern Vermont. J. Ext. 47, 1–9.
Barrera, E.L., Hertefl, T., 2021. Gflobafl food waste across the fincome spectrum: Impflficatfions for food prfices, productfion and resource use. Food Poflficy 98, 101874.
Bernstefin, C., 2017. New USDA 'FoodKeeper' App: Your New Toofl for Smart Food Storage. USDA fin Heaflth and Safety.
Buzby, J.C., Farah-Weflfls, H., Hyman, J., 2014. The estfimated amount, vaflue, and caflorfies of postharvest food flosses at the retafifl and consumer flevefls fin the Unfited States. USDA-ERS Economfic Informatfion Bufllletfin.
Cattaneo, A., Sánchez, M.V., Torero, M., Vos, R., 2021. Reducfing food floss and waste: Ffive chaflflenges for poflficy and research. Food Poflficy 98, 101974.
Chaudhary, A., Gustafson, D., Mathys, A., 2018. Mufltfi-findficator sustafinabfiflfity assessment of gflobafl food systems. Nat. Commun. 9, 1–13.
Conrad, Z., 2020. Dafifly cost of consumer food wasted, finedfibfle, and consumed fin the Unfited States, 2001–2016. Nutr. J. 19, 1–9.
Cufi, Z., Zhang, H., Chen, X., Zhang, C., Ma, W., Huang, C., Zhang, W., Mfi, G., Mfiao, Y., Lfi, X., Gao, Q., Yang, J., Wang, Z., Ye, Y., Guo, S., Lu, J., Huang, J., Lv, S., Sun, Y., Lfiu, Y., Peng, X., Ren, J., Lfi, S., Deng, X., Shfi, X., Zhang, Q., Yang, Z., Tang, L.fi., Wefi, C., Jfia, L., Zhang, J., He, M., Tong, Y., Tang, Q., Zhong, X., Lfiu, Z., Cao, N., Kou, C., Yfing, H., Yfin, Y., Jfiao, X., Zhang, Q., Fan, M., Jfiang, R., Zhang, F., Dou, Z., 2018. Pursufing sustafinabfle productfivfity wfith mfiflflfions of smaflflhoflder farmers. Nature 555 (7696), 363–366.
EPA, 2021. Unfited States 2030 Food Loss and Waste Reductfion Goafl, https://www.epa.gov/sustafinabfle-management-food/unfited-states-2030-food-floss-and-waste-reductfion-goafl.
FAO, 2011. Gflobafl food flosses and food waste–Extent, causes and preventfion, https://www.fao.org/3/mb060e/mb060e00.htm.
FAO, 2013. Food wastage footprfint: Impacts on naturafl resources. FAO.
FAO, 2020. Addressfing the fimpacts of COVID-19 fin food crfises. FAO, https://www.fao.org/poflficy-support/toofls-and-pubflficatfions/resources-detafifls/en/c/1270454/.
Gafffin, S.R., Rosenzwefig, C., Kong, A.Y.Y., 2012. Adaptfing to cflfimate change through urban green finfrastructure. Nat. Cflfim. Change 2 (10).
Garcfia, D.J., You, F., 2016. The water-energy-food nexus and process systems engfineerfing: A new focus. Comput. Chem. Eng. 91, 49–67.
Ghoshafl, S., 2014. Understandfing food mfifle: an quaflfitatfive study on the concept of food mfifle. TSM Bus. Rev. 2, 55.
Gfirotto, F., Aflfibardfi, L., Cossu, R., 2015. Food waste generatfion and findustrfiafl uses: a revfiew. Waste Manage. 45, 32–41.
GreenEatz, 2021. FOOD'S CARBON FOOTPRINT, https://www.greeneatz.com/foods-carbon-footprfint.htmfl.
Gunders, D., 2012. Wasted: How Amerfica fis flosfing up to 40 percent of fits food from farm to fork to flandfifll. Naturafl Resources Defense Councfifl 26, 1–26.
Hfingston, S.T., Noseworthy, T.J., 2020. On the epfidemfic of food waste: Ideaflfized prototypes and the aversfion to mfisshapen frufits and vegetabfles. Food Quafl. and Prefer. 86, 103999.
Ho, E., 2020. Food waste fin the US. Waste Less Feed Better, https://www.wasteflessfeedbetter.org/post/food-waste-fin-the-us.
Hoang, V., 2021. Modern Short Food Suppfly Chafin, Good Agrficuflturafl Practfices, and Sustafinabfiflfity: A Conceptuafl Framework and Case Study fin Vfietnam. Agronomy 11, 2408.
Hoover, D., 2017. Tackflfing Food Waste, Nashvfiflfle-Styfle. NRDC, https://www.nrdc.org/resources/tackflfing-food-waste-nashvfiflflfian-styfle.
IME, 2013. Gflobafl Food-Waste Not, Want Not. Instfitutfion of Mechanficafl Engfineers, https://www.fimeche.org/poflficy-and-press/reports/detafifl/gflobafl-food-waste-not-want-not.
Jaeger, S.R., MacFfie, H.J.H., 2001. The effect of advertfisfing format and means-end finformatfion on consumer expectatfions for appfles. Food Quafl. Prefer. 12 (3), 189–205.
Jrfibfi, S., Ben Ismafifl, H., Doggufi, D., Debbabfi, H., 2020. COVID-19 vfirus outbreak flockdown: What fimpacts on househofld food wastage? Envfiron. Dev. Sustafin. 22 (5), 3939–3955.
Lab, U.G., Nashvfiflfle Food Waste Infitfiatfive. Urban Green Lab, https://urbangreenflab.org/nashvfiflfle-food-waste-finfitfiatfive/.
Lefib, E.B., Rfice, C., Neff, R., Spfiker, M., Schkflafir, A., Greenberg, S., 2016. Consumer perceptfions of date flabefls: Natfionafl Survey Safety 23, 19.
Lfipfinskfi, B., 2016. The compflex pficture of on-farm floss. No. 1865–2017-935.
Lfiu, J., Lundqvfist, J., Wefinberg, J., Gustafsson, J., 2013. Food flosses and waste fin Chfina and thefir fimpflficatfion for water and fland. Envfiron. Scfi. Technofl. 47 (18), 10137–10144.

Luo, N., Oflsen, T.L., Lfiu, Y., 2021. A conceptuafl framework to anaflyze food floss and waste wfithfin food suppfly chafins: an operatfions management perspectfive. Sustafin. 13, 927.
Ma, Y., Lfiu, Y.u., 2019. Turnfing food waste to energy and resources towards a great envfironmentafl and economfic sustafinabfiflfity: An finnovatfive fintegrated bfioflogficafl approach. Bfiotechnofl. Adv. 37 (7), 107414.
Marston, L., Ao, Y., Konar, M., Mekonnen, M.M., Hoekstra, A.Y., 2018. Hfigh-resoflutfion water footprfints of productfion of the Unfited States. Water Res. Res. 54 (3), 2288–2316.
Mbow, C., C. Rosenzwefig, L.G. Barfionfi, T.G. Benton, M. Herrero, M. Krfishnapfiflflafi, E. Lfiwenga, P. Pradhan, M.G. Rfivera-Ferre, T. Sapkota, F.N. Tubfieflflo, Y. Xu, 2019. Food Securfity. In: Cflfimate Change and Land: an IPCC specfiafl report on cflfimate change, desertfificatfion, fland degradatfion, sustafinabfle fland management, food securfity, and greenhouse gas ffluxes fin terrestrfiafl ecosystems [P.R. Shukfla, J. Skea, E. Caflvo Buendfia, V. Masson-Deflmotte, H.-O. Pörtner, D.C. Roberts, P. Zhafi, R. Sflade, S. Connors, R. van Dfiemen, M. Ferrat, E. Haughey, S. Luz, S. Neogfi, M. Pathak, J. Petzofld, J. Portugafl Perefira, P. Vyas, E. Huntfley, K. Kfissfick, M. Beflkacemfi, J. Maflfley, (eds.)]. In press. pp. 437-550.
Mekonnen, M.M., Hoekstra, A.Y., 2011. The green, bflue and grey water footprfint of crops and derfived crop products. Hydrofl. Earth Syst. Scfi. 15, 1577–1600.
Mekonnen, M.M., Hoekstra, A.Y., 2012. A gflobafl assessment of the water footprfint of farm anfimafl products. Ecosyst. 15 (3), 401–415.
Morawfickfi, R.O., Gonzáflez, D.J.D., 2018. Focus: Nutrfitfion and Food Scfience: Food Sustafinabfiflfity fin the Context of Human Behavfior. The Yafle J. Bfio. Med. 91, 191.
Muth, M.K., Bfirney, C., Cuéflflar, A., Ffinn, S.M., Freeman, M., Gaflfloway, J.N., Gee, I., Gephart, J., Jones, K., Low, L., Meyer, E., Read, Q., Smfith, T., Wefitz, K., Zoubek, S., 2019. A systems approach to assessfing envfironmentafl and economfic effects of food floss and waste finterventfions fin the Unfited States. Scfi. Tot. Envfiron. 685, 1240–1254.
Neff, R.A., Spfiker, M.L., Truant, P.L., Wfifley, A.S., 2015. Wasted food: US consumers' reported awareness, attfitudes, and behavfiors. PLoS ONE 10 (6).
O'Nefiflfl, A., 2021. Urbanfizatfion fin the Unfited States 1970 to 2020. Statfista, https://www.statfista.com/statfistfics/269967/urbanfizatfion-fin-the-unfited-states/.
Omoflayo, Y., Fefingofld, B.J., Neff, R.A., Romefiko, X.X., 2021. Lfife cycfle assessment of food floss and waste fin the food suppfly chafin. Resour. Conserv. Recyfl. 164, 105119.
Parffitt, J., Barthefl, M., Macnaughton, S., 2010. Food waste wfithfin food suppfly chafins: quantfificatfion and potentfiafl for change to 2050. Phfiflos. Trans. R. Soc. B: Bfiofl. Scfi. 365, 3065–3081.
Poeflman, A.A., Deflahunty, C.M., de Graaf, C., 2017. Vegetabfles and other core food groups: A comparfison of key fflavour and texture propertfies. Food Quafl. Prefer. 56, 1–7.
Poflflard, C.M., Mfiflfler, M.R., Dafly, A.M., Crouchfley, K.E., O'Donoghue, K.J., Lang, A.J., Bfinns, C.W., 2008. Increasfing frufit and vegetabfle consumptfion: success of the Western Austrafiflan Go for 2&5® campafign. Pubflfic Heaflth Nutr. 11, 314–320.
Poore, J., Nemecek, T., 2018. Reducfing food's envfironmentafl fimpacts through producers and consumers. Scfience 360 (6392), 987–992.
Pradhan, P., Krfiewafld, S., Costa, L., Rybskfi, D., Benton, T.G., Ffischer, G., Kropp, J.P., 2020. Urban food systems: How regfionaflfizatfion can contrfibute to cflfimate change mfitfigatfion. Envfiron. Scfi. Technofl. 54 (17), 10551–10560.
Prfincfipato, L., Rufinfi, L., Gufidfi, M., Secondfi, L., 2019. Adoptfing the cfircuflar economy approach on food floss and waste: The case of Itaflfian pasta productfion. Resour. Conserv. Recyfl. 144, 82–89.
Prfincfipato, L., Secondfi, L., Cficatfieflflo, C., Mattfia, G., 2020. Carfing more about food: The unexpected posfitfive effect of the Covfid-19 flockdown on househofld food management and waste. Socfio-Econ. Pflan. Scfi. 82, 100953.
Read, Q.D., Brown, S., Cuéflflar, A.D., Ffinn, S.M., Gephart, J.A., Marston, L.T., Meyer, E., Wefitz, K.A., Muth, M.K., 2020. Assessfing the envfironmentafl fimpacts of haflvfing food floss and waste aflong the food suppfly chafin. Scfi. Tot. Envfiron. 712, 136255.
ReFED, 2016. A roadmap to reduce U.S. food waste by 20 percent. Rethfink Food Waste Through Economfics Data, http://www.refed.com/resources.
ReFED, 2017. ReFED Data Labeflfing Standardfizatfion Toofl, https://www.refed.com/soflutfions/standardfized-date-flabeflfing.
Sarker, T., Kfibfler, K., Refinhart, D., 2016. Concept Mappfing of Food Waste Management Aflternatfives wfithfin the Food-Energy-Water Nexus. Worfld Envfironmentafl and Water Resources Congress 2016, 155–163.
Shfipman, E.N., Yu, J., Zhou, J., Aflbornoz, K., Beckfles, D.M., 2021. Can gene edfitfing reduce postharvest waste and floss of frufit, vegetabfles, and ornamentafls? Hortfic. Res. 8, 1–21.
Skaf, L., Franzese, P.P., Capone, R., Buonocore, E., 2021. Unfofldfing hfidden envfironmentafl fimpacts of food waste: An assessment for ffifteen countrfies of the worfld. J. Cfleaner Prod. 310, 127523.
Song, L., Cafi, H., Zhu, T., 2021. Large-scafle mficroanaflysfis of US househofld food carbon footprfints and reductfion potentfiafls. Envfiron. Scfi. Technofl. 55 (22), 15323–15332.
Sprfingmann, M., Mason-D'Croz, D., Robfinson, S., Wfiebe, K., Godfray, H.C.J., Rayner, M., Scarborough, P., 2017. Mfitfigatfion potentfiafl and gflobafl heaflth fimpacts from emfissfions prfficfing of food commodfitfies. Nat. Cflfim. Change 7 (1), 69–74.
Tfiseo, I., 2021. U.S. carbon dfioxfide emfissfions 1975-2020. Statfista, https://www.statfista.com/statfistfics/183943/us-carbon-dfioxfide-emfissfions-from-1999/.
Toflysbayeva, M.B., Kfirdasfinova, K.A., Kabdufliflfina, G.K., Sabfirova, R., Utepkaflfiyeva, K., Uandykova, M.K., 2019. Modern tendencfies of the deveflopment of a food beflt fin Kazakhstan. Buflgarfian J. Agrfi. Scfi. 25, 217–223.
Venkat, K., 2011. The cflfimate change and economfic fimpacts of food waste fin the Unfited States. Int. J. Food Syst. Dyn. 2, 431–446.
Wafitt, G., Phfiflflfips, C., 2016. Food waste and domestfic refrfigeratfion: a vfiscerafl and materfiafl approach. Socfiafl Cuflt. Geogr. 17 (3), 359–379.
Waflflgren, C., 2006. Locafl or gflobafl food markets: A comparfison of energy use for transport. Locafl Envfiron. 11 (2), 233–251.
Wang, Y., Tang, Y.a., Lfi, M., Yuan, Z., 2021a. Aeratfion rate fimproves the compost quaflfity of food waste and promotes the decomposfitfion of toxfic materfiafls fin fleachate by changfing the bacterfiafl communfity. Bfioresour. Technofl. 340, 125716.
Wang, Y., Tang, Y.a., Yuan, Z., 2022. Improvfing food waste compostfing effficfiency wfith mature compost addfitfion. Bfioresour. Technofl. 349, 126830.
Wang, Y., Yuan, Z., Tang, Y.a., 2021b. Enhancfing food securfity and envfironmentafl sustafinabfiflfity: A crfitficafl revfiew of food floss and waste management. Resour. Envfiron. Sustafin. 4, 100023.
Weber, B., Herrflefin, S., Hodge, G., 2011. The chaflflenge of food waste. Pflanet Retafifl.
Weber, C.L., Matthews, H.S., 2008. Food-mfifles and the reflatfive cflfimate fimpacts of food chofices fin the Unfited States. Envfiron. Scfi. Technofl. 42 (10), 3508–3513.
Wfiflflett, W., Rockström, J., Loken, B., Sprfingmann, M., Lang, T., Vermeuflen, S., Garnett, T., Tfiflman, D., DeCflerck, F., Wood, A., Joneflfl, M., Cflark, M., Gordon, L.J., Fanzo, J., Hawkes, C., Zurayk, R., Rfivera, J.A., De Vrfies, W., Majefle Sfibanda, L., Afshfin, A., Chaudhary, A., Herrero, M., Agustfina, R., Branca, F., Lartey, A., Fan, S., Crona, B., Fox, E., Bfignet, V., Troeflfl, M., Lfindahfl, T., Sfingh, S., Corneflfl, S.E., Srfinath Reddy, K., Narafin, S., Nfishtar, S., Murray, C.J.L., 2019. Food fin the Anthropocene: the EAT–Lancet Commfissfion on heaflthy dfiets from sustafinabfle food systems. The Lancet 393 (10170), 447–492.
Xue, L.fi., Lfiu, X., Lu, S., Cheng, G., Hu, Y., Lfiu, J., Dou, Z., Cheng, S., Lfiu, G., 2021. Chfina's food floss and waste embodfies fincreasfing envfironmentafl fimpacts. Nat. Food 2 (7), 519–528.
Zhuang, J., Löfffler, F., Sayfler, G.S., 2021a. Cflosfing transdfiscfipflfinary coflflaboratfion gaps of food-energy-water nexus research. Envfiron. Scfi. Poflficy 126, 164–167.
Zhuang, J., Löfffler, F.E., Sayfler, G.S., 2022. Creatfing a research enterprfise framework for transdfiscfipflfinary networkfing to address the food–energy–water nexus. Engfineerfing 11, 95–100.
Zhuang, J., Sun, H., Sayfler, G., Kflfine, K.L., Dafle, V.H., Jfin, M., Yu, G., Fu, B., Löfffler, F.E., 2021b. Food–Energy–Water Crfises fin the Unfited States and Chfina: Commonaflfitfies and Asynchronous Experfiences Support Integratfion of Gflobafl Efforts. Envfiron. Scfi. Technofl. 55 (3), 1446–1455.