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Food loss and waste: A carbon footprint too big to be ignored

You Siming^a, Christian Sonne^b, Young-Kwon Park^c, Sunil Kumar^d, Kun-Yi Andrew Lin^e, Yong Sik Ok^f and Feng Wang^g

^aJames Watt School of Engineering, University of Glasgow, Glasgow, UK; ^bDepartment of Ecoscience, Aarhus University, Roskilde, Denmark; ^cSchool of Environmental Engineering, University of Seoul, Seoul, Korea; ^dCSIR-National Environmental Engineering Research Institute, Maharashtra, India; ^eDepartment of Environmental Engineering & Innovation and Development Center of Sustainable Agriculture, National Chung Hsing University, Taichung, Taiwan, China; ^fKorea Biochar Research Center, APRU Sustainable Waste Management Program & Division of Environmental Science and Ecological Engineering, Korea University, Seoul, Korea; ^gDalian Institute of Chemical Physics, Chinese Academy of Sciences, Dalian, Liaoning, China

ABSTRACT

Eight to ten percent of total global greenhouse gas emissions are associated with food loss and waste. Tackling the challenges of food loss and sustainable food waste management is key to fulfilling the Paris Agreement. However, among the Nationally Determined Contributions to the Paris Agreement, very few countries make references to food loss and waste. In this work, we reviewed the problem of food loss and waste from a global viewpoint and highlighted the opportunities of managing food loss and waste towards carbon mitigation and beyond. The importance of developing a coherent collaboration among all associated stakeholders was implied. Some recent policy developments and the impacts of COVID-19 pandemic are discussed followed by the summarization of potential solutions to tackling the food loss and waste challenge.

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The problem

Food loss and waste is of increasing concern as it comes with substantial socio-economic and environmental implications. The food supply chain typically consists of five main stages including production, handling and storage, processing, distribution, and consumption (Shafiee-Jood & Cai, 2016). Food loss is relevant to the first four stages while food waste applies to the last phase of consumption. Accordingly, the mechanisms of food loss and waste are different. Food loss and waste is related to a variety of factors such as improper harvesting timing, inefficient sorting, undesirable weather conditions, limited and/or inefficient processing and packaging facilities, inefficient storage of food for consumption, etc (Table 1). It is worth noting that the data in Table 1 are mostly for developed economies, while associated data for developing economies are relatively few but highly desired for constructing a global overview of the problem. Food loss and waste and associated management are a complex, dynamic problem involving multiple stakeholders, which suggests its widespread influences along the whole food supply chain.

The significance and scale

8–10% of total global greenhouse gas (GHG) emissions are associated with food loss and waste with a monetary value of 1 trillion USD per year (Mbow et al., 2019). The annual generation of food waste is around 931 million tonnes (MT), accounting for approximately 17% of the total global food production in 2019 (United Nations Environment Programme, 2021). The United States being at the top of the food waste generation list generates about a total of 40 million tonnes of food waste each year, which accounts for 30–40% of the country's food supply or 22% of the country's municipal waste (RTS, 2021). In China, food loss and waste accounts for 27% of the food annually produced for human consumption (349MT) and 45% and 13% of this are contributed by postharvest handling and storage and out-of-home consumption activities (Xue et al., 2021). 88 million tonnes of food waste are generated annually in the European Union, which is equal to 143 billion euros or 170 million tonnes of CO₂.

A recent report showed that there were only minor differences in household food waste generation per capita between lower-middle income and high-income

CONTACT Siming You  Siming.You@glasgow.ac.uk  James Watt School of Engineering, University of Glasgow, UK

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Table 1. Food loss and waste statistics along the supply chain

Stages	Factors	Exemplary loss/waste rate	Reference(s)
Production	Improper harvesting timing, undesirable weather conditions, inefficient sorting, harvest wasting, etc.	Harvesting: 1–9% (Austria and Germany) 1–5% (UK) On farm: 10–20% (USA) 24% (Switzerland) 25% (Australia)	Shafiee-Jood and Cai (2016), Schneider et al. (2019) Shafiee-Jood and Cai (2016), Schneider et al. (2019)
Storage	Limited or inefficient drying and storage facilities, inefficient transportation and logistical management for food distribution	~2.5% (China) 15–25% (Tanzania)	Shafiee-Jood and Cai (2016), Luo et al. (2020), Abass et al. (2014)
Processing (e.g. Packaging)	Limited and/or inefficient processing and packaging facilities	20–25% (Sweden) 40% (EU)	Shafiee-Jood and Cai (2016), Williams et al. (2012), Dora et al. (2020)
Retail/distribution	Inefficient transportation and logistical management for food distribution, failed marketing and sale strategies	5% (EU) 4.3% (Sweden)	(Shafiee-Jood & Cai, 2016), Cicatiello et al. (2016)
Consumption	Excess purchase, inappropriate food consumption behaviour, misunderstanding of food labelling, inefficient storage of food for consumption, etc.	25% (EU) 34% (Arab countries)	Shafiee-Jood and Cai (2016), Kulikovskaja and Aschemann-Witzel (2017), Abiad and Meho (2018)

countries (United Nations Environment Programme, 2021). This is in clear contrast with a previous belief that food waste could be significantly higher in developed countries (Shafiee-Jood & Cai, 2016). A previous study estimates that the per capita food loss and waste in developed countries is 100 kg/year higher than that in developing countries (FAO, 2011). This highlights a greater country-specific variation for food loss and waste along the whole food supply chain as compared to household food waste. The food loss in the early stage of the supply chain could be much greater in developed economies. A global solution is needed to reduce per capita global food waste by 50% at the retail and consumer levels around year 2030 as part of UN Sustainable Development Goal (SDG) target 12.3 (FAO, 2022). Tackling these challenges of food loss and sustainable food waste management is key to fulfilling the Paris Agreement and the 1.5 °C goal.

Recent development

Among the Nationally Determined Contributions (NDC) to the Paris Agreement, not a single country mentioned food waste and only eleven made references to food loss (Schulte et al., 2020). This reflects that the environmental benefits of sustainable food loss and waste management have not been fully exploited so far. Meanwhile, the significance of the food loss and waste issue has stimulated the emergence of actions and initiatives towards mitigating the problem. Just ahead of the 26th UN Climate Change Conference of the Parties (COP26), the Waste and Resources Action Programme (WRAP) UK urged global policy-makers and businesses that 35% of UK's GHG emission was from the food thereby providing opportunities for

carbon mitigation (WRAP, 2021). In November 2021, China launched a nation-wide action plan to reduce food loss and waste with such guidelines as improved grain storage and transportation and regulation of food-based bioenergy production (General Office of the State Council, 2021).

The COVID-19 pandemic exposed the lack of resilience in the existing food loss and waste management chain against the disaster. A survey by the UK Association of Directors of Environment, Economy, Planning & Transport (ADEPT) showed that around 30% of respondents experienced disruption in food waste collection services during the COVID-19 lockdown, the second highest among domestic waste (ADEPT, 2020). Uncollected food waste was mixed with general waste and sent to landfills or incineration plants, likely leading to higher GHG emissions and a waste of renewable resources. It was estimated that the carbon emissions and economic costs associated with food loss and waste generation during the first weeks of the COVID-19 pandemic increased by 10% and 11% (Aldaco et al., 2020). As emphasized by the Department for Environment, Food & Rural Affairs (Defra), UK, temporary stoppage of food waste collections might make it harder for households to resume efficient food waste recycling, exerting a long-term adverse influence on waste recycling (Defra, 2020).

Opportunities and solutions

The significance of food loss and waste indicates huge socio-economic opportunities underlying the problem. The global market for food waste management is projected to increase from 34.6 to 45.6 billion USD by 2026 reflecting a compound annual growth rate of 4.5% (Global Industry

Analysts Inc, 2021). The economic value of food loss and waste management needs to align with its socio-environmental benefits and GHG emission targets. This calls for a coherent collaboration among food producers, consumers, governments, media, waste companies, campaigners and non-governmental organizations (NGOs) in defining a clear roadmap to mitigate the problem and associated socio-economic and environmental impacts (Aschemann-Witzel, 2016).

Different measures are required to mitigate the food loss and waste in the various stages of food supply and consumption chain. In the production stage, smart technologies and systems are the trend and include, e. g. crop and soil monitoring systems for improved nutrition, artificial intelligence-based systems for accurate field supply and demand predictions, software platforms and algorithms for production and stock planning, bio-stimulants and “intelligent/smart fertilizers” for efficient nutrients supply, etc. (Ciccullo et al., 2021). For example, machine learning combined with unmanned aerial vehicle (UAV) remote sensing has been established to estimate nitrogen nutritional status of paddy rice fields in China (Zha et al., 2020). The method demonstrate reasonable precision as a promising tool for monitoring and managing crop growth effectively. Argento et al. (2021) incorporated multi-spectral images from a UAV with available mineral nitrogen content data to estimate in-field nitrogen status variabilities and guide variable nitrogen (fertiliser) applications. The method could help to reduce nitrogen fertiliser application by 5–40% and improve the nitrogen use efficiency by 10%. Associated variable rate fertiliser application is suitable for small- to medium-scale agriculture systems. Smart fertilisers may achieve controlled nutrient release and bioformulations based on the use of nanomaterials (nanofertilisers) and/or microorganisms (biofertilisers). This new agricultural technology has the potential to improve nutrient use efficiency and reduce the environmental footprints of fertiliser applications.

Feng et al. (2015) developed a type of controlled/slow release fertiliser by surface-initiated atom-transfer radical polymerization, which exhibit excellent temperature- and pH-responsive nutrient release behaviour including accelerated nutrient release at an acidic pH condition or a low temperature and basic pH condition. This nutrient release was decelerated at a high temperature and basic pH condition. The stimuli-responsive feature of the fertiliser could be applied to improve nutrient availability thereby mitigating adverse impacts of excessive release of nutrients, and increasing the fertiliser use efficiency. However, such large scale applications of smart fertilisers and associated benefits remain to be demonstrated.

Increased and improved food storage facilities (e.g. cold storage) are required and need to be sustained with policies and governmental incentives from an economic feasibility perspective. In China, it has been shown that the food loss in government-run storage facilities was less than 0.5% as compared to over 50% in farmers’ households (Liu, 2014). The lack of cold chain storage being <25% for meat and <5% for fruit and vegetable stored at refrigeration, causes a loss and waste of 12 million tonnes of fruit, 130 million tonnes of vegetable and 6.9 million tonnes of meat in China representing a value >100 billion CNY (~15 billion USD for an exchange rate of 0.15; Hu et al., 2019). A previous UK study shows that reducing domestic food storage temperature from 7°C to 4 °C could effectively extend food storage and save 162.9 million GBP annually (~200 million USD for an exchange rate of 1.22; Brown et al., 2014). A study on home delivery cold chain services in Taiwan shows that abusive temperature during the service would reduce the shelf life of frozen shrimp by >70% and a temperature range of -18 ± 3 °C was desired for preserving the shelf life and preventing quality degradation of frozen shrimp (Ndraha et al., 2019). Cold chain transportation facilities play an essential role in tackling transportation-associated food waste, while new food packaging technologies with improved temperature control and logistics further facilitate food protection and damage prevention during food distribution (Surucu-Balci & Tuna, 2021; Thyberg & Tonjes, 2016). However, it is worth noting that technologies or systems like cold chains are energy intensive and represent a significant carbon footprint. Their applications help to reduce food loss and waste; however, associated carbon saving benefits from reduced food loss and waste may be offset by their significant embodied energy and carbon footprints. For example, Heard and Miller (2018) evaluated the carbon footprints of cold chain development in sub-Saharan Africa based on two configurations. One configuration is similar to the cold chain development in North America and another to Europe. The study showed that introducing the cold chain development in sub-Saharan Africa would reduce postharvest food loss by 23%; however, it would increase the net food-related carbon footprints by 10% and 2% for the North American and European configurations, respectively. This was because the emissions from cold chain operation were greater than the saved emissions related to avoided food losses. Hence, from a whole system perspective, the applications of advanced technologies for saving food loss and waste do not necessarily lead to overall carbon footprint reductions. The approaches of multi-objective optimisation and multi-criteria decision analysis can be applied to design and select optimal technologies and configurations, achieving a balance between carbon saving and food saving.

Towards food waste mitigation during consumption stage such as household food waste reduction, several barriers have been identified by a UK-based study (Graham-Rowe et al., 2014). First, there is a “good” provider identity factor for which hosts tend to better treat guests and parents tend to supply plenty of healthy and nourishing to their kids, which often lead to over-purchasing and subsequent food waste. Second, people tend to minimise inconvenience by stockpiling perishable products and throwing food on or past its use-by dates. Third, people have a low priority on food waste minimisation and thus do not actively engage with issues surrounding food waste. Fourth, there is a feeling of exemption from responsibility and people perceive that the food industry and supermarkets are mainly responsible for the food waste issue. It is therefore important to change consumers’ behaviour and attributes, i.e. perceived behavioural control and food-related routines including shopping and reuse of leftovers through public information campaigns and environmental education (Stancu et al., 2016). A “Clean dish, clean conscience!” initiative consisting of an education campaign was tested at a canteen of the University of Lisbon, Portugal for raising food waste reduction awareness (Pinto et al., 2018). In the campaign, informative posters were displayed at the canteen with such messages as “not to accept food they knew they would not eat” and it was found that the initiative reduced the waste consumption index by ~15%. Soma et al. (2020) compared the efficacy of three consumer awareness education campaign approaches which include a passive approach (handouts), a community engagement approach and a gamification approach. It was shown that passive and gamification approaches were linked to higher self-reported food waste awareness which lowered food waste as compared to the control group. The study also found that frequent gamers generated less food waste than infrequent gamers and suggested that gamification served as a potential education campaign tool for food waste reduction.

Dedicated environmental education campaigns and initiatives improve stakeholders’ awareness of courses and consequences of the food loss and waste problem and help change consumers’ attitudes and behaviour. They can be designed to bridge scientific facts and the interests of stakeholders to prompt behavioural changes. Based on a lesson learned from marine plastic pollution, people do not see their lives and livelihoods as being intertwined with the problem and identify their own behaviours as contributing to that problem. As a result of that, they can hardly be incentivised to change behaviours and adopt more sustainable modes of production, consumption and waste generation and management (Marks et al., 2020). Social media also play an important role in

education campaigns and interventions towards food waste reduction. A recent scoping review showed that around 60% of surveyed studies suggested a positive impact of social media usage towards awareness raising for consumer food waste reduction (Jenkins et al., 2022). The study recommended to combine social media with behaviour change strategies including workshops and challenges to study the impacts on the encouragement of consumer behaviour change and food waste reduction. This highlighted that associated future research should focus on the development of guidelines for practitioners in planning, developing, evaluating, and measuring the impact of social media campaigns and it was important for practitioners, researchers, and consumers to work together to co-design social media content for greater effectiveness. It is worth noting that environmental education materials and associated channels need to be sustained by ambitious policies and regulations to fulfil effective and long-lasting knowledge exchange and dissemination.

Last but not least, food loss and waste affect the overall effort in hunger eradication: reducing food waste could help to reduce the food demand by 9% towards the hunger eradication efforts targeted on under-nourished population as compared to a 3% increase without food waste reduction (Hasegawa et al., 2019). Additionally, food waste reduction has such benefits as reduced consumption of resources such as water and nitrogen and reduced pressure on land and the environment. This means that sustainable mitigation of food loss and waste relies on the coherent, multi-dimensional efforts from a whole supply chain perspective of its connections with the five stages of food supply chain, while projecting wider impacts beyond the supply chain itself.

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Notes on contributor

Dr. Siming You, Senior Lecturer in the James Watt School of Engineering at the University of Glasgow, UK, specialises in

the design and analysis of environmental and energy systems with a focus on water treatment and waste management systems. Before joining the School, he worked as a Research Fellow at NUS (National University of Singapore) Environmental Research Institute. He also served as a Postdoctoral Fellow at Nanyang Technological University and the Massachusetts Institute of Technology in 2014 and 2015, respectively. Dr. You received his Ph.D. in Thermofluids from Nanyang Technological University in 2014. Dr. You was awarded the Outstanding Young Researcher Award by the American Institute of Chemical Engineers (AIChE), SLS in 2018. Dr You has published over 90 papers in top-tier journals including Science, Bioresource Technology, Journal of Hazardous Materials, etc.

ORCID

You Siming  <http://orcid.org/0000-0003-2175-7291>

Data Availability Statement

All data supporting this study are provided in full in this paper.

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