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How does COVID-19 affect the life cycle environmental impacts of U.S. household energy and food consumption?

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Abstract

The COVID-19 pandemic has reduced travel but led to an increase in household food and energy consumption. Previous studies have explored the changes in household consumption of food and energy during the pandemic; however, the economy-wide environmental implications of these changes have not been investigated. This study addresses the knowledge gap by estimating the life cycle environmental impacts of U.S. households during the pandemic using a hybrid life cycle assessment. The results revealed that the reduction in travel outweighed the increase in household energy consumption, leading to a nationwide decrease in life cycle greenhouse gas emissions (−255 Mton CO_2 eq), energy use (−4.46 EJ), smog formation (−9.17 Mton O_3 eq), minerals and metal use (−16.1 Mton), commercial wastes (−8.31 Mton), and acidification (−226 kton SO_2 eq). However, U.S. households had more life cycle freshwater withdrawals (+8.6 Gton) and slightly higher eutrophication (+0.2%), ozone depletion (+0.7%), and freshwater ecotoxicity (+2.1%) caused by increased household energy and food consumption. This study also demonstrated the environmental trade-offs between decreased food services and increased food consumption at home, resulting in diverse trends for food-related life cycle environmental impacts.

1. Introduction

The coronavirus (COVID-19) pandemic has had an enormous impact on society. As of July 2021, more than 4 million COVID-19 deaths have been reported globally [1], of which over 600 000 deaths have occurred in the United States [2]. Social distancing and mobility restrictions have been enforced across the world [3], which have disrupted people's daily routines and social contact, leading to a dramatic shift towards increased household and indoor activities. Many studies have investigated the impacts of pandemic lockdown and restrictions on the environment [4, 5], energy [6, 7], social well-being [8, 9], and economy [10–12]. However, to the best of the author's knowledge, no study has explored the life cycle environmental implications of energy and food consumption in U.S. households that have substantially changed in the pandemic.

Several studies have examined the impacts of COVID-19 on direct household energy consumption in different countries, such as China [6], Australia [13], Serbia [14], Canada [15], Poland [16], and the United States [17]. Several studies reported an overall increase in household electricity usage due to higher occupancy but different heating and cooling energy trends given regional differences in weather and human behavior [13–15, 17]. Although the changes in household energy consumption in the pandemic are temporary, some impacts may last longer, depending on the potential transition to remote working and extended indoor stays after the pandemic [6]. These impacts can also lead to energy security issues, especially in low-income populations [18, 19]. Although previous studies have primarily focused on variations in direct household energy consumption during the pandemic, few have investigated the corresponding changes in environmental burdens, such as greenhouse gas (GHG) emissions and resource use across the life cycle of fuel and electricity.

Studies on household food consumption during the pandemic primarily explored the impact of

COVID-19 on food security, consumption, and waste generation. Numerous studies investigated household food availability, utilization, and stability in different countries, and identified an increase in household food insecurity in developing countries [20–24] and minority groups [25]. Some studies discussed supply chain disruptions during the pandemic, such as the shortage of workers, shutdown of food production facilities, and restricted policies on food trade, which resulted in food price increases and panic buying [26, 27]. Others used surveys to collect self-reported data and observed an increase in food purchases but a decrease in food wastes [28, 29] and improved awareness of food waste generation [30, 31] during the pandemic. Cosgrove *et al* reported that although the perceived food waste in households decreased significantly, food stockpiling, which is an indicator of food waste, increased during the pandemic [32]. Everitt *et al* conducted a direct measurement of food waste generated by 100 single-family households across the city of London in Ontario, Canada and revealed that 52% of the wastes were avoidable [33]. They also concluded that previous studies relying on self-reported data could have underestimated the household food waste generation in the pandemic [33]. Roe *et al* demonstrated that disruptions during the pandemic were likely to result in an intermediate surge in food waste but could improve household food management [34]. In addition to food waste, other materials used along the food supply chain (e.g. packaging materials) will likely change due to the changing demand for food [26]. Environmental and human health impacts of agricultural systems are often driven by food consumption patterns [35]. However, no study has examined the impacts of changes in household food consumption on the life cycle environmental impacts across the food production supply chain (from agriculture activities to food production).

Before the pandemic, household energy and food consumption had significant environmental impacts. In the United States, 16% of the national energy consumption was attributed to residential use in 2019 [36]. In the same year, residential CO_2 emissions were as high as 336.8 million metric tons (Mton), accounting for 6% of the national GHG emissions [37]. Dietary choices and consumption patterns primarily affect food production, which contributes to global GHG emissions, environmental degradation, and mortality [38]. Restrictions in human activities due to the pandemic affect household consumption, which may affect the environmental burdens across the life cycle of energy and food products. Thus far, such environmental burdens have not been thoroughly investigated in the literature. Understanding how changes in household consumption can alter the life cycle environmental impacts of household activities will inform workforce management from a sustainability perspective after the pandemic.

This study fills the critical knowledge gap using a hybrid life cycle assessment (LCA) that uses environmental input-output LCA (EIO-LCA) and process-based life cycle inventory (LCI) data to quantify the changes in the potential life cycle environmental impacts of U.S. household energy (i.e. direct energy use and transportation) and food consumption in 2019 (before the pandemic) and 2020 (during the pandemic). This study does not intend to address the life cycle environmental effects of everything that happened in 2020 in the United States. USEEIO v2.0 [39] was used to estimate the environmental burdens of upstream activities (cradle-to-gate) of energy and food products. The GHG emissions from fuel combustion (e.g. gasoline in transportation and natural gas for heating) were included using a process-based approach. The path exchange method [40, 41] was used to include the latest energy and GHG emission data of the electricity generation sector. In total, 18 environmental impact categories were investigated, including GHG emissions, energy use, human health impacts, use of natural resources (i.e. land, water, minerals, and metals), commercial waste, smog formation, acidification, eutrophication, ozone depletion, and freshwater ecotoxicity.

2. Methodology

This study used USEEIO v2.0, which is the latest U.S. Environmentally Extended Input-Output (EEIO) with high-resolution industrial sectors (421 sectors) [39], to estimate the life cycle (cradle-to-gate) environmental impacts using equation (1) [42]:

$$E = CB\,(I - A)^{-1}y \tag{1}$$

where, A is the direct requirement matrix that includes the economic transactions among 421 sectors (dimension 421×421). This study used the domestic A matrix in USEEIO as the scope is the domestic environmental impacts within the United States; I is the identity matrix; y is the final demand, which is a vector that has all entries as zero, except for the sectors that are studied for household consumption (see table S1 available online at stacks.iop.org/ERL/17/034025/mmedia for sector matches); C is the indicator matrix that includes the characterization factors for 18 environmental impact categories investigated in this study (dimension 18×2668); B is the environmental flow coefficient matrix that includes 2668 emission factors per dollar of output for 421 sectors (dimension 2668×421).

The final demand was estimated based on the household consumption data of 2019 (before the pandemic) and 2020 (during the pandemic). Household food expenditure data for food at home (FAH) and food away from home (FAFH) were collected for 2019 and 2020 [43] from the U.S. Department of

Agriculture (USDA) (table S2). Expenditure data for alcohol consumed at home and away from home were collected from the same source [43]. As the collected data are aggregated expenditure for the entire U.S. household sector in 2019 and 2020, FAH expenditure was further broken down into specific food items based on the U.S. Consumer Expenditure Surveys [44] (table S4, which shows the average percentages of U.S. household expenditure breakdown by food items for 2018–2019). As the data on expenditure breakdown for different food items consumed at home are not available for the year 2020, in this study, the same percentages of different food items (table S4) were used for FAH in 2020, except for fresh fruits and tree nuts that were adjusted based on the latest USDA data [45]. Although this study has certain limitations, the overall changes in household expenditure are well reflected by the aggregated FAH and FAFH data collected from the USDA [43]. In the future, these limitations can be addressed when U.S. household expenditure details are available for the year 2020.

Household expenditure data for direct energy use, including electricity, natural gas, fuel oil, propane, and kerosene were estimated based on residential energy consumption and price data collected from the U.S. Energy Information Administration (EIA) [46]. Detailed data on residential consumption and prices of electricity, natural gas, and other fuels before and during the pandemic are documented in tables S6 and S7. Natural gas delivered to U.S. households is mostly used for space heating and water heating (e.g. about 50% of U.S. homes use natural gas for heating), drying clothes, and cooking [47]. Electricity usage in U.S. households varies by region and house type; on average, the largest electricity end uses in the United States include air conditioners, heaters (including both space and water heaters), lights, and refrigerators [48]. In 2015, air conditioning contributed to 17% of the total U.S. residential electricity usage, and the shares for space and water heating were 15% and 14%, respectively [48]. Other fuels used for heating include fuel oil, propane, and kerosene. Propane is used for cooking in the United States [49]. Additionally, U.S. personal spending data on transportation items were collected from the U.S. Department of Transportation (table S8) [50]. Each food and energy item was matched with the economic sector based on the North American Industry Classification System (NAICS) [51]. All expenditure data were converted to 2012 using the Consumer Price Index (CPI), which measures the difference in the prices paid over time by purchasers for various goods [52]. The conversion equation is documented in section 1 of the Supplementary Materials (SM). Furthermore, the data were converted to the producer price using the ratios of producer price to purchaser price for different U.S. sectors, provided by USEEIO [39]. The producer price-based expenditure used in the final demand vector is shown in table S5.

As the latest USEEIO is in the year 2012, this paper first tested the applicability of USEEIO in estimating the total requirement (in millions of dollars) of several important industrial sectors directly related to household food and energy consumption (e.g. fertilizer manufacturing and electricity generation). The total requirement was estimated using the Leontief matrix $(I-A)^{-1}$ timed with final demand y, as shown in equation (1). The Leontief matrix converts the direct requirement matrix A into the total requirement matrix that estimates all upstream purchases related to the final demand [42]. In addition to the total requirement, the results of total energy use, including both renewable and renewable energy, were compared with benchmarks. Estimating the benchmarks for the life cycle of U.S. household energy and food consumption is challenging, as most data (e.g. sales of electricity and fertilizers) are reported by literature at the national level that covers all uses. Therefore, in this study, the benchmarks were estimated by allocating national-level energy, meat, fresh fruits, and tree nuts, and fertilizer consumption to activities that were the most relevant to the life cycle of U.S. household energy and food consumption. The estimated benchmarks were then used for the validation test. The test included energy, food, and fertilizer items only, owing to limited data availability. Detailed estimations of the benchmarks are documented in SM section 4 titled Benchmark Estimations.

After validation, USEEIO was used to estimate the cradle-to-gate impacts, including raw material extraction, transportation, and production. The GHG emissions of fuel combustions were added to the cradle-to-gate GHG emissions generated by the USEEIO, because previous studies showed significant contributions of fuel combustion to the life cycle GHG emissions of energy products, such as gasoline and natural gas [53, 54]. SM section 2 documents the GHG estimations of fuel combustion. To include changes in electricity production during the pandemic, the path exchange method [40, 41] was used to replace the energy use (including renewable and non-renewable energy) and GHG emissions associated with the electricity sector by the process-based energy and GHG emission data derived from the latest data reported by the U.S. EIA [46, 55] for 2019 and 2020 (SM section 1).

3. Results

The total requirement of several sectors was compared with product sales in the same year allocated to U.S. households. The total energy consumption, including both renewable and non-renewable energy, was compared with the benchmarks based on real-world energy consumption data in the U.S [46, 56].

Table 1. Validation of some results of this study.

	2019			2020		
	This study	Estimated benchmark[a]	Diff[b]	This study	Estimated benchmark[a]	Diff[b]
Validation of total domestic requirement (million $ in 2012 producer price)						
Electricity	191 078	189 437	0.9%	222 630	195 081	14.1%
Fertilizer	7312	6566	11.4%	7296	8266	−11.7%
Packaged meat[c]	102 789	108 056	−4.9%	102 816	109 753	−6.3%
Fresh fruits and tree nuts	26 993	25 343	6.5%	26 163	24 056	8.8%
Validation of total energy consumption (EJ)						
Renewable Energy	4.7	5.4	−13.0%	5.6	5.6	−0.6%
Non-renewable Energy	46.5	45.2	2.9%	41.2	41.3	−0.3%
Total Energy	52.1	50.6	2.9%	47.6	46.9	1.4%

[a] Detailed estimations of benchmarks are documented in SM section 4 Benchmark Estimations.
[b] Difference percentage = (Results of this study—Benchmark)/Benchmark.
[c] This sector excludes poultry.

The results and estimated benchmarks in table 1 are for the activities involved in the life cycle of U.S. household food and energy consumption, which are different from the direct energy and food consumption of the entire U.S. For example, the total economic requirement of the electricity sector in table 1 reflects the total electricity output (produced by the electricity generation sector) required by all other sectors involved in the upstream supply chain of energy and food consumed by U.S. households. Such requirements increased in 2020, which was consistent with the benchmarks estimated in table 1. This trend was different from the total U.S. electricity consumption trend, which included electricity used for all activities in the economy and tended to decrease in 2020 (according to the EIA, 3811 billion kWh in 2019 and 3664 billion kWh in 2020 [46]). However, residential electricity accounted for ∼40% of the total U.S. electricity consumption among different electricity uses and increased substantially in 2020 [46]. The benchmark value in table 1 increased as it included only electricity consumption of the residential sector, the transportation sector, and a small part of the industrial sector that are directly related to food and energy production (SM section 4).

In general, the results of this study are consistent with the estimated benchmarks. The total energy consumption estimated by this study, including both renewable and non-renewable energy, showed minor differences from the benchmarks (<5%, except for renewable energy in 2019). For total requirement validation, the differences between the result and estimated benchmarks are <15%. The results of this study showed higher values than the benchmarks for most sectors, except packaged meat. This could be explained by the broader coverage of the input-output approach, which included electricity, fertilizers, and fresh fruits and tree nuts required by all sectors involved in the upstream supply chain of U.S. household food and energy consumption. In comparison, the benchmarks were estimated by allocating product sales only to activities that were identified as being directly related to U.S. households (see section 2). This estimation has some uncertainties, which are discussed in SM section 4 Benchmark Estimations.

The life cycle environmental impacts of U.S. household energy and food consumption before and during the pandemic as well as the net differences are presented in figure 1. Different environmental impacts are grouped by grid lines for further discussion. Direct energy consumption includes the usage of electricity, natural gas, fuel oil, propane, and kerosene in U.S. households. Transportation includes the use of gasoline and other fuel products for driving and transportation services, such as public transportation and ride-sharing services. Food consumption includes common food items consumed by households according to the U.S. Consumer Expenditure Surveys [44].

During the pandemic, reduced travel lowered the life cycle environmental impacts of U.S. households (purple bars in figure 1(a)). Direct energy usage of households showed an opposite trend, that is, it increased during the pandemic (blue bars in figure 1(a)). For most environmental impact categories, the life cycle environmental reduction due to reduced travel in the pandemic outweighed the impacts of increased household direct energy consumption, except for freshwater withdrawal, eutrophication, ozone depletion, and freshwater ecotoxicity. Household food consumption had a mixed impact on life cycle environmental burdens (orange bars in figure 1(a)). The changes in U.S. household food

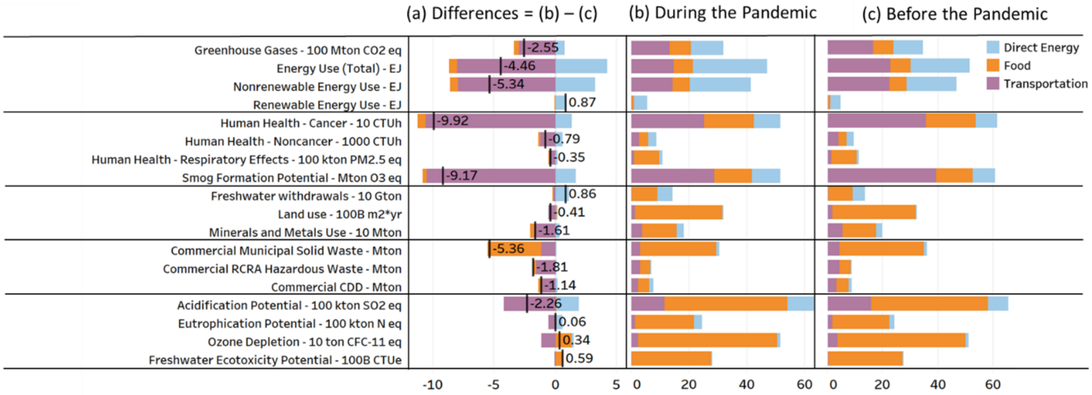

Figure 1. Life cycle environmental impacts of household food and direct energy consumption and transportation (b) during the pandemic (c) before the pandemic, and (a) the difference between the two.

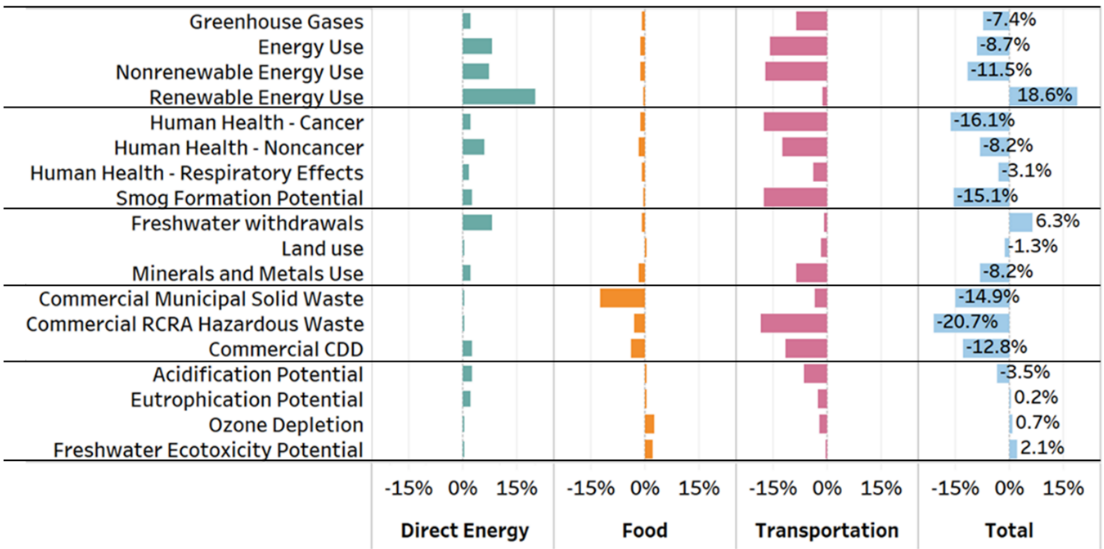

Figure 2. Percentage breakdown of life cycle environmental impact changes of U.S. households.

consumption in the pandemic caused decreases in several impacts such as energy use, GHG emissions, human health impacts, freshwater withdrawals, minerals and metals use, and commercial waste generations. However, they increased land use, eutrophication, ozone depletion, and freshwater ecotoxicity. Before and during the pandemic, food consumption dominated most environmental impacts, except for human health, energy, and GHGs dominated by transportation and energy.

3.1. GHG and energy use reduction in the pandemic

During the pandemic, 255 Mton CO_2 eq of life cycle GHG emissions were reduced by U.S. households (figure 1(a)), accounting for a 7.4% decrease, as compared to the GHG emissions before the pandemic. This reduction was due to decreased transportation (8.7% reduction) and food consumption (1% decrease), and increased direct energy consumption (2.3% growth) (figure 2). This decrease in GHG emissions because of reduced transportation was driven by the reduced use of gasoline and fuel products for vehicles (figure 3(a)), which accounted for 82%–83% of the total life cycle GHG emissions associated with transportation before and during the pandemic (tables S10 and S11). The remaining GHG emissions were associated with transportation services that were also halted during the pandemic. An increase in life cycle energy-related GHG emissions was mainly attributed to the growth of household electricity consumption (figure 3(b)). Electricity accounted for 62.8% of the total life cycle GHG emissions of household direct energy consumption before the pandemic (table S13), which increased to 68.3% during the pandemic (table S14).

Similar to the GHG emissions results shown in figure 1(a), the energy results in the same figure show a reduction of life cycle energy use (4.46 EJ, 8.7% reduction) as a result of 5.34 EJ reduction of

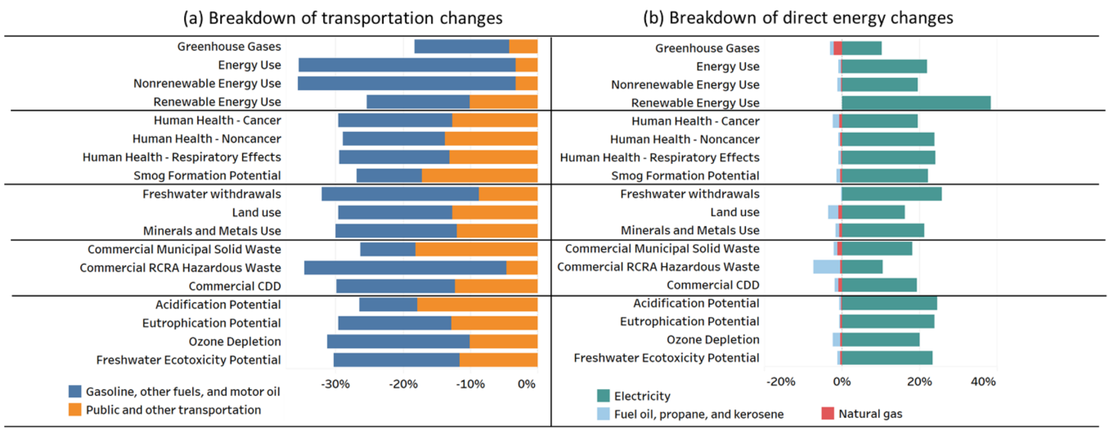

Figure 3. Breakdown of the life cycle environmental impact changes for U.S. household transportation (a) and direct energy consumption (b). The percentage change was estimated as the ratio of the environmental impact differences (in the pandemic—before the pandemic) to the environmental impacts before the pandemic.

non-renewable energy (driven by the declined gasoline usage, figure 3(a) and 0.87 EJ growth of renewable energy (driven by increased electricity consumption, figure 3(b). The contribution of household food consumption to reductions in energy use and GHG emissions was minimal (∼1%) (figure 2). The increase in the use of renewable energy should not be interpreted as an increase in renewable energy use in households but as an increase in renewable energy across the life cycle of electricity used by households. This interpretation is more consistent with the data collected by the U.S. EIA, which showed an 8.6% increase in renewable energy consumed for electricity generation [46]. On the other hand, the renewable energy directly consumed by the U.S. residential sector decreased by 5.7% (table S22) [46]. Although renewable energy consumption reached a record high of 12% of total U.S. energy consumption in 2020 [57], previous studies have pointed out the potential adverse long-term effects of COVID-19 on renewable energy transition by decreasing economy-wide demand [58] and decelerating clean energy innovation [4].

The net differences in life cycle GHG emissions and energy use between decreased transportation and increased direct energy consumption of U.S. households were quantified in this study. Such differences are likely to decrease during the post-pandemic period with resumed travel. Previous studies [4, 6] pointed out that workers and employers may be comfortable with remote working, and this may reduce travel but increase building energy use; however, they have not explored the net differences. The results of this study can be used as a foundation for future analysis of trade-offs regarding remote working and lifestyle changes in the post-pandemic period.

3.2. Human health impacts reduction during the pandemic

Four human health impact categories were investigated in this study: cancer and non-cancer-related human health impacts, respiratory effects, and smog formation. All four human health-related impacts were reduced during the pandemic due to reduced travel. The health impacts are in the unit of Comparative Toxic Unit for Humans (CTUh), which estimated an increase in morbidity, in other words, disease cases [59, 60]. Cancer-related human health impact decreased 99 CTUh and non-cancer-related impact showed a decrease of 790 CTUh (disease cases), which were far less than the deaths caused by COVID-19.

The respiratory effects were estimated in terms of particulate matter equivalent ($PM_{2.5}$ eq). This study showed a net decrease of 35 kton $PM_{2.5}$ eq (figure 1(a)) across the life cycle of food and energy consumed by U.S. households. According to the U.S Environmental Protection Agency (EPA), national $PM_{2.5}$ primary emissions excluding miscellaneous emissions (e.g. emissions from forest fires) were 1.33 Mton in 2019 and 1.32 Mton in 2020 [61]. These values were similar to the estimates of this study (1.1 Mton for 2019 and 1.09 Mton for 2020). The EPA's estimations were larger as they covered all emissions sources in the U.S. that had a broad scope. On the other hand, this study had a narrower scope as it specifically quantified the changes in life cycle respiratory effects associated with U.S. household consumption of food, energy, and transportation. The life cycle respiratory effects before and during the pandemic were dominated by food (figures 1(b) and (c)). These results are consistent with those in the reported literature that showed significant $PM_{2.5}$-related emissions contributed by the agriculture sector in the U.S [62]. A large portion of PM emissions were attributed to the production of FAH, such as meat and miscellaneous foods (figure 4(b)). Meat consumed at home, including beef, pork, poultry, and other meats, accounted for 36% of the life cycle respiratory effects of household food consumption during the pandemic (figure 4(b)). This is consistent with the literature

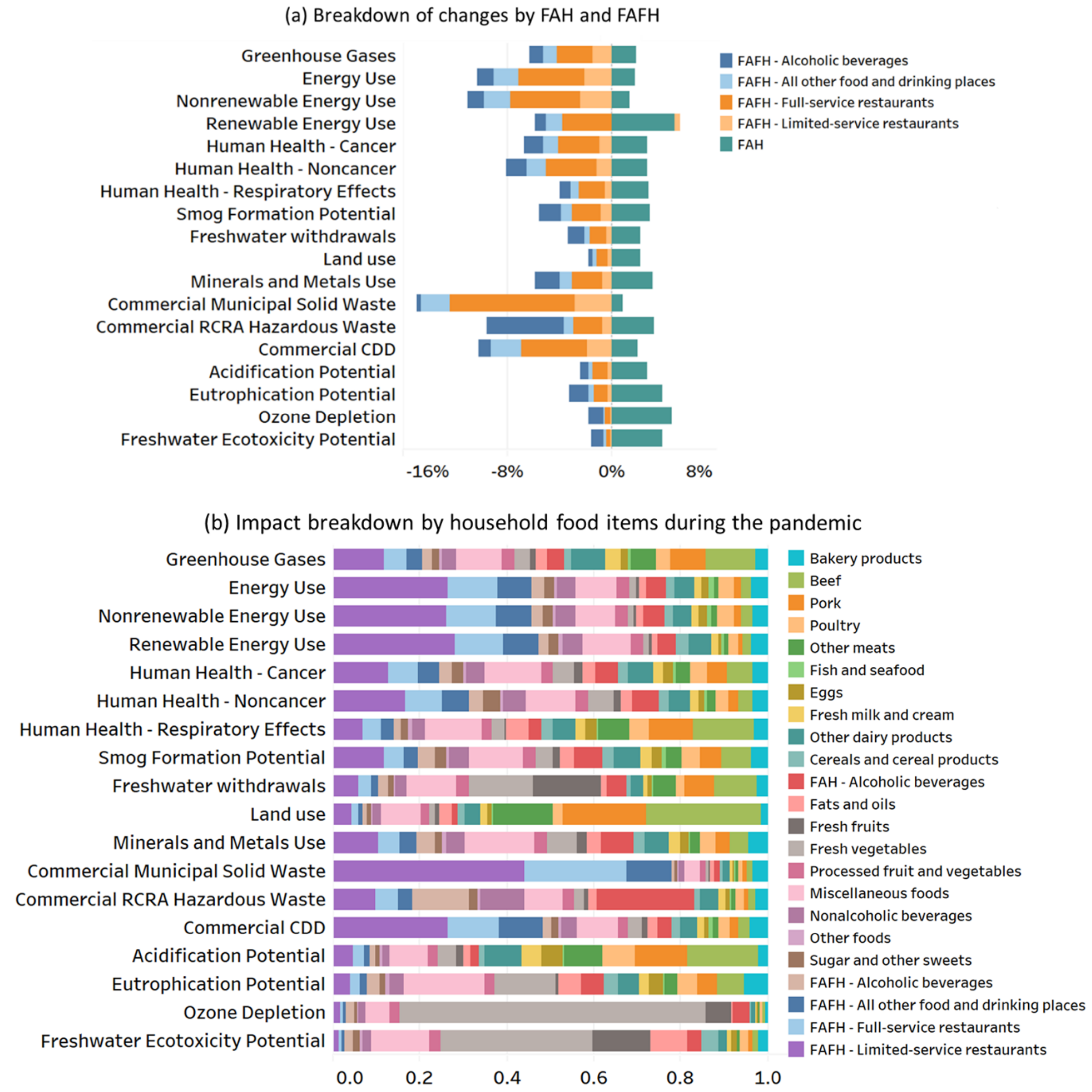

Figure 4. (a) Life cycle environmental impact changes in U.S. household food consumption; (b) life cycle environmental impact breakdown by food items during the pandemic. Percentage changes in (a) were estimated as the ratio of the environmental impact differences (during the pandemic—before the pandemic) to the environmental impacts before the pandemic. FAH—food at home. FAFH—food away from home. The impact breakdown of food items before the pandemic is provided in figure S1.

demonstrating that 80% of air-quality-related health damages from food production were contributed by activities involved in the life cycle of animal-based foods, including animal production and growing biomass for animal feed [63]. Miscellaneous foods, including crackers, seasoning and dressing, cookies, snacks, and frozen food contributed 13%. This significant contribution of FAH to the life cycle respiratory effect is unlikely to be reduced even when the pandemic is over, given the similar patterns shown in figure S1 for 2019, unless U.S. households purchase less meat and miscellaneous food. Consumption-based strategies (e.g. reducing food purchases by minimizing food waste and stockpiling) and production-based efforts to reduce PM emissions and corresponding respiratory effects in agricultural practices are needed for effective air quality management in the post-pandemic period.

Another human-health-related environmental impact is the smog formation potential related to ground-level ozone caused by air pollutants NO_x and volatile organic compounds (VOCs) [64]. Previous studies reported a reduction in free tropospheric ozone by up to 5 parts per billion globally during the pandemic due to reduced anthropogenic NO_x emissions, with substantial emission reductions in Asia and the Americas [65]. This observation is consistent with the results of this study. Figure 1(a) shows a net life cycle decrease of 9.17 Mton O_3 eq due to reduced travel that offsets increased household energy and food consumption. This is not surprising because the tailpipe emissions of on-road transportation contributed 40%–60% of the precursors of ground-level ozone in the U.S [66]. Globally, ∼8.8 million excess deaths were estimated to be caused by long-term exposure to $PM_{2.5}$ and ozone pollution [67]. Previous literature has also revealed a significant relationship between ground-level ozone and positive COVID cases [68]. Therefore, mitigating ground-level ozone is particularly meaningful during the pandemic and remains essential for post-pandemic recovery.

3.3. Resources use changes during the pandemic

Freshwater, land use, and mineral and metal use showed different trends during the pandemic. The net increase of life cycle freshwater withdrawals is 8.6 Gton, accounting for 2% of national water use (based on the USGS estimation of national water use as 322 billion gallons per day in the U.S., equivalent to 445 Gton yr^{-1} [69]). Energy consumption (particularly electricity, figure 3(b)) contributed to the greatest increase in life cycle freshwater withdrawals. This conclusion should not be interpreted as an increase in water consumption of the electricity sector driven by an increase in household energy consumption, as EIO-LCA only quantifies the life cycle environmental impacts associated with a specific product or consumption [70]; this study did not intend to use EIO-LCA to investigate the drivers of water consumption in the U.S. electricity sector.

The life cycle use of land, and minerals and metals showed a net decrease of 41 billion m^{2}*year and 16.1 Mton, respectively, although the reduction of land use appeared to be minor (−1.3%; figure 2). Similar to other impact results, this decrease was mainly attributed to the lower usage of gasoline and other fuel products for vehicles (figure 3(a)). Land, minerals, and metals are mainly used in the production of fuels and relevant infrastructure; therefore, this reduction is temporary. Improving land management and material efficiency is essential to curb the increase in resource use when the pandemic ends.

Household food consumption dominated all three resource uses before and during the pandemic (figures 1(b) and (c)); however, it had minor contributions to the changes in resource use (figure 1(a)) and showed varied trends for different resources. Specifically, changes in U.S. household food consumption led to increased life cycle land use but decreased freshwater withdrawals and mineral and metal use (orange bars in figure 1(a)). Meat consumption (i.e. beef, pork, poultry, and other meats) drove the results of life cycle land use associated with food (∼61%; figure 4(b)). Most meats such as beef are consumed at home [71], which may explain why the shutdown did not bring considerable reductions in life cycle land use.

The trend was opposite for mineral and metal use, where the reduced FAFH led to more reductions than increased FAH. Before and during the pandemic, FAFH (including full- and limited-service restaurants, other drinking and eating places, and alcoholic beverages consumed outside homes) was the most significant contributor to the life cycle mineral and metal use. FAFH contributed 28.7% of the total mineral and metal use (figure S1), and this contribution reduced to 23.4% during the pandemic. However, this was still higher than that of the other individual food items consumed at home (figure 4(b)).

Regarding freshwater withdrawals, reduced FAFH due to lockdown compensated for the effects of increased household food consumption, as shown in figure 4(a). About 30% of the life cycle freshwater withdrawal associated with food was attributed to fresh fruits and vegetables consumed at home before and during the pandemic (figure 4(b)). Interestingly, the contribution of fresh fruits to the life cycle freshwater withdrawal decreased slightly from 16.2% in 2019 to 15.8% in 2020, while the contribution of fresh vegetables increased from 13.7% to 14.7% during the pandemic (figures 4(b) and S1). This can be explained by the different patterns of fresh vegetables and fruit consumption. According to the USDA, U.S. households consumed fewer fresh fruits but more fresh vegetables during the pandemic [45, 72].

These results indicate the trade-offs between FAH and FAFH, as well as the complications in life cycle resource use associated with various food items. Regardless of where the food is consumed, increasing resource use efficiency and directing consumers to less resource-intensive food choices is essential to avoid a dramatic increase in resource consumption when the economy returns to normal. Several studies have shown changes in customers' perspectives on energy management technologies [73, 74] and improved awareness of food waste during the pandemic [30, 31]. These changes may offer opportunities to limit the system-wide increase in resource consumption caused by higher occupancy during the pandemic and support better household resource management in the future.

3.4. Commercial waste generation

Three types of commercial wastes were assessed in this study: commercial municipal solid waste (MSW), RCRA hazardous waste (Resource Conservation and Recovery Act), and construction and demolition debris (CDD). RCRA is a public law regulating solid wastes in the U.S. [75], and USEEIO provides RCRA hazardous waste generation factors for all industrial sectors across the U.S. economy [39]. Overall, 8.31 Mton of commercial wastes were reduced across the life cycle of U.S. household activities during the pandemic, including reductions in commercial MSW (5.36 Mton), RCRA hazardous waste (1.81 Mton), and commercial CDD (1.14 Mton). This decrease in commercial MSW was mostly attributed to food consumption, specifically, the reduced consumption of FAFH (figure 4(a)). Closure of full-service restaurants, which were the major contributors of commercial MSW both before and during the pandemic, helped the most in commercial MSW reduction (figures 4(b) and S1). For commercial RCRA hazardous waste and CDD, reduced travel dominated the decrease (figure 1(a)), although food consumption had a larger or similar contribution to the two waste categories across the life cycle compared to transportation (figures 1(b) and (c)). Some news articles attributed the reduction in commercial waste to the closure of businesses and isolation measures [76, 77], which was consistent with the findings of this study. However, comprehensive and quantitative real-world data on waste generation in cities are lacking. The latest waste generation data by the U.S. EPA are for the year 2018 [78]. Most landfills, institutions, and recycling facilities do not report recent data on their websites [79]. Collecting location-specific waste generation data will help tailor effective waste management strategies after restaurants re-open.

All wastes assessed in this study are commercial wastes across the life cycle of household activities. Residential wastes, such as food waste, were not included due to the lack of data [80]. The U.S. EPA estimated food waste generation to be as high as 63.1 million short tons in 2018 (equivalent to 57.2 Mton), 39% of which were generated by the residential sector [81]. Assuming a linear relationship between the food waste increase and the expenditure growth of food consumption at home (11.7% increase in 2020 compared to 2018 according to the data from the USDA [43]), the increase in food wastes during the pandemic was estimated to be 2.6 Mton; that is smaller than the reduction in commercial MSW estimated in this study (8.31 Mton reduction of commercial wastes as discussed previously). When restaurants and food services re-open, temporary MSW reduction is likely to vanish unless more effective waste management is implemented for post-pandemic recovery. More data collection efforts are needed to investigate consumer behavior and food waste generation at homes and restaurants.

3.5. Other environmental impacts

Other environmental impacts evaluated in this study include acidification, eutrophication, ozone depletion, and freshwater ecotoxicity. Household food consumption affected all four environmental impacts before and during the pandemic (figures 1(b) and (c)). Furthermore, changes in food consumption dominated changes in ozone depletion and freshwater ecotoxicity (figure 1(a)). Acidification potential quantifies the mid-point impacts of precursors to acid rain, such as sulfur dioxide (SO_2) and nitrogen oxides (NO_x) [82]. During the pandemic, there was a net decrease of 226 kton of SO_2 eq across the life cycle of household activities. Reduced travel significantly decreased these precursors, which compensated for the effects of increased consumption of energy and food, particularly electricity (accounting for over 90% of life cycle acidification potential related to household direct energy consumption in tables S13 and S14) as well as meat and dairy (∼60% of life cycle acidification potential related to household food consumption in figure 4(b)).

The remaining three environmental impacts showed net increases during the pandemic, as shown in figure 1(a). Eutrophication potential quantifies the impacts of excessive nutrients in water and soil [83]. As compared to 2019, net life cycle increase was estimated to be 6 kton N eq during the pandemic. As fertilizers are primarily used for agriculture, food production plays a dominant role in the life cycle eutrophication potential for household activities (figures 1(b) and (c)). Illinova *et al* showed that the fertilizer industry remained strong during the pandemic; moreover, the global demand for fertilizers has increased due to the growing food consumption [84]. Higher domestic energy consumption, particularly electricity, also contributed to an increase in life cycle eutrophication potential (figure 3(b)). The life cycle eutrophication potential of different power generation technologies was assessed in previous LCA studies, and it highlighted the need to improve the current electricity generation systems [85]. For ozone depletion, the net life cycle increase was estimated to be 3.4 ton CFC-11 eq. Methyl bromide, a primary pesticide in the agriculture sector [86], was the primary contributor to life cycle ozone depletion (table S16). Across different food types, fresh vegetables accounted for approximately 70% of the total life cycle ozone depletion before and during the pandemic (figures 4(b) and S1). Freshwater ecotoxicity potential (in CTUe, comparative toxic units for ecotoxicity) estimates the potentially affected fraction of species due to pollutants emitted to the aquatic environment [83]. This study showed a net increase in freshwater ecotoxicity impact during the pandemic, largely due to an increase in food consumption. The major emissions contributing to this impact include lambda-cyhalothrin, cyfluthrin, fenpropathrin, and many others used as pesticides (table S17).

3.6. Limitations and future research directions

Several impacts of COVID-19 that were not addressed in this study included: (a) supply chain disruption caused by increased household consumption and activities. For example, lumber prices in the U.S. and Canada reached a record high during the pandemic due to the high demand for home repair and renovation activities, closure of non-essential industries, and shortage of workers [87, 88]; (b) rapid growth of food delivery in the pandemic [89, 90], which could offset the benefits of reduced household transportation. Future research could focus on the environmental impacts of increased construction demand and food delivery when expenditure or consumption data are available. This study investigated the life cycle impacts of U.S. household energy use in 2019 and 2020, but it did not explore the energy efficiency differences between household cooking and restaurant cooking due to the lack of disaggregated data for cooking activities. Data from the Energy Star program showed large variations in the energy efficiency of conventional oven (72%–86%) [91] and residential cooking (85% for induction cooking tops, and 32% and 75%–80% for conventional cooking tops using gas and resistance heating elements, respectively) [92]. However, there were no data on the number and sizes of different cooking appliances used in the United States, which will need future data collection efforts to inform cooking and food choices in the pandemic recovery. In addition, some exogenous changes between 2019 and 2020 (e.g. change in heating degree days) could have affected the results, which can be removed when higher-resolution data are available in the future. Additionally, the impacts of household variability, such as households in different regions or income groups can be explored when region-specific household expenditure data by demographic groups are made available.

In addition to the hybrid LCA, other modeling options include global environmental multiscale models (GEMMs) and general equilibrium models (GEMs). The GEMM focuses on environmental predictions at regional or global scales. It has been used for weather and air quality forecasting; however, it may not be a suitable tool for tracking the impact of one specific activity in one region or supply chain activities across different regions [93–95]. The GEM can cover economic activities in the whole economy. However, previous studies have been limited to carbon emissions and have not considered the full life cycle perspective [96–98]. Several studies have linked GEM with LCA. However, they have mainly focused on specific industrial sectors because of the intensive LCI data requirement [97, 99]. Overall, these models can be coupled with hybrid LCA to address the time lag issue of EEIO in future research.

4. Conclusions

The pandemic significantly reduced the life cycle GHG emissions (7.4%), energy use (8.7%), human health impacts (3%–16%), smog formation (15%), minerals and metal usage (8.2%), acidification (3.5%), and commercial wastes (13%–21%) of U.S. households, but led to increases in life cycle freshwater withdrawals (6.3%) and freshwater ecotoxicity (2.1%). Furthermore, there were minor changes in life cycle land use (−1.3%), ozone depletion (+0.7%), and eutrophication (+0.2%). This decrease in life cycle environmental impacts was mainly driven by reduced travel that outweighed the increase in household energy and food consumption. However, reduced transportation was insufficient to offset the impacts of increased energy consumption on life cycle freshwater withdrawals or the impacts of increased food consumption at home on life cycle ozone depletion and freshwater ecotoxicity. This resulted in a net increase in these environmental burdens during the pandemic. Closure of restaurants and food services during the pandemic reduced the impact of energy, GHG, and commercial MSW. However, such benefits were canceled out by increased food consumption at home in a few other impact categories, including life cycle land use and eutrophication. Thus, there was an environmental trade-off between the reduction of travel and eating outside and the increase of energy and food consumption at home. The life cycle results of household activities also indicated the importance of including consumption-based strategies for households, and production-based strategies for the energy and food sectors during post-pandemic recovery.

Data availability statement

All data that support the findings of this study are included within the article (and any supplementary information files).

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How does COVID-19 affect the life cycle environmental impacts of U.S. household energy and food consumption?

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Supplementary Materials

Contents

Section 1 Household expenditure

Table S1 Household consumption items matched with sectors in the USEEIO v2.0[1]

Sector number in USEEIO	Sector name in USEEIO	Household consumption items
111200/US	Fresh vegetables, melons, and potatoes	Fresh vegetables
111300/US	Fresh fruits and tree nuts	Fresh fruits
112300/US	Poultry farms	Eggs
311225/US	Refined vegetable, olive, and seed oils	Fats and oils
311230/US	Breakfast cereals	Cereals and cereal products
311300/US	Sugar, candy, and chocolate	Sugar and other sweets
311410/US	Frozen food	Miscellaneous foods
3118A0/US	Cookies, crackers, pastas, and tortillas	
311910/US	Snack foods	
311940/US	Seasonings and dressings	
311990/US	All other foods	Food prepared by consumer unit on out-of-town trips
311920/US	Coffee and tea	Nonalcoholic beverages
311930/US	Flavored drink concentrates	
312110/US	Soft drinks, bottled water, and ice	
311420/US	Fruit and vegetable preservation	Processed fruit and vegetables
311513/US	Cheese	Other dairy products
311520/US	Ice cream and frozen desserts	
312120/US	Breweries and beer	Alcoholic beverages
312130/US	Wineries and wine	
312140/US	Distilleries and spirits	
722110/US	Full-service restaurants	Full service restaurants
722211/US	Limited-service restaurants	Limited service restaurants
722A00/US	All other food and drinking places	All other food and drinking places for food away from home
221100/US	Electricity	Electricity
221200/US	Natural gas	Natural gas
324110/US	Gasoline, fuels, and by-products of petroleum refining	Fuel oi, propane and kerosene. Gasoline used for transportation
481000/US	Air transport	Public and other transportation
483000/US	Water transport (boats, ships, ferries)	
485000/US	Passenger ground transport	

Table S2 U.S. household food expenditure (millions of dollars)[2]

	Food at home	Food away from home*	Alcohol at home	Alcohol away from home
2019	790,086.25	759,774.88	105,378.75	98,446.93
2020	856,949.44	632,252.63	115,976.80	66,938.96

*Food away from home expenditure only includes household purchasers, excluding government and business purchasers.

Table S3 Breakdown of food away from home[2]

	Full service restaurants	Limited service restaurants	Other eating and drinking places	Total
2019	33.1%	38.7%	28.2%	100%
2020	27.7%	44.4%	27.9%	100%

Table S4 U.S. household expenditure breakdown of food at home (2018-2019), derived from[2]

Food at home	100%
Cereals and bakery products	
Cereals and cereal products	3.97%
Bakery products	8.70%
Meats, poultry, fish, and eggs	
Beef	5.75%
Pork	4.02%
Other meats	2.83%
Poultry	4.06%
Fish and seafood	3.29%
Eggs	1.34%
Dairy products	
Fresh milk and cream	3.14%
Other dairy products	6.79%
Fruits and vegetables	
Fresh fruits	7.03%*
Fresh vegetables	6.35%
Processed fruits	2.48%
Processed vegetables	3.18%
Other food at home	
Sugar and other sweets	3.47%
Fats and oils	2.55%
Miscellaneous foods	19.94%
Nonalcoholic beverages	9.79%
Food prepared by consumer unit on out-of-town trips	1.30%

*As the data do not include tree nuts that are included in the sector 111300 in Table S1. The final demand of fresh fruits and tree nuts was adjusted based on the value of production reported by the USDA[3] and documented in Table S5.

Consumer Price Index (CPI) was used to transfer all expenditure in 2020 and 2019 to the 2012 year. CPI measures the average changes of consumer prices over time for different goods[4], and it has been widely used in EEIO to convert prices to the same year. CPI can be used to covert prices using the equation below[5]:

$$Price_{2012} = \frac{CPI_{2012}}{CPI_{recent}} \times Price_{recent} \quad (1)$$

Table S5 The U.S. Household expenditure before and in pandemic in 2012 producer price (Million $)

	Sector Name	2020	2019
111200/US	Fresh vegetables, melons, and potatoes	27225	25750
111300/US	Fresh fruits and tree nuts	16344	16893
112300/US	Poultry farms	9039	8688
221100/US	Electricity	173626	136754
221200/US	Natural gas	46106	48340
311225/US	Refined vegetable, olive, and seed oils	19877	18572
311230/US	Breakfast cereals	19909	18692
311300/US	Sugar, candy, and chocolate	20146	19194
311410/US	Frozen food	20941	19980
311420/US	Fruit and vegetable preservation	30492	29088
311513/US	Cheese	22352	21103
31151A/US	Fluid milk and butter	17194	16726
311520/US	Ice cream and frozen desserts	20698	19541
311615/US	Packaged poultry	25680	25002
31161A/US	Packaged meat (except poultry)	76913	76078
311700/US	Seafood	19129	18210
311810/US	Bread and other baked goods	38709	36538
3118A0/US	Cookies, crackers, pastas, and tortillas	20482	19542
311910/US	Snack foods	20863	19906
311920/US	Coffee and tea	20741	19805
311930/US	Flavored drink concentrates	20931	19986
311940/US	Seasonings and dressings	20644	19697
311990/US	All other foods	26715	25457
312110/US	Soft drinks, bottled water, and ice	15976	15255
312120/US	Breweries and beer	29234	33206
312130/US	Wineries and wine	27300	31009
312140/US	Distilleries and spirits	35997	40888
324110/US	Gasoline, fuels, and by-products of petroleum refining	321672	504119
481000/US	Air transport	84938	110625
482000/US	Rail transport	84938	110625
483000/US	Water transport (boats, ships, ferries)	84938	110625
485000/US	Passenger ground transport	84938	110625
722110/US	Full-service restaurants	142609	210338
722211/US	Limited-service restaurants	225943	243208
722A00/US	All other food and drinking places	143996	180011

Table S6 U.S. residential energy consumption[6]

	Natural Gas (trillion Btu)	Electricity (trillion Btu)	Fuel Oil (trillion Btu)	Propane (trillion Btu)	Kerosene (trillion Btu)
2019 (before the pandemic)	5204.854	4914.266	470.583	563.405	10.754
2020 (during the pandemic)	4818.444	4988.199	404.652	516.997	12.356

Table S7 Prices of energy delivered to the U.S. household ($ in the year listed)[6, 7]

	Natural gas ($/thousand cubic feet)	Electricity (cents/kWh)	Fuel oil ($/gallon)	Propane ($/gallon)	Kerosene ($/gallon)
2019 (before pandemic)	10.51	10.54	3.09	2.18	2.02
2020 (during the pandemic)	10.84	13.20	2.55	1.91	1.31

Table S8 U.S. personal spending on transportation (in chained 2012 dollar)[8]

	Gasoline and Other Energy Goods (billion $)	Transportation Services (billion $)
2019	445	$443
2020	389	$340

The path exchange method was used to incorporate more recent energy and GHG emission data of the electricity generation sector. The total energy use of the U.S. electric power sector was 37003 Trillion Btu in 2019 and 35744 Trillion Btu in 2020[6], which were divided by the electricity sales[9] (raw data in Table S18 that were converted to 2012) to derive the energy use factors for the same year. The energy use factors were timed with the total requirement of electricity that was estimated using the Leontief matrix and the final demands of the U.S. household energy and food consumption. The estimated energy use was used to replace the total energy use estimated by the USEEIO for the electricity sector. The same approach was used to estimate the renewable and non-renewable energy use and GHG emissions using the data collected from the U.S. EIA[6, 10].

Section 2. GHG Emissions of Fuel Combustion

As the system boundary of EIO-LCA is cradle to gate, the GHG emissions of fuel combustion in the use phase are not included. Excluding the emissions of fuel combustion underestimates the impacts of household energy consumption. In this study, the GHG emissions of fuel combustion were estimated and added to the GHG emissions estimated using the USEEIO[1].

For gasoline used in transportation, the CO_2 emission factor of gasoline was 8.89 kg/Gallon based on the data from the U.S EIA[11]. The gasoline price data were collected from the U.S. EIA[12] and then converted to 2012 dollar using the CPI[4] to be consistent with the expenditure data. The converted prices were 3.6128 $/gallon in 2019 and 3.6075 $/gallon in 2020, expressed in 2012$. The price data were used to estimate the volume of gasoline consumption before and in the pandemic. For other fuels used by U.S. households, the emission factors from U.S. EPA were used and documented in Table S9.

Table S9 Emission factors of fuels[13]

	kg CO_2 per mmBtu	g CH_4 per mmBtu	g N_2O per mmBtu
Natural Gas	53.06	1	0.1
Fuel Oil	73.96	3	0.6
Propane	62.87	3	0.6
Kerosene	75.2	3	0.6

Section 3 Additional Results

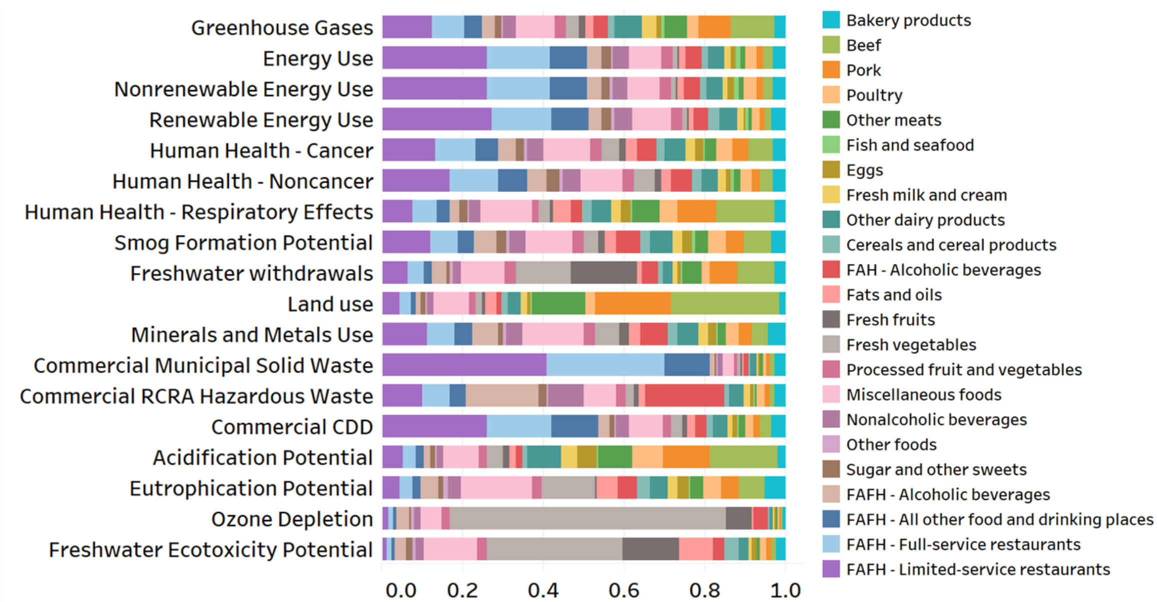

Figure S1 life-cycle environmental impact breakdown by household food consumption types before the pandemic

Table S10 Environmental impacts associated with transportation (before the pandemic)

Impact categories	Gasoline, other fuels, and motor oil	Transportation services	Total
Acidification Potential	23%	77%	100.0%
Commercial Construction and Demolition Debris	47%	53%	100.0%
Commercial Municipal Solid Waste	22%	78%	100.0%
Commercial RCRA Hazardous Waste	80%	20%	100.0%
Energy Use	86%	14%	100.0%
Eutrophication Potential	45%	55%	100.0%
Freshwater Ecotoxicity Potential	50%	50%	100.0%
Freshwater withdrawals	62%	38%	100.0%
Greenhouse Gases	82%	18%	100.0%
Human Health - Cancer	45%	55%	100.0%
Human Health - Noncancer	40%	60%	100.0%
Human Health - Respiratory Effects	44%	56%	100.0%
Land use	45%	55%	100.0%

Minerals and Metals Use	48%	52%	100.0%
Nonrenewable Energy Use	86%	14%	100.0%
Ozone Depletion	56%	44%	100.0%
Renewable Energy Use	48%	52%	100.0%
Smog Formation Potential	26%	74%	100.0%

Table S11 Environmental impacts associated with transportation (during the pandemic)

Impact categories	Gasoline, other fuels, and motor oil	Transportation services	
Acidification Potential	20%	80%	100.0%
Commercial Construction and Demolition Debris	42%	58%	100.0%
Commercial Municipal Solid Waste	18%	82%	100.0%
Commercial RCRA Hazardous Waste	77%	23%	100.0%
Energy Use	83%	17%	100.0%
Eutrophication Potential	40%	60%	100.0%
Freshwater Ecotoxicity Potential	45%	55%	100.0%
Freshwater withdrawals	57%	43%	100.0%
Greenhouse Gases	83%	17%	100.0%
Human Health - Cancer	40%	60%	100.0%
Human Health - Noncancer	36%	64%	100.0%
Human Health - Respiratory Effects	39%	61%	100.0%
Land use	40%	60%	100.0%
Minerals and Metals Use	43%	57%	100.0%
Nonrenewable Energy Use	84%	16%	100.0%
Ozone Depletion	51%	49%	100.0%
Renewable Energy Use	43%	57%	100.0%
Smog Formation Potential	22%	78%	100.0%

Table S12 Changes of environmental impacts associated with transportation (Change% = (During the pandemic – before the pandemic)/before the pandemic)

Impact categories	Gasoline, other fuels, and motor oil	Transportation services	Total
Acidification Potential	-8.6%	-17.9%	-26.5%
Commercial Construction and Demolition Debris	-17.5%	-12.4%	-29.9%
Commercial Municipal Solid Waste	-8.1%	-18.2%	-26.3%
Commercial RCRA Hazardous Waste	-30.0%	-4.6%	-34.6%
Energy Use	-32.2%	-3.3%	-35.5%
Eutrophication Potential	-16.7%	-12.9%	-29.6%
Freshwater Ecotoxicity Potential	-18.8%	-11.6%	-30.4%
Freshwater withdrawals	-23.4%	-8.7%	-32.1%
Greenhouse Gases	-14.0%	-4.3%	-18.3%
Human Health - Cancer	-16.9%	-12.7%	-29.7%

Human Health - Noncancer	-15.1%	-13.8%	-29.0%
Human Health - Respiratory Effects	-16.4%	-13.1%	-29.5%
Land use	-17.0%	-12.7%	-29.7%
Minerals and Metals Use	-18.1%	-12.0%	-30.1%
Nonrenewable Energy Use	-32.4%	-3.2%	-35.6%
Ozone Depletion	-21.1%	-10.1%	-31.3%
Renewable Energy Use	-15.3%	-10.2%	-25.4%
Smog Formation Potential	-9.7%	-17.2%	-26.9%

Table S13 Environmental impacts associated with household direct energy consumption (before the pandemic)

Impact categories	Electricity	Natural gas	Fuel oil, propane, and kerosene	Total
Acidification Potential	90.6%	6.8%	2.7%	100.0%
Commercial Construction and Demolition Debris	71.3%	21.8%	6.9%	100.0%
Commercial Municipal Solid Waste	67.1%	26.8%	6.1%	100.0%
Commercial RCRA Hazardous Waste	39.1%	8.8%	52.1%	100.0%
Energy Use	88.7%	5.9%	5.4%	100.0%
Eutrophication Potential	88.1%	9.6%	2.3%	100.0%
Freshwater Ecotoxicity Potential	86.3%	8.5%	5.2%	100.0%
Freshwater withdrawals	95.5%	4.1%	0.4%	100.0%
Greenhouse Gases	62.8%	29.3%	7.9%	100.0%
Human Health - Cancer	72.4%	16.2%	11.5%	100.0%
Human Health - Noncancer	88.3%	7.9%	3.7%	100.0%
Human Health - Respiratory Effects	88.8%	6.6%	4.6%	100.0%
Land use	59.8%	20.4%	19.8%	100.0%
Minerals and Metals Use	78.2%	14.6%	7.3%	100.0%
Nonrenewable Energy Use	87.6%	6.2%	6.2%	100.0%
Ozone Depletion	74.1%	12.8%	13.2%	100.0%
Renewable Energy Use	96.5%	3.3%	0.3%	100.0%
Smog Formation Potential	82.4%	10.7%	7.0%	100.0%

Table S14 Environmental impacts associated with household direct energy consumption (during the pandemic)

Impact categories	Electricity	Natural gas	Fuel oil, propane, and kerosene	Total
Acidification Potential	92.9%	5.2%	1.9%	100.0%
Commercial Construction and Demolition Debris	77.2%	17.7%	5.1%	100.0%
Commercial Municipal Solid Waste	73.4%	22.0%	4.6%	100.0%
Commercial RCRA Hazardous Waste	48.1%	8.1%	43.7%	100.0%

Energy Use	91.6%	4.6%	3.8%	100.0%
Eutrophication Potential	91.0%	7.4%	1.6%	100.0%
Freshwater Ecotoxicity Potential	89.6%	6.7%	3.7%	100.0%
Freshwater withdrawals	96.6%	3.1%	0.2%	100.0%
Greenhouse Gases	68.3%	25.2%	6.5%	100.0%
Human Health - Cancer	78.4%	13.2%	8.5%	100.0%
Human Health - Noncancer	91.2%	6.1%	2.6%	100.0%
Human Health - Respiratory Effects	91.7%	5.1%	3.2%	100.0%
Land use	67.5%	17.3%	15.2%	100.0%
Minerals and Metals Use	83.1%	11.6%	5.3%	100.0%
Nonrenewable Energy Use	90.5%	5.0%	4.5%	100.0%
Ozone Depletion	79.9%	10.3%	9.7%	100.0%
Renewable Energy Use	97.5%	2.3%	0.2%	100.0%
Smog Formation Potential	86.6%	8.4%	5.0%	100.0%

Table S15 Changes of environmental impacts associated with household direct energy consumption (Change% = (During the pandemic – before the pandemic)/before the pandemic)

Impact categories	Electricity	Natural gas	Fuel oil, propane, and kerosene	Total
Acidification Potential	24.4%	-0.3%	-0.4%	23.7%
Commercial Construction and Demolition Debris	19.2%	-1.0%	-0.9%	17.3%
Commercial Municipal Solid Waste	18.1%	-1.2%	-0.8%	16.0%
Commercial RCRA Hazardous Waste	10.5%	-0.4%	-6.9%	3.2%
Energy Use	22.7%	-0.3%	-0.7%	21.7%
Eutrophication Potential	23.8%	-0.4%	-0.3%	23.0%
Freshwater Ecotoxicity Potential	23.3%	-0.4%	-0.7%	22.2%
Freshwater withdrawals	25.8%	-0.2%	0.0%	25.5%
Greenhouse Gases	10.8%	-2.1%	-0.9%	7.8%
Human Health - Cancer	19.5%	-0.7%	-1.5%	17.2%
Human Health - Noncancer	23.8%	-0.4%	-0.5%	23.0%
Human Health - Respiratory Effects	24.0%	-0.3%	-0.6%	23.0%
Land use	16.1%	-0.9%	-2.6%	12.5%
Minerals and Metals Use	21.1%	-0.7%	-1.0%	19.4%
Nonrenewable Energy Use	20.2%	-0.3%	-0.8%	19.1%
Ozone Depletion	20.0%	-0.6%	-1.8%	17.6%
Renewable Energy Use	38.3%	-0.1%	0.0%	38.1%
Smog Formation Potential	22.2%	-0.5%	-0.9%	20.8%

Table S16 Flow contribution breakdown for ozone depletion potential

	During the pandemic (2020)	Before the pandemic (2019)
Methyl bromide/emission/air/troposphere/rural/ground-level/kg	77.02%	74.37%
Methyl bromide/emission/air/kg	7.73%	8.22%
Carbon tetrachloride/emission/air/kg	5.93%	6.75%
CFC-113/emission/air/kg	3.46%	3.92%
CFC-114/emission/air/kg	1.99%	2.26%
Halon 1301/emission/air/kg	1.15%	1.40%
HCFC-22/emission/air/kg	1.05%	1.22%
Chloromethane/emission/air/kg	0.41%	0.43%
CFC-11/emission/air/kg	0.38%	0.44%
1,1,1-Trichloroethane/emission/air/kg	0.32%	0.34%
CFC-12/emission/air/kg	0.18%	0.20%
Halon 1211/emission/air/kg	0.15%	0.18%
CFC-115/emission/air/kg	0.08%	0.10%
HCFC-142b/emission/air/kg	0.07%	0.08%
HCFC-123/emission/air/kg	0.03%	0.04%
CFC-13/emission/air/kg	0.03%	0.03%
HCFC-124/emission/air/kg	0.01%	0.02%
HCFC-133a/emission/air/kg	0.01%	0.01%
Other emissions	0.0004%	0.0005%
Total	100%	100%

Table S17 Flow contribution breakdown for freshwater ecotoxicity potential

	During the pandemic (2020)	Before the pandemic (2019)
.lambda.-Cyhalothrin/emission/water/fresh water body/kg	24.16%	23.90%
Cyfluthrin/emission/water/fresh water body/kg	19.80%	19.58%
Fenpropathrin/emission/water/fresh water body/kg	11.37%	11.83%
Chlorothalonil/emission/water/fresh water body/kg	10.51%	10.28%
Chlorpyrifos/emission/water/fresh water body/kg	5.37%	5.43%
Chlorothalonil/emission/air/troposphere/rural/ground-level/kg	2.38%	2.32%
Diflubenzuron/emission/water/fresh water body/kg	2.13%	2.24%
Cyfluthrin/emission/air/troposphere/rural/ground-level/kg	1.87%	1.85%
Bifenthrin/emission/water/fresh water body/kg	1.86%	1.85%
Chlorothalonil/emission/ground/human-dominated/agricultural/rural/kg	1.64%	1.60%
Esfenvalerate/emission/water/fresh water body/kg	1.13%	1.15%
Atrazine/emission/water/fresh water body/kg	1.12%	1.11%
S-Metolachlor/emission/water/fresh water body/kg	0.96%	0.98%
Propanil/emission/air/troposphere/rural/ground-level/kg	0.85%	0.87%
Propanil/emission/ground/human-dominated/agricultural/rural/kg	0.76%	0.78%
Beta Cypermethrin/emission/water/fresh water body/kg	0.60%	0.62%
Acetochlor/emission/water/fresh water body/kg	0.60%	0.61%

Phosmet/emission/water/fresh water body/kg	0.59%	0.59%
.lambda.-Cyhalothrin/emission/air/troposphere/rural/ground-level/kg	0.59%	0.58%
Pendimethalin/emission/water/fresh water body/kg	0.56%	0.57%
Tefluthrin/emission/water/fresh water body/kg	0.56%	0.57%
Other emissions	10.6%	10.7%
Total	100%	100%

Section 4 Benchmark Estimations

A test was performed to compare the results from the USEEIO with a few benchmarks estimated using real-world data. Most data reported by the U.S. government agencies, such as U.S. EIA or the U.S. Department of Agriculture (USDA), are at the national level that covers all activities happened in the U.S. As this study only focuses on the activities related to the life cycle of U.S. household energy and food consumption (instead of everything consumed in the U.S.), it is necessary to disaggregate these national-level data and exclude activities that may not be associated with the supply chains of energy and food consumed by the U.S. households. The following paragraphs document the detailed estimations of each benchmark.

Electricity Benchmark Estimation

The total domestic requirement of electricity (in million $ in 2012 price) was benchmarked against the total sales of electricity to ultimate consumers in the U.S. in 2019 and 2020. The total electricity sales data were obtained from the U.S. EIA[9]. The sales data include all sectors in the U.S. economy, namely residential, commercial, industrial, and transportation sectors. The data of 2019 and 2020 in million dollars are shown in Table S18.

Table S18 Electricity sales to ultimate customers in the U.S. in 2019 and 2020 (in million dollars)[9]

Year	Residential	Commercial	Industrial	Transportation	All Sectors
2019	187,436	145,280	68,285	737	401,738
2020	192,663	136,372	63,956	648	393,639

The residential and transportation can be considered as fully related to the life cycle of U.S. households. The industrial sector is complicated as some activities are related (e.g., fertilizer production, gasoline production), but not all industrial sectors are related. Therefore, the U.S. Manufacturing Energy Consumption Survey (MECS)[14] data were used to identify and estimate these industrial sectors that are mostly related to the upstream production of food and energy consumed by U.S. households. Specifically, Table S19 shows the sectors identified for their direct relevance to U.S. household food and energy consumption. Other sectors such as petrochemicals also include products that are used in the upstream supply chain of food and energy products consumed by U.S. households. However, it is challenging to disaggregate these sectors further. Similarly, some commercial use of electricity (e.g., cooking services) are related. However, EIA only reports total commercial electricity uses without further details on the use breakdown[6]. Thus, only the energy consumption of sectors listed in Table S19 was included to estimate the percentage of total electricity consumption related to the life cycle of U.S. household food and energy consumption (see Equation 2). Furthermore, some products made in the U.S. are exported and thus not consumed by U.S. households. The energy consumption of making these products should be excluded in the benchmark estimation. The shares of export in the total production of relevant industrial sectors were collected and documented in Table S20.

$$Pin = \sum_{1}^{n} E_n \times (1 - E_p) \Big/ To \quad (2)$$

Pin is the total percentage of electricity consumption related to the life cycle of U.S. household food and energy consumption in the total U.S. electricity consumed by the industrial sectors. n include industrial sectors identified in Table S19 and E_n is the electricity consumption of each industrial sector identified (data available in MECS[14]). E_p is the percentage of exports in the total production of each industrial sector as documented in Table S20. To is the total electricity consumption of the U.S. industrial sector. Pin was estimated as 16.3% using the latest MECS data in 2018[14].

The total electricity benchmark was then estimated as the summation of electricity consumed by residential, transportation, and 16.3% of industrial use listed in Table S18, which was then converted to 2012 price using the CPI index[4]. The USEEIO[1] shows that the purchaser to producer price ratio for the electricity sector was 1 in the past (latest in the 2018 year), which was used to convert the benchmark sales to 2012 producer price as listed in Table 1 in the paper.

Table S19 Industry sectors in 2018 MECS identified by this study for their direct relevance to the U.S. household energy and food consumption

NAICS Code	
311	Food
3121	Beverages
324110	Petroleum Refineries
325311	Nitrogenous Fertilizers
325312	Phosphatic Fertilizers

Table S20 Export share of production by industrial sectors in 2018*

Sector	Share of export
Food	24.9%[15]
Beverages	24.9%[15]
Petroleum Refineries	16.5%[16]
Nitrogenous Fertilizers	19.9%[17]
Phosphatic Fertilizers	19.9%[17]

*The latest year of data from the USDA is 2018. Using the data in 2018 is also consistent with the MECS data that reports the latest U.S. industrial energy consumption by sectors in 2018.

Total Energy Benchmark Estimation

The total energy consumption benchmarks were estimated using the similar approaches discussed above. The primary energy consumption of main sectors in the U.S. was collected from the U.S. EIA Monthly Energy Review, and the raw data were documented in Table S21[6]. The commercial sector was not included given the difficulties in further disaggregating and identifying activities the most relevant to the life cycle of U.S. household food and energy consumption.

Table S21 Primary energy consumption by main sectors in the U.S. in 2019 and 2020 (Trillion Btu)[6]

Year	Residential	Industrial	Transportation	Electric Power
2019	7088.212	22939.804	28596.828	37003.283
2020	6616.842	22024.882	24372.597	35744.049

As discussed previously, not all industrial activities are related to the life cycle of U.S. household food and energy consumption. Therefore, a similar approach (Equation 2) was used to estimate the percentage of industrial energy use that is the most relevant to U.S. household food and energy consumption. Using the latest MECS data[14], it was estimated that 22% of all industrial energy consumption in the U.S. was the most related. Using the EIA data, it was estimated that 70.6% of transportation energy is related, excluding energy used for military, commercial freight, and pipeline transport[18]. For the electric power sector, the share of each sector was documented in Table S24, estimated based on the data in Table S23. The percentage of electricity uses that are the most relevant to the life cycle of household energy and food consumption were estimated by the summation of the shares of residential, transportation, and 16.3% of the industrial sector (estimated in the previous section for industrial electricity use) in Table S24 for year 2020 and 2019, respectively. The resulting percentages of relevant electricity usage are 44% for 2020 and 42% for 2019. Then the benchmark of total energy consumption was estimated as the summation of energy consumed by the residential sector, transportation sector multiplied by 70.6%, industrial energy consumption multiplied by 22%, and electric power energy use multiplied by 44% for 2020 and 42% for 2019. The same approach was applied to renewable energy consumption, and the data of different sectors were collected from the U.S. EIA (Trillion Btu) and documented in Table S22[6]. The non-renewable energy consumption benchmarks were estimated as the differences between total energy consumption and renewable energy consumption.

Table S22 Renewable energy consumption of main sectors in the U.S. (Trillion Btu)[6]

Year	Residential	Industrial	Transportation	Electric Power
2019	835.442	2423.142	1496.593	6401.59
2020	787.671	2298.456	1361.771	6952.028

Table S23 Electricity consumption by sectors in the U.S. (million kWh)[6]

Year	Residential	Commercial	Industrial	Transportation	Total
2019	1440288.909	1360876.555	1002352.849	7632.15	3811150.463
2020	1461957.642	1275718.315	919533.398	6531.987	3663741.342

Table S24 Electricity consumption shares by sectors in the U.S. (calculated based on the data in Table S23)

Year	Residential	Commercial	Industrial	Transportation	Total
2019	37.8%	35.7%	26.3%	0.2%	100%
2020	39.9%	34.8%	25.1%	0.2%	100%

Fertilizer Benchmark Estimation

The benchmark of fertilizer usage (Fb in million dollars) was estimated using Equation (3).

$$Fb = Fs \times (1 - Di) \times PC \times (1 - Fe) \quad (3)$$

Fs is the farm expenditure on fertilizers in the U.S., which were $22,300 million in 2019 and $24,400 million in 2020, according to the USDA data[19]. Di is the ratio of fertilizers that are met by import (as the total requirement estimated by USEEIO is only for domestic production, therefore the fertilizers imported should be excluded). The IBISWorld industrial database reports that 34.3% and 29.9% of domestic fertilizer demands were imported in 2019 and 2020, respectively[17]. PC is the ratio of producer price to purchaser price, which was 0.56 in the year 2018[1] and assumed to be the same for the year 2019 and 2020 due to the lack of data. Not all crops grown in the U.S. are consumed by U.S. households. Therefore, the fertilizer used to produce food exported to other countries should be excluded. Fe is the average export value share of the total production of crops and food in the U.S., which was estimated as 39.7% in the year 2019 based on the data collected from USDA for crops, food grains, feed grains, oilseeds, vegetables and melons, fruits and tree nuts[15]. The estimated Fb for the year 2020 and 2019 were converted to the same 2012 year using the Producer Price Index (PPI) published by the U.S. Bureau of Labor Statistics[20]. As the export data of food and crops in the U.S. are not available for 2020, this estimation has uncertainties, which may explain the differences between the estimated benchmarks and the results of this study in Table 1.

Packaged Meat Benchmark Estimation

The benchmark of packaged meat (PMb in million dollar) was estimated using the Equation (4).

$$PMb = \sum_{1}^{n} D_n \times P_n \tag{4}$$

D_n is the total consumption (in other words, disappearance) of meat *n* (including beef and pork, two main meat types consumed in the U.S.). Poultry was not included in this industrial category. The total disappearance of beef in the U.S. was reported as 27,275 and 27,561 million pounds in 2019 and 2020, respectively[21]. The total disappearance of pork in the U.S. was reported as 22,189 and 22,121 million pounds in 2019 and 2020, respectively[21]. P_n is the retail price of the meat *n*. For beef, the average retail price of all fresh beef in 2019 was 582 cents/pound, this price increased to 639 cents/pound in 2020[21]. For pork, the retail price in 2019 was 384 cents/pound, and the price increased to 403 cents/pound in 2020[21]. The estimated benchmark for packaged meat was then converted to 2012 producer price using CPI index for beef and pork[4] and producer to purchaser price ratio estimated based on the retail values and wholesale value reported by the USDA[21].

Fresh Fruits and Tree nuts Benchmark Estimation

USDA reported the value of production of total fruits (including citrus and noncitrus fruits) and tree nuts as $29,027 million in 2019 and $28,119 million in 2020[3]. These two values were converted to 2012 values using the PPI index[20].

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