Supplementary information: Additional data

Reducing food’s resource and climate footprints via food waste upcycling

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Summary description of AC, AD, and Re-Feed

Food waste materials can vary a great deal in physical-chemical properties. Broadly speaking, consumer-level food waste contains roughly 20-22% dry matter. The nutrient content on the dry matter basis averages 38.6% carbohydrates, 19.2% crude protein, and 21.5% lipids, with a Ca:P ratio of 2.3\(^1\). The organic and inorganic constituents contained in food waste can be resources to be recovered for productive re-use through food waste treatment technologies such as aerobic composting (AC), anaerobic digestion (AD), or conversion of recovered food waste into feed for livestock (Re-Feed).

AC as a food waste recycling option has been increasingly adopted by communities, organizations, and businesses\(^2\). In AC, yard trimmings or straw is added to increase the porosity for the aerobic process. Energy is required for mixing and aeration; leachate generated requires treatment, which impacts both energy and water. The end product, compost, consists primarily of complex recalcitrant substrates and mineral nutrients\(^3\) and is typically used as soil amendment. Consequently, use of compost can offset synthetic fertilizers, saving energy and water needed for fertilizer manufacturing. Compost utilization is also associated with more diffuse effects such as enhanced soil organic matter, improved soil moisture retention\(^3\), which in the long run can improve soil productivity. Organic degradation by aerobic microbes during AC releases NH\(_3\) and other odorous compounds, which need to be removed to prevent air pollution\(^4\).

AD is also increasingly adopted as a food waste management alternative\(^5\). In AD, organic materials are degraded under oxygen-free conditions through four microbial metabolic steps: hydrolysis, acidogenesis, acetogenesis, and methanogenesis. Biogas as
the main product consists of methane (53-70%) and CO₂ (30-50%) plus small amounts of other gaseous compounds. Biogas is mainly used for heat and electricity generation. Digestate as by-product is similar to compost from AC in terms of N-P-K content, but with proportionally more ammonia-N; the latter is more readily available to crops than organic-N. In addition to the need for treating liquid waste and digestate to prevent subsequent water or pathogen pollution, there remains a technical challenge for AD using food waste as the sole feedstock: rapid conversion of easily-degradable foodstuffs to volatile fatty acids can lower pH drastically, disrupting microbial functions and leading to system instability. The problems remain to be properly addressed through research.

Re-Feed can be a game changer in food waste valorization. Contemporary treatment processes used in South Korea include sorting and screening raw food waste materials, combined with steps of grinding, dewatering, heating, and drying. This is different from the age-old practice of ‘garbage feeding’ to backyard pigs. The contemporary technologies can recover most of the nutrients in the form of feeds that are safe and nutritious for monogastric animals. South Korea uses this technology to convert 45% of its food waste into animal feed nationwide, as high as 70% in some cities. The novel feeds produced via Re-Feed can substitute a portion of maize and soybeans in pig and poultry diets, this substitution avoids the use of land, water, fuel, fertilizer, and pesticides that are normally required for producing the feed grains. Nutrient losses and GHG emissions associated with grain production would be avoided, and other ecosystem and human health benefits may ensue as well. Re-Feed technologies consume energy to operate; the feed-drying and the treatment of liquid waste can be energy intensive. On the other hand, fats, oils and grease (FOG) can be recovered and
processed into biodiesel, thereby offering energy credits\textsuperscript{10,15}.

**Food loss and waste: Some cross-study and cross-region comparisons**

Food loss and waste occurs at every stage of the food system from farm to fork. The landmark publication by Gustavsson et al. (2011) examined FLW in 5 sectors/stages\textsuperscript{16}. In the current study, we expanded food loss and waste factors based on literature data-mining of peer-reviewed papers published in both Chinese and English Journals up to October 2021. These factors included in-field production and harvest loss (P1), postharvest handling and storage loss (P2), manufacturing loss (P3), distribution loss (P4), retail and market waste (P5), and consumer in-home waste (P6a) as well as out-of-home waste (P6b). We explore loss/waste factors for specific food commodities, region, and food supply chain stages. By combining these loss factors and national food availability data from Food and Agriculture Organization's (FAO) database\textsuperscript{17}, we then estimate the mass of each commodity for a given country-stage pair to estimate the quantity of the commodity (see method).

Our finding of global FLW totaling 1.67 billion metric tons (Bt) is close to Porter et al. (2016) of 1.6 Bt\textsuperscript{18}. Our finding is about 25% greater than the 1.3 Bt reported by Gustavsson et al. (2011)\textsuperscript{16}, due probably to differences in food availability amounts as well as FLW parameters.

We examined food loss and waste patterns for high/medium-income countries (Europe, North America and Oceania, Industrialized Asia) vs. low-income countries (North Africa, West and Central Asia, Latin America, Sub-Saharan Africa, South and
Southeast Asia) (Supplementary Table 2)\textsuperscript{16}. In high/medium-income countries, nearly half (48\%) of total FLW occurred at the end of the food chain (P5-P6). In these regions, consumer food waste amounted to 107 Mt for Europe, 73 Mt for Northern America and Oceania, 172 Mt for Industrialized Asia; totaling 351 Mt). This is almost as much as the total net food production in Northern America and Oceania (385 Mt). Also, consumer out-of-home waste totaled 272 Mt, which is 1.84 times of the in-home food waste (148 Mt). In contrast, for low-income countries FLW occurred mostly in earlier stages, with $<1/3$ being allocated to consumer waste (P5-P6, Extended Data Table 3).

Per capita FLW (P1-P6, Supplementary Table 2) in high/medium-income countries was 257 kg yr\textsuperscript{-1}, compared to 197 kg yr\textsuperscript{-1} in low-income countries. Per capita consumer food waste (P6a and P6b) by consumers in high/medium-income countries is 95 kg yr\textsuperscript{-1}, compared to 31 kg yr\textsuperscript{-1} in low-income countries.
Biosafety of novel feeds for livestock feeding

In the U.S., the Swine Health Protection Act\textsuperscript{19} requires that food waste containing animal tissues be thermally processed at 100 °C for 30 minutes at licensed facilities to destroy all disease-causing agents before feeding to pigs. Similarly, “ecofeed” manufacturers in Japan are required to thermally process food waste containing animal tissues for at least 30 minutes at 70°C or 3 minutes at 80°C\textsuperscript{20}. In South Korea, all types of food waste must be heated at a temperature of at least 80°C for 30 minutes\textsuperscript{14}. These thermal processing conditions are adequate for inactivating major endoparasites (\textit{Trichinella, Toxoplasma}), pathogenic foodborne bacteria, and several viruses\textsuperscript{11}. García et al. (2005) confirmed that heating food waste at 65°C for 20 minutes is adequate for reducing \textit{Salmonella}, \textit{Escherichia coli}, and \textit{Staphylococcus aureus} below levels deemed safe for animal feed\textsuperscript{21}. Therefore, use of appropriate thermal treatment protocols can adequately inactivate endoparasites, bacteria, and viruses that may be present in various sources of food waste to minimize feed biosafety risks for monogastric species, even if they contain animal-derived food products.

Importantly, thermal treatment does not destroy prions, which are abnormal proteins associated with transmission of bovine spongiform encephalopathy (BSE) from infected ruminant tissues\textsuperscript{11}. Therefore, feeding post-consumer food waste (which may contain bits of animal-source food residues) to ruminants is prohibited. Since food waste differs in types and sources and varies in its makeup ingredients, species-specific feeding strategies would offer the best opportunity for animal-based upcycling\textsuperscript{22}, so as to match food waste types/sources with animal species for maximum extraction of the biological value of nutrients while minimizing animal and public health risks. For
example, unsalable fruit and vegetables account for 13–14% of supermarket inventories in the US\textsuperscript{23}. A recent study projected fruit and vegetable wastes to reach 170 Mt in China by 2030\textsuperscript{24}. These plant-based food discards are relatively high in dietary fiber content and thus most suitable for ruminants, given the animals’ ability to utilize fiber as an energy source. Other discarded food products, such as meat, dairy, and bakery waste from supermarkets, together with post-consumer food waste from homes and restaurants, can be made into nutritious feeds for monogastric animals.

It is worth mentioning that the EU ban on using animal meal in livestock feeding, which was introduced in 2001 during the BSE crisis, is partly lifted now: animal meal from poultry and insects may be used in pig feed; animal meal from pigs and insects allowed in poultry feeding. But the ban on animal meal in ruminant feed as well as the ban on consumer-level food waste in livestock feeding remains in force.
### Supplementary Table 1. Summary of different databases assembled from peer-reviewed publications and used for analyses in the present study.

<table>
<thead>
<tr>
<th>Subset</th>
<th>Number of studies</th>
<th>Number of observations</th>
<th>Related parameters</th>
</tr>
</thead>
</table>
| **FWTTs database**      | 93                | 476                    | **Basic information:** name of country, food waste treatment method  
(i) Material and energy parameters: water, electricity, diesel, liquefied natural gas, by-product  
(ii) Environmental parameters: greenhouse gas emission, acidification potential, eutrophication potential, human toxicity potential  
(iii) Economic parameters: cost of food waste treatment and benefit of substitution  
**Remarks:** These observations provided the basis for comparison of food-energy-water nexus, environmental impacts.  
**Sources:** Supplementary Information-References: Database I |
| **FLW database**        | 117               | 1,135                  | **Basic information:** name of country, FLW percentages  
**Calculated data:** FLW percentages for each commodity group in each step of the FSC, including agricultural production and harvesting (P1), postharvest handling and storage (P2), manufacturing (P3), distribution (P4), retailing (P5), and consumer waste (both in household (P6a) and out-of-home (P6b))  
**Remarks:** These observations provided the basis for estimation of food loss and waste during food supply chain.  
**Sources:** Supplementary Information-References: Database II |
| **Maize & Soy database**|                   |                        | **Basic information:** name of country, crop yield, agricultural inputs (N, P$_2$O$_5$, K$_2$O, herbicides, insecticides, seed)  
**Remarks:** These observations provided the basis for avoidance analysis of Re-Feed of environment-energy-water in U.S. and China.  
**Sources:** Statistical data |
### Basic information:
- Name of country, crop yield, season precipitation, irrigation, soil water supply, fuel and energy use for agricultural input.
- Remarks: These observations provided the basis for avoidance analysis of Re-Feed of environment-energy-water in U.S. and China.
- Sources: Meta-analysis via literature data-mining^25-27^.

<p>| | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Irrigation, fuel use</td>
<td>841</td>
<td>8,364</td>
</tr>
<tr>
<td>Nr losses</td>
<td>186</td>
<td>930</td>
</tr>
</tbody>
</table>

### Calculated data:
- Emission factor of Nr losses (as N₂O, NO₃⁻ or NH₃)

### Remarks:
- These observations provided the basis for avoidance analysis of Re-Feed of environment-energy-water in U.S. and China.

### Sources:
- Supplementary Information-References: Database III
**Supplementary Table 2. Estimated food waste per capital for each commodity group in each step of the food supply chain for medium/high-income and low-income countries.** P1 for in-field loss, P2 for postharvest handling and storage loss, P3 manufacturing loss, P4 distribution loss, P5 retail and market waste, P6a for consumer in-home waste and P6b for consumer out-of-home waste.

<table>
<thead>
<tr>
<th>Stages</th>
<th>Medium/high-income kg per capita</th>
<th>Low-income kg per capita</th>
</tr>
</thead>
<tbody>
<tr>
<td>P1</td>
<td>50</td>
<td>42</td>
</tr>
<tr>
<td>P2</td>
<td>33</td>
<td>36</td>
</tr>
<tr>
<td>P3</td>
<td>36</td>
<td>31</td>
</tr>
<tr>
<td>P4</td>
<td>14</td>
<td>27</td>
</tr>
<tr>
<td>P5</td>
<td>29</td>
<td>29</td>
</tr>
<tr>
<td>P6a</td>
<td>38</td>
<td>8</td>
</tr>
<tr>
<td>P6b</td>
<td>57</td>
<td>23</td>
</tr>
<tr>
<td>Total</td>
<td>257</td>
<td>197</td>
</tr>
</tbody>
</table>
Supplementary Table 3. Water and fuel consumption in maize and soy production of U.S. and China. Estimation of water consumption is based on proportions of irrigated vs. rainfed planting area in each country. Energy consumption included that used for planting, tillage, spraying, fertilization and irrigation. Data are derived from meta-analysis of data assembled via literature data-mining.

<table>
<thead>
<tr>
<th>Crop</th>
<th>Country</th>
<th>Irrigation</th>
<th>n</th>
<th>Water productivity kg ha(^{-1}) mm(^{-1})</th>
<th>Yield kg ha(^{-1})</th>
<th>Water consumption mm</th>
<th>Fuel consumption MJ ha(^{-1})</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maize</td>
<td>U.S.</td>
<td>Irrigated</td>
<td>813</td>
<td>17.1</td>
<td>10300</td>
<td>603</td>
<td>24232</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Rain-fed</td>
<td>221</td>
<td>16.3</td>
<td>8000</td>
<td>492</td>
<td></td>
</tr>
<tr>
<td></td>
<td>China</td>
<td>Irrigated</td>
<td>2740</td>
<td>17.4</td>
<td>9300</td>
<td>536</td>
<td>19112</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Rain-fed</td>
<td>3986</td>
<td>18.7</td>
<td>7500</td>
<td>402</td>
<td></td>
</tr>
<tr>
<td>Soybean</td>
<td>U.S.</td>
<td>Irrigated</td>
<td>103</td>
<td>7.7</td>
<td>5100</td>
<td>663</td>
<td>11616</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Rain-fed</td>
<td>74</td>
<td>7.1</td>
<td>2500</td>
<td>350</td>
<td></td>
</tr>
<tr>
<td></td>
<td>China</td>
<td>Irrigated</td>
<td>128</td>
<td>7.0</td>
<td>3100</td>
<td>443</td>
<td>9511</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Rain-fed</td>
<td>299</td>
<td>5.3</td>
<td>1800</td>
<td>337</td>
<td></td>
</tr>
</tbody>
</table>
### Supplementary Table 4. Greenhouse gas (GHG) emission factors of agricultural input.

<table>
<thead>
<tr>
<th>Item</th>
<th>Unit</th>
<th>GHG emissions (kg CO₂ eq per unit input)</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>N fertilizer production and transportation</td>
<td>kg N</td>
<td>8.21</td>
<td>28-31</td>
</tr>
<tr>
<td>P fertilizer production and transportation</td>
<td>kg P</td>
<td>0.32</td>
<td>30-34</td>
</tr>
<tr>
<td>K fertilizer production and transportation</td>
<td>kg K</td>
<td>0.46</td>
<td>30-34</td>
</tr>
<tr>
<td>Seed production and transportation (maize/soy)</td>
<td>kg</td>
<td>1.56/0.88</td>
<td>35,36</td>
</tr>
<tr>
<td>Herbicide production and transportation</td>
<td>kg</td>
<td>19.12</td>
<td>30,31,37</td>
</tr>
<tr>
<td>Insecticide production and transportation</td>
<td>kg</td>
<td>21.67</td>
<td>30,37</td>
</tr>
<tr>
<td>Irrigation</td>
<td>kg</td>
<td>7.33</td>
<td>30,33</td>
</tr>
<tr>
<td>Item</td>
<td>Unit</td>
<td>Energy consumption (MJ per unit input)</td>
<td>References</td>
</tr>
<tr>
<td>----------------------</td>
<td>------</td>
<td>---------------------------------------</td>
<td>------------</td>
</tr>
<tr>
<td>N fertilizer production</td>
<td>kg N</td>
<td>50.7</td>
<td>35,38,39</td>
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<tr>
<td>P fertilizer production</td>
<td>kg P</td>
<td>8.1</td>
<td>35,38,39</td>
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<tr>
<td>K fertilizer production</td>
<td>kg K</td>
<td>6.1</td>
<td>35,38,39</td>
</tr>
<tr>
<td>Seed production (maize/soy)</td>
<td>kg</td>
<td>27.2/21</td>
<td>35,39</td>
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<tr>
<td>Herbicide production</td>
<td>kg</td>
<td>344.4</td>
<td>35,39</td>
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<tr>
<td>Insecticide production</td>
<td>kg</td>
<td>359.6</td>
<td>35,39,40</td>
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<tr>
<td>Irrigation</td>
<td>mm</td>
<td>36</td>
<td>41</td>
</tr>
</tbody>
</table>
References


19. U.S. Congressional Record (96th Congress), 1980. Swine Health Protection Act, H.R. 6593 and


