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BACKGROUND AND CHALLENGES

The food system has tremendous potential to contribute to climate change solutions while helping to meet global food demand, reducing dependence on inorganic fertilizers, improving soil and human health, and achieving sustainable development goals. Currently, the food system is a large source of global greenhouse gas emissions. In 2015, 18 gigatons (GT) of carbon dioxide equivalent (CO_2e) were emitted to the atmosphere from the food system, amounting to 34% of total global emissions (Crippa et al. 2021). China was responsible for the largest proportion of food system emissions (13.5%) with Indonesia (8.8%) and the U.S. (8.2%) as the second and third highest emitters.

Reducing and repurposing food loss and waste (FLW) together with associated improvements in nitrogen fertilizer use efficiency are among the greatest opportunities for emissions reduction in the food system (Read et al. 2020). We define food loss as the edible food that inadvertently does not reach a consumer because of agricultural or technological limitations in storage, infrastructure, packaging, or marketing. Food waste is defined as edible food that is discarded by a consumer (WRI 2013). Approximately 1.3 GT of food is lost or wasted each year at a global scale, amounting to 30% of the food produced for human consumption (FAO 2015, UNEP 2021, Muth et al. 2019). Global greenhouse gas emissions from FLW increased by 30% between 1990 (764 million metric tons (MMT) CO_2e) and 2018 (996 MMT CO_2e) (Tubiello et al. 2021). Food waste alone accounts for over 10% of greenhouse gas emissions from the food systems in both the U.S. and China (Crippa et al. 2021). Tackling the food waste problem is one of the United Nations Sustainable Development Goals with a target of 50% reduction by 2030 (United Nations 2015). Reducing and repurposing FLW carries many co-benefits including helping to alleviate food scarcity, hunger, and malnutrition and associated diseases, in addition to contributing to climate change mitigation (Willet et al. 2019, Chen et al. 2020).

The carbon and nutrients embedded in FLW exacerbate climate change by depleting soils of essential resources and forcing farmers to use fertilizers to maintain agricultural yields. Inorganic fertilizers, also known as synthetic or chemical fertilizers, are often made from oil or gas-intensive processes, particularly in the case of synthetic nitrogen fertilizers. Current trends in the management of FLW results in the displacement of millions of tons of nutrients from agricultural soils (Silver et al. 2021). Harvested products are transported from farms to domestic and international markets that are often concentrated in urban centers as opposed to agricultural regions (Kaza et al. 2018). Using FLW to produce soil additives (termed amendments) such as compost (food and other organic wastes processed into a slow-release fertilizer in aerated piles) or anaerobic digestate (controlled decomposition of food and other organic waste in the absence of oxygen) can provide a mechanism to reutilize harvested carbon and nutrients as organic fertilizer, while lowering greenhouse gas emissions. This not only helps to offset inorganic fertilizer use, but also increases soil carbon sequestration (Kutos et al. in press), improves soil water holding capacity and associated drought resilience (Flint et al. 2018), reduces erosion (Kutos et al. in press), lowers overall fertilizer requirements (DeLonge et al. 2013), improves soil nitrogen retention, and lowers nitrous oxide (N_2O) emissions. Nitrous oxide is a powerful greenhouse gas with a global warming potential 298 times that of CO_2 (IPCC, 2007). Anaerobic digestion has the added benefit of producing alternative fuels (Levis and Barlaz 2011).

Fertilizers are essential to sustain our global food supply chain and current global population. To meet demand, global inorganic nitrogen fertilizer use increased over 350% between 1970 and 2020 (FAOSTAT 2022). There is considerable potential to improve fertilizer use efficiency, decrease the use of fossil-fuel intensive inorganic nitrogen fertilizers, and lower N_2O emissions from fertilization. Nitrogen fertilizer application commonly exceeds the nitrogen needed to maximize crop yields, resulting in the loss of applied nitrogen from the system. Excess nitrogen can end up in groundwater, potentially contaminating water supplies, or surface runoff leading to large-scale algal blooms and coastal dead zones (Albornoz 2016, Erisman et al. 2013 Martinez-Dalmau et al. 2018). Global estimates suggest that 50% of added nitrogen is lost due to overfertilization (Zhang et al. 2021).

Overfertilization places a heavy burden on CO_2 emissions. Production of inorganic ammonia-nitrogen fertilizer is energy intensive; it is largely produced using fossil fuels and accounts for 2% of the world's energy use and 4% of the global natural gas supply, emitting 450 MMT CO_2e annually (IEA, 2021). In 2021, China produced 26% of the world's ammonia fertilizer, and the U.S. produced 9% (USGS 2022). Overfertilization also results in high rates of avoidable N_2O emissions. Approximately 1% of applied nitrogen is lost as N_2O (IPCC 2006). Agriculture is responsible for 43% of worldwide N_2O emissions, predominantly due to nitrogen fertilizer applied to croplands (Tian et al. 2020). Simultaneous increases in nitrogen fertilizer use efficiency and replacement of inorganic fertilizers with food- and manure-based organic compost or anaerobic digestate fertilizers can result in substantial greenhouse gas emissions reductions.

U.S. BACKGROUND AND CHALLENGES

Food Loss and Waste

Food loss and waste in the U.S. ranged from 73 to 152 MMT per year with a per capita rate of 223 to 468 kilograms (kg) annually, more than double the global average based on recent estimates (US EPA 2021). Roughly half of the FLW in the U.S. supply chain is produced during the consumption stage (35-61% from restaurants and households) followed by losses in the primary production (17-37%), retail sector (6-27%), and distribution and processing (5-21%) stages (US EPA 2021). An analysis of the amount of food waste found in municipal solid waste (MSW) showed similar rates between rural and urban areas in the U.S. (Thyberg et al. 2015). The U.S. has a surplus of food produced. Model estimates suggest the U.S. produces 3,796 to 4,000 calories per person per day, almost double the average intake (2,081 calories per day) (US EPA 2021 and references therein). This exacerbates FLW. On a per capita basis, the U.S. has the world's largest environmental footprint embedded in food wasted in the consumption stage from greenhouse gas emissions, cropland area, and freshwater, nitrogen, and phosphorus utilization (Chen et al. 2020). The most important FLW management pathways in the country are landfilling (56%), controlled combustion (12%), co-digestion/anaerobic digestion for energy production (8%), sewer/water treatment (6%), and composting (4%) (US EPA 2020). Food waste in landfills contributes between 20 to 46 MMT of CO_2e of the 109 MMT CO_2e emitted annually as methane[1] (US EPA 2022). Food waste disposal in landfills

[1] Calculation based on 56% of total US food waste disposed in landfills, corrected for 70% of water content and using only the non-collected methane emissions rate of 1800 kg CO_2e per dry tonnes (Lee et al. 2017).

is responsible for the largest fraction of easily degradable organic carbon when compared to other organic matter (wood, paper and yard trimming), and thus is responsible for the highest emission factors (from 2603 to 2708 kg CO_2e per dry ton of material) (Lee et al. 2017). The generation of FLW excluding landfill emissions releases an additional 170 MMT of CO_2e per year (US EPA 2020).

Fertilizer

Agricultural soils emitted 316 MMT CO_2e as N_2O in 2020, equivalent to 74% of the total U.S. N_2O emissions inventory and 5.3% of total greenhouse gas emissions for the U.S (US EPA 2022). Approximately 68% of direct emissions came from cropland with the remainder from rangelands. Nitrogen fertilizer additions to croplands emitted 64 MMT CO_2e as N_2O in 2020 (US EPA 2022). Estimates of inorganic nitrogen fertilizer use in the US range from 11 to 16 MMT annually (USDA 2015, Sellars 2021, FAOSTAT 2022), with 86% produced domestically (USGS 2022). The U.S. is the world's fourth-largest producer of inorganic nitrogen fertilizer (The Fertilizer Institute 2019). Most ammonia production occurs near large natural gas reserves in Louisiana, Oklahoma, and Texas due to its use as both a feedstock and to fuel the high temperature and pressure needed to produce ammonia (USGS 2022).

Nitrogen fertilization is critical to optimize short-term crop yields in staple grains worldwide. Corn agriculture alone is responsible for 46% of annual nitrogen fertilizer use in the U.S. (USDA 2019). Corn production is an important crop for food, feed, and fuel, and thus demand for nitrogen amendments is unlikely to decline (Edgerton 2009). However, an excess of 8 MMT of nitrogen fertilizer per year is applied across all U.S. croplands (West et al. 2014), representing substantial potential for direct reduction in nitrogen fertilizer use and associated greenhouse gas emissions. County-level hotspots spanning 20 states across the Midwest, Mountain West, and Western US, represent approximately 63% of excess nitrogen use but only 24% of cropland (Roy et al. 2021). Importantly, reductions in nitrogen fertilizer inputs in these regions are less likely to reduce crop yields, suggesting that immediate reductions in nitrogen fertilizer use would have minimal effects on food production.

In 2022, the U.S. launched the "Global Fertilizer Challenge, which aims to increase the adoption of innovative, alternative, and efficient fertilizer practices to alleviate pressure on fertilizer and natural gas supplies, increase global fertilizer availability, lower N_2O emissions, and increase global food security (White House 2022). The Global Fertilizer Challenge aims to raise $100 million leading up to the COP 27 climate conference in Egypt to support research, demonstrations, and training to help countries with high fertilizer use adopt efficient nutrient management and alternative fertilizer sources.

CHINA BACKGROUND AND CHALLENGES

Food Loss and Waste

As the most populous country in the world, China is also the largest global contributor of FLW. China produces approximately one quarter of the world's FLW, this proportion having increased from 5 to 27% from 1992 to 2013 (Gustavsson et al. 2011, Lopez Barerra & Hertel, 2021). Of the 1.3 GT of food produced in China, approximately 349 ± 4 MMT is wasted or lost (Xue et al. 2021). Greenhouse gas emissions from FLW have climbed over the past two decades: FLW treatment emissions doubled from 2001 to 2018, from 64 ± 14 MMt CO_2e to 137 ± 26 MMt CO_2e (Zhang et al. 2020).

The largest proportion of FLW in China occurs during pre-consumer stages such as distribution and storage, while post-consumer (household and restaurant) waste makes up 17% of FLW nationally (Xue et al. 2021). It is important to note that China and other emerging economies tend to produce a smaller proportion of their FLW as post-consumer material than most wealthier nations. This is particularly true of patterns in household FLW. Restaurant FLW accounted for 13% of total waste in China while kitchen FLW only accounted for 4%, far below the average of wealthier nations (40-70%) (Xue et al. 2021).

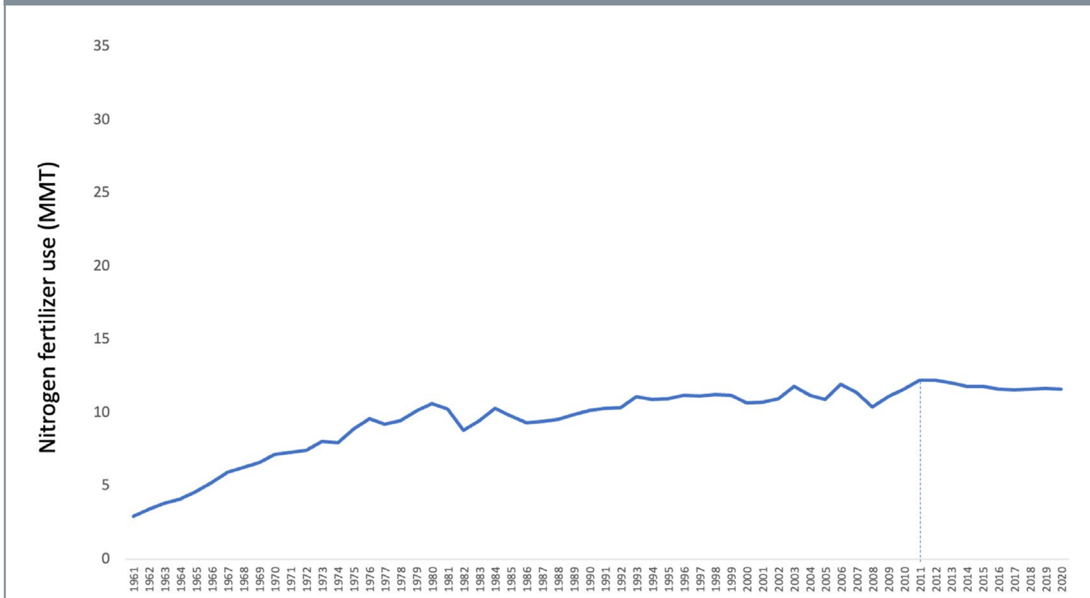
While China's total FLW is the highest in the world, per capita household FLW generation is moderate, averaging at approximately 23-64 kg per capita per year (Song et al. 2015, UNEP 2021), less than the 74 kg per capita per year global average. Differences exist in FLW generation between urban and rural communities. The generation of FLW in cities amounted to 150 kg per capita annually, whereas a study that focused on rural villages in Shandong found households produced just 21 kg per capita (Zhang et al. 2020, Li et al. 2021). The large differences in FLW generation indicate that the greatest benefits from changes in behavior and management in China could be realized in urban environments. Generation of FLW is related to dietary habits and patterns in income. Data from 37,000 households from the China Health and Nutrition Survey from 1991 - 2009 showed that per capita FLW from households has decreased by 20% even as average income increased, a trend that is usually associated with increased FLW (Qi et al. 2020, Chalak et al. 2019). The proportion of meals eaten outside of the home has increased over time in China (Wang et al. 2017, Li et al. 2022). Restaurant meals in the country generate more FLW per meal than in-home meals (Qi et al. 2020), thus out-of-home consumption will likely become a greater concern for controlling FLW-related emissions. Nationally, 49% of FLW is incinerated, and 41% is landfilled. The remaining 10% is anaerobically digested (Davison et al. 2022, Liu et al. 2022).

Fertilizer

China is the world's largest producer and consumer of inorganic nitrogen fertilizer, using upwards of 30% of the global supply (Wang et al. 2022, Zhang et al. 2013). In 2020, 18.3 MMT of inorganic nitrogen fertilizer were applied to soils (Chinese Statistical Yearbook 2021). While average Chinese nitrogen fertilizer intensity has fallen in recent years (Fig. 1), it is still one of the highest in the world, reaching a peak of 219 kg per hectare (ha) in 2014, and was 190 kg/ha in 2020, 2.6 times the global average (FAOSTAT, 2022). Grain agriculture in particular is a heavy user of inorganic nitrogen fertilizer, with upland wheat farmers applying an average of 222 kg/ha in 2015, more than the calculated optimal application rate of 110 - 150 kg/ha (Chai et al. 2019, Chai et al. 2013).

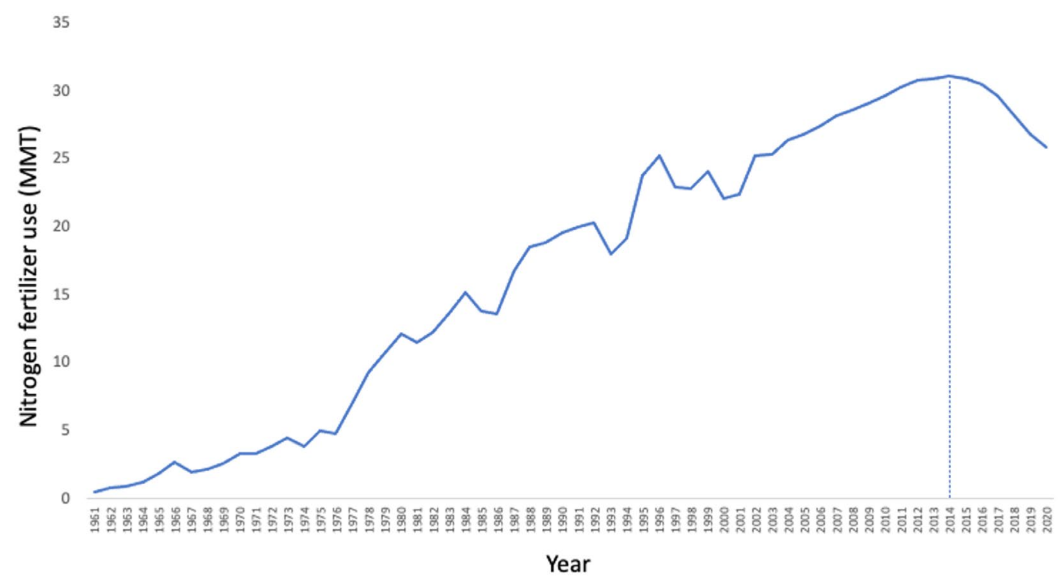
Between 1980 and 2000, N_2O emissions from nitrogen fertilizer use grew at a rate of 2.7 MMT CO_2e per year, rising from 23 to 75 MMT CO_2e per year (Zou et al. 2010). Approximately 6% of China's total greenhouse gas emissions and 57% of its agricultural greenhouse gas emissions stem from inorganic fertilizer use, with the majority of emissions stemming from nitrogen applications (Wu et al. 2021). In 2018, fertilizer and manure emissions from China accounted for 20% and

Figure 1 | Patterns in nitrogen fertilizer use over time in the U.S. (below) and China (next page). Dotted lines denote years where fertilizer use peaked.



Data from FAOSTAT (2022).

Figure 1 | (continued). Patterns in nitrogen fertilizer use over time in the U.S. (previous page) and China (below). Dotted lines denote years where fertilizer use peaked.



Data from FAOSTAT (2022).

23% of global agricultural emissions of N_2O and ammonia, respectively (Ma et al. 2021). The high emissions rate was primarily driven by fertilizer additions to maize, wheat, and rice which make up over half of all emissions and comprise 70% of all cultivated land in China (Wu et al. 2021, Zhang et al. 2016a, Chinese Statistical Yearbook, 2021). Eastern and Central/Southern China, densely populated agricultural areas with significant staple grain production, are hot spots of reactive nitrogen fertilizer-based emissions (Ma et al. 2021).

To control the negative environmental impacts of agricultural run-off and greenhouse gas emissions—and to optimize the energy use, cost, and nitrogen-use efficiency of farming-–the Chinese Ministry of Agriculture has phased out fertilizer manufacturing subsidies and in 2015, implemented the Action Plan for the Zero Increase of Fertilizer Use. Fertilizer use has since declined from 23.6 MMT in 2015 to 18.3 MMT of nitrogen in 2020, with an average annual rate of decline of 1 MMT per year (Chinese Statistical Yearbook, 2021, Ji et al. 2020, Jin & Zhou 2018, Ju et al. 2016).

CARBON REDUCTION POTENTIAL

Building a circular economy

Diverting FLW from high emitting waste streams to compost or anaerobic digestion has the potential to lower landfill emissions and provide a nutrient-rich, slow-release organic fertilizer that could reduce inorganic nitrogen fertilizer emissions and increase soil carbon capture and sequestration. In Table 1 we provide an example of some of the potential greenhouse savings associated with FLW capture and use. At the field scale, eliminating overfertilization would result in a reduction in N_2O emissions from soils and a savings of 32 and 37 MMT of CO_2e for the U.S. and China, respectively. If composted or anaerobically digested FLW is used as fertilizer, it could decrease the amount of inorganic nitrogen fertilizer needed to 3.5 and 4.9 MMT of nitrogen annually in China and the U.S., respectively. This would result in annual savings at the field scale of 60 MMT CO_2e in China and 40 MMT CO_2e in the U.S. from decreased N_2O emissions alone.

Using less nitrogen fertilizer confers fossil fuel savings from fertilizer manufacturing. A recent estimate found that China produces 161 ± 30 MMT CO_2e from fertilizer production while the U.S produces 40 ± 4 MMT CO_2e (Menegat et al. 2022). If land application of inorganic nitrogen fertilizer could be reduced by 50%, the fossil fuel emissions reduction would amount to 80 and 20 MMT CO_2e for China and the U.S., respectively. Eliminating overfertilization combined with the substitution of composted or digested FLW fertilizer could theoretically save 97 MMT CO_2e for China, and 11 MMT CO_2e for the U.S. (Table 1). Overall, the savings from just these two actions could save 157 and 51 MMT CO_2e from China and the U.S., respectively.

Additional emissions reduction could be achieved from the diversion of FLW from landfilling and incineration. Composting FWL results in a reduction of methane emissions of approximately 61 to 82% relative to landfilling (Perez et al. submitted). Although the contribution of FLW to landfill methane emissions is unquantified at a national level for the U.S. and China, it is noteworthy that emissions saving is likely to be significant. Diverting FLW from landfills and incineration and increasing the proportion of FLW treated via anaerobic digestion to 40% could save approximately 33.8 MMT CO_2e by 2050 in China (Liu et al. 2022).

Table 1 | Emissions and potential greenhouse gas savings from repurposing food loss and waste (FLW) for nitrogen (N) fertilizer use and the displacement of inorganic nitrogen fertilizer (INF). Values are in million metric tonnes (MMT).

Agriculture	China	U.S.	Units
Nitrogen in FLW[1]	5.5	1.6	MMT N y^{-1}
Nitrogen added in INF	18	13	MMT N y^{-1}
N_2O from field applied INF	75	64	MMT CO_2e y^{-1}
50% reduction in INF use	9	6.5	MMT N y^{-1}
50% reduction in INF use	37.5	32	MMT CO_2e y^{-1}
INF needed if FLW used	3.5	4.9	MMT N y^{-1}
N_2O from reduced INF + FLW fertilizer use1 ,2	14.6	24.1	MMT CO_2e y^{-1}
Savings from reduced INF + FLW fertilizer use	**60**	**40**	MMT CO_2e y^{-1}
Production	**China**	**U.S.**	**Units**
INF CO_2 emissions	161	40	MMT CO_2e y^{-1}
50% INF production	80.5	20	MMT CO_2e y^{-1}
50% INF production combined with FLW fertilizer use	64.4	28.8	MMT CO_2e y^{-1}
Savings from reduced INF less FLW fertilizer use	**97**	**11**	MMT CO_2e y^{-1}
Total savings from reduced INF and FLW fertilizer use	**157**	**51**	**MMT CO_2e y^{-1}**

1. Assumes 100% of FLW is captured; does not account for emissions from composting or anaerobic digestion or savings from diverting FLW from high emitting waste streams. 2. Assumes in-field FLW derived fertilizer N_2O emissions are negligible (Ryals & Silver 2013)..

Adding livestock manure as a feedstock when composting or anaerobically digesting FLW could help lower inorganic fertilizer requirements and offer additional greenhouse gas emissions reductions. Raw livestock manure is the most common organic fertilizer used in the U.S. (US EPA 2022). Raw manure application emits 26.3 MMT CO_2e as N_2O annually when applied to cropland and grassland in the U.S., equivalent to 41% of N_2O emitted from inorganic fertilizer application to cropland. Prior to land application, manure management (mostly lagoon storage) is an important source of methane (59.6 MMT CO_2e) and N_2O (19.7 MMT CO_2e) (US EPA 2022). Diverting 50% of U.S. land-applied manure to composting could lower emissions by 15 to 46% relative to current manure management strategies, from 12 to 37 MMT CO_2e[2]. A similar reduction could be obtained for using livestock manure anaerobic digestion without accounting for fuel generation (Walling & Vaneeckhaute 2020).

[2] The total emissions would be between 3 to 28 MMT CO_2e using an emission factor range from cattle manure of 28 to 250 kg CO_2e per tonne of waste (Walling and Vaneeckhaute 2020).

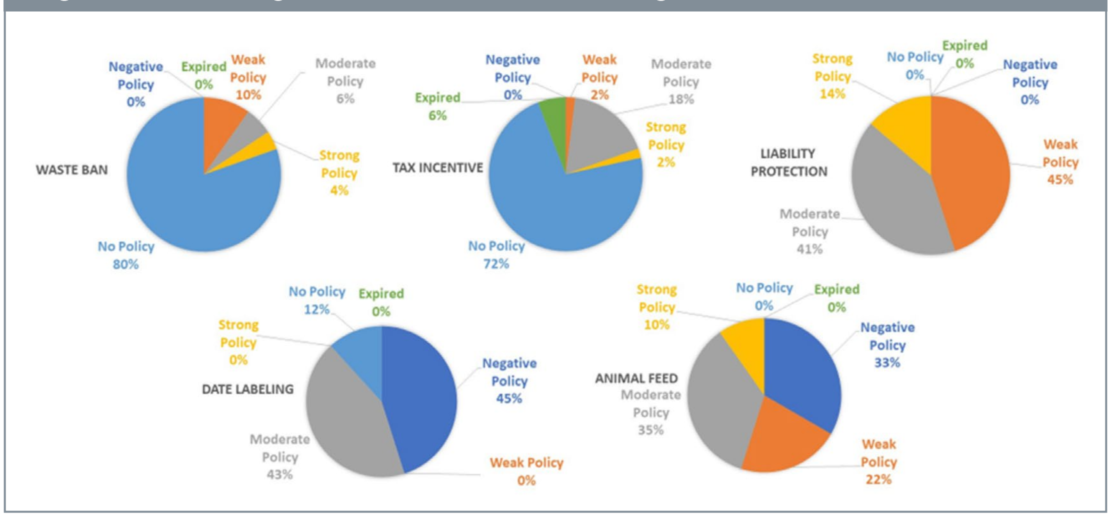
Finally, land application of composted or anaerobically digested FLW is likely to increase the sequestration of carbon in soils (Ryals & Silver 2013, Kutos et al. in press). A recent review found that compost application to rangelands increased plant growth by 43 ± 13% and soil carbon stocks by 50 ± 22%; results were robust even following a single application (Kutos et al. in press). Similar results have been found for crop agriculture (e.g., Tautges et al. 2019). Although not quantified at a national scale, soil carbon sequestration and the associated soil health benefits (improved water holding capacity, reduced erosion, greater nutrient availability) from compost application will add value to programs that repurpose FLW for agricultural management.

RECOMMENDATIONS FOR THE U.S.

1. Reduce FLW and increase capture

There currently are no waste management regulations at the federal level addressing FLW and only 20% of U.S. states have implemented laws (Fig. 2), although a framework has been established to facilitate legislation. Federal plans have been in place since 2015 with the goal of cutting FLW in half by 2030 (US EPA 2015). Federal, state, and municipal regulations would target FLW reduction including date labeling of food products, liability protection, tax incentive animal feed policies, distribution of organic waste bans, and recycling laws (ReFED 2022, https://policyfinder.refed.org/). Although organic waste ban laws are generally considered the most effective measure to minimize FLW, most of the U.S. (80%) has not implemented legislation at the state level (Fig. 2).

Figure 2 | Percentage of US States with laws assessing FLW



(Data from ReFED 2022, https://policyfinder.refed.org/).

Only 10 states have FLW reduction laws, with California and Vermont leading with the strongest policies. Federal laws also provide tax deductions and liability protection to incentivize food donation from the business sector. However, most states (75%) have not implemented tax laws, and liability laws tend to be weak (45% of states) or moderate (41% of states). Providing tax incentives and strengthening liability protection could facilitate donors and nonprofit participation in the distribution of food for people in need while ensuring that food safety requirements are met. The widespread implementation of these laws could be a game changer to minimize FLW from the business sector on a national level (Fig. 2).

Implementing laws that require date labeling is another way to minimize FLW waste from the business sector. Although there are no federal laws in place, some states have instituted requirements to add “Best if used by” labels to food. Most labels are intended by the manufacturers as references to freshness but not safety. Almost half of U.S. states (Fig. 2) have negative policies (i.e. prohibiting sale or donation of food after its labeled date); changing policy to facilitate donation of edible food could save a significant amount of FLW from the business sector. Using food waste as animal feed has the potential to decrease disposal. Federal laws are in place and most states (70%) have some regulation requiring safety measures (such as heat treatments) to prevent animal disease associated with food waste use. This could be expanded to the other 30% of states with no regulations in place. Proposals for school food recovery, food donation improvement, and zero food waste are currently under revision at a federal level (ReFED 2022). The U.S. EPA food recovery hierarchy emphasizes three actions: prevention (source reduction), diversion, and disposal (landfilling and incineration) as last resort (US EPA 2021). To better quantify the relative impact of FLW diversion, the U.S. EPA also introduced six new food waste management pathways to be included in greenhouse gas emission inventories (animal feed, bio-based materials/biochemical processing, codigestion/ anaerobic digestion, composting/aerobic processes, controlled combustion, and donation) (US EPA 2020). Other emerging approaches for FLW reduction actions include food waste apps oriented to surplus food sharing from restaurants and retail such as OLIO in the United Kingdom (Harvey et al. 2020). Although their impact at a broader scale has not been assessed yet, it is likely that by themselves might not be large enough if institutional efforts are not implemented (Hanson and Ahmadi 2022).

2. Expand composting and anaerobic digestion

Analyses suggest that anaerobic digestion and composting have significant potential to lower emissions from FLW relative to landfilling and combustion (Levis & Barlaz 2011, Morris et al. 2017, Harrison et al. 2020). Landfilling is generally a source of greenhouse gases with emission values up to 1100 kg CO_2e per unit of FLW (Levis and Barlaz 2011). Diverting FLW from traditional waste streams to anaerobic digestion is estimated to save 395 kg CO_2e per unit of FLW, and composting could save up to 148 kg CO_2e per unit of FLW. These values do not include use of digestate or compost as fertilizer, nor do they consider soil carbon sequestration, which would further increase the benefits of these approaches. Anaerobic digestate can also be used as a soil nutrient amendment, although pre-processing through a composting system may help lower N_2O emissions. The economic feasibility of these alternative pathways suggests that composting and “wet” anaerobic digestion are more suitable for local scale and rural facilities (< 50 kiloton (kT) per year) whereas “dry” anaerobic digestion is more appropriate for larger and urban facilities (150 to 250 kT/y) where substantial FLW is available (Badgett & Milbrandt 2021). Anaerobic digestion implementation for rural areas would require improving technology (optimizing the ratio of biogas produced per organic matter mass unit, pretreatment of feedstocks, dry fermentation, additives, etc., Dalke et al. 2021).

California is an example of a subnational government that has made substantive progress in FLW minimization. California is the largest food producer in the U.S. In 2018, organic waste represented 34% of total solid waste disposal with 44% of that discarded as FLW (CalRecycle 2020a). Most of the 5.9 MMT of FLW is landfilled. In 2022, California launched an aggressive policy of 75% diversion of organic waste from landfilling to alternative management, as well as redirecting edible food for consumption (CalRecycle 2015; CalRecycle 2020b). This program serves as an excellent example of potential actions that can be taken to reduce emissions and support a circular FLW economy. New infrastructure is needed to increase alternative management capabilities (Table 2). The state expects to produce 8.7 MMT of organic waste for compost management and 7.6 MMT for other alternative managements by 2025 (CalRecycle 2020b). To achieve this goal they are: 1) providing $140 million in grants and loans for organic waste infrastructure, 2) implementing regulatory structures to facilitate private sector investment, 3) launching customizable model franchise agreements and model enforcement ordinances for jurisdictions, and 4) increasing markets and demand for products derived from organic waste, including agricultural producers.

Table 2 | California's estimated Composting, Anaerobic Digestion, and Chip-and-Grind Capacity in 2025			
Technology	**Estimated Anticipated Capacity, 2025***	**Estimated Needed Capacity, 2025**	**Difference**
Compost	4.8	8.7	-3.9
Anaerobic Digestion	0.9	2.4	-1.5
Co-Digestion†	0.2	2.2	-2.0
Chipping and Grinding	3.2	3.0	0.2
Total	9.1	16.3	-7.3

(Values are in million metric tonnes (MMT)) (CalRecycle 2020).

* Estimated anticipated capacity to divert additional tonnes from landfills to compost, anaerobic digestion, and chip and grind.
† The State Water Resources Control Board estimates that WWTPs have digester capacity to co-digest at least 2.2 MMT of food waste.

3. Reduce over-fertilization and substitute with composted or digested FLW

Improving nitrogen fertilizer use efficiency is accomplished by synchronizing nitrogen supply with crop nitrogen demand. Pathways to achieve this include supporting technological (precision agriculture), regulatory, or fiscal (targeted subsidies) approaches to reduce nitrogen overapplication. Investments into precision agriculture can develop technologies that optimally apply fertilizer across a field, limiting overapplication while maintaining crop yields (Chlingaryan et al. 2018). Fiscal approaches for nitrogen fertilizer reduction include targeted subsidies such as the National Resource Conservation Service's (NRCS) Conservation Stewardship (NRCS 2017) and Environmental Quality Incentives Program (NRCS 2017), although there has been limited voluntary uptake of these for nitrogen management (Kanter & Searchinger 2018). Legal and regulatory approaches, including programs modeled after the Corporate Average Fuel Economy (CAFE) standards (Kanter & Searchinger 2018), may be more effective as they would provide flexibility in how manufacturers comply with increases in nitrogen use efficiency while utilizing technological advances from these other pathways. Additionally, focusing on the smaller number of manufacturers would be easier to monitor, more politically feasible than regulating farmers, and target submarkets with greater potential for improvement (Kanter & Searchinger 2018).

Land application of composted or anaerobically digested organic FLW has potential to reduce emissions and sequester carbon in soils. Environmental gains (via lower nitrogen losses) of using FLW composting can further reduce greenhouse gas emissions and increase nitrogen use efficiency when compared to inorganic nitrogen fertilizer (Ryals et al. 2015, Swan et al. 2015). More facilities will be needed to process FLW to better realize greenhouse gas reduction goals.

RECOMMENDATIONS FOR CHINA

1. Reduce FLW and increase capture

Standardizing government-supported nationwide efforts to quantify and report FLW is necessary to plan mitigation strategies (Xue et al. 2021). Policies and campaigns to raise awareness about restaurant waste may have a particularly important impact, because it is the largest proportion of post-consumer waste (Xue et al. 2021). In 2021, Xi Jinping enacted the Anti-Food Waste Law of the People's Republic of China (Feng et al. 2022, UNEP 2021). This law bans excessive ordering and wastage from restaurant diners. Considering the large proportion of waste generated pre-consumer, regulations on FLW should also take into account food lost during production, storage, and transport.

2. Expand composting and anaerobic digestion

Diverting food waste from landfills and incineration to anaerobic digestion provides the dual benefits of managing food waste and generating renewable energy, and will likely reduce total greenhouse gas emissions from FLW disposal. Processing FLW via anaerobic digestion could result in a cumulative mitigation potential of 1900 MMT CO_2e (compared to business-as-usual scenarios) between 2019 and 2040 (Zhang et al. 2020). Even if only 40% of FLW is diverted to anaerobic digestion, annual greenhouse gas emissions could fall by 33.8 MMT CO_2e between 2020 and 2050 (Liu et al. 2022). China's FLW treatment facilities do not yet have the capacity to treat all FLW (~20%), and anaerobic digestion is by far the most common form of FLW management available in treatment facilities, accounting for ~76% of treatment capacity as of 2015, while composting accounted for a much smaller proportion (~20%) (Li et al. 2019). Expanding facility treatment capacity of both anaerobic digestion and composting has great potential for mitigating environmental impacts of FLW.

3. Reduce over-fertilization and substitute with composted or digested FLW

One of the most promising strategies to lower greenhouse gas emissions from fertilizers is improving efficiency of fertilizer application (Wu et al. 2021, Van Groenigen et al. 2010, Ju et al. 2009). Reducing inorganic fertilizer production and usage to fit optimized application rates has the potential to cut greenhouse gas emissions from transportation, manufacturing, and in-field usage by 42 to 70 MMT CO_2e annually (Chai et al. 2013). Alongside minimizing overuse of nitrogen fertilizers, updating technology used in the fertilizer production chain has the potential to cut China's greenhouse gas emissions associated with inorganic nitrogen fertilizer by 20-63%, or 102–357 MMT CO_2e annually (Zhang et al. 2013). Possible avenues to reduce emissions are improving methane recovery from coal mining (the primary energy source for fertilizer manufacturing), switching factory power source to natural gas, and updating machinery used to produce ammonia.

OPPORTUNITIES FOR COLLABORATION

There are several opportunities for collaboration between the U.S. and China. Generating standardized approaches to document FLW generation and fate can facilitate comparisons and development of broadly beneficial solutions. Collaboration is needed on strategies to reduce nitrogen fertilizer application and improve the efficiency of nitrogen fertilizer use by supporting the development of technological approaches. The development of scalable solutions for composting and anaerobic digestion is a particularly promising opportunity for collaboration. Engaging scientists, producers, and urban and rural communities could help ensure sustainable alternatives to FLW management from landfilling and incineration. Strategies to facilitate the development of a supply chain to provide replacement of inorganic fertilizers with FLW-based fertilizers can lead to substantial emissions reductions and carbon removal. A prime example of this at the state level includes California's Short-Lived Climate Pollutant Reduction Strategy. It aims to simultaneously reduce methane emissions from landfills and provide a slow-release organic fertilizer to increase soil carbon sequestration across California's working lands (The Compost-Carbon-Climate Connection, 2018). Data sharing and collaboration across academic and agricultural institutions between the U.S. and China will improve the outlook for a successful transition to a more climate friendly circular economy in the global food system.

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