THE VALUE OF FOOD LOSS AND WASTE: NOT ALL FOOD IS CREATED EQUAL

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THE VALUE OF FOOD LOSS AND WASTE: NOT ALL FOOD IS CREATED EQUAL

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EDITORIAL
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Editorial: Food Loss and Waste: Not All Food Waste Is Created Equal

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Editorial on the Research Topic

Food Loss and Waste: Not All Food Waste Is Created Equal

Action on reducing food loss and waste (FLW) is imperative to mitigate the impacts of climate change worldwide and to achieve the Sustainable Development Goals on food security, hunger eradication, and sustainable production and consumption. Next year (2022) will be the UN summit of food systems ("the COP for food"), as articles in this special issue illustrate, FLW will stay as one of the major levers to pull for food system transformation and sustainable consumption.

The objective of this Research Topic is to go beyond a linear approach to FLW and to look at it from a systemic perspective, measuring it not just using the standardized metric of mass but multiple valuation frameworks. Considering nutritional value, environmental impact, social impact, costs (explicit and hidden), or potential for nutrient recycling, and the various points of view of the stakeholders in the food system. The premise is that better understanding of FLW and potential interventions and solutions will come from multiple and complementary ways of analyzing and valuing it. In this editorial we summarize the papers in the Research Topic and end with a call to action.

Toti et al. present the novel perspective of "metabolic food waste" i.e., overeating. One hundred and forty gigatons of food was found to be metabolically wasted globally, mostly driven by North America and Europe. Dairy, milk, and eggs were key over consumed products that also have relatively high greenhouse gas intensity (kg CO_2-eq per kilogram) suggesting future work can focus on balancing consumption of these products.

Horton et al. reframe FLW as the result of process inefficiencies across the entire agri-food value chain, giving rise to overall food chain inefficiency. Nine conversion efficiency factors are presented, some of them already regularly calculated -such as harvesting or processing efficiency- and others only now gathering salience, such as consumption efficiency or dietary efficiency (the latter is addressed also in this Research Topic by Toti et al.). The approach is illustrated by evaluating the bread supply chain in the UK. Ultimately, providing sustainable food security to humankind depends absolutely upon increasing the efficiency of the agri-food system, whilst at the same time ensuring it is resilient, resourceful, and environmentally sustainable. This can be achieved if we first establish a uniform approach to analyse each step in the system, as begun here.

van Dooren et al. provided valuable insight into a practical solution to tackling FLW at a household level 1.6 million "*Eetmaatje* Cups" were made available to Dutch households to measure portions for pasta and rice, two foods often overestimated in volumes before cooking, which not only can be wasted but could lead to overconsumption. Users of the cup self-reported less FLW of these two foods, with measured losses trending downwards. These types of practical solutions should be highly welcomed and, when used in conjunction with education and awareness, will

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need to be part of the solution space for the complex issue of household FLW.

March et al. provide a straightforward evaluation of FLW in fresh milk, paired with identification and measurement of causes at farm level and carbon footprinting. This paper highlights the possible application of Horton et al., where inefficiencies at farm level are proposed. This paper also contributes to the literature by contributing and corroborating primary data for dairy FLW. We encourage this work to be carried out for all value chains, all archetypes, and all regions.

von Massow et al. consider the nutritional, economic, and environmental impacts of avoidable FLW in Canadian households. Nearly 70% of FLW in the surveyed households was classified as avoidable and was largely composed of fruits and vegetables. There was a large variation of wastes between households suggesting future work can focus on interventions for a subset of consumers.

This article by Isah and Ozbay provides a review of FLW valorisation, with the focus on biofuels and chemicals products. It adds to the growing body of literature that highlights the potential of these technologies to help recapture value, minimize impacts, and create new products from FLW.

Goossens et al. highlight the importance of bringing together FLW prevention and treatment actions with the final purpose of indexing the performance of these measures. For this, the effectiveness of reducing FLW throughout supply chains should be accompanied by monitoring the actions established with a set of economic, social, and environmental indicators, which are currently treated in an uneven manner in the literature. This way they argue that effective FLW minimization can be coupled with metrics that guarantee an efficient treatment of monetary, environmental, or nutritional aspects, avoiding unwanted trade-offs between indicators. Therefore, the authors advocate for the implementation of harmonized evaluation criteria to consistently determine the appropriateness of FLW prevention and mitigation schemes.

Winans et al. analyze the food loss that occurs at a farm in California from an LCA perspective. They compare the conventional production of 4 different specialty crops considering optimal harvest with the integration of food losses and the treatment (e.g., energy from biomass) or recovery of these losses. Environmental impacts showed to be highly dependent on the food loss ratio reported for each crop as well as on the circularity measures adopted to recover these losses.

The papers in this special issue present FLW not just using the standardized metric of mass but multiple valuation frameworks. These now sit alongside multiple other reports (1–3) and peer reviewed publications providing powerful evidence that globally, nationally, and locally, we need FLW reduction and minimization. However, it is telling that only one of our papers evaluates an intervention (the *Eetmaatje* measuring cup). To reduce FLW (and to achieve SDG12.3), we now need to go beyond measurement to test interventions, and provide peer reviewed evidence that reductions are possible, with solutions and evaluations provided. Circular and bio- economy are emerging as key concepts for sustainable development. Assessing the consequences of targets to reduce food waste and at the same time improve destination management (e.g., anaerobic digestion and composting) within a circular economy could be an interesting area of future work that was not covered in the submissions to this special issue.

AUTHOR CONTRIBUTIONS

All authors contributed with the review of manuscripts and preparation of this Editorial.

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We also thank all the peer reviewers who took time to review for this special issue. A challenge moving forward with urgent sustainability topics is to move quickly and simultaneously in a way that is robustly based on evidence. Sharing data, methods, and validating these through the review process brings value to the issue of addressing FLW, and this validation process takes time and resources. Beyond the peer reviewed process there is also a wealth of information that is quickly being generated within the sustainability community, e.g., through tools and databases. As we move forward with mitigation of FLW there will be a balance between the value of peer reviewed literature, and the value brought by tools and other knowledge that is generated quickly and independent of peer-review.

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ORIGINAL RESEARCH
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Metabolic Food Waste and Ecological Impact of Obesity in FAO World's Region

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Obesity represents a titanic cost for the world's health systems but also a substantial ecological cost to the environment. High energy foods have been shown to be the major contributor to Greenhouse Gas (GHG) emissions, challenging the diet-environment-health triangle. The waste of resources and the unnecessary ecological cost due to an excessive consumption of foods leading to obesity have been ignored so far. Metabolic Food Waste [$MFW_{(kg\ of\ food)}$] corresponds to the amount of food leading to Excess Body Fat (EBF) and its impact on the environment, expressed as carbon [$MFW_{(kgCO_2eq)}$], water [$MFW_{(\times 10\ L)}$] and land footprint [$MFW_{(\times 10\ m^2)}$]. We aim to estimate the $MFW_{(kg\ of\ food)}$ in the seven FAO regions, Europe (EU), North America and Oceania (NAO), Latin America (LA), Sub-Saharan Africa (SSA), Industrialized Asia (IA), North Africa, West and Central Asia (NAWCA) and South and Southeast Asia (SSEA), and evaluate its impact on ecological footprints. The overall impact of $MFW_{(tons\ of\ food)}$ in the world corresponds to 140.7 million tons associated to overweight and obesity. Between the different regions, EU is responsible of the greatest amount of $MFW_{(tons\ of\ food)}$ volume (39.2 million tons), followed by NAO (32.5 million tons). In terms of ecological impact, EU and NAO displayed the highest values for all three MFW footprints, about 14 times more than SSA. We provide evidence of the enormous amount of food lost through obesity and its ecological impact. Reducing metabolic food waste associated with obesity will contribute in reducing the ecological impact of unbalanced dietary patterns through an improvement of human health.

Keywords: sustainable nutrition, obesity, metabolic food waste, functional diet, ecological footprints, food balance sheets, human, animal products

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INTRODUCTION

Obesity is a chronic metabolic disorder with a complex etiology representing a remarkable risk factor for the onset of different chronic diseases, such as cardiovascular disease (CVD), diabetes type 2 and cancers, responsible for 60% of deaths worldwide (1). Over the past decade, the obesity burden in western and in developing countries has more than doubled: the WHO estimates that more than 1.9 billion adults and 41 million children under the age of five are overweight or obese (2). Between the different causes, obesity is basically due to an excess consumption of calories over time being turned into body fat, with abdominal fat as a reliable index of negative impacts on health (3).

However, obesity condition, other than being an excessive fat deposit, is characterized by excessive and uncontrolled cytokines, free radicals and adhesion molecule production, a condition defined as "low-grade chronic inflammation" associated with the development of degenerative diseases (4, 5). Moreover, due to the uncontrolled high intake of nutritionally unbalanced meals, characterized by elevated caloric, sugars, and fat consumption, obesity condition is also associated with continuous postprandial metabolic stress, characterized by a deep raising of CVD risk factors such as blood pressure, insulin resistance, LDL oxidation, triglycerides and high glucose blood levels.

Consumption of food that is constantly above the recommended calorie requirements by a growing number of people not only represents a risk to health, but it also puts more pressure on natural resources and on the environment (1), including overeating among food waste (6). The calculated progressive increase of food waste suggests that the worldwide obesity epidemic has been the result of a "push effect" of increased food availability and marketing. Since 1974 the energy content of diet has increased 50%, reaching more than 1,400 kcal per person per day or 150 trillion per year (7). In this view, obesity condition represents a considerable cost for the environment (8). Recently, we introduced a new index to calculate the ecological impact of obesity, Metabolic Food Waste [$MFW_{(kg\ of\ food)}$], corresponding to the amount of food leading to Excess Body Fat (EBF) and its impact on the environment expressed as carbon [$MFW_{(kgCO_2eq)}$], water [$MFW_{(\times 10\ L)}$], and land footprint [$MFW_{(\times 10\ m^2)}$] (8). We estimated $MFW_{(kg\ of\ food)}$ of 63.1 and 127.2 kg per capita in an observational study on 60 overweight and obese subjects, and of 2.081 million kg of food for the Italian population, with the highest contributor from animal products in terms of carbon emissions, water consumption and land use. We claim that increased population adiposity, because of its contribution to climate change from unnecessary food consumption, should be recognized, in addition to being a health and sociological issue, as an environmental problem.

Therefore, the aim of our work is to estimate the $MFW_{(kg\ of\ food)}$ in the seven FAO regions and evaluate its impact on climate, water, and land footprints for food commodity groups in order to provide a global picture of the phenomenon.

MATERIALS AND METHODS

Prevalence of overweight and obesity at a global level from the WHO Global Database on Body Mass Index (BMI) relative to the year 2017 (9) has been used in combination with population data (10) to assess the number of individuals belonging to BMI categories of overweight and obese subjects. In order to assess global Excess Body Fat (EBF) in terms of mass (kg), the difference between average body weight at a national level and "*ideal body weight*," given by BMI inverse function, has been calculated. The "*ideal BMI*" estimated by the midpoint between lowest and highest values using WHO cut-off points for BMI resulted to be 21.7 kg/m^2 for normal the weight category [(18.5 + 24.9)/2 = 21.7]; while average body height by country was obtained from DHS projects (11) on all completed population-based surveys, the national statistical databases were also used for missing data.

The attained EBF was multiplied for the energy content of 1 kg of body fat (32.2 MJ) to reach the energy from EBF and distributed among the different foods according to their percentage contribution to total energy intake. An estimation of food items contributing to the EBF has been calculated associating energy from EBF with kilocalories from food, determined from the Food Balance Sheets (FBS) in FAOSTAT (12). The percent energy contribution of each food item at the national level was multiplied with the total amount of energy from EBF for each specific country to achieve the amount of energy of each food item contributing to the EBF, with the value translated into amount of food wasted through overweight/obesity [$MFW_{(tons\ of\ food)}$]. Food waste was based on total production through FBS food items grouped into nine main groups: dairy products/milk/eggs, starchy roots, alcoholic beverages, cereals, meat/offals, sugar and sweeteners, fish/seafood, added fats, and pulses. The acquired data allowed us to provide a worldwide estimation of the impact of over-nutrition on planet health through the new index $MFW_{(tons\ of\ food)}$ and its impact on the environment as carbon [$MFW_{(kgCO_2eq)}$], water [$MFW_{(m^3\ water)}$], and land footprint [$MFW_{(m^2\ land)}$] (13, 14). Complete information has been reached for 86 countries, categorized in the seven FAO world regions: Europe (EU), North America and Oceania (NAO), Latin America (LA), Sub-Saharan Africa (SSA), Industrialized Asia (IA), North Africa, West and Central Asia (NAWCA), and South and Southeast Asia (SSEA).

RESULTS

As displayed in **Table 1**, the overall impact of $MFW_{(tons\ of\ food)}$ in the world correspond to 140.7 million tons of food waste

TABLE 1 | Metabolic Food Waste [$MFW_{(kg\ of\ food)}$] corresponding to Excess Body Fat by BMI categories (OW, Overweight; OB, Obesity).

	$MFW_{(tons\ of\ food)}$	% From	
		OW	OB
EU	39,201,410,847	48.6	51.4
NAO	32,465,755,707	32.3	67.7
LA	20,022,343,875	44.9	55.1
IA	17,190,412,965	71.7	28.3
NAWCA	14,595,049,642	35.7	64.3
SSEA	12,181,476,616	59.6	40.4
SSA	5,079,066,441	47.4	52.6
Total worldwide	140,735,516,093		

EU, Europe; NAO, North America and Oceania; LA, Latin America; IA, Industrialized Asia; NAWCA, North Africa, West and Central Asia; SSEA, South and Southeast Asia; SSA, Sub-Saharan Africa.

Abbreviations: GHGs, Greenhouse Gases; MFW, Metabolic Food Waste; EBF, Excess Body Fat; EU, Europe; NAO, North America and Oceania; LA, Latin America; SSA, Sub-Saharan Africa; IA, Industrialized Asia; NAWCA, North Africa, West and Central Asia; SSEA, South and Southeast Asia; CVD, Cardiovascular disease; WHO, World Health Organization; BMI, Body Mass Index; FBS, Food Balance Sheets.

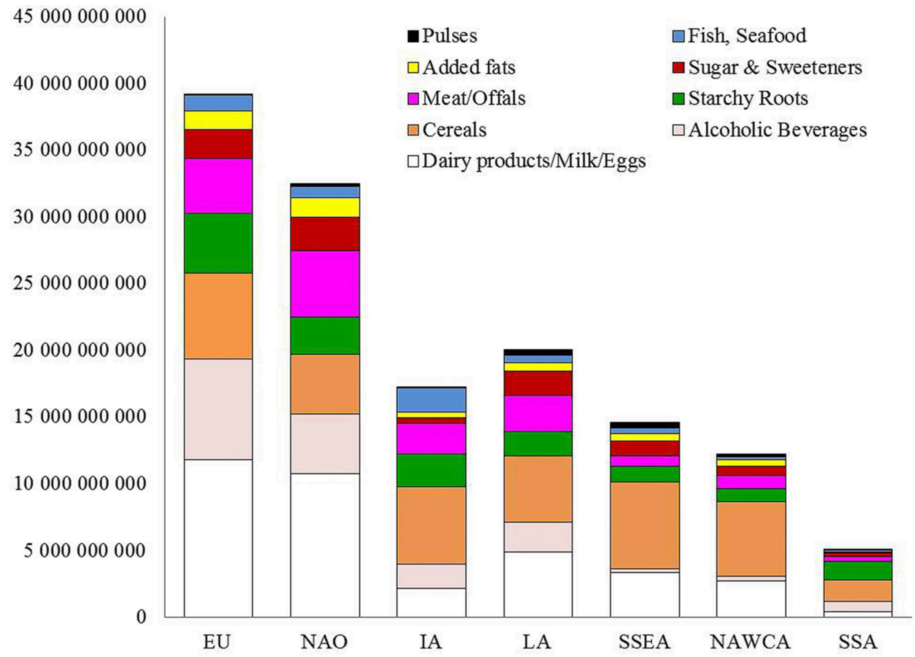

FIGURE 1 | Metabolic Food Waste corresponding to excess body fat from FBS commodities in overweight and obese population expressed as amount of food [$MFW_{(kg\ of\ food)}$]. EU, Europe; NAO, NorthAmerica and Oceania; LA, Latin America; IA, Industrialized Asia; NAWCA, North Africa, West and Central Asia; SSEA, South and Southeast Asia; SSA, Sub-Saharan Africa.

associated with overweight and obesity. Between the different regions, Europe (EU) is responsible of the greatest amount of $MFW_{(tons\ of\ food)}$ volume (39.2 million tons), followed by North America and Oceania (32.5 million tons) (NAO) and Latin America (20 million tons) (LA), while the lowest extent of MFW was recorded in Sub-Saharan Africa (SSA) with 5 million tons as described in **Table 1**. It is interesting to note that the highest percentage of $MFW_{(tons\ of\ food)}$ in NAO came from obese people (67.7%), however, EU with a similar percentage between OW and OB accounted for the highest volume of MFW.

As described in **Figure 1**, dairy products/milk/eggs, were the highest contributor to $MFW_{(tons\ of\ food)}$ in the EU (about 12 million tons corresponding to 30.2%) and NAO (33.1%), followed by alcoholic beverages (19.1%) and cereals (16.4%) in EU, meat/offals (15.2%) and alcoholic beverages (13.9%) in NAO. Cereals and dairy products were the two largest contributors to $MFW_{(tons\ of\ food)}$ in LA (24.8 and 24.4%, respectively), SSEA (44.6 and 22.8%) and NAWCA (46.0 and 22.2%), while in IA and SSA the highest impact came from cereals (33.8 and 31.5%, respectively) and starchy roots (14.2 and 28.0%).

In terms of ecological impact, EU and NAO displayed the highest values for all three MFW footprints (water, land, carbon), about 14 times more than SSA that, as for the $MFW_{(tons\ of\ food)}$, is the area with lowest ecological impact (**Table 2**). The water footprint for EU and NAO was similar but almost double with respect to LA and 10 times more with respect to the ones with lowest impact (SSA). In terms of GHG emissions, EU was in first place followed by NAO and LA, also here the footprint of EU was almost 10 times more than SSA. Regarding land use, EU was the first followed by NAO and LA, with a land use of about 15 times higher than SSA.

TABLE 2 | Metabolic Food Waste (MFW) expressed as water (millions m^3), GHG emissions (millions kg/CO_2eq), land (millions m^2).

	Water (millions m^3)	GHGs (millions kg/CO_2eq)	Land (millions m^2)
EU	93,926,391	66,477,365	1,085,945,294
NAO	92,446,368	58,419,124	1,034,147,016
IA	36,982,188	31,403,573	416,548,943
LA	50,769,141	34,343,457	531,386,727
NAWCA	28,631,298	18,885,007	289,849,101
SSEA	32,220,628	22,626,903	355,688,254
SSA	8,339,655	7,253,364	71,353,289
Total worldwide	343,315,669	239,408,793	3,784,918,624

EU, Europe; NAO, North America and Oceania; LA, Latin America; IA, Industrialized Asia; NAWCA, North Africa, West and Central Asia; SSEA, South and Southeast Asia; SSA, Sub-Saharan Africa.

Figure 2A shows the contribution of commodities to total GHG emissions by geographical area. Dairy products/milk/eggs and meat/offals have the highest values in EU and NAO, two geographical areas where overweight and obesity are at epidemic proportions, followed by alcoholic beverages. Meat/offals are the highest contributor in IA followed by cereals and fish/seafood, while in LA, SSEA and NAWCA, the first three places were occupied by cereals, dairy products/milk/eggs and meat/offals whereas in SSA cereals were the highest contributor.

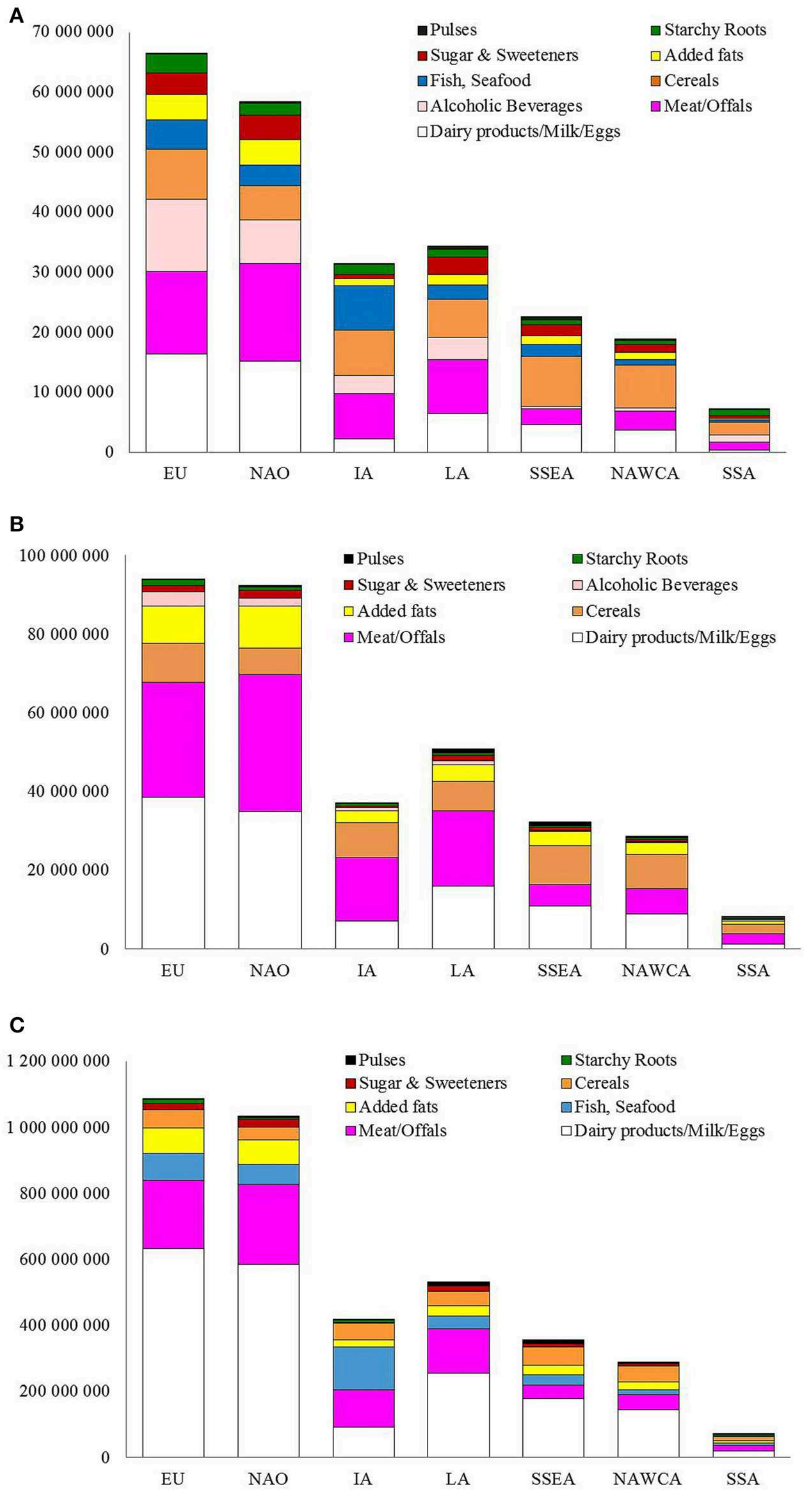

FIGURE 2 | Metabolic Food Waste corresponding to Excess Body Fat from FBS commodities in overweight and obese population expressed as **(A)** GHG emission, $MFW_{(millions\ kgCO_2eq)}$; **(B)** water consumed, $MFW_{(millions\ m^3)}$; and **(C)** land used, $MFW_{(millions\ m^2)}$. EU, Europe; NAO, North America and Oceania; LA, Latin America; IA, Industrialized Asia; NAWCA, North Africa, West and Central Asia; SSEA, South and Southeast Asia; SSA, Sub-Saharan Africa.

Figure 2B shows total water footprint (as millions m^3) from MFW in the seven regions: dairy products/milk/eggs and meat/offals as a whole contribute to more than 70% in EU and NAO. In IA meat/offals was in first place (43.7%), followed by cereals (23.8%). In LA, SSEA, and NAWCA dairy products/milk/eggs and cereals were the two highest contributor to MFW water footprint.

Animal commodities, dairy products/milk/eggs, meat/offals and fish, were the highest contributors to the $MFW_{(millions\ m^2)}$ for land footprint with about 80% of the contribution in EU and NAO, as displayed in **Figure 2C**. Specifically, dairy products/milk/eggs and meat/offals were at the first two places for all regions, with the only exception of IA where the first contributor to land use was fish/seafood (31.0% against <10% in the other geographical areas). Data on MFW for land footprint does not include alcoholic beverages because they were not available in the footprints database.

DISCUSSION

Obesity is a social challenge that is rising in almost all countries with detrimental effects for human and planet health. In this work we showed that the overall impact of $MFW_{(tons\ of\ food)}$ associated with overweight and obesity in the world is 140.7 million tons of food waste, with EU and NAO with the highest ecological impact for water, land and carbon footprints. We proved that obesity burden represents a significant additional increment to the already high global statistics on food wastage causing an unsustainable ecological cost for the planet. However, if we consider that increase in body fat is the result of a long period of reduced physical activity as well as a diet rich in energy-dense food and an intake of calories much higher than metabolic needs, our figures might have underestimated the amount of food wasted through the increase in body fat. In order to properly assess the amount of food wasted through obesity, MFW should be calculated in long-term observational/epidemiological studies together with measurements of metabolic parameters.

Our results show that industrialized regions such as EU and NAO display a much higher ecological impact, associated with excess body fat, compared to developing regions like NAWCA and SSA. Our results mirror the main findings from a previous FAO report (15) showing higher values of food waste in the EU and NAO compared to non-industrialized countries, highlighting the responsibility of high-income countries in food waste. It is important to study approaches to address behavior changes in the developed regions, raising the consciousness on the importance of reducing the waste of food and to prefer dietary patterns suited for individual energy needs, to avoid a further increase of the environmental and health impacts associated with unbalanced western dietary habits.

Between the different commodities, meat/offals and dairy products/milk/eggs were shown to be major contributors to $MFW_{(tons\ of\ food)}$ and the ecological footprints of EU and NAO and in almost all FAO areas, with few exceptions like cereals in SSEA and NAWCA (**Figure 2A**). It has been widely shown that animal products have much higher ecological costs compared to plant-based foods (16); however, the role of animal products in people's diet must be carefully considered within the context of each region without neglecting the higher nutritional values of these products for populations suffering from malnutrition. As stated from the EAT-Lancet Commission (17), meat consumption in the world is about 288% times higher than the amount suggested for a balanced and healthy diet. Obviously, reducing meat, dairy, milk, and egg consumption in industrialized countries must be a priority to reduce the ecological burden of animal products.

Finally, it shall be emphasized that our data provide important information because they quantify the effects of over-nutrition on the GHGs emissions, water and land use related to the availability of food at worldwide level, through food balance sheets. However, it must be considered that our results are based on national availability of the main food commodities, providing a valuable insight into diets but not corresponding to average food intake or average food consumption.

Strategies of disease prevention should also be focused on overweight people, representing an excellent target to avoid the development of obesity condition and to minimize the ecological cost of excessive food intake. Overall, we think that it is extremely important to raise awareness in the population at large of the impressive waste of food and natural resources associated with overweight and obesity. At a public health level, it should be highly desirable to develop a specific campaign for obesity prevention focused on increasing physical activity as well as in reducing metabolic food waste through a wise and ethical approach to food consumption.

CONCLUSION

We provide evidence, at world level, of the enormous amount of food lost through obesity and its ecological impact. As expected, animal products were the highest contributor to MFW; however, large epidemiological studies are needed in order to clearly identify major dietary contributors to MFW in humans. Reducing metabolic food waste associated with obesity will contribute to reducing the ecological impact of unbalanced dietary patterns through an improvement of human health.

DATA AVAILABILITY

The datasets generated for this study are available on request to the corresponding author.

AUTHOR CONTRIBUTIONS

MS designed the experiment. ET performed data analyses. MS, ET, and CD contributed to data interpretation and manuscript drafting.

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Corrigendum: Metabolic Food Waste and Ecological Impact of Obesity in FAO World's Region

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Keywords: sustainable nutrition, obesity, metabolic food waste, functional diet, ecological footprints, food balance sheets, human, animal products

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In the original article, there was a mistake in the legend for **Figure 2** as published.

It was not written as millions of kg in $MFW_{(kgCO_2eq)}$.

The correct legend appears below.

Figure 2. Metabolic Food Waste corresponding to Excess Body Fat from FBS commodities in overweight and obese population expressed as **(A)** GHG emission, $MFW_{(millions\ kgCO_2eq)}$; **(B)** water consumed, $MFW_{(millions\ m^3)}$; and **(C)** land used, $MFW_{(millions\ m^2)}$. EU, Europe; NAO, North America and Oceania; LA, Latin America; IA, Industrialized Asia; NAWCA, North Africa, West and Central Asia; SSEA, South and Southeast Asia; SSA, Sub-Saharan Africa.

In the original article, there was an error in **Table 1** as published. It was written $MFW_{(tons\ of\ food)}$ instead of $MFW_{(kg\ of\ food)}$.

The correct title appears below.

Table 1. Metabolic Food Waste [$MFW_{(\mathbf{kg\ of\ food})}$] corresponding to Excess Body Fat by BMI categories (OW, Overweight; OB, Obesity).

In the original article, there was an error. The values of $MFW_{(tons\ of\ food)}$ were expressed in gigatons instead of millions of tons.

Corrections have been made to the **Abstract:**

The overall impact of $MFW_{(tons\ of\ food)}$ in the world corresponds to 140.7 **million tons** associated to overweight and obesity. Between the different regions, EU is responsible of the greatest amount of $MFW_{(tons\ of\ food)}$ volume (39.2 **million tons**), followed by NAO (32.5 **million tons**).

Corrections have been made to **Results, Paragraph 1:**

As displayed in Table 1, the overall impact of $MFW_{(tons\ of\ food)}$ in the world correspond to 140.7 **million tons** of food waste associated with overweight and obesity. Between the different regions, Europe (EU) is responsible of the greatest amount of $MFW_{(tons\ of\ food)}$ volume (39.2 **million tons**), followed by North America and Oceania (32.5 **million tons**) (NAO) and Latin America (20 **million tons**) (LA), while the lowest extent of MFW was recorded in Sub-Saharan Africa (SSA) with 5 **million tons** as described in Table 1.

As described in Figure 1, dairy products/milk/eggs, were the highest contributor to $MFW_{(tons\ of\ food)}$ in the EU (about 12 **million tons** corresponding to 30.2%).......

A correction has been made to **Discussion, Paragraph 1:**

In this work we showed that the overall impact of $MFW_{(tons\ of\ food)}$ associated with overweight and obesity in the world is 140.7 **million tons** of food waste…

The authors apologize for these error and state that this does not change the scientific conclusions of the article in any way. The original article has been updated.

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ORIGINAL RESEARCH
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Valuing the Multiple Impacts of Household Food Waste

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The Commission for Environmental Cooperation (CEC) has estimated that Canadian households waste 85 kg of food per person annually. Food waste has become an increasingly common focus for policy, regulation, interventions, and awareness-raising efforts in Canada. However, there is still a relative dearth of data to inform such decision-making processes or to provide narratives to contextualize behavior change efforts. In this paper, we describe the results of an uncommonly detailed observational study of household food waste. A total of 94 families with young children living in Guelph, Ontario chose to participate in this study. Over the course of multiple weeks, we collected data on their food purchases, food consumption, and waste generation. All three streams of waste (garbage, recycling, and organic waste) were audited and the food type, degree of avoidability, and weight of each individual component of the organic waste stream was recorded. Using this highly granular data set, we found that the average household in our study generated approximately 2.98 kg of avoidable food waste per week. This estimate was then contextualized in terms of economic losses (dollar value), nutritional losses (calories, vitamins, and minerals) and environmental impacts (global warming potential, land, and water usage). In short, weekly avoidable food waste per household was calculated to be equivalent to $18.01, 3,366 calories, and 23.3 kg of CO_2. These multiple valuation frameworks, which are based in detailed observations of family food behaviors rather than estimations derived from system-wide data, will enable more informed and urgent conversations about policy, programming, and interventions in order to reduce the volume of wasted food at the consumer level.

Keywords: food waste, household waste, composition audit, nutrition loss, environmental impact, economic cost

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INTRODUCTION

At the international scale, there has been a relatively recent increase in attention to food waste in both research and policy (1–4), suggesting that conversations about this topic have gained prominence and momentum in our collective consciousness. Reducing food waste was included as one of the United Nations Sustainable Development Goals under the priority of "Responsible Consumption and Production" (5). The Food and Agriculture Organization has issued reports and produced public commentary on food loss and waste over the past decade (6), and the European Union has prioritized food waste measurements and interventions since 2012 under the FUSIONS and REFRESH projects (7, 8). In Canada, food waste has recently become the subject of municipal, provincial, and national policy discussions. The creation of multi-stakeholder organizations to inform food waste policy-making and intervention design [e.g., see (9–11)] is another indicator of rising attention to food waste as an issue of concern in the Canadian context.

In order to meaningfully address this critical issue which has important environmental, economic, and nutritional consequences, food waste policy-making and intervention-testing must be supported by high-quality evidence. In this study, we discuss the results of a highly granular waste composition audit conducted with 94 households in Guelph, Ontario. We highlight the uniqueness of our data set and discuss the potential for using high quality data to inform the emergence of food waste discourses. We then analyze our data from different vantage points in order to frame our results in terms of the economic losses, nutritional losses, and environmental impacts of household food waste in Canada. This analysis can be used to inform messaging choices for policy-making, advocacy activities, and educational and behavior-change interventions.

MEASUREMENT AND CHARACTERIZATION OF FOOD WASTE

Measuring and monitoring food waste generation is a challenging task. The Commission for Environmental Cooperation recently worked to create a comprehensive estimate for organic waste in Canada. Their methodology relied on the extrapolation of a limited number of composition audits from the residential and ICI (industrial, commercial, and institutional) sectors to generate national level data. Their final estimates suggest that Canada generates 12.6 million tons of organic waste that is sent to final disposal, and an additional 5.8 million tons of organics that are diverted to alternative treatment. They estimate that individuals generate approximately 85 kg of food waste per year in the residential sector (12). Using a different approach, Gooch et al. (13) used surveys, interviews, and secondary data to inform their estimates of food loss and waste (FLW) at different points in the Canadian food value chain. They estimate that 35.5 million metric tons of food are lost or wasted in Canada, including 11.2 million metric tons of avoidable food waste. They characterize this waste as representing 58.1% of the commodities entering the food system, at a cost of $49.5 billion. In this study, household food waste was not directly observed, but was estimated using aggregate food availability data from Statistics Canada.

Canadian municipalities often conduct audits of their residential waste streams in order to learn about their composition, which may include organic waste generation rates. However, these audits often collect aggregate data (rather than observations at the individual household level), and their methodologies can vary widely [see (10) for a food waste audit guide that would allow for improved cross-site data comparability]. There is little academic literature that systematically observes household food waste generation in Canadian contexts [for exceptions see (14, 15)]. Similarly, there are relatively few direct observations of organic waste in other parts of the world [see (16) for a detailed exception based in the UK]. Xue et al. (2) note that over half of the published articles in their systematic review of food waste across the supply chain relied on secondary data, whereas only about 20% of these studies used direct observations. Furthermore, the category of direct observations included self-report methods such as surveys and diaries: research shows that such observational methods can be unreliable and tend to underestimate food waste generation (17–19). We are unaware of any other research in Canada that systematically records each item of food waste generated at the individual household level, and we believe that our highly granular dataset enables a different framing of food waste as a policy-relevant issue.

BUILDING STORY-LINES: A PROJECT OF ENVIRONMENTAL DISCOURSE

How has food waste come to gain prominence and visibility in our modern world? In his classic analysis of environmental discourse, Hajer (20) observes that certain issues become emblematic at distinctive times, garnering public and political attention. Even when issues become emblematic, they are not necessarily coherent. For example, Hajer discusses how the issue of acid rain emerged as a topic pertaining to multi-disciplinary ecological understandings, economic implications, and the social and financial impacts of interventions and abatement techniques, as well as ethical discussions regarding blame and responsibility. Therefore, environmental discourses do not refer solely to the discussion of environmental science, but also to related issues of interest to diverse actors in society.

Hajer's analysis focuses on the enabling capacity of discourses, and the ability of individuals to strategically deploy discursive strategies. In other words, discursive formations can be influenced and designed. He argues that the struggle for discursive hegemony is a political project whereby different actors "try to secure support for their definition of reality" (p.59). One such discursive approach is the creation of story-lines:

> A story-line, as I interpret it, is a generative sort of narrative that allows actors to draw upon various discursive categories to give meaning to specific physical or social phenomena. The key function of story-lines is that they suggest unity in the bewildering variety of separate discursive component parts of a problem like acid rain... Finding the appropriate story-line becomes an important form of agency [(20), p.56].

An indicator that a discourse has become hegemonic is that it has become institutionalized; that is, the discourse is manifest in institutional arrangements, such as policies, institutional structures, or formal practices. The dominant discursive framings of environmental issues thus have implications for how these issues are perceived by the public, which institutional actions are deemed appropriate as interventions, and whether such issues are seen as actionable in the first place (21).

With respect to food waste in Canada, we have seen the proliferation of discursive framings of these issues in the past 5 years. We believe that this is an important moment for designing public messages that are evidence-based, action-oriented, and relevant to public policymakers. In this article, we draw upon our highly granular food waste audit data to suggest different means of communicating the impacts of food waste in health, economic, and environmental terms to both policymakers and the public at large. In essence, we are suggesting story-lines that "illustrate where [our] work fits into the jigsaw" [(20), p.63]. In the following section, we map out some of the other puzzle pieces that constitute the sometimes incoherent realm of food waste discourses in the contemporary Canadian context [also see (22) for a discourse analysis of food waste in the United Kingdom].

EXISTING FOOD WASTE STORY-LINES IN CANADA

The federal government in Canada has indicated its interest in addressing food waste, although it has not yet issued policies or regulations that would institutionalize this commitment. Environment and Climate Change Canada (the federal environment ministry) has recently taken leadership on the food waste file, convening multi-stakeholder workshops and commissioning reports on this topic. While they are in the process of articulating their position on this topic, they have not been the primary source of environmental discourse on food waste to date. Similarly, in a study on the prospective creation of a Canadian food policy, the House of Commons Standing Committee on Agriculture and Agri-Food made recommendations that "the Government, in conjunction with all members of the supply chain, establish education tools and take action to reduce industry food loss and consumer food waste," and also that the Government work with community groups and NGOs to address a suite of food-related issues, including food loss and waste (23). The details of these mechanisms were not clearly articulated in the study, and the food policy-making process is still underway at the time of writing.

Provincial governments in Canada have primary responsibility for waste management legislation in Canada, and some provinces have foregrounded food waste in their policy and regulations. For example, Prince Edward Island and Nova Scotia have banned organic wastes from landfills, and Quebec is implementing a staged ban as well (12). Although they have been responsible for legislation that enables the diversion of organic wastes, provincial governments have otherwise not been as active in the generation of discourse around the impacts of food waste or interventions to address this issue. An exception is the province of British Columbia, which has developed a suite of toolkits and resources to enable different actors to prevent and reduce their food waste (24). Ontario's Ministry of the Environment, Conservation, and Parks (MECP) recently released a Discussion Paper entitled "Reducing Litter and Waste in Our Communities" that addresses food waste, among other topics. Under the heading "Build a culture of food waste avoidance," the document suggests the following:

> . . .the province will work with partners to develop educational tools and resources, including guidance on the implementation of the policy statement, to support more standardized promotion and education outreach (e.g., best practices for meal planning and food storage, including tips on how to extend the life of food, such as freezing food where appropriate and safe) [(25), p.16]

This framing of food waste focuses on influencing individual-level behaviors as a policy mechanism. The Discussion Paper iterates an interest in developing a landfill ban for organic materials as a more systemic intervention, and also broaches the expansion of organics diversion programs "where it makes sense" [(25), p.18]. This document alludes to the potential for food rescue as a solution for food waste, which is discussed as a discursive phenomenon below. Overall, the current Ontario government's perspective on food waste as an environmental issue is that win-win solutions are possible: "Avoiding food waste, rescuing surplus food, and diverting unavoidable food and organic waste is both good for the environment and good for business" [(25), p.15].

Much of the policy and planning work on food waste in Canada occurs at the scale of municipal or regional governments. Some municipalities have their own local communications and awareness-raising programs, such as York Region's Good Food Program. This campaign focuses on healthy eating and food skills messaging to encourage residents to eat the food that they have already purchased, and thereby reduce food waste (26). Metro Vancouver's "Hey! Food Isn't Garbage!" campaign was designed to encourage diversion of food scraps and was rolled out in conjunction with a regional Organics Disposal Ban and increased residential access to source separated organics collection programs (27). Municipalities have also worked together to create story-lines about waste. For example, the Ontario Food Collaborative is a group of municipal waste managers and public health staff working to address food waste and shift local cultures around this issue. They recently published a Food Waste Audit Guide (discussed above) meant to encourage municipalities to measure and monitor food waste generation in order to better prevent it. They also published a Food Waste Reduction and Healthy Eating Communications Strategy whose goal is "To inform, motivate, and empower people to live a more sustainable lifestyle by providing education, tools and resources to promote and support healthy eating and food waste prevention and reduction" [(11), p.6].

The National Zero Waste Council (NZWC) is a multi-stakeholder initiative that was initiated by the regional government of Metro Vancouver with the objective of advancing a waste prevention agenda across Canada. This organization includes major Canadian municipalities, businesses, and non-profits. Notably, the NZWC has licensed Love Food Hate Waste—a successful awareness-raising campaign designed in the United Kingdom by the Waste and Resources Action Programme (WRAP)—for use in Canada. Municipalities, provinces, and businesses can sign on as partners to access the campaign materials and social media platforms, which include messages around the reduction of household food waste. The campaign focuses on food skills (i.e., the provision of recipes, tips, and the tagline "Plan it Out, Use it Up, Keep it Fresh"), and also conveys messages about the economic costs of household food waste ("Wasted food costs an average Canadian household over

$1100 per year"), the scale of household food waste ("Over 60% of household food waste in Canada is avoidable"), and information about the carbon footprint of this waste ["Reducing 1 ton household food waste = 1 car off the road each year"; (28)].

The NZWC also published "A Food Loss and Waste Strategy for Canada" in 2017. This document frames the problem of food waste as follows:

> The strategy calls for the federal government to publicly announce a national target and takes a systems approach that aims to change practices and policies at key leverage points along the value chain and in the mandates of governments, as well as encourage new behaviors. It is anchored by three broad objectives: Prevent food waste from occurring in the first place; Recover safe and nutritious food for people and food scraps for animals; and Recycle energy and nutrients from the remaining, unavoidable food waste [(9), p.7]

This strategy thus frames food waste as a systemic and policy-relevant issue that requires attention across the food value chain. It references the environment and economic costs of food waste and alludes to the potential for food recovery from this waste stream.

Another major source of food waste discourse in Canada is a series of reports generated by Value Chain Management International (13, 29, 30), the most recent of which was commissioned by the non-profit food rescue organization Second Harvest. These often-referenced reports investigate the source and scale of food waste in Canada, and the messaging has changed over time as new data have come to light. The 2010 report focused on the negative economic and environmental repercussions of an estimated $27 billion in food loss and waste in Canada, noting that "While the majority of food waste occurs at the consumer level, improving the management of agri-food value chains would have the greatest long-term impact on reducing food waste" (30). In 2014, the estimate of the value of food loss and waste was adjusted to $31 billion, it was noted that consumers were still the leading source of food waste, and a main theme in food waste generation was adversarial relationships along the food value chain (30). The 2019 report used different methods to generate their estimates for food loss and waste, which was reported as the equivalent of $49.5 billion. Notably, the increase in food waste was observed at the manufacturing and processing stages, which then displaced consumers as the leading source of waste. This most recent report identifies broad structural and cultural causes for the high volume of food waste observed in Canada:

> The root causes of the FLW that occurs in Canada include a culture of accepting waste. A direct correlation can be drawn between some business and governmental decisions and the creation of avoidable FLW. Other root causes of FLW include the true cost of FLW not being internalized by industry and consumers. In addition, there is no common template for redistributing food that would otherwise go to landfill or non-food use [(13), p.6].

In this discursive framing, food waste is posited as a series of structural and cultural short-comings that span the food system. It is a lost opportunity that negatively impacts multiple stakeholders.

In the Canadian context, food security has often been invoked when discursively defining food waste as a problem. For example, the NZWC called for a tax credit for corporate food donations to incentivize the diversion of wasted food to non-profit organizations in 2015–6; this strategy was framed as one among many needed to prevent the generation of food waste. A business case study prepared by the Conference Board of Canada for the NZWC listed "Increasing, Improving, or Enhancing Household Food Security" as one of the benefits of a donation tax incentive, alongside environmental and economic benefits [(31), p. 15]. Many high-profile food security advocates in Canada responded to the framing of food waste as a food security issue, pointing out that because food security is primarily an issue of inadequate income, food donation can never address the root causes of hunger in Canada. They also noted that incentivizing large-scale donations of wasted food discourages systemic interventions that prevent or reduce this waste stream, and that this approach may overwhelm under-resourced non-profit organizations with high volumes of varying quality food (32–35). Proponents of the tax credit (including the NZWC) subsequently deemphasized the food security argument in acknowledgment of the issues raised by food security advocates, noting that the prevention of food waste was always their primary aim. For example, in September 2016, the Federation of Canadian Municipalities (FCM) expressed their support for the tax credit, but did not mention food security as a motivator for this endorsement: "That FCM support the National Zero Waste Council's food waste reduction federal tax incentive proposal … thereby helping reduce food waste, lower municipal costs for waste disposal and decrease the environmental impact of food waste" (36).

While food waste discourse in Canada is not coherent, there are some common themes that emerge in the messaging from key influencers. Food waste is described as a multifactorial problem: its impacts are environmental, economic, social, and health related. However, health issues are usually framed around the benefits of eating commonly wasted food, rather than focusing on the nutrients that are lost when food is wasted. Food waste occurs at multiple sites, and so many actors can be read as responsible for its generation. Some framings focus on preventing food waste, while others see this as a problem to be mediated via reduction or treated through diversion and composting. The tenor of discussion surrounding interventions varies depending on which parties are responsibilized for food waste. For example, interpretations that focus on the consumer as the appropriate site of intervention tend to focus on skill building and education, whereas structural analyses focus on policy mechanisms and regulatory interventions (these messages are often not mutually exclusive within a given discourse, however). Different discourses often reference the potential for synergies, such as the ability to save money and reduce environmental impact at the same time, or to improve the quality of one's diet while also reducing pressure on municipal waste management infrastructure.

Welch et al. (22) conducted a similar discourse analysis of food waste in the United Kingdom, finding that the discourse coalition that has emerged there has assumed the dominant framing of food waste is one of "responsibility distributed throughout the production–consumption system" (p.1). They also observed narratives framing food waste as a "perfect storm" of issues, including environmental, social, and economic impacts. These authors argue that the discourse collation that has emerged in the United Kingdom around food waste has reached the stage of discursive hegemony. In contrast, food waste discourse is still emergent in Canada, and there is room to shape the story-lines that are framing the public conversation about this issue. In the following sections, we mobilize our household food waste audit data with the aim of informing some of these discursive framings. Our goal is to provide framings that may help to convince diverse policy-makers of the gravity of this issue, that may educate and motivate consumers to change their individual behaviors and to advocate for civic action on food waste, and that may inform future research on the effectiveness of different messages, as well as discursive analyses of "wicked" environmental problems in the current age. The following analysis focuses on providing evidence for the key discursive framings of food waste that are already at play in Canada, including the economic, health / nutritional, and environmental impacts of avoidable household food waste.

MATERIALS AND METHODS

This study took place in the city of Guelph, Ontario, and was conducted in accordance with the University of Guelph's Research Ethics Board protocols. This study was carried out as part of the Family Food Skills Study, a cross-sectional study that aimed to examine family food behaviors and assess their impact on family diets. The study reported in this paper added a food waste composition audit to the Family Food Skills protocol to assess the relationship between family food skills, food behaviors, and food waste. Data reported in this paper includes results from the weekly household waste audits and results from the analysis of receipts collected for all food purchases, including grocery stores and meals purchased outside of the home.

Eligibility for this study required that families have at least one child between 2 to 8 years of age and that parents have no prior nutrition or food training. Recruitment took place at daycares and community health centers as well as through social media and word of mouth. As an incentive for voluntary participation, each family was offered a $100 grocery gift card. Prior to beginning the study, the study team performed home visits to each family in order to answer questions and explain expectations. Data was collected from 54 families in 2017 and 40 families 2018, for a total of 94 participating households.

The household waste audits were conducted over four consecutive weeks in 2017 and three consecutive weeks in 2018 over the summer. The shorter audit period in 2018 was driven by logistical constraints (i.e., availability of auditors and a holiday long-weekend, which can change waste behaviors). Waste was collected each week on the day the family would have expected their regular waste pick-up by the municipality. All three waste streams were collected, including source-separated organics, recycling, and residual garbage. Families who had a home composter were asked to place all of their organics in the green bin for the weeks that they were being audited. In this case, we were unable to observe food waste that was disposed of by other means (i.e., sink garburators, fed to animals etc.). It is also possible that the waste audits failed to capture some liquid items from the dairy group (i.e., milk, yogurt) as these products tend to be disposed of in the sink rather than in garbage or organics bins. Collected waste was then taken to a central municipal facility where it was audited to evaluate food waste volume and composition.

Auditors identified and weighed each individual food item found in any of the three streams. Waste was categorized into six broad categories based on the criteria used by the Guelph Food Waste Research Group in previous work in Guelph. These categories were adapted from WRAP Household Food Waste Collections Guide[1]. The six categories are: fruits and vegetables, meat and fish, grains and cereals, dairy (milk, cheese, and eggs), fats and sugars, and other (primarily coffee grounds and tea). The categories are also divided into avoidable (could have been eaten at some point), unavoidable (inedible portions of foods), and possibly avoidable (could be eaten but some people choose not to, e.g., potato peels). Our focus for this paper is on food that could have been eaten, and so we aggregated the avoidable and possibly avoidable categories.

Food scraps that were already mid-decomposition or blended in with other food scraps were labeled as "Unidentifiable" or "Unknown [food group category]." We proportionally distributed the weights of the these unknown/unidentifiable foods into known food categories. For example, if a household had "asparagus" food scraps which constituted 10% of that household's known vegetable weight for that week, the "asparagus" category would receive 10% of that household's "Unknown Vegetable" category. For composite meals involving several different food items mixed together, we first attempted to sort out the individual foods from the component foods. When this proved to be impossible, the food item was labeled according to all components present. For example, a mixture of rice and broccoli that was thoroughly blended was categorized as "Rice and Broccoli." These composite meals would then be listed in the food group of its primary component, in this case "Rice."

Once each food item was categorized, we generated a list of 316 avoidable food items found in the waste streams. We compared the total mean weights of the 2017 and 2018 sub-samples using a Mann-Whitney test and found that these were comparable sub-groups that could be combined for subsequent analysis.

QUANTIFICATION METHODOLOGY

We subsequently characterized the economic, nutritional, and environmental footprint of the avoidable food waste observed in the audits. For the economic analysis, the dollar value for each avoidable food item by weight was calculated using receipt data collected during the study. Any food items for which receipt data was not available (∼12% of the data) were searched on the website of the grocery chain with the largest market share in Ontario.

[1] http://www.wrap.org.uk/content/household-food-waste-collections-guide.

This store also represented a significant portion of the receipt tapes submitted. In some cases, weights were not available for the products and instead were purchased by units. When this occurred, the online weight converter at Hannaone.com[2] was used to estimate the weight of unit-based foods.

The Canadian Nutrient File (CNF), created by Health Canada, is the standard reference food composition database outlining the amount of nutrients in foods commonly consumed in Canada. It is a comprehensive, computerized, bilingual database with information on up to 152 nutrients in over 5,690 foods[3]. The CNF was used to calculate wasted nutrient values in the avoidable waste observed in this study. During the audit process, many food items were labeled somewhat generically in order to facilitate sorting and characterization of food items (e.g., "bread"). When the word "bread" was entered in the online search criteria, 145 entries were retrieved and ranged in both form and nutritional value. In cases like this where the exact food item was unclear, we selected an entry that represented a mid-point with regard to nutritional quality. Versions of the composite meals observed in the audit were typically available in the CNF.

The selection of nutrients for the nutritional analysis was based on two criteria: nutrients that carry a daily value recommendation in Canada, and nutrients that are below recommended intake levels among Canadians. According to Health Canada, the prevalence of inadequate intakes among adults is highest for vitamin A, vitamin D, magnesium and calcium. Of additional concern are vitamin B12, fiber and vitamin C (37). Among Canadian children, fiber, calcium and vitamin D are also listed as nutrients of concern (38). Energy (kcal) was also included in this analysis. Health Canada suggests that on average, adults and youth (age 13 and older) require approximately 2,000 kcal per day and children (ages 4–12) need 1,500 kcal per day (39).

Daily values for the selected nutrients are publicly available and can be observed in the nutrition facts table required by law on most packaged foods in Canada. Current daily values in Canada are based on the recommended daily intake for vitamins and minerals as well as reference standards for various nutrients. Daily value suggestions have been calculated for infants (aged 6 months to 1 year), children (aged 1 to 4 years) and adults (any other case) (40).

Once the unique code numbers for all 316 food products were recorded, data from the CNF was used to generate nutrient profiles for every food item. The total lost nutritional value for each of the study households was calculated by multiplying the total weight of each item wasted by the amount of each nutrient listed for that food [i.e., Nutrient Loss = Food Waste Amount (grams) × Nutrition Concentration (nutrient amount/gram of edible food)].

There are several different assessments that could have been used to determine the environmental impacts of avoidable food waste. Based on the availability of data and an evaluation of measures used in common environmental discourse, three areas of environmental impact were prioritized. These areas were carbon dioxide (CO_2) produced (i.e., global warming potential), land usage, and water usage. Global warming potential (GWP) is frequently used in the life-cycle-assessment (LCA) literature as a means of measuring the relative environmental impact of food production and waste. This is done by estimating how much CO_2 is produced to not only grow, but also distribute agri-food products along their value-chain. Because LCA studies rely on very particular data for specific agri-food products, they are typically only concerned with a few commodities or classes of commodities. These estimates tend to be very region-specific. Furthermore, LCA studies face a "boundary problem" whereby the value-chain beginning and end for commodities is unclear. For example, there is inconsistency in determining the end of the environmental impact of a processed agri-food commodity depending on whether the LCA finishes once the product reaches the processor, retailer, or end-user.

Meta-analysis papers in the LCA literature are useful in this regard because they can combine and assess these varied studies to generate average estimates of environmental impacts for different food products. An LCA meta-analysis study conducted by Clune et al. (41) contains GWP estimations for over 150 food categories. This paper outlines estimations of the kg of CO_2 produced per kg of edible food product. The authors convert the various boundaries of the LCA studies to a common benchmark of "farm to regional distribution center" (41). Two tables from this study are especially useful. Table 4 contains GWP statistics for animal products, proteins, and aggregate produce categories, while Table 5 contains GWP statistics for many specific food items. The total 316 avoidable food items in our audit data were matched with the most appropriate food item or food category in Tables 4 and 5 from Clune et al. (41). This matching provided each avoidable food waste item with a GWP figure and thus an estimate of CO_2 produced per kg of food. While the tables in Clune et al. (41) include both mean and median GWP values, we only imported the median values to limit the impact of outliers.

Along with GWP, land usage is also commonly evaluated in LCA studies. While CO_2 dispersion is esoteric and may be difficult for individuals to visualize, the amount of land used to produce food may be more concrete and relatable. Land usage is related to agricultural production yield, and the Food and Agricultural Organization (FAO) of the United Nations has data resources on yield figures for a wide variety of commodities around the world (6). Using data on crop yield from 1998 to 2018 in the FAOSTAT database, we generated the land in m^2 necessary to produce a kg of over 150 food products. In the same manner as the GWP figures, the 316 avoidable food waste items were matched with the most appropriate food product from the FAOSTAT data which linked a land usage value to the unique food waste items in this study. The FAOSTAT yield data is mainly restricted to crops while data relating to animal products are mostly expressed in terms of total production per capita within a region. Thus, the remaining food waste items without land usage values were almost exclusively animal products. To fill in these gaps, we turned to another LCA meta-analysis study. Using the midrange values from Table 3 in Nijdam et al. (42), we estimated the land usage of the remaining protein-rich food items found in our audits.

[2]https://hannaone.com/category/food-infohistory/weight-equivalents.
[3]https://food-nutrition.canada.ca/cnf-fce/index-eng.jsp.

Water usage is another common way of evaluating the environmental impact of different agri-food practices. The Water Footprint Network is an international group of academics and professionals which measures and tracks water usage statistics for many agri-food products and practices. They have created water usage databases for crops (43) and animal products (44) that are accessible for use and interpretation. Using these two databases, the m^3 of water necessary to produce one kilogram of various food products was calculated. The avoidable food waste items from the audit data were linked with the water usage databases.

RESULTS

The average amount of total food wasted per household was 4.41 kg per week. This represents an average annual generation of 229.32 kg of total food waste per household. However, our focus in this analysis was on the avoidable and possibly avoidable quantities as this is the edible portion of the organic stream. The average avoidable food waste across the sample was 2.98 kg per week, which is consistent with our previous work in Guelph. The sample mean weights for the total basket and each category are shown in **Table 1**. The mean weights for the first and fourth quartiles of households are also reported. Fruits and vegetables made up approximately two thirds of the avoidable weight. Breads and cereals also made up a large portion (24%) of the avoidable weight.

There was considerable variability between the waste generation rates of households. **Figure 1** shows a histogram of weekly avoidable household food waste. The mean for the entire sample was 2.98 kg but the median was 2.53 kg. There were a small number of high waste households that increased the sample averages. There was also considerable variation within households from week to week.

The distribution of waste by categories across the four quartiles and on average is shown in **Figure 2**. While there was considerable variation from house to house and significant differences in total waste generation, the average composition of the organic waste stream did not change much as volume grew. Some households clearly disposed of more edible food, but the increase was consistent across all the food categories rather than being driven by a specific category.

There was a relationship between the variety of food items discarded and the total weight of avoidable food waste (**Figure 3**). Our analysis yielded a Spearman correlation coefficient of 0.76 ($p < 0.01$) indicating that variety of food items discarded and food waste generation increase together, but there remains some unexplained variation. This concept merits future research.

The 25 items that represented the largest share of the avoidable food waste weight are presented in **Table 2**. These products represented almost 60% of the total weight of avoidable food waste generated by the sample. While there was a total of 316 edible food items in the total sample, after the top 25, no single item represented more than 1% of the total weight of the whole sample. However, it is critical to include the entire sample when calculating costs, lost nutrition and environmental impact, as the full-basket analysis generated substantially different results than an analysis of the top 25 items alone.

ECONOMIC ANALYSIS

The total average household value of avoidable food waste was $18.01 per week (**Table 3**), or $936.52 per year. The median cost of avoidable food waste per household was $16.60 per week. The first quartile of households had an average cost of $6.47 per week while the fourth quartile had an average cost of $31.35 per week.

Fruits and vegetables represented a lower proportion of total cost than they did of total weight, although they still represented more than 50% of the total cost of avoidable food waste. Meat and fish represented a small proportion of the total weight (6%) but a much larger proportion of total cost (13%). One would expect that more expensive items would be managed with more care and be wasted less, which appears to be the case in our sample.

There was a strong linear relationship between volume of waste and total value of waste (Spearman correlation coefficient of 0.92; $p < 0.01$). Eighty-four percent of the variation in value was explained by total weight of wasted food, and total cost increased by approximately $5.70 per kilogram of avoidable food waste. There were a small number of high volume and value households that drove up the average weekly cost of wasted food (**Figure 4**).

NUTRITIONAL ANALYSIS

The average household wasted 3,366 kcal per week (**Table 4**) or the equivalent of 175,032 kcal annually. This quantity of weekly food waste weight represents the suggested recommended daily caloric intake for 1.7 adults or 2.2 children. In other words, the average household could have provisioned an additional

TABLE 1 | Composition of avoidable food waste.

	Total items	Mean weight (grams)	Percent of total	1st quartile weight (grams)	4th quartile weight (grams)
Full basket	316	2,978	100%	1,027	5,493
Fruits and vegetables	133	1,951	65.5%	693	3,671
Meat and fish	43	178	6.0%	66	322
Bread and cereals	74	722	24.2%	200	1,306
Dairy and eggs	17	63	2.1%	33	89
Fats and sugars	18	16	0.5%	4	23
Other	31	48	1.6%	31	83

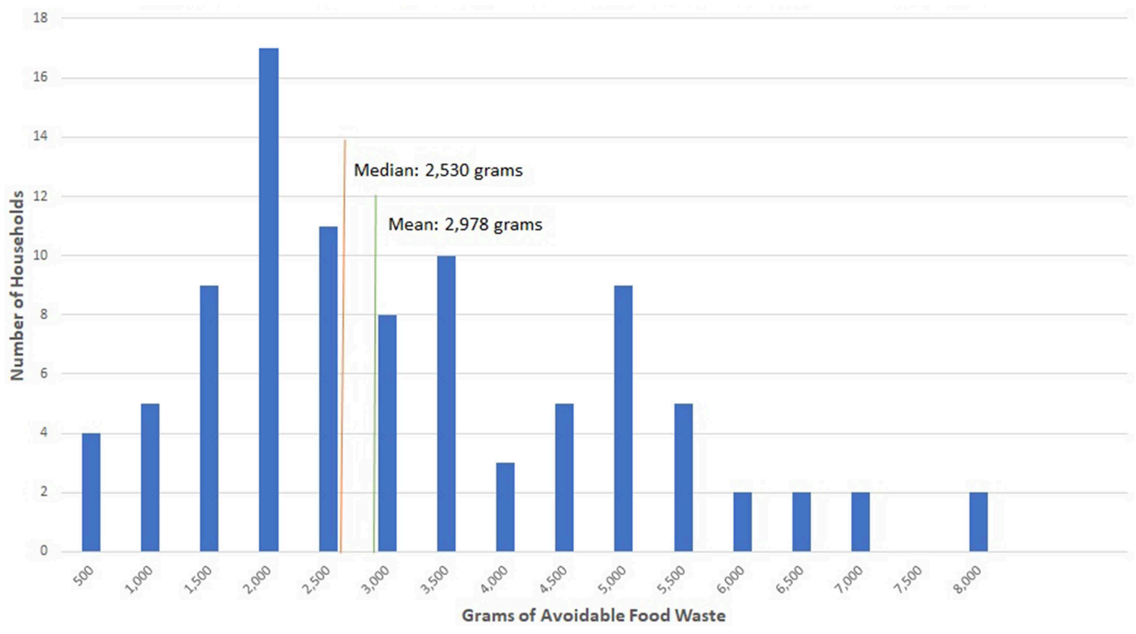

FIGURE 1 | Household frequency of weekly avoidable food waste weight.

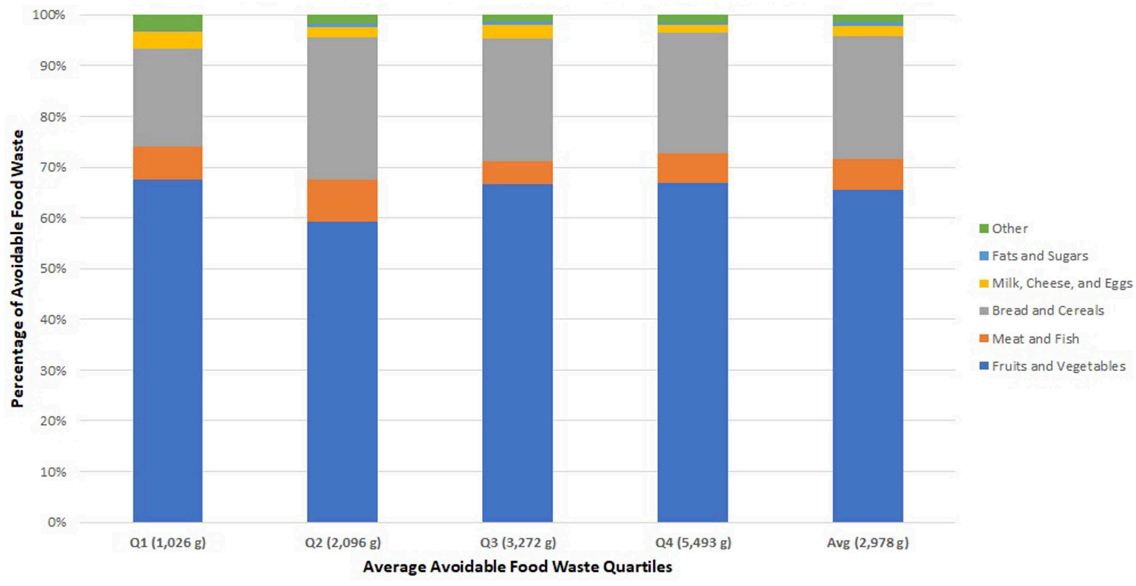

FIGURE 2 | Comparison of avoidable food waste composition between quartiles.

five adult meals or almost seven child meals per week based on the edible items they wasted. Annual avoidable food waste represents the suggested daily caloric intake for an adult for 88 days of the year, and for a child for 117 days. Calories appear to be relatively normally distributed with a slightly long tail to the right (**Figure 5**). We see a strong relationship between weight of avoidable food waste and calories. In this case, we observed a Spearman correlation coefficient of 0.87 ($p < 0.01$). The calories became more variable as weight increased and this likely reflects specific products that are consumed in these high waste households.

When assessing the nutritional value of wasted food, it is important to look beyond calories to consider a range of nutrients required to support overall health. A focus on food quality rather than food quantity is critical. In this study, fruits and vegetables contributed 66% of total avoidable food waste. The nutrients derived from fruits and vegetables (e.g., fiber and Vitamin C) were higher relative to the other nutrients, as one would expect,

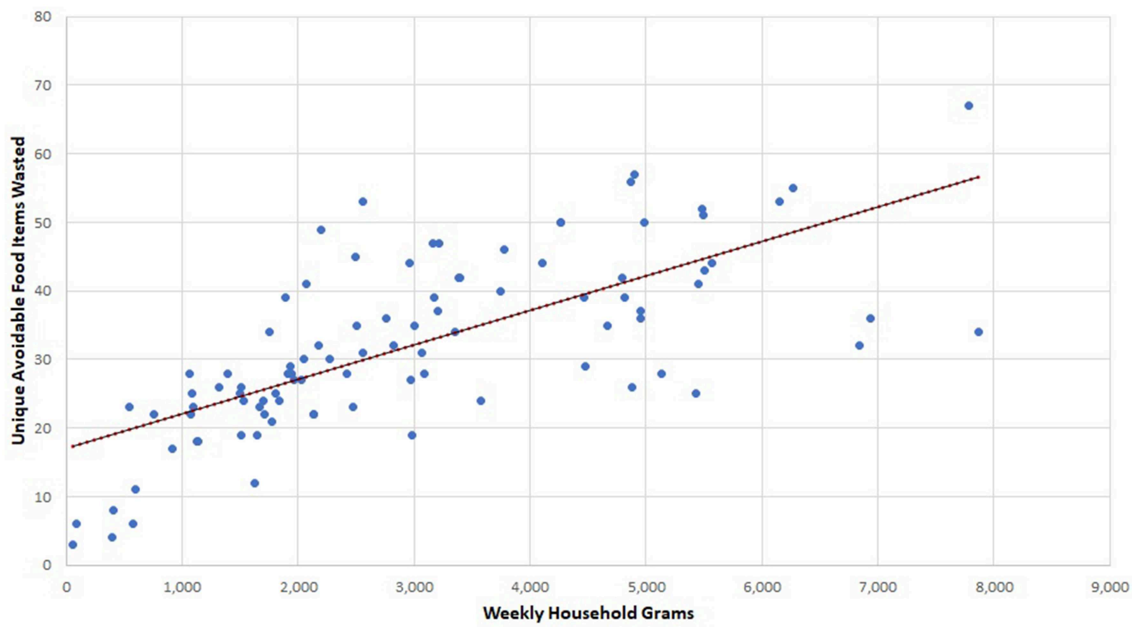

FIGURE 3 | Avoidable food waste variety and avoidable food waste weight.

but vitamin D (derived from meat and fish) was also important. For a full breakdown of nutrient loss by food group, please refer to **Figure 6**. In this sample, wasted fruits and vegetables contributed 62% of wasted fiber, 48% of wasted magnesium, 85% of wasted vitamin A and 96% of wasted vitamin C.

The distributions of wasted nutrients expressed as daily adult serving requirements differ by nutrient and are presented in **Figure 7**. Based on this figure, we determined that the majority of households included in this study are wasting at least one daily adult serving of most nutrients analyzed.

ENVIRONMENTAL ANALYSIS

Global Warming Potential

The global warming potential (GWP) associated with avoidable household food waste calculated in this study was 23.3 kg CO_2 per household per week, and the median value was 16.9 kg (**Table 5**). This equates to 1.2 tons of carbon dioxide from avoidable food waste per household per year, which is equivalent to one quarter of the emissions from a car being driven for a year, or 2.8 barrels of oil consumed based on a US Environmental Protection Agency calculator (45). The distribution of GWP (along with land and water use) per household per week is shown in **Figure 8**. Fruits and vegetables represented 66% of the total weight of the avoidable food waste and almost 40% of the CO_2 generated by the total avoidable food waste. The meat and fish and milk, cheese, and egg categories represented a larger share of the CO_2 generation than they represented of the total weight.

Land Usage

Avoidable household food waste was estimated to be equivalent to 6.7 m^2 of land per household per week. The median value was 5.6 m^2. On an annual basis, the land used to produce avoidable food waste equated to 348.0 m^2 per household per year. Once again, avoidable waste from fruits and vegetables represented the largest share of land use but was a lower proportion of land use relative to the proportion of total avoidable food waste weight. Avoidable waste from breads and cereals represented a larger share of land use than of weight. Meat and fish also represented a substantial proportion of the land used to produce avoidable food waste.

Water Usage

Water usage associated with avoidable household food waste was calculated to be 5.0 m^3 per household per week (the median value is 4.6 m^3), or the equivalent of 260.0 m^3 annually. This means that the avoidable food waste generated by a household represented 5,000 liters of water use weekly and 260,000 liters annually. The average 5-min shower uses 35 liters of water, which equates to 7,429 showers per year (46). Fruits and vegetables, meat and fish, and milk, cheese and eggs all contributed substantially to the water used to produce avoidable food waste.

DISCUSSION

Overview

Overall, the sample of households that we audited in this study generated similar amounts of food waste to a more extensive sample in the same locale, discussed in Parizeau et al. (14), and similar food group proportions were observed in a randomly-selected sample from Guelph (unpublished data). The per capita total food waste generation rate in our sample of 1.1 kg per week, or 57.2 kg per year, is lower than the 85 kg per year estimate of per capita total residential food waste generated by the Commission for Environmental Cooperation (12). However,

TABLE 2 | Top 25 avoidable food waste items.

Food item	Mean weight (grams)	Percentage of avoidable waste	Cumulative percentage
Bread	268	9.0%	9.0%
Tomato	175	5.9%	14.9%
Apple	113	3.8%	18.7%
Watermelon	101	3.4%	22.1%
Potato	93	3.1%	25.2%
Pasta	78	2.6%	27.8%
Peach	72	2.4%	30.2%
Rice	70	2.4%	32.5%
Lettuce	66	2.2%	34.8%
Lemon	63	2.1%	36.9%
Pepper (incl. pepper top)	65	2.2%	39.1%
Chicken	60	2.0%	41.1%
Grapes	59	2.0%	43.1%
Cucumber	52	1.7%	44.8%
Broccoli stalks	51	1.7%	46.5%
Potato peels	46	1.6%	48.1%
Onion	45	1.5%	49.6%
Cabbage	44	1.5%	51.1%
Carrot	43	1.4%	52.5%
Banana	41	1.4%	53.9%
Celery	34	1.1%	55.0%
Broccoli	33	1.1%	56.1%
Tomato sauce	32	1.1%	57.2%
Carrot peels	31	1.0%	58.2%
Pear	31	1.0%	59.3%

the CEC estimate is not based on actual audit measurement of household food waste. Despite the difference in values, per capita waste generation remains unacceptably high.

Our analysis has demonstrated that avoidable household food waste can be understood from multiple perspectives, and that diverse framings highlight different aspects of the food waste problem. A summary of the results from our analysis can be found in **Table 6**. We posit that these diverse framings can support the creation of evidence-based story-lines that foreground the issue of food waste in Canada. We now turn to a discussion of the potential discursive implications of our analysis.

A focus on the total weight of avoidable food waste in each household highlights that there is a relatively small group of households that waste very high amounts of food. It may be worth targeting this sub-group with interventions in order to address the hotspots of avoidable food waste in the residential sector. For example, messaging that focuses on the upper range (i.e., Q4 means or upper-end values) of health, economic, and environmental impacts may be more effective in convincing high-wasting households to change their waste-related behaviors, rather than exclusively focusing the overall mean impacts in these realms. In this case, the economic impacts could be framed as follows: "The average household wastes $936.52 buying food they do not eat each year, but some households lose over $1,600 annually through avoidable food waste." The variability of food wasting habits across our sample also suggests that there are varying levels of food skills in these households that may be associated with food waste generation [e.g., meal planning, shopping, preparing and storing food: (14, 47–51)]. Targeted interventions focused on improving these food-based skills could help to change these behaviors among high-wasting households.

Looking at household food waste through the lens of a composition audit reveals that the proportions of wasted food across food groups are fairly consistent from low- to high-wasting households. Fruits and vegetables make up most of the avoidable food waste generated by all households, followed by bread and cereals, and then meat and fish. Other categories were much smaller in comparison. The prevalence of wasted fruits and vegetables is concerning from a nutritional perspective, as produce is a common source of key nutrients. This finding suggests that wasted food is a health policy issue: households are routinely purchasing large amounts of nutritious produce that they are not consuming. The very high rates of avoidable fruit and vegetable waste also have environmental and economic implications, as noted in **Table 6**. The prevalence of fruits and vegetables in the waste stream suggests that targeting these food groups may be a high policy priority to reduce total food waste volumes. We note that Cooper et al. (16) conducted a similar analysis using UK food waste data. Although the food waste categories differ between our two studies, Cooper et al. (16) found fruits and vegetables to be a smaller proportion of total edible food waste than was found in this study. The food categories fresh vegetables and salad, fresh fruit, and processed vegetables and salad contributed a total of 34% of total edible food waste (16), compared to our 66%. Differences in data collection methods, food preferences, shopping habits and definitions of edibility may account for these different results.

The significant relationships between the amount of avoidable food waste produced in a household and both total spending on food and number of items found in the waste stream indicates that over-purchasing is a major driver of avoidable food waste. People who bought high volumes of food or who bought a high diversity of items generated more wasted food. This may be the result of various household shopping and cooking practices, such as experimentation or impulse buying at the store. It might also suggest that more diversity in the diet creates a greater volume of waste. This finding speaks to the importance of influencing individual shopping behaviors in order to reduce food waste, but also in addressing the factors that encourage consumers to buy more in the first place, including retail strategies and broader cultural norms that support over-consumption.

We have framed our results as a list of most wasted items in order to make the sometimes nebulous issue of food waste seem more tangible. The list includes very common items in Canadian grocery baskets, enabling individuals to better imagine their own purchasing, consumption, and wasting behaviors around these specific items. The list also points to implications for retailers who make decisions about promotions, discounts, packaging, and in-store reprocessing of commonly wasted foods, which may impact consumer choices and behaviors (52–54). The list format allows for discursive framings centered on

TABLE 3 | Economic value of avoidable food waste.

	Mean weight (grams)	Cost (CAD)	Percent of total	1st quartile dollars (CAD)	4th quartile dollars (CAD)
Full basket	2,978	$18.01	100.0%	$6.47	$31.35
Fruits and vegetables	1,951	$9.36	52.0%	$3.34	$17.06
Meat and fish	178	$2.29	12.7%	$0.84	$4.37
Bread and cereals	722	$4.52	25.1%	$1.30	$7.39
Dairy and eggs	63	$0.71	3.9%	$0.43	$0.88
Fats and sugars	16	$0.12	0.7%	$0.08	$0.15
Other	48	$1.01	5.6%	$0.49	$1.51

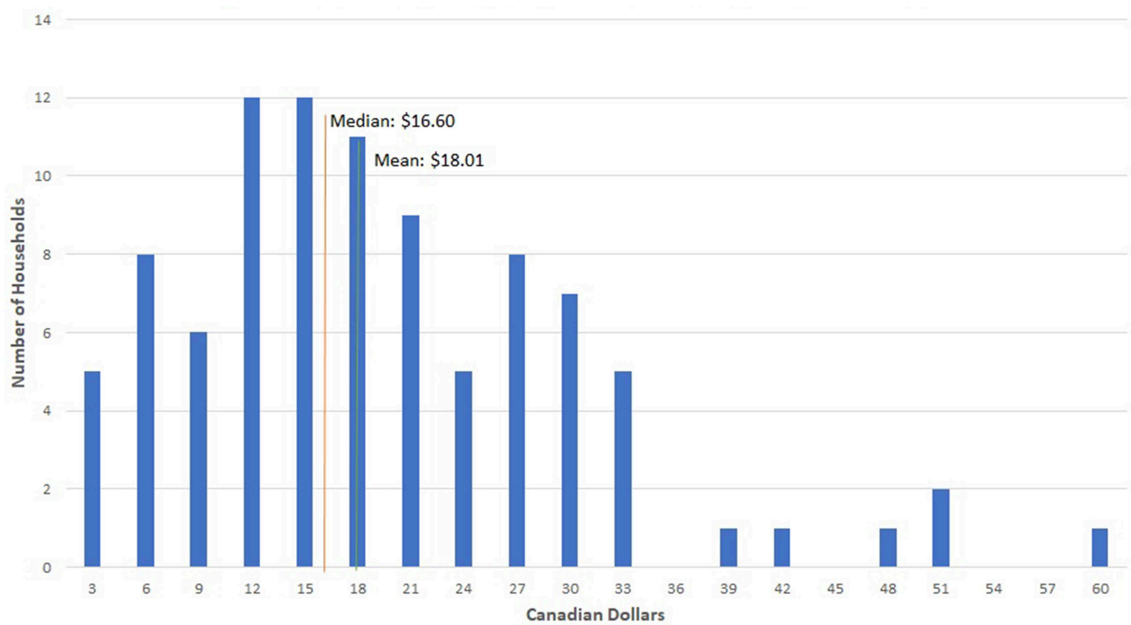

FIGURE 4 | Household frequency of avoidable food waste cost.

high-volume wasted items, while the economic, health and environmental analyses allow for framings focused on high-impact wasted foods.

Economic Analysis

The economic analysis indicates that households spent an average of $936.52 per year on avoidable food waste. This is the equivalent of 16% of the average Canadian household expenditures on food bought from stores in 2017 [$5,934; (55)]. Meat and fish are relatively expensive foodstuffs, and so had a disproportionate impact on the cost of wasted food. As expected, households wasted a small overall amount of these high value proteins, but it is clear that interventions to reduce protein waste would have an important economic benefit for households.

Our analysis suggests that the study households wasted $18.01 per week on avoidable food waste. Another commonly cited value for food waste in Canada is $28 per week, but this estimate was not based on audits and likely included the value of unavoidable waste (56). In fact, $18.01 scaled to represent the total weight of both avoidable and unavoidable food waste would create a value of $27.29 per week. The National Zero Waste Council undertook efforts to quantify waste in Metro Vancouver to support their Love Food Hate Waste campaign. They estimated that an average household wastes more than $1,100 in edible food per year. This equates to $21.12 per week. The difference in value is likely attributable to food cost differences between Vancouver and Guelph.

Nutritional Analysis

From a health perspective, our analysis shows that households have access to a breadth of nutrients that they are not consuming, including fiber, vitamins, and minerals. This is an especially concerning finding given the rates of inadequate intake in typical Canadian diets of fiber and many vitamins and minerals including vitamin B12, vitamin A, vitamin D, vitamin C, calcium, and magnesium. Furthermore, the prevalence of inadequate intake of calcium is a particular concern for older adults (37), which is noteworthy given Canada's aging

TABLE 4 | Dietary composition of avoidable food waste.

	Total	Daily servings adult	Daily servings child	1st quartile total	4th quartile total
Energy (kcal)	3,366	1.7	2.2	1,191	5,993
Fiber (g)	64	2.3	4.6	21	115
Vitamin D (mcg)	50	2.5	3.3	12	113
Vitamin B12 (mcg)	2	1.0	2.8	1	5
Vitamin C (mg)	434	4.8	28.9	155	749
Vitamin A (mcg)	1,729	1.9	5.8	596	3,312
Calcium (mg)	1,192	0.9	1.7	403	2,061
Magnesium (mg)	675	1.6	8.4	218	1,190

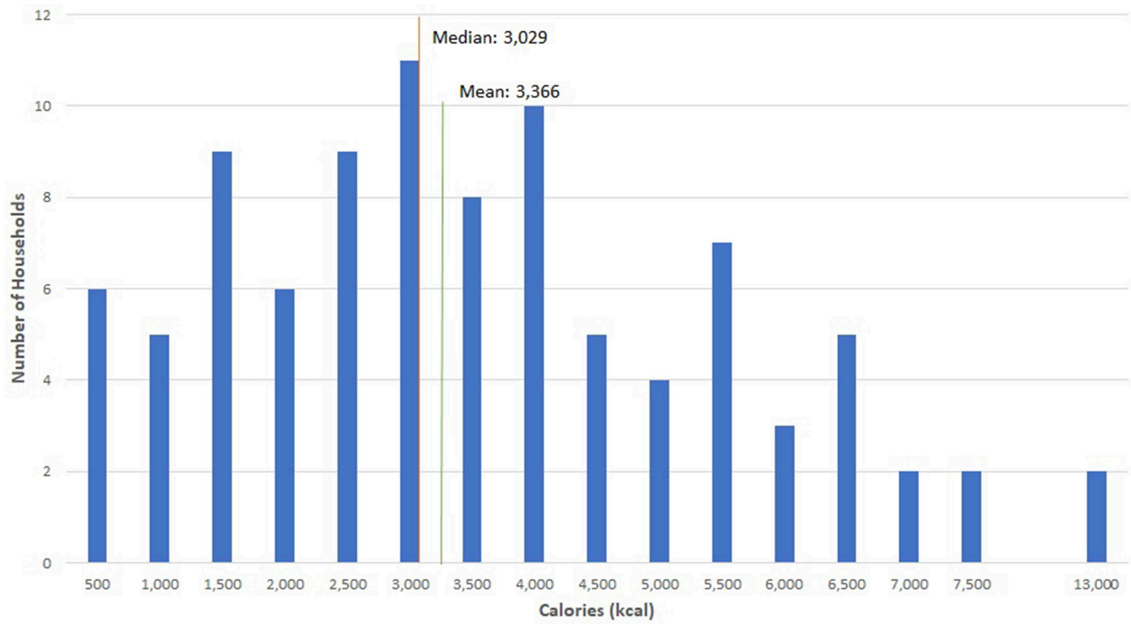

FIGURE 5 | Household frequency of avoidable food waste calories.

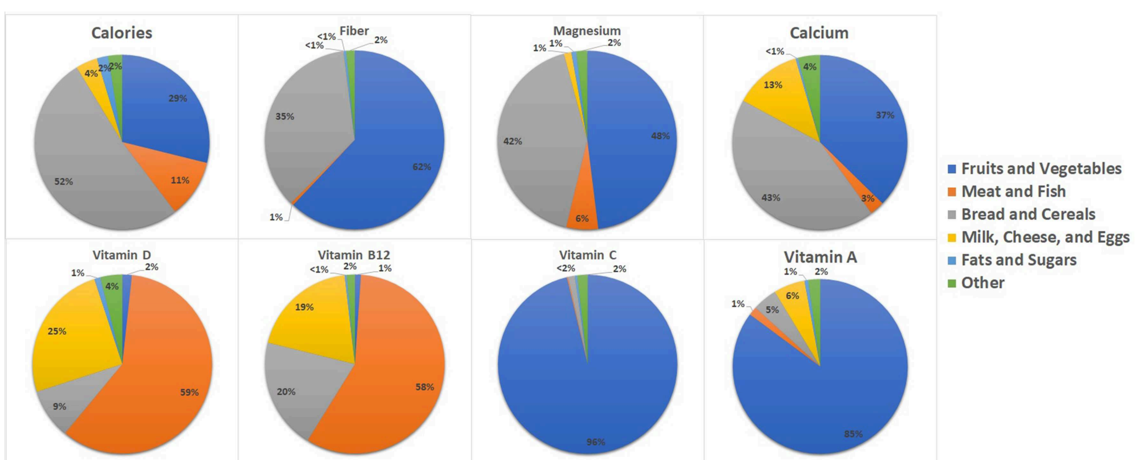

FIGURE 6 | Breakdown of nutrient loss from avoidable food waste by food group.

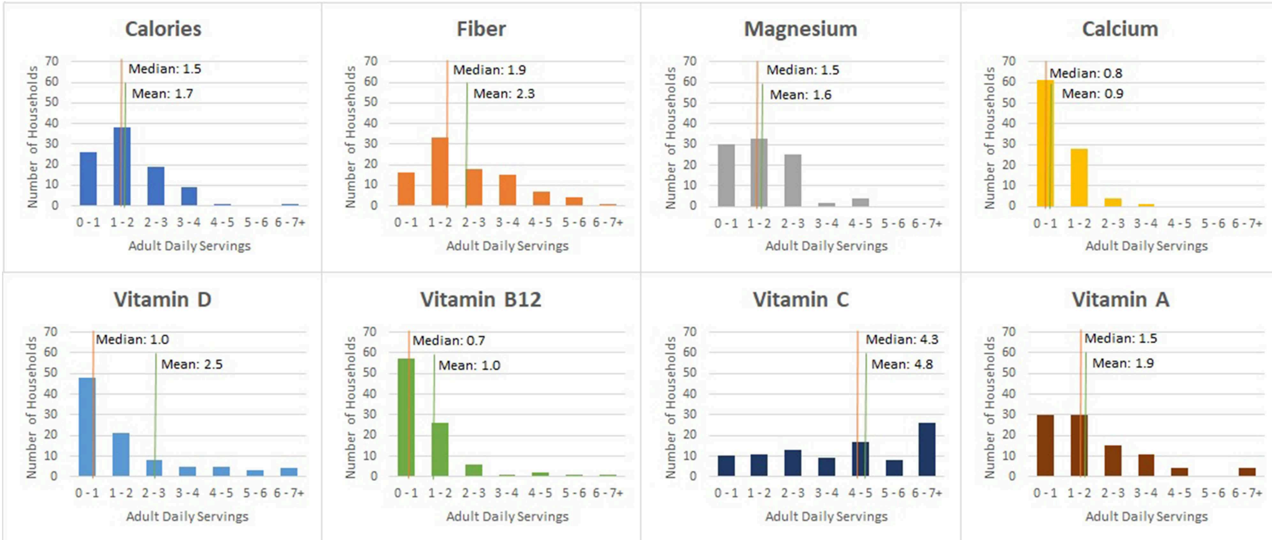

FIGURE 7 | Household frequency of nutrient servings in weekly avoidable food waste.

TABLE 5 | Environmental impacts of avoidable food waste.

	GWP (kg CO_2)	Land (m^2)	Water (m^3)	GWP %	Land %	Water %
Full basket	23.3	6.7	5.0	100.0%	100.0%	100.0%
Fruits and vegetables	9.2	2.0	1.9	39.3%	29.1%	38.0%
Meat and fish	7.8	1.8	1.2	33.6%	26.8%	24.6%
Bread and cereals	3.9	2.4	1.4	16.7%	35.6%	28.1%
Milk, cheese, and eggs	1.7	0.3	0.2	7.1%	4.8%	3.7%
Fats and sugars	0.4	0.1	0.1	1.7%	1.2%	1.5%
Other	0.4	0.2	0.2	1.6%	2.5%	4.1%

population and the importance of both calcium and vitamin D in supporting healthy bone growth and maintenance (57). The high amounts of wasted fruits and vegetables represent the loss of calories, fiber, vitamins and minerals. Bread and cereal wastes also represent lost calories, fiber, and vitamins, and minerals. Meat, fish, dairy, and egg wastes represent lost calories, vitamins and minerals. The framing of food waste as a potential health risk may be a compelling one for individuals and policy-makers.

Cooper et al. (16) also considered nutrients for which adequate intake was a concern among the UK population. Similar to our results, Cooper et al. (16) found fresh vegetables and salad to be the largest contributor by food group to wasted fiber. Dairy and eggs and bakery were found to each contribute 27% of wasted calcium. Our findings reveal that 43% of lost calcium was from breads and cereals and 13% was from milk, cheese and eggs.

Some might argue that given the current global obesity epidemic (58), throwing out calories may not necessarily be a bad thing. However, focusing on calories alone does not accurately represent nutrient losses. According to Spiker et al. (59), focusing only on the caloric value of food waste risks over representing the influence of calorie-dense foods that typically carry fewer health benefits. This may result in nutrients of concern being overlooked. For example, nutrient-dense but low-calorie foods such as fruits and vegetables are better examined based on their nutritional quality rather than their caloric density.

Focusing on these nutrients presents a promising opportunity to develop nutrition-based narratives that would be relevant to most households. When food waste is contextualized as wasted servings of nutrients of concern, value and utility can be re-allocated to the wasted food. Had individuals consumed the foods in which these nutrients are commonly found, there would have been potential health benefits to be gained.

Similar to work conducted by Cooper et al. (16), our results support a mutual benefit to initiatives seeking to increase consumption (and therefore decrease waste) of fruits and vegetables. This is further supported by a study conducted by Black and Billette (60) suggesting that the majority of Canadians failed to meet Health Canada's 2007 recommendations for fruit and vegetable intake. Results presented in this study also support previous findings identifying wasted food as having a high influence on the availability of important micronutrients (59). If families can successfully lower their food waste generation by eating the fruits and vegetables they procure, they may also improve the quality of their diets.

It is worth noting that the nutritional numbers presented here are considerably lower than those reported in Conrad et al. (61). In that paper, authors estimated that the average American consumer wasted approximately 5,600 kcal per week, as compared to a weekly family waste generation of 3,366 kcal found in this study. However, Conrad et al. (61) did not measure food waste but estimated it based on aggregate USDA data. They found that fruits and vegetables were a much lower proportion

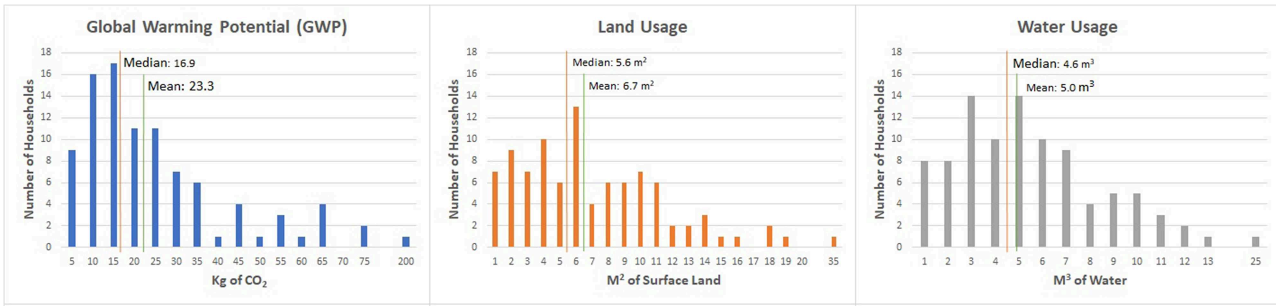

FIGURE 8 | Household frequency of environmental impacts from weekly avoidable food waste.

of total waste than was the case in our data and that 422 grams of avoidable food waste was generated per day. This disconnect in results highlights the value of direct measurement of granular data to quantify both the volume and composition of household food waste. Conrad et al. (61) also suggest that healthier diets, as measured by the Healthy Eating Index, create more waste. This is based on estimates of the proportion of each food type wasted rather than on direct measurements of households with healthier diets. This hypothesis merits investigation at the household level as those who eat healthier diets may have a different propensity to waste. For example, Parizeau et al. (14) found that households with greater "food awareness" generated less organic waste.

Environmental Analysis

Consumers tend to see food waste as an economic or social issue, more than an environmental issue (14, 47, 62–64). Given increased public attention to environmental issues of climate change, water, and agricultural land use in Canada, providing data to effectively communicate the environmental impacts of food waste may help to better frame this issue as a sustainability challenge in addition to a pocket-book issue. Our analysis reveals that avoidable household food waste is a substantial contributor to global heating, inefficient agricultural land use, and water loss. Cooper et al. (16) attribute 6.1 kg of CO_2 from avoidable food waste per capita weekly in the United Kingdom. The average household in our sample had four occupants which means that our results from Canada (5.82 kg CO_2 per capita per week) are consistent with those from the UK. The avoidable food waste water use estimates from our sample are lower than those from Cooper et al. (16), who suggest that avoidable food waste used 6.3 cubic meters per person per week. Our estimate is approximately one-quarter of that estimate.

Methodological Strengths and Limitations

Methodologically, our study contributes a highly granular analysis of household food waste composition to the field of waste studies. We are unaware of any other published studies that have used this methodology with Canadian data, or that base their estimates of food waste impacts on direct observation of individual items in the residential waste stream. Our research also problematizes dietary research that relies on purchase records and self-reported consumption logs, but that does not assess the proportion of nutritious food that ends up in waste streams.

We note that there are limitations to this study design. A perennial methodological difficulty when studying household waste is the high variability both within and between households. The voluntary nature of participation in this study may have led to some self-selection bias. It is possible that only families with a pre-existing interest in and understanding of food chose to participate. Additionally, this study was time-intensive, requiring families to collect all grocery receipts, keep a 3-day food diary and withhold their waste for collection by the study team. These requirements may have served as a disincentive for families who were less organized, possibly correlating with poor food planning skills and higher food waste generation. Furthermore, participants were aware that their waste was being audited. Although this can result in some change in waste behaviors, it would have been difficult for families to hold back or attempt to hide their food waste in other waste streams as we collected all streams of waste in this study for an extended period of time. Furthermore, the City of Guelph is active in providing educational content on waste management topics through their website, the distribution of informational material to households, and participation in community events. As a result, community members may have a greater baseline understanding of food waste reduction strategies than people living in other communities. Another limitation is based in our relatively small sample size of 94 households. This is not representative of the socio-demographic diversity of the study city as a whole. Rather, this study focused on families with young children who had the time and interest in committing to this study.

CONCLUSION

Our analysis is not only oriented to convincing householders and consumers that they need to change their perceptions and behaviors around food waste. Food waste is a systemic issue, and these framings are also meant to encourage systems-level interventions, including policy, regulations, infrastructure

TABLE 6 | Summary of economic, nutritional and environmental impacts of avoidable household food waste.

	Weight of edible food waste	Economic	Environmental			Nutritional							
		Cost	**GWP**	**Land**	**Water**	**Calories**	**Fiber**	**Magnesium**	**Calcium**	**Vitamin D**	**Vitamin B12**	**Vitamin C**	**Vitamin A**
Fruits and vegetables	65.5%	52.0%	38.0%	29.1%	38.0%	28.9%	62.0%	48.0%	37.4%	1.7%	1.1%	96.3%	85.2%
Meat and fish	6.0%	12.7%	24.6%	26.8%	24.6%	10.8%	0.5%	5.8%	2.7%	59.3%	57.7%	0.2%	1.6%
Bread and cereals	24.2%	25.1%	28.1%	35.6%	28.1%	51.6%	35.4%	42.0%	42.9%	9.0%	20.0%	1.2%	4.6%
Milk, cheese, and eggs	2.1%	3.9%	3.7%	4.8%	3.7%	4.0%	0.1%	1.3%	12.6%	24.9%	19.3%	0.0%	5.8%
Fats and sugars	0.5%	0.7%	1.5%	1.2%	1.5%	2.1%	0.5%	0.9%	0.4%	1.1%	0.4%	0.4%	0.7%
Other	1.6%	5.6%	4.1%	2.5%	4.1%	2.6%	1.5%	2.0%	4.1%	4.0%	1.5%	1.9%	2.2%
Total	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%

development, corporate practice, and culture change more broadly. Given the recent policy attention to food waste at different scales of government in Canada, it is clear that this issue will soon reach a stage of discursive institutionalization. However, there are still diverse and non-coherent discourses at play, and none have become hegemonic at this stage. We are not advocating for any one framing as the ideal discursive framing for food waste, but rather we encourage advocates, practitioners, and policy-makers to develop evidence-based communications and interventions. It is likely that multiple synergistic messages can support one another and allow for discursive framings that are diverse and tailorable for different audiences.

We acknowledge that this snapshot of the waste of families with children in Guelph is likely not generalizable to other contexts, although we encourage other researchers to conduct similarly specific and extensive observations so that we can collectively generate high quality information about the state of household food waste.

DATA AVAILABILITY

The datasets for this manuscript are not publicly available because of restrictions related to our Research Ethics Board requirements. Requests to access the datasets should be directed to MM, mvonmass@uoguelph.ca

AUTHOR CONTRIBUTIONS

MM and KP contributed to the conception and design of the composition audit. JH, AD, and DM designed the Family Food Skills Study. AW, NC, and MW organized the database used for this study. MW conducted data analysis. MM, KP, and MG interpreted the analyses. MM and KP wrote the first draft of the manuscript. MG and JH wrote sections of the manuscript. All authors contributed to manuscript revision, read, and approved the submitted version.

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Food Chain Inefficiency (FCI): Accounting Conversion Efficiencies Across Entire Food Supply Chains to Re-define Food Loss and Waste

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Achieving global food security requires a new approach that integrates not only all aspects of the growing, harvesting and processing of food (necessary to ensure sufficient affordable and sustainable production to alleviate hunger) but also the complexities associated with food consumption including deterring unhealthy overconsumption. Inefficiencies occur at various points along the agri-food supply chain but at present they are inadequately conceptualized via separate accounts of food loss, food waste, supply chain management, and public health. Here we re-define food loss and waste through the concept of conversion efficiency applied to the entire system, an approach up to now only applied to the primary processes of crop productivity. Nine conversion efficiencies are defined: sunlight capture efficiency; photosynthesis use efficiency; biomass allocation efficiency; harvesting efficiency; storage and distribution efficiency; processing efficiency; retailing efficiency; consumption efficiency; and dietary efficiency. Using the production and consumption of bread in the UK as an example, we demonstrate how efficiencies may be estimated and thus where the main inefficiencies lie, so indicating where the most significant improvements could be made. We suggest that our approach, which introduces the term Food Chain Inefficiency (FCI) to re-define food loss and waste, provides a rational and effective way to devise the practical interventions and policies needed to deliver a sustainable agri-food system.

Keywords: food supply chain, food security, food loss and waste, food consumption, agrifood systems, agriculture

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INTRODUCTION

Providing food security for the growing human population without widespread environmental degradation is one of the biggest challenges of the twenty-first century (Godfray et al., 2010), one which underpins many of the United Nations Sustainable Development Goals (Rockström and Sukhdev, 2016). The agri-food system is the largest single contributor of greenhouse gases, a significant source of pollution of land, water courses and oceans, and depletes non-renewable resources. It relies upon input of unsustainable amounts of agrochemicals, leading to a degradation of the soil upon which it depends (Horton, 2017). Its failures are the obesity epidemic from over consumption and the undernutrition of nearly 1 billion people. Food security is a complex or wicked problem, often considered intractable (DeFries and Nagendra, 2017). Progress will only be made if the many parts of the agri-food system are viewed as a whole (Horton et al., 2017), with integrated, joined up thinking across the issues of environment and biodiversity to all aspects of the growing, harvesting and processing of food, and the processes associated with food consumption including nutrition and health. Furthermore, scientific and technical knowledge has to be considered in a political, cultural, and economic context (Horton and Brown, 2018).

Reducing food loss and waste has been identified as an essential requirement in achieving global food security (Parfitt et al., 2010; Institution of Mechanical Engineers, 2013) and is also seen as a key objective of SDG 12, Responsible Consumption and Production (UNEP, 2015). Five key global drivers of food waste have been identified: lack of consumer awareness, poor infrastructure, inefficiency, lack of collaboration, and a poor policy environment (BCG, 2018). The issue of food waste has assumed great significance in many parts of the world, although the bulk of these actions have focused on re-distribution of waste, often re-characterized as "surplus," rather than addressing these underlying drivers (WRAP, 2018a). For example, the French government introduced legislation requiring retailers to donate surplus food (Gore-Langton, 2017) and in Denmark, the Danmark Mod Madspild (Denmark Against Food Waste) cross-sector campaign was launched (Askew, 2018). In the UK, there are similar programmes led by a range of stakeholders, for example businesses donating surplus product to food banks (Cohen, 2016a). Major UK food retailers have also attempted to address the causes of food waste: re-branding sub-standard b-grade produce as "too good to waste" and retailing it directly; and removal of "best before dates" in an attempt to reduce losses through adherence to relatively arbitrary shelf-lives (Smithers, 2018). Similarly, local UK government and charities have worked together to encourage behavior change in the home (Restorick, 2018).

DEFINING PROCESS EFFICIENCIES IN THE AGRI-FOOD SYSTEM

One problem with such initiatives is that they often operate in isolation, divorced from the wider issues that link food production and consumption, and human health, fragmenting both agri-food research and agri-food policy. Indeed, how we separately define food loss and waste is evidence of the lack of joined up thinking: loss and waste are expressed in different ways with different meanings, and discussed by different sectors, leading to confusion about their relative importance and what should be done to reduce them. Food loss is often seen as something that is unavoidable, such as the effect of weather on a crop yield, whereas food waste is frequently viewed as resulting from a poor human practice that should be (easily) avoided. Furthermore, only rarely is the ill-health that results from overconsumption of food described in a "food waste" context.

The UK waste charity WRAP has developed a "waste roadmap" attempting to cover the entire "field to fork" value chain and has enlisted major manufacturers and retailers to work on a common set of metrics (WRAP, 2018b). Similarly, the Global Champions 12.3 group is a coalition of executives from governments, businesses, international organizations, research institutions, farmer groups, and civil society dedicated to inspiring ambition, mobilizing action, and accelerating progress toward reducing food waste (Hanson and Mitchell, 2017). Nevertheless, these approaches still fall short of considering the entirety of the agri-food system.

Food loss and waste are both indicators of the inefficiency of the process at which they occur, and therefore they should be viewed together in the wider context of all the factors that reduce the efficiency of the agri-food system; food loss and waste across an entire food supply chain could be defined as Food Chain Inefficiency (FCI). In agriculture, the productivity of crops has long been described in terms of radiation-use-efficiency (RUE), a term which relates the amount of biomass produced by a crop to the amount of intercepted solar radiation, and the Harvest Index (HI), which describes the proportion of biomass in the harvestable yield (Monteith, 1977; Mitchell et al., 1998; Mitchell and Sheehy, 2018). Linked to these terms are Yield Potential, the maximum productivity of a crop and the Yield Gap, which describes the difference between this and the actual recorded yield. These terms define the performance of a crop at the local and global level (Guilpart et al., 2017). Moreover, they define food loss in terms of conversion efficiencies. In this article, we propose an extension to this terminology to redefine food loss and waste in terms of FCI, which invokes a single accounting methodology to cover the entire food system, linking aspects of environment, plant physiology, agronomy, harvesting, processing, distribution, consumption, and nutrition. We define nine process conversion efficiencies (defined simply as output as a proportion of input) in the agri-food system, and we outline the range of factors which determine their value (**Table 1**). We then describe these process efficiencies in an illustrative FCI case study, the wheat-bread supply chain.

Sunlight Capture Efficiency (SCE)

Firstly we consider the efficiency with which sunlight falling on cultivated land areas is used. Sunlight Capture Efficiency (SCE) has the following components.

The Proportion of Sunlight Incident on Leaf Surface

This is determined by a range of agronomic and physiological factors: the density of planting, the rate at which the plant canopy develops, and how long it stays "green" as the product develops. A frequently used term is "canopy closure" to describe the point at which all sunlight is incident upon leaf surfaces (Duncan, 1971). Other factors include the three dimensional architecture, how many leaves are produced, the dynamics of the plant canopy, and the direction of sunlight. Canopies of rice for example have erect leaves which preferentially absorb sunlight at the beginning and end of the day (Murchie et al., 1999), whereas other crop species adjust leaf angle to either track or avoid direct sunlight (Denison et al., 2010).

TABLE 1 | The nine indicators of process conversion efficiency that contribute to Food Chain Inefficiency.

Indicator	Abbreviation	Sector	Contribution to FCI
Sunlight capture efficiency	SCE	Farm	Incident sunlight not absorbed by plant leaves
Photosynthesis use efficiency	PUE	Farm	Absorbed light not converted with maximum efficiency into biomass
Biomass allocation efficiency	BAE	Farm	Plant biomass not converted to harvestable product
Harvesting efficiency	HE	Farm	Harvestable product lost or remaining in field
Storage and distribution efficiency	SE	Transport/store	Food raw material lost during transport and storage
Processing efficiency	PE	Factory	Food raw material lost during processing
Retailing efficiency	RE	Shop/market/outlet	Food available greater than that acquired by the consumer
Consumption efficiency	CE	Consumer	Consumption less than that purchased
Dietary efficiency	DE	Consumer	Consumption in excess of that necessary for optimum nutrition

The Proportion of Incident Photons That Are Absorbed

Light can be reflected from the leaf surface, although this is not significant in most crops. In all crop species, chlorophylls a and b (and some carotenoid) absorb the sunlight capturing only a portion of the solar spectrum, Photosynthetically Active Radiation (PAR). PAR is ~50% of sunlight (Mitchell et al., 1998) and the extinction coefficient is determined by leaf structure and composition including the pigment content per chloroplast membrane area, the membrane area per chloroplast, the chloroplast number per leaf cell and the number of cells. All of these are determined genetically and acclimate to the environment. There are ambitions to manipulate the type and concentration of chlorophyll in the chloroplast to increase the efficiency of absorption or even extend PAR (Chen and Blankenship, 2011; Ort et al., 2011).

Photosynthesis Use Efficiency (PUE)

If all absorbed photons are used with maximum efficiency, the maximum amount of carbon fixed in photosynthesis is determined by the quantum yield. Although in theory it is possible to extract more photosynthesis per photon absorbed, in practice, quantum yield is best regarded as a constant, being highly conserved through evolution and unlikely to see improvement by plant breeding or genetic modification. Thus, we propose a move away from using RUE, a term that includes quantum yield and instead introduce the term PUE to describe the factors that cause the conversion of absorbed sunlight into biomass to be less that that theoretically expected from the quantum yield. These factors include responses to the external environment and internal physiological processes, both of which vary between species. A key benefit of using PUE is that it introduces those factors which could be manipulated in order to increase efficiency (Zhu et al., 2008; Murchie et al., 2009). These are numerous and include the following.

Photorespiration

Photorespiration, resulting from the binding of oxygen rather than CO_2 to the carbon fixation enzyme ribulose bisphosphate carboxylase oxygenase (Rubisco) is acknowledged to be a principal source of lost potential photosynthesis. International programmes of research are aimed at suppressing photorespiration (Zhu et al., 2008; Murchie et al., 2009), through alteration of the properties of Rubisco, modification of the photorespiratory pathway or by introducing CO_2 concentrating pathways.

Respiration

Not all photosynthetic product is converted to biomass, some being lost as respiration (Mitchell et al., 1998). Energy from respiration is needed to maintain plants during periods of darkness and to fuel growth, making plant structures, accumulate nutrients by roots and so on. Some pathways of wasteful respiration are a source of lost potential yield.

Rate of Photosynthesis

Photosynthesis has a finite capacity limited by the rates of the enzyme catalyzed reactions of carbon metabolism, and therefore the intensity of sunlight can be high enough to lead to light saturation, and consequent reduction in PUE (Horton and Murchie, 2000). This capacity is highly variable between species and is affected by the light intensity and spectral quality experienced during growth. The availability of nutrients from the soil is also a factor. The rate of photosynthesis at any time is also determined by ambient environmental conditions: drought and extremes of temperature may limit photosynthetic rate and cause yield loss. Specific enzymes have been identified as targets through which capacity could be increased (Driever et al., 2017). The light environment is rarely constant in nature (due to clouds, movement of leaves etc.), and therefore the efficiency with which light is used in photosynthesis is in part determined by the rate at which various internal regulatory mechanisms adjust to the change in light intensity and spectral quality (Kromdijk et al., 2016).

Biotic Factors

In addition to the effect of environmental conditions, plant pests and pathogens may considerably reduce the amount of crop biomass. Animals, insects, viruses, bacteria, and fungi either consume plant material directly, reducing the leaf area supporting photosynthetic activity, or siphon away metabolites to promote their growth at the expense of plant growth (e.g., Berger et al., 2007). Parasitic plants also take metabolites from their crop plant hosts, reducing that available for crop biomass accumulation (Frost et al., 1997).

Biomass Allocation Efficiency (BAE)

BAE measures the proportion of total plant biomass allocated to harvestable product. The development of the product usually involves complex physiological and developmental changes including remobilisation of resources from vegetative tissues. BAE also incorporates consideration of "secondary" food sources, such as the conversion of primary plant biomass into animal biomass. As with PUE, there is a maximum attainable value for allocation for each crop species, and so BAE is estimated as the extent to which that limit is reached. Factors affecting BAE include the following.

Plant Morphology and Physiology

Intrinsic properties of plants determine how much biomass can be trapped in the harvestable product. Breeding for increased product was important in crop redesign during the Green Revolution and is already maximal for most cereal crops, though probably not so for many others (Shearman et al., 2005). In a cereal such as rice, grain filling coincides with leaf senescence which allows nitrogen from protein degradation to be deposited in the grain, but flag-leaf photosynthesis is essential to provide carbohydrate for grain filling; thus, optimisation of these two potentially conflicting demands is required for maximizing BAE (Horton and Murchie, 2000).

Environmental Conditions

BAE can fall below the potential set by plant morphology because environmental conditions affect all stages of product development (Shearman et al., 2005; Murchie et al., 2009). For example, a restriction of photosynthetic rate during the period of flower initiation can reduce the number of flowers formed, whilst high temperature can lead to loss of flowers or developing fruits. Crop management can also affect BAE: high planting density, whilst important for high SCE, can reduce BAE through competition between plants and over-investment in stem and leaf growth (Deng et al., 2012); and fertilizer application can stimulate excess vegetative growth and reduce that allocated to the fruit or grain (Unkovich et al., 2010).

Biotic Factors

Pests and diseases can severely inhibit the formation and development of harvestable products, which are rich in nutrients and hence major targets for such pests. The list of pests that destroy potential food products is huge. Loss of biomass to biotic factors is a major cause of the yield gap—leading to an "arms race" to develop effective and sustainable chemical control and huge research efforts to breed varieties that are resistant or have increased tolerance (Oerke, 2006).

Structure of the Food Chain

Biomass from grasses and other plants is used for animal grazing, either directly or after harvesting and storage. This is a very efficient use of above-ground plant biomass. However, the production of meat from the animals is much less efficient (McMichael et al., 2007) because the consumed plant biomass is used for the growth and maintenance of the animal during its lifetime and because not all of the animal biomass is suitable for food.

Harvesting Efficiency (HE)

Not all harvestable product is collected. Inevitably, even with modern technology, the harvesting process cannot be 100% efficient. Factors determining HE include the following.

Method of Harvesting

Depending upon the geographical area and the type of crop, there are varying extents of mechanization of harvesting. Generally, mechanization increases the efficiency of harvesting (McGuire et al., 2011). Various kinds of work practices are also important: e.g., payment by the amount harvested encourages more complete harvesting. The combine harvester and its many derivatives dominate industrial agriculture, with purpose-built machines for many types of crops. Crops are bred for hardy products—those less susceptible to damage by machinery. However, mechanization can also reduce flexibility within the harvesting process: e.g., the configuration of equipment may be such that under- or over-sized product is rejected in the field.

Conditions During Harvest

Adverse conditions may damage a crop, making harvesting impossible, for instance through lodging, or by preventing operation of machinery. The suitability (and therefore economic value) of the crop product for subsequent processing may also be lowered: e.g., the effect of rainfall on the wetness of cereal crops or the visual appearance of a fruit or vegetable.

Markets

Because of the costs involved, it may not be profitable for a crop to be harvested if the market value for the product is lower than expected. Related to this is the extent to which all parts of the crop are harvested. Historically, in subsistence farming every part of an animal or a crop plant would be used. Today, there is a renewed emphasis on similarly making use of biomass not directly suitable for human consumption, according to the new principles of the circular economy, which can make the harvest more profitable and hence increase HE.

Availability of Labor

Despite extensive mechanization, harvesting relies upon the availability of labor. Often this involves low skill, low wage and physically demanding tasks that are largely taken by migrant labor in developed countries such as the USA and UK. Such labor enables profitability of the harvesting of many crops and thereby serves to increase HE (Murali and Balakrishnan, 2012). However, the hostile immigration environment developing in the UK is resulting in a reduction in seasonal migrant labor movement and threatens agricultural efficiency. In the future, increased use of robotic harvesting could reduce the requirement for labor (Dong et al., 2011).

Storage and Distribution Efficiency (SE)

Very rarely does a crop product immediately become a food that is consumed on site: harvested product has to be collected, transported and stored, and then made available for processing or consumption. Factors affecting SE include the following.

Storage Conditions

Many food products, such as wheat grain, are stored in large volumes for long periods of time. Risks of infestation by fungi, insects and small mammals are high unless optimally managed conditions are adhered to. Large storage facilities where grain is collected and stored are commonplace in developed countries, usually found near transport hubs and sea ports. In less developed countries, the absence of such storage infrastructure is a significant source of loss. For some products, such as vegetables or sea fish, harvested product is quick-frozen on site, preventing natural deterioration post-harvest.

Transport Infrastructure

Effective transport is particularly important in the transfer of agricultural produce from the farm to the storage or processing facility (Gustavsson et al., 2011). In developed countries, the quality of transport infrastructure is high, for example with dedicated rail links and fine-tuned collection and delivery road transport operations. This is not always the case in less developed countries (Hodges et al., 2011). Serious issues can arise even in well-developed economies when sectors seek to reduce costs. For example, in the UK, a change in distributer to save costs resulted in severe disruption in chicken supply to food outlets (Wood, 2018).

Supply Chain Logistics

Deterioration of harvested product due to poor supply chain logistics can be a significant cause of food waste (Kader, 2004). The integrity of food being distributed depends upon a mix of skills and technologies, such as temperature controlled vehicles and specialist warehousing, which need to be optimized for maximum efficiency. For example, bananas are transported in temperature controlled containers (at 13.5°C) to their ripening centers where the conditions are altered to secure ripening at a time when the retailer requires stock (Wilson, 1996). Many food processors and manufacturers are examining how the adoption of blockchain technology (Kim and Laskowski, 2018) could help with quality control and transparency, for example across borders to ensure that fiscal and regulatory requirements are met with minimal additional cost and delay. Other accounting tools, such as Open Book and Vendor Managed Inventory, are starting to play a significant part in improving efficiency (Martinez Ramos, 2004).

Packaging

Packaging, mostly with single-use plastic, is used in part to protect food from damage and decay, hence extending shelf life and reducing waste. Unnecessary over-packaging is an issue that is being addressed by the industry, but as with many such issues, there are many dilemmas e.g., the shelf life of cucumber is enhanced considerably by being wrapped in plastic. Consumer resistance to packaging reduction can also be an issue; a pizza manufacturer lost sales through dispensing with cardboard box packaging because consumers prefer to stack items on top of the pizza boxes in the refrigerator.

Processing Efficiency (PE)

The food processing industry is highly competitive, sophisticated and complex, resulting in maximization of the amount of raw material converted to food product. There are potential conflicts with food standards, with supply chain transparency and factory processes sometimes falling short of expectations: for example, horse meat used as a beef substitute (Van der Meulen et al., 2015) and the relabelling of poultry at processing plants to extend saleable shelf life, are both recent examples of food fraud. Factors affecting PE include the following.

Factory Logistics

Modern food processing plants in developed countries, such as millers or bakers have increasingly sought to minimize waste and resource use, driven by the need to reduce costs and maximize profit. The principles of recycling, finding economic uses for materials previously regarded as waste, and the ideas of the circular economy have become increasingly dominant. Increased automation, use of robotics in all stages from initial food produce selection (and rejection) to final processing to the end product are now commonplace.

Economics of Food Processing

Cost per saleable unit is a key metric that does not always lend itself to optimisation of material yield. Low-cost, low-quality raw material may deliver a cheaper product, even at the cost of reduced yield. For instance, abrasive peeling of lower cost irregularly shaped and variable size potatoes removes flesh as well as skin and generates a lower PE.

Product Quality Control

Food production has strict requirements on the quality of raw materials to ensure particular aspects of food quality, texture, taste, and suitability for effective processing. All of these can lead to reductions in PE. An important step forward would be the capability to predict the quality of a crop product pre-harvest, and ideally to be able to manipulate conditions in the field to enhance quality. Bakers and millers regard this as a crucial area for further research. Many quality controls relate to secondary features of food such as size, shape and weight to meet the uniformity requirements for packaging, resulting in rejection of potentially edible product. To increase profit, rejected materials are used for other purposes, but this may actually encourage food waste; for example, rejected bread crusts and end slices from sandwich producers are used as an ingredient in beer making (Melikoglu and Webb, 2013). Very significant of course is maintenance of food safety—the presence of toxins, contaminants or microbial infection or infestation render food products unsafe. Production facilities are audited and inspected and there are a series of legal frameworks imposed on suppliers by retailers covering environmental, safety, and ethical issues.

Consumer Preferences

Visual appearance is a crucially important feature of food, which has perverse consequences: so-called "wonky" products (such as carrots and potatoes) are suitable to eat but are rejected because of aesthetic appearance (Topolansky Barbe et al., 2017).

What is acceptable as a food in a particular culture is also an important factor. For example, Western consumers generally prefer white over dark poultry meat with some parts of the bird being viewed as totally unacceptable. Cultural factors similarly determine willingness to consume some parts of livestock, such as offal. However, cultural norms can change, exemplified by the growing interest in Western societies in novel food sources, such as insects (House, 2016), and current trends such as "nose to tail" eating.

Retailing Efficiency (RE)

Manufactured food is distributed to various retailers and food outlets. But not all of it is sold to the consumer. Retailing efficiency is a well-documented source of waste. In some countries, surplus food is increasingly redistributed to food banks where it is also available to be consumed (Galli et al., 2019). This alternative route to consumption hence contributes to reducing waste and increasing RE. Three inter-related factors dominate the value of RE.

Wide Choice and Full Shelves

Retailers, particularly large supermarkets strive to have full shelves of food with ever-increasing variety to give wide consumer choice. Because of the complexity of the supply chains that make this possible and the finite shelf life of most foods, waste is inevitable (Parfitt et al., 2010; Eriksson et al., 2016). However, in the highly competitive retail market, the cost of such waste is absorbed and part of the business model. In the UK, the recent move away from a single weekly shop to more frequent, smaller basket shops has seen a reduction in waste as stock turnover is faster, with less waste through out-of-date produce.

Freshness and Safety

Deterioration of food quality and the imperative to prevent customer illness results in disposal of food. Retailers, manufacturers and processors have been working together to reach new levels of extended shelf-life for perishable foods. Technological innovations include a longer shelf-like milk through the use of ceramic filtration of milk post-pasteurization, which removes bacteria that otherwise act to render the milk sour and unusable (Martinez-Ferez et al., 2006). The resultant shelf-life increase is very significant, therefore increasing RE.

Information and Labeling

Misunderstanding of date labels, including confusion between "best-before" and "use-by" labels, can also lead to unintended waste based on a conflation of guidance about food quality and safety standards (WRAP, 2017). In fact, consumer behavior is a root cause of much food waste and difficult to change (Reynolds et al., 2019). For example, a UK supermarket invested £10 m in a 5-year "waste less, save more" initiative project intended to establish how information, tools and community events could help reduce food waste, but the results fell short of target with householders telling the retailer that the issue was not a priority (Weinbren, 2017).

Consumption Efficiency (CE)

Not all food that is purchased is consumed, and the food that is consumed may not be eaten with peak nutritive value. CE therefore is estimated not only from the mass of food consumed but the potential nutritive value acquired from that consumption. The following are the two principal factors influencing CE.

Food Purchase

The supermarket environment encourages over-purchase, through "special offers" and attractive displays, backed up by extensive advertising. The reduced unit cost in larger pack sizes and the unavailability of small packs are also important factors. Over-purchased food is often not eaten due to it passing beyond what is culturally and medically safe to eat. Moreover, the nutritive value of food changes over time (i.e., as fruit ripens the nutritional composition changes), and therefore misjudgement about when to consume foods means that the optimal nutrition may not be gained. In addition, if food is over-purchased, the food may have to be consumed over a longer time period (from under to over ripe), with some of the foods eaten at a non-optimal nutrition level. The edible nature of a product can be extended through food preservation methods such as canning, drying, salting, and freezing, though these may also reduce the nutritive value of the product.

Food Handling

Methods used to prepare foods (i.e., cooking style and gastronomic traditions) alter how much of the food is available for final eating and the nutritive value of the edible food. For example, different methods of preparing and cooking potatoes (i.e., steamed whole, baked in skin, fried as chips) result in different amounts of edible potato and different nutritive value. In fruits and vegetables in general there is significant variation in the nutritional content through the skin and flesh, so that peeling can similarly reduce nutritive value. There is also a tendency to prepare more food than is needed, "better to serve too much than too little."

Dietary Efficiency (DE)

Over-consumption of food should be regarded as a waste, and this can be calculated by estimating what proportion of consumption is in excess of that needed to provide the level of nutrition required to maintain good health. Methodologies exist for making these estimates (e.g., Hall et al., 2011). Measurement of food intake at the population level (from estimates of gross food consumption) and from survey of individual consumption (and purchase) behavior can be used to measure the level of overconsumption, although the consumption of certain foods is often incorrectly reported (Stubbs et al., 2014). For example, surveys indicate a consumption of <2,000 kcal per person in the UK, inconsistent with over 60% of the population being obese or overweight. Moreover, not all foods have the same nutritional benefit or health penalty, so DE, like CE cannot simply be estimated in terms of food mass. Thus, consumption (and production) of "unhealthy" food should also be considered a symptom of an inefficient system. Factors affecting DE therefore include the following.

Calories and Nutrients

There are two distinct issues here, one of which is the total calorie intake—the other is per person nutrient intake. Over-consumption of calories and nutrients can both result from over-consumption of food. However, over-consumption of calories is by far the larger health risk, the root cause of the obesity and the non-communicable disease (NCD) epidemic occurring in all countries. Different foods contribute differentially to NCDs and there is debate over the relative harm from high fat and high carbohydrate food (Dehghan et al., 2017).

Physiology and Genetics

The optimum consumption of energy is related to human physiology and genetics (Van Zant, 1992). The process by which nutrients are extracted by the human body from eaten foods also varies and there are many factors that affect the rate at which food is digested in the alimentary tract and absorbed into the bloodstream. One issue of contemporary concern is gut health—or the efficiency of a person's gut microbial community. The gut microbiome changes according to what is eaten, and this in turn influences the efficiency of nutrient metabolism (Kau et al., 2011). An efficient and healthy gut microbiome requires a balanced and varied diet.

Culture and Behavior

There are a myriad of reasons, many not understood, for the over-consumption of food. Some relate to over-purchase (CE) and the increased availability of food, others to particular culturally-embedded social practice or individual behaviors. In a range of countries, survey data show that the major driver of the obesity epidemic is the increased food energy supply (Vandevijvere et al., 2015). Ultraprocessed foods are increasingly available globally and viewed as contributing significantly to obesity (Monteiro et al., 2018). The extent to which a given amount of food consumption leads to obesity is determined by a number of factors including the level of physical exercise and basal metabolic rate, both of which depend on body weight (Hall et al., 2009). The challenge therefore is to discover ways to bring about change in behavior and practice, for example through incentives, taxation, product reformulation and education.

IMPLICATIONS FOR AGRICULTURAL LAND USE

All of the above processes which govern the efficiency of the agri-food system in effect determine the number of humans that can be properly fed per unit of agricultural land area. Creation of agricultural land has involved deforestation and destruction of other natural habitats such as savannahs and grasslands. This has implications not only for biodiversity (Tilman et al., 2017), but also for the provision of other ecosystem services and the emission of greenhouse gases that follows land use change (Tubiello et al., 2015). There is competition for land not only between urban development and agriculture but also for non-food cropping such as biofuel production, maize for anaerobic digesters, intensive solar panel infrastructure and land "set aside" to enable restoration to a more natural state to increase biodiversity. With a world population growing toward 10 billion, it is only by decreasing the FCI within the agri-food system that agricultural land use can be stabilized and even reduced. As an example, it has been estimated that 540 Mha could be saved by 2050 through the global adoption of a (more efficient) vegetarian diet compared to the (inefficient) meat-rich diet associated with increasing prosperity (Tilman and Clark, 2014).

It is important to consider not only the process efficiencies in the agri-food system but also the geographical distribution of the factors that govern these efficiencies: temperature, rainfall, soil quality and the intensity and duration of solar radiation govern SCE, PUE, BAE, and HE. Of equal importance are the logistic considerations (proximity to transport links, markets etc), availability of labor, and the socio-economic and political environment, which determine SE, PE, RE, CE, and DE. Moreover, we need to consider the amount of land used for a particular crop or livestock; each one has a geographical distribution based mainly on environmental adaptation, but local and global demand for products is a key determinant of how much of the potential land area is used. This is not fixed: genetic improvement extends the dynamic range of a species, societal change alters demand, and climate change shifts environmental boundaries. Thus, it is not just about how much land area is used for agriculture, but about which land areas promote the highest agri-food system efficiency.

AN ILLUSTRATIVE CASE STUDY

In this section we illustrate how our FCI approach can lead to an integrated view of the performance of a food supply chain. The wheat-bread agri-food system has been analyzed and the environmental impact determined for each of the process stages, from wheat growth on the farm through to production of a loaf of bread by the food manufacturer (Goucher et al., 2017). We have used the same system, extended to include bread consumption to illustrate the application of the above nine process conversion efficiencies (**Figure 1**). We stress that this case study is an illustrative one only. In the real world, as reported by Goucher et al. (2017), primary data with a high

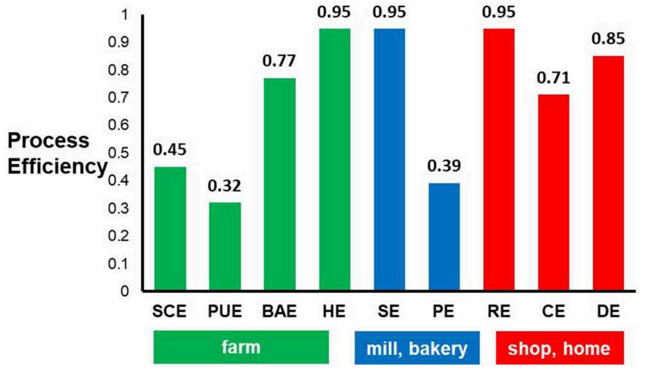

FIGURE 1 | Illustrative case study: estimated processes efficiencies during the production and consumption of bread in the UK. Processes on the farm, mill & bakery, and shop & home are defined and estimated as described in the text.

degree of granularity is needed, data from an identified supply chain—farmer to processor to retailer to consumer—in which specific inefficiency values can be measured and appropriate local remedies for improvement suggested.

Sunlight Capture Efficiency (SCE). The important determinant for the wheat crop is the rate of development of leaf area, and also the senescence of leaves during grain maturation. It is estimated that ∼47% of incoming sunlight is incident on leaves over the growing season (AHDB, 2015) with ∼95% absorbed.

Photosynthesis Use Efficiency (PUE). Wheat is a C3 crop and hence significant losses occur through photorespiration and "canopy factors," the difference between photosynthesis of individual leaves and the photosynthesis of the canopy (Mitchell and Sheehy, 2018).

Biomass Allocation Efficiency (BAE). A typical value for the allocation of photosynthate to roots relative to above ground growth is 0.85. Approximately 48% is an average value for the proportion found in the mature grain (Shearman et al., 2005) and this value is close to what might be considered the theoretical maximum value of 0.62 (Reynolds et al., 2009).

Harvesting Efficiency (HE). For UK wheat, there has been investment to maximize harvesting, through mechanization and other aspects of logistics such as field size and shape.

Storage and Distribution Efficiency (SE). Modern grain storage facilities in UK have refined control over environmental conditions (temperature and humidity) and great attention to biocontrol. Barring rare cases of infestation, losses are hence very low.

Processing Efficiency (PE). The quality of wheat grain determines its suitability for bread making, a function of the Hagberg Falling Number (indicator α-amylase activity), protein and water content. These vary considerably from year to year, dependent upon weather conditions. In the 2017 UK wheat harvest, as a result of adverse environmental conditions, only 53% of the group 1 and 2 harvest was of the high and medium bread making quality, with a mean value of 60% for the years 2015–2017 (NABIM, 2017). Losses through milling of whole grain are relatively low (3%) and loss during baking (10%) is also low in modern commercial establishments, and arise primarily from rejections based on flour quality (Goucher et al., 2017). In the UK over 80% of bread is baked with refined white flour, which results in further ∼25% loss of wheat grain mass. A typical value for PE would therefore be about 0.39.

Retailing Efficiency (RE). RE was estimated (Cohen, 2016b) using 2016 supermarket self-reported food waste data (213,000 tons), and multiplied by an estimate of bread product waste (i.e., 41%) as a percentage of its total food waste stream (WRAP, 2015). Applied to the retail industry we estimate that 87,000 tons of supermarket food waste in 2016 were bread and bakery products out of a total 1,848,000 tons of bread purchased in 2015, ∼4.5%.

Consumption Efficiency (CE). The "household food and drink waste: a product focus" report states that 460,000 tons of bread was thrown away from UK homes in 2012 [estimated to be ∼29% of that purchased—see Gov.UK (2018)] most of which was avoidable and due to not being used in time, cooking or serving too much and accidents (Quested and Murphy, 2014).

Dietary Efficiency (DE). DE was estimated using the National Diet and Nutrition Survey (NDNS), which provides high quality data on dietary intake and nutritional status in a representative sample of the UK population. Twenty-three percent of the sampled population were found to have a bread consumption that was either partly or totally overconsumption (Public Health England Food Standards Agency, 2016). The average amount of bread partly or totally over-consumed per day was 17 g. Scaled up to the total UK population, this would mean that 96,000 tons of bread are partly or totally over-consumed in the UK every year out of an estimated total bread consumption of 1,126,000 tons.

The FCI in the wheat-bread supply chain is illustrated in **Figure 1**. Four processes stand out. The inefficiencies in wheat growth are almost entirely intrinsic features of wheat physiology and morphology. There is scope to improve PUE by manipulation of photosynthesis and to raise SCE by increasing the rate of canopy development and extending the period of light capture by delaying leaf senescence as grains fill. Wheat PE is also particularly low, mostly because of the stringent grain composition requirements for the bread making process, imposed in turn by the high demand for uniform, high quality white bread by the retailers and consumers. Inefficient consumption (CE), due to over-purchase and product deterioration is also the source of significant waste.

CONCLUSIONS

The comprehensive rationalization of the wastes and losses in the agri-food system into a series of process conversion efficiencies allows analysis to determine how best to bring about improvements. Different food supply chains in different countries will show different FCI, with different values for the efficiency of the nine process steps we describe. This points to the need for granularity in our food datasets. It is important to map each food chain, including the origins of primary food stuffs, such as grains, where and how processing occurs, how it is distributed and so on. As discussed previously, this requires an unprecedented level of co-operation of the actors across the food chain (Horton et al., 2016; Horton, 2017). But only with such data will it be possible to know on a case by case basis where the inefficiencies lie and therefore to direct attention to where there is maximum potential gain. All too often attention is focussed on making further gains on processes already highly efficient rather than focussing of the most inefficient steps.

Having a methodology that allows all of these issues to be analyzed and assessed together is a significant advance. Crop physiology and agricultural productivity can then be considered alongside the food businesses involved in processing and retailing, together with the issues of diet, nutrition and health. We can discuss all of these in terms of a baseline of agri-food efficiency and not become distracted by unnecessary fragmentation, which leads to bias in decision-making as to where to focus attention for intervention. Similarly, an integrated account also helps avoid the attribution of unwarranted blame on different food system actors, instead focussing on a more rational distribution of responsibilities (Evans, 2011). It also provides a mechanism to include assessment of the various trade-offs between different parts of system. For example, the drive to increase the efficiency of production at the farm level (defined in terms of product mass or number) may increase waste further down the chain, and contribute to over-consumption as well as under-nutrition (Horton, 2017).

It is to be emphasized that an analysis in terms of FCI alone is inadequate. The analysis should be extended in various ways to include: metrics of economic efficiency, a potentially vital trade-off in interventions to reduce food loss and waste; parallel analyses of the efficiency of use of various inputs such as water, fertilizers and packaging materials; and extent of environmental impact, such as greenhouse gas emission (Goucher et al., 2017). Thus, an intervention to reduce FCI may lead to greater environmental impact, for example by increased use of fertilizer and water on the farm, increased energy use from refrigeration and transport or increased pollution from plastic waste in packaging designed to increase product shelf-life and reduce damage. Furthermore, a highly efficient, high throughput food supply chain with consequent low levels of waste (i.e., implying lower excess capacity) may have reduced resilience in the face of global shocks and the effects of climate change (Horton, 2017).

Of course many challenges remain. It first needs to be demonstrated that these conversion parameters can be successfully applied across a range of food chains, many of which are much more complicated than in our illustrative example. We need to deliberate carefully on the impact of measures used to reduce inefficiency, such as recycling of waste and redistribution of surpluses, and how these affect estimates of conversions efficiencies. These wastes often have economic and social benefits (Galli et al., 2019), and hence the concept of "unavoidable waste" is useful—it is impossible and indeed not desirable (given the trade-offs discussed above), to have a 100% efficient food chain, and then the challenge is how best to deal with any waste that is produced. Thus, broader issues also need to be addressed: who is in charge of the reduction in FCI; who collects, collates and analyses the data; and who directs the interventions required. Various social, ethical and political issues arise: what incentives/penalties are needed to drive change; what is the role of national governments; and how is international co-operation developed.

Ultimately, providing sustainable food security to humankind, depends absolutely upon increasing the efficiency of the agri-food system, whilst at the same time making sure it is resilient and keeping resource use and environmental impact within sustainability limits. This can only be achieved if we first establish a uniform approach to analyse each step in the system, as begun here.

AUTHOR CONTRIBUTIONS

PH conceived the idea, planned the paper, provided expertise on plant biology and agriculture, and wrote the first draft. CR contributed knowledge of food waste, food consumption, and nutrition. RB provided expertise on food business and the food supply chain. GM made contributions to the areas of agriculture, food waste and food retail business. All authors helped in manuscript preparation, and editing.

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frontiers in Sustainable Food Systems

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Sustainability Assessment of Food Waste Prevention Measures: Review of Existing Evaluation Practices

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The last few years, a lot of measures addressing food waste have been proposed and implemented. Recent literature reviews call for more evidence on the effectiveness or food waste reduction potential of these measures. Furthermore, very few information is available on the extent to which food waste measures have been evaluated based on their economic, environmental and social performance. This review closes this knowledge gap by looking at the methodologies currently used in literature to evaluate food waste prevention measures, using a pre-defined assessment framework with quantitative evaluation criteria. In total, evaluations were examined for 25 implemented measures with measured outcomes and 23 proposed measures with projected outcomes. The paper concludes that there is a great variety in how an evaluation is performed. Additionally, in many cases, economic, environmental, or social assessments are incomplete or missing, and efficiency is only seldom calculated. This is particularly true for implemented measures whereas proposed measures with projected outcomes tend to have a more thorough evaluation. This hampers practitioners and decision-makers to see which measures have worked in the past, and which ones to prioritize in the future. Moreover, more complete information on the effectiveness and efficiency of measures would make incentives for reducing food waste at various levels along the food chain more visible. At European level, work is ongoing on the development of a reporting framework to evaluate food waste actions. This paper complements these efforts by providing an overview of the current gaps in evaluation methodologies found in literature regarding food waste prevention measures within EU and beyond.

Keywords: food waste, prevention, measure, evaluation, performance, effectiveness, efficiency, sustainability

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INTRODUCTION

Urgency of Tackling Food Waste

Food losses and wastes are generated throughout the food chain, from cultivation, over harvest, processing, storage and distribution up until the final consumption by private households and the food service sector. In 2011, the FAO provided a comprehensive overview of the amount of food losses and waste generated at global level (Gustavvson et al., 2011). Globally, about 1.3 billion tons of edible food, or about one third of the mass of edible food produced for human consumption, is annually lost or wasted. At EU level, 88 million tons of edible and inedible food was lost or wasted in 2012. This equals about 20% of the total food produced in the EU and up to 173 kg of food waste per person per year (FUSIONS, 2016).

Based on the 2011 Food Balance Sheets, the FAO estimates that the annual global volume of food wastage generated has a carbon footprint of 3.6 Gt of CO_2 eq (excluding land use change). If food wastage were a country, it would be the third largest emitter in the world, after USA and China (FAO, 2015). Furthermore, 24% of freshwater resources and 23% of the cropland used to produce food in 2011, was lost throughout the food supply chain (Kummu et al., 2012). At EU level, food waste has an annual climate change impact of 186 Mt CO_2 eq., representing almost 16% of the carbon footprint of the total food chain (Scherhaufer et al., 2018).

Based on 2009 commodity prices at producer level, the FAO estimates the economic costs of global wastage of agricultural food products, thus excluding fish and seafood, at $750 billion (FAO, 2013a). In 2014, FAO adapted the figures to 2012 prices and replaced the producer prices for post-agricultural wastage with import/export market prices. This leads to a final monetary value of $936 billion for global food wastage (FAO, 2014). At European level, costs of edible waste are estimated to be at around €143 billion for EU-28 in 2012, based on the value of the edible food at each specific stage along the food chain where it is lost (FUSIONS, 2016). Two-thirds of these costs, or €98 billion, relates to food waste from households whereas the second largest contributor is the food service sector, with a food wastage cost of €20 billion.

Finding the Most Promising Measures to Tackle Food Waste

In order to reduce or prevent food waste, many measures have been put forward of which a great deal of them has been implemented. To know which measures provide the best opportunities and what actions are the most promising, a thorough evaluation of food waste interventions is needed.

For businesses, applying food waste prevention measures only makes sense if there is an economic incentive to do so. As preventing food waste comes at a cost, actors along the food chain could be expected to only implement a certain measure if the benefits resulting from saving food gone wasted outweigh the costs associated with the implementation of the measure (HLPE, 2014; WRAP, 2015). At production level, not harvesting all crops may be a strategic decision in case of low market prices or in case these leftover crops positively affect the yield of the next season. At business level, transaction costs associated with food waste prevention may be so high that it becomes "rational" to let food go wasted. This could be the case for correctly matching food supply and demand or for increasing delivery frequency and buying smaller quantities. At household level as well, consumers might prefer buying more products at once to going shopping on a more frequent basis, with the risk of a part of them not being consumed in time (FAO, 2014; Teuber and Jensen, 2016). In these cases, one might say there is an "optimal" amount of food waste (Teuber and Jensen, 2016).

To overcome these challenges, players along the food chain need an economic incentive for tackling food waste. Other than economic concerns, there may be ethical, social, or ecological benefits resulting from food waste prevention measures that could for example contribute to a company's positive image or corporate social responsibility (FAO, 2014; WRAP, 2015). For private consumers as well, ethical, social, or ecological concerns, next to economic ones, may results in generating less food waste.

A clear understanding of the net economic benefits associated with each measure, as well as its associated environmental and social effects, increases transparency, and could create incentives for (further) reducing food waste by the various players along the food chain.

The Knowledge Gap Regarding the Performance of Food Waste Measures

In its review on food waste literature, Schneider (2013) stated that "papers introducing evaluation methodology or presenting reliable results of evaluating implemented food waste prevention measures are lacking." Rutten et al. (2013) further concluded that literature on the quantification of food waste reduction potential is scarce and that impacts of food waste prevention initiatives are often not quantified.

Since 2013, a couple of reviews were published looking into the extent to which reports or studies consider the food waste diversion potential of food waste measures. Pirani and Arafat (2014) reviewed solid waste management in the hospitality sector. For many of the food waste initiatives they collected, information on the associated food waste reduction potential is missing. Aschemann-Witzel et al. (2017) collected information on the key characteristics and success factors of 26 supply chain initiatives tackling consumer-related food waste. It is however, from this review, not clear whether these initiatives actually led to measurable food waste reduction, as "success was not defined as an actual reduction of food waste, given it was expected that few initiatives can actually measure this." As such, actual proof of success might as well be "the extent to which information or supportive items had been distributed to consumers" (e.g., measuring cups for preparing the right amount of rice or pasta) as this is assumed to lead to food waste reduction on the long run. Stöckli et al. (2018b) and Reynolds et al. (2019) both looked at the effectiveness of food waste interventions at consumption level. Interestingly, informational interventions were found to be the most commonly used intervention type while at the same time they are seldom evaluated, resulting in a lack of proof of their effectiveness (Stöckli et al., 2018b). Furthermore, for some initiatives that are often reported to be effective and promising, such as cooking classes, food sharing apps, advertising and information sharing, no actual evidence could be found on whether or not they were effective (Reynolds et al., 2019). From these reviews, it can be concluded that the potential of food waste measures to reduce food waste is only being evaluated to a limited extent. Stöckli et al. (2018b) and Reynolds et al. (2019) therefore specifically call for more information on the actual effectiveness of food waste measures.

Given the fact that the amount of food waste prevented by a measure is seldom taken into account, neither the ecological impacts nor monetary costs associated with food waste measures can be assessed. To our best knowledge, no reviews currently exist assessing the extent to which ecological impacts, monetary costs or savings, and efficiency of food waste measures are considered. Several authors have however stressed that, in case monetary aspects are taken into account, these tend to be restricted to the costs embodied in the food itself (based on for example retail prices), whereas disposal related costs are neglected (Rutten et al., 2013; Teuber and Jensen, 2016; Cristóbal et al., 2018; Koester et al., 2018). Furthermore, Koester et al. (2018) concluded that costs incurred by the measure itself, namely the costs for implementing a measure, are rarely considered. Cristóbal et al. (2018) further conclude there is only "limited knowledge on the evaluation of food waste prevention and management strategies including both economic and environmental dimensions" and that data on performance of measures is scarce.

To close this knowledge gap on the evaluation of measures, the present paper reviews the methodologies applied in literature for evaluating food waste prevention measures, focussing on a wide range of factors beyond food waste diversion potential. This is done through a three-step literature search and analysis. Firstly, information is gathered on the range of prevention measures currently being proposed in literature to tackle food waste. Secondly, the search is narrowed to those sources containing an evaluation of the proposed food waste measure(s). Finally, an assessment is made on how the evaluation has been performed in the respective studies. This paper thereto proposes an assessment framework with quantitative criteria against which the evaluation methodologies are assessed.

This paper hereby builds on and complements ongoing work of the EU Platform on Food Losses and Food Waste[1], and more particularly the framework for evaluating food waste prevention measures that is currently being developed by the EU Joint Research Centre (JRC) in Ispra (EU FLW, 2017). The innovation in this paper therefore does not lay in the assessment framework proposed, but rather in providing an overview of recent advancements in literature and the state of art of the extent to which measures have been evaluated so far.

This paper was written within the context of the German ELoFoS research project on "Efficient Lowering of Food waste in the Out-of-home Sector"[2]. As such, focus is given to the food service or out-of-home (OoH) sector whereas other sectors along the food chain are investigated to a lesser extent. Nevertheless, as the paper focusses on methodologies for evaluating food waste prevention measures rather than the measures itself, the findings of this paper apply to all sectors along the chain.

MATERIALS AND METHODS

Food Waste Definition and Categorization of Food Waste Measures

The definition of food waste used within this paper follows the definition proposed by the European FUSIONS project: "Food waste is any food, and inedible parts of food, removed from the food supply chain to be recovered or disposed (including composted, crops plowed in/not harvested, anaerobic digestion, bio-energy production, co-generation, incineration, disposal to sewer, landfill or discarded to sea)" (Östergren et al., 2014). The food supply chain hereby consists of a "connected series of activities used to produce, process, distribute and consume food," starting with raw materials and products ready for harvest or slaughter (Östergren et al., 2014), thus including those products that are in the end not harvested/slaughtered and for example left on the field.

Using this definition, food (or inedible parts of food) that is removed from the food supply chain and sent to animal feed, bio-material processing or other industrial uses is not considered as "food waste," but as "valorization and conversion."

Based on the definitional framework set out by Östergren et al. (2014) and the management hierarchy from Huber-Humer et al. (2017), food waste measures are categorized as follows:

- Measures preventing food from becoming food waste:
    - Category 1: Avoidance measures aimed at reduction of food surplus at source, such as avoiding food overproduction and avoiding purchasing more than what is needed;
    - Category 2: Redistribution or donation measures such as redirecting food surplus to people in need;
    - Category 3: Valorization or conversion of food and inedible parts of food removed from the food supply chain, such as redirecting food waste to the bio-based industry or to animal feed;
- Measures managing food waste:
    - Category 4: Recycling (anaerobic digestion or composting) and recovery (energy recovery) of food and inedible parts of food removed from the food supply chain in order to avoid landfilling.

Literature Search

The literature search was conducted between September 2018 and February 2019 and comprised both searching gray literature as well as academic literature. The search was done using Web of Science, Scopus, Science Direct, Directory of Open Access Journals and Google (Scholar) search engines. For practical reasons, the academic literature search was conducted in English whereas the search for gray literature entailed publications in English and in German. No date restrictions were set.

Following the focus of the ELoFoS project, the literature search concentrates on developed regions and the OoH sector. Furthermore, this paper concentrates on those measures aimed at preventing food from leaving the food supply chain, namely avoidance measures (Category 1) and redistribution or donation measures (Category 2).

The methodology used for the literature search is based on the rapid review approach as a less time-consuming alternative to a systematic review. The search and subsequent analysis followed a three-step approach as illustrated in **Figure 1**. Step 1 aimed at collecting measures dealing with food waste throughout the food chain, in order to get an insight in the measures that have been proposed in literature. In total, the search resulted in a collection of 88 sources (academic and gray literature) listing in total over 200 food waste prevention measures, with the majority

[1] https://ec.europa.eu/food/safety/food_waste/eu_actions/action-implementation_en
[2] https://elofos.de

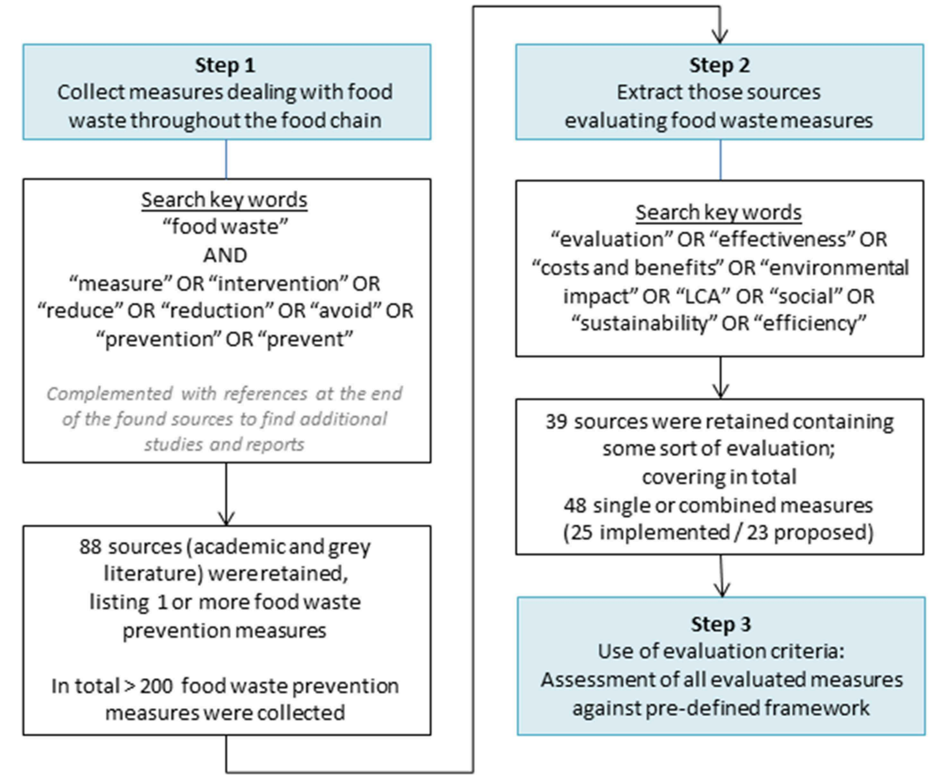

FIGURE 1 | Flowchart and outline of the literature search methodology.

of sources proposing or describing more than one measure. All found sources (with the exception of two studies) were published after 2010.

Step 2 of the search narrowed the sources to those studies or reports containing an evaluation of implemented or proposed measures to prevent food waste. In total, 39 sources were retained containing some sort of evaluation of one single measure or of combined measures. Combined measures hereby refer to measures applied and evaluated simultaneously or grouped into for example a voluntary agreement or a large-scale campaign.

Of the 39 retained sources, 15 were peer reviewed journal articles, 2 referred to proceedings or presentations at a scientific congress, whereas the remainder are gray literature or reports (see also **Supplementary Table S3**). These 39 sources included the evaluation of in total 48 single and combined measures. For the evaluated (combined) measure(s), the following metadata was collected: life cycle stage or sector in focus, country and scale of application, and nature of evaluation results (measured vs. projected outcomes).

During Step 3 of the process, the methodologies and criteria used for evaluating food waste measures were put against a predefined framework for evaluating measures (as described in section Assessment Framework: Evaluation Criteria for Food Waste Measures). The assessment done hereby focussed on the methodologies used in literature, rather than on identifying the best performing measure. Additionally, no attempt was made to evaluate the measures ourselves; only readily available information on the performance of the food waste measures was collected. The evaluation assessment itself comprised looking at the extent to which each of the evaluation criteria was taken into account. A distinction is hereby made into (sets of combined) measures that have been implemented and for which outcomes were measured, and measures that have not been implemented but for which projected outcomes are given. In case the information available online did not allow for a conclusive answer on whether or not a certain criterion was assessed, this is indicated with a question mark ("?"). For practical reasons, these were later on in the analysis treated as "criterion not considered."

Assessment Framework: Evaluation Criteria for Food Waste Measures

The assessment framework proposed within the context of this paper builds on publicly available information on the ongoing work within the EU Platform on Food Losses and Food Waste (EC-JRC, 2018a,b, 2019). The framework is based on three overarching quantitative criteria that need to be considered when evaluating food waste measures. The first criterion refers to the potential of a measure to reduce food waste: its effectiveness. Secondly the extent to which all three dimensions of sustainability have been taken into account is assessed: environmental impacts or savings brought about by the measure (such as emission savings), economic costs and benefits, and resulting social effects. Lastly, we look at how the efficiency of a measure is calculated.

Figure 2 provides for a schematic overview of the criteria and their sub-criteria; a detailed description of the framework is presented in the following sections.

Effectiveness or Food Waste Reduction Potential

The effectiveness of a measure or its potential to decrease food waste requires a quantification on a mass basis of food waste prevented (Cristóbal et al., 2018). An assessment of methodologies for quantifying food waste is out of scope of this paper. Guidance on how to measure food waste can be found in the global Food Loss and Waste Accounting and Reporting Standard developed by the Food Loss and Waste Protocol, which is a multi-stakeholder initiative (WRI, 2016). A recent overview of existing methodologies for food waste accounting, as well as an identification of current challenges and opportunities can further be found in the studies from Caldeira et al. (2017), Corrado and Sala (2018), and Corrado et al. (2019).

Sustainability Assessment

Secondly, the sustainability of a measure needs to be analyzed. This involves looking at the three dimensions of sustainability (environmental, economic and social dimension).

Environmental dimension

Environmental impacts or savings arising from the implementation of a food waste prevention measure can be calculated using a life cycle assessment (LCA) approach. As food waste is being prevented, the embodied impacts associated with the food that is now no longer being wasted are avoided. These include all the impacts generated along the different stages of a product's life cycle. The further along the chain food is wasted, the higher its associated embodied impacts as these accumulate along the chain.

The prevention of food waste further means that the end-of-life (EoL) stage is being eliminated. The associated avoided disposal impact hereby depends on the formerly chosen waste management option (FAO, 2013b). These avoided impacts relate to both the waste collection as well as the waste treatment.

Note that for measures belonging to Category 3 (valorization/conversion) or Category 4 (recycling/recovery), the avoided disposal impacts would need to be complemented with other impacts related to what happens with food leaving the food chain. These measures are however out of scope of this paper.

Both the avoided embodied impacts as well as the avoided disposal impacts directly refer to the amount of food waste that is prevented or reduced. An additional source of environmental impacts relates to the implementation of the measure itself. This could refer to changes in logistics or transport (related to for example food redistribution to charities), changes in electricity or water usage, changes in use of packaging or additional use of paper for leaflets and brochures.

Economic dimension

In line with the approach taken in the environmental dimension, food waste prevention measures need to be assessed based on the

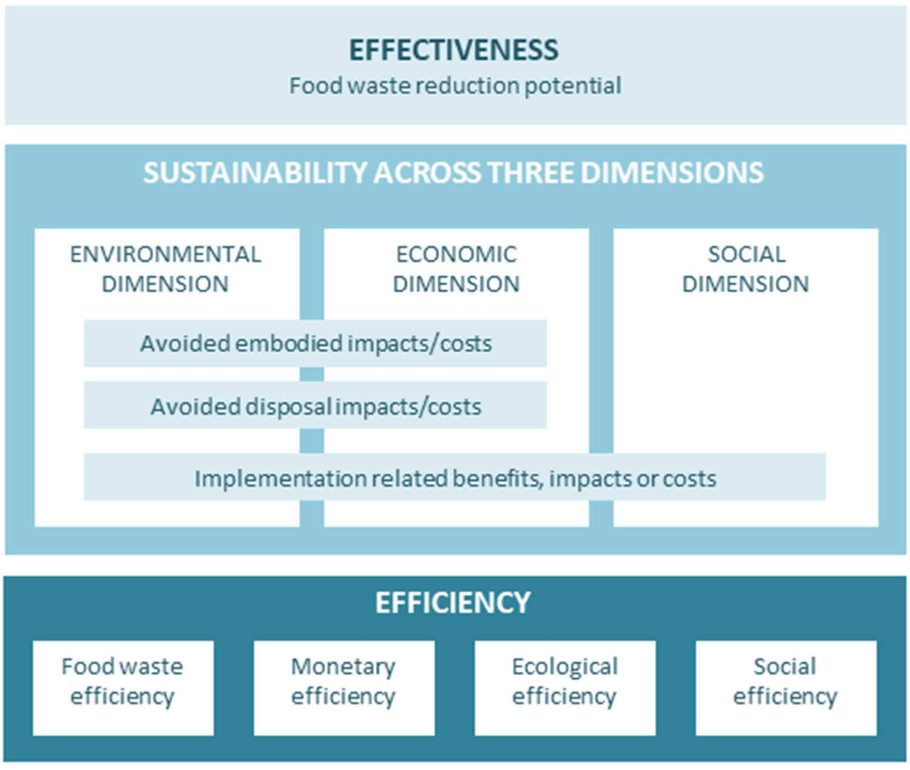

FIGURE 2 | Assessment framework—Quantitative evaluation criteria for food waste prevention measures, inspired by the reporting template developed by the EU JRC within the context of the EU Platform on Food Losses and Food Waste.

avoided economic embodied costs, the avoided disposal costs and the implementation costs or savings.

The avoided economic value or embodied cost of food can be determined using the commodity price of a product. Commodity or market prices incorporate the (overhead) costs borne by several actors along the food chain up until the moment of sale, complemented with a certain percentage of profit gain (mark-up) between each of the actors along the chain. In the case of restaurants for example, menu prices are based on the procurement price of each ingredient complemented with operational costs (such as energy and water use, waste management, and cleaning) and personnel costs for preparing and cooking the food. Along the same lines, retail prices incorporate operational and personnel costs borne by a supermarket. As each stage adds up to the cost of food, commodity prices go up as the product moves further along the food supply chain with lowest prices at grower level and highest prices at the end of the supply chain (Teuber and Jensen, 2016; Bellemare et al., 2017). Both menu prices and retail prices however also include a mark-up charged by the restaurant or seller in order to make profit. As a result, using menu and retail prices to estimate the value of food gone wasted, leads to an overestimation of its value (Bellemare et al., 2017).

The avoided costs for food waste disposal include costs for waste sorting (such as removing bad and spoiled produce in supermarkets), waste collection and treatment, as well as all related administrative costs.

In 2013, WRAP (2013d) calculated "the true cost of food waste" in the UK hospitality sector. Food purchasing prices were found to contribute 52.2% to the total cost of food waste. The second largest contributors were labor costs for kitchen staff associated with preparation and cooking of meals (37.4%). Other cost elements referred to energy and water use for preparation and cooking of meals (excl. fixed costs such as energy costs for lighting, water costs for cleaning the restaurant), waste management, and transport costs associated with the collection of food supplies.

Another approach to calculate the costs associated with the food that is no longer being wasted (and its avoided disposal), is the Life Cycle Costing (LCC) approach which takes into account all costs associated with a product or service over its entire life cycle. Next to the obvious costs related to raw materials acquisition, manufacturing and distribution, LCC considers operating and labor costs, research expenditures and waste collection and disposal costs as well, thereby also including foreseeable costs in the future (Hunkeler et al., 2008; Kim et al., 2011; Swarr et al., 2011; Asselin-Balençon and Jolliet, 2014; Martinez-Sanchez et al., 2015; De Menna et al., 2016, 2018). This approach is particularly important in case of Category 3 and 4 measures to fully account for by-products such as animal feed, compost, and electricity.

The third cost item refers to the implementation costs and savings associated with the food waste measure itself, covering both fixed and variable costs. Fixed costs for example include investments in new technologies or materials, investments in new logistics, expenses for printing leaflets and brochures at the start of a campaign, or expenses for personnel training. Variable costs or savings on the other hand refer to changes in daily or continuous activities such as time spent for food production, time spent for waste administration, personnel hours, daily campaign costs, or changes in electricity and water usage.

Social dimension

Next to the environmental and economic effects, there may also be social effects. Redistribution of food waste to food charities for example results in a number of meals given to people. As such, the number of meals saved and subsequently donated can serve as a social indicator.

Another indicator relates to the opportunities for job creation brought about by food waste measures. New jobs may be created in the life cycle stage where food waste is being prevented, as well as in other sectors or stages along the food chain where the food is being reused, recovered, or recycled, such as in food charities or food recycling.

Efficiency

Finally, the efficiency of a measure needs to be calculated using the indicators mentioned above. Evaluating the efficiency of a measure can be done by putting the costs of a measure against its economic benefits, against its waste diversion potential (the amount of food waste that was reduced or prevented), or against the resulting ecological savings such as avoided emissions (Teuber and Jensen, 2016; Cristóbal et al., 2018).

Economic or monetary efficiency

The most common methods to calculate the efficiency of a measure are the benefit-cost ratio and the net benefits. The benefit-cost ratio is obtained through division of the benefits resulting from the implementation of a measure by the costs it took to get there (Investopedia, 2018). The net benefits on the other hand are obtained by subtracting the costs from the benefits.

The investment payback period refers to the amount of time it takes to recover the cost of an investment. The return on investment (ROI) can be calculated by dividing the net benefits by the costs, and expressing this ratio as a percentage (Investopedia, 2019a,b).

For these calculations, only monetary data is taken into account. As such, there are no clear linkages to the food waste reduction volumes or to the ecological savings resulting from food waste reductions. However, if these reduced food waste volumes or ecological savings are expressed in monetary values (such as the economic retail value of food no longer gone wasted or the economic value of the avoided emissions), these could be included in the benefits obtained through the implementation of a food waste measure.

Food waste efficiency, ecological efficiency and social efficiency

The cost for reducing 1 ton of food waste or for abating 1 ton of carbon emissions (CO_2 eq.) through a specific measure is calculated through the ratio of the costs of this measure to its food waste reduction potential or emission savings. The most preferable measures would then be those with the lowest per unit cost for food waste reduction or for emission abatement.

A marginal abatement cost (MAC) curve facilitates the visualization of the efficiency of different measures and, more specifically, of these measures with the greatest cost efficiency in terms of reducing food waste volumes or abating carbon emissions. It is based on the costs for reducing 1 ton of food waste or 1 ton of carbon emissions as it plots the cost of each of the measures against the cumulative amount of waste saved by the various measures. The waste diversion or emissions abatement potential of each measure is hereby visualized (Defra, 2012; ReFED, 2016a).

Along the same lines as ecological or food waste efficiency, social efficiency of for example a donation measure can be calculated as the cost for donating 1 meal.

In line with the benefit-cost ratio for monetary efficiency, one could also calculate how much food waste can be reduced, how much emissions can be abated or how many meals can be donated for each euro or dollar put in.

RESULTS

Food Waste Measures and Their Evaluation in Literature

During Step 1 of the literature search, a wide range of measures was found, covering the various players and actors along the food chain from primary production, over storage and processing, retail and wholesale to private consumers and OoH consumption. **Supplementary Table S1** gives an overview of over 200 collected measures. To deal with the multitude of measures and/or descriptions of measures found, measures were organized and grouped based on the main theme or aspect the measures focus on. The "Food service—Portion sizes and side dishes" group for example (see group 61 in **Supplementary Table S1**) contains measures related to adapting portion sizes to target groups, offering smaller portion sizes, offering customers to choose their side dishes, and providing bread or butter on demand. The grouping of the many measures found in literature resulted in 75 groups of measures: 73 groups of avoidance measures and 2 groups of redistribution/donation measures.

Supplementary Table S1 further lists which actors or sectors are, according to their literature sources, involved in each measure. Since this paper focusses on methodologies for evaluating measures rather than on evaluating the measures itself, no further analysis of the measures obtained through this exercise is done.

Step 2 of the literature search resulted in a list of 48 measures for which an evaluation could be found, as shown in **Table 1**. Following the focus of this paper, those measures identified in Step 1 of the literature search for which no evaluation could be found, are not considered any further. The practical and academic interventions included in **Table 1** widely differ in scale: whereas some measures were applied at society level, others were applied within one single company. Furthermore, some of the measures listed in the table, refer to a combined measures applied and evaluated simultaneously or grouped into for example a voluntary agreement or a large-scale campaign, whereas others refer to a single intervention.

Out of the 48 (combined) measures, 25 refer to implemented single and combined measures. The other 23 cases concern single interventions that have been proposed but have not necessarily been implemented and for which the evaluation data refers to projected (not measured) food waste reductions, complemented with foreseen (not measured) environmental, economic, and social impacts where applicable.

The last few years have seen a wide range of (proposed) food waste measures, especially in the UK. Many interventions were part of (or followed from) the UK "Love Food hate Waste" campaign set up by the Waste & Resources Action Programme (WRAP) or from voluntary agreements with the retail sector ("the Courtauld Commitment") or with the hospitality and food service (HaFS) sector ("HaFS Agreement"). Many of these measures have been evaluated and a wide range of case studies can be found on the WRAP website. In the US, the multi-stakeholder group ReFED ("Rethink Food Waste through Economics and Data") was set up in 2015 to tackle food waste. In 2016, they presented "A Roadmap to Reduce US Food Waste by 20%" entailing 27 single solutions (12 avoidance, 7 redistribution, and 8 recycling/recovery) together with their projected outcomes for each individual proposed measure (ReFED, 2016a).

It can be noted that many of the evaluations found, concern interventions taking place in the UK and in the US. One important reason being the fact that the literature search was conducted in English. This does however not mean that non-English speaking countries have not evaluated food waste measures. It may merely be that these are to a lesser extent documented in English.

Assessment of Use of Evaluation Criteria in Literature

Step 3 of the literature search involved looking at the extent to which the various evaluation criteria contained in the assessment framework as visualized in **Figure 2** are considered and calculated in literature.

Figure 3 summarizes the number of single and combined measures for which effectiveness, sustainability across the three dimensions and efficiency have been evaluated. Results are given for both the implemented measures with measured outcomes as well as for proposed measures with projected outcomes.

Table 1 provides for a schematic summary of the findings for each (combined) measure assessed. These findings are discussed in the next sections; more details on the actual methodology applied in literature for evaluating each (combined) measure, as well as the associated results, can be found in **Supplementary Table S2**.

It should be noted that all 12 avoidance measures and all 7 donation measures proposed within the ReFED Roadmap are evaluated according to the same methodology when it comes to foreseen food waste reductions, and foreseen environmental, economic, and social effects. As such, the avoidance and donation are taken up together in two single lines in **Table 1**, whereas in

TABLE 1 | Use of evaluation criteria in literature—Summarizing table: Degree to which effectiveness (food waste reduction), sustainability (environmental, economic and social dimension), and efficiency are considered or calculated when evaluating food waste prevention measures.

Measure (Source)	LC stage or sector in focus	Location & scale	Effectiveness	Sustainability across three dimensions							Efficiency			
				Environmental			Economic			Social				
				p	d	i	p	d	i		m	fw	e	s
• Imperfect produce: co-op "Fruta Feia" buys ugly produce from farmers and sells it to consumers through delivery points (Ribeiro et al., 2018)	Agric.	PT, 1 co-op	+	+	+	+	+	–	+	+	+	–	–	–
• Reduced storage temperature for cheese, dairy, deli, and meat (Eriksson et al., 2016)	Retail	SWE, 6 supermarkets	+	+	–	+	+	–	+	–	+	–	–	–
○ Better use of fridges (WRAP, 2013b, 2015; Brown et al., 2014b)	Households	UK, society	+	+	–	+	+	-	+	–	+	–	–	–
○ Freezing at home (Brown et al., 2014a)	Households	UK, society	+	+	–	+	+	–	+	–	+	–	–	–
• Love Food Hate Waste (LFHW) campaign: large-scale communications campaigns, local engagement and changes to products, packaging, labeling, media advertising (WRAP, 2015; Hanson and Mitchell, 2017)	Households, authorities, businesses	UK, society	+	+	+	–	+	+	+	–	+	–	–	–
• Courtauld Commitment—Voluntary agreement (phase 1 and 2). Example measures: setting of clear targets; communication campaigns; improved packaging; community engagement and support; design changes; improved forecasting in retail; provision of tools, guidance and support to supply chain (WRAP, 2010, 2013a,c)	Households, supply chain	UK, society and business level	+	+	+	–	+	+	?	–	–	–	–	–
○ Novel portion packs for fresh meat (WRAP, 2015)	Households	UK, society	+	–	–	–	–	–	+	–	–	–	–	–
• Campaign "Food: Too Good to Waste (FTGTW)": behavior change strategies and tools, messaging and outreach tools (EPA, 2016)	Households	US, society	+	–	–	–	–	–	+	–	–	–	–	–
• Bin Cam system capturing and sharing images of waste to online platform (Thieme et al., 2012; Comber and Thieme, 2013)	Households	US, 4 shared households	–	–	–	–	–	–	–	–	–	–	–	–
• Written messages in student dining hall reminding diners to "eat what you take" (Whitehair et al., 2013)	OoH, university dining	US, 1 mensa	+	–	–	–	–	–	–	–	–	–	–	–
• Using 2nd grade vegetables in commercial kitchens (Lynnerup, 2016; Teuber and Jensen, 2016)	OoH	DK, 8 industrial kitchens	+	–	–	–	+	–	+	–	+	–	–	–
• Reduce amounts of food being ordered or prepared; change menus (more child friendly), reduce continuous availability of food on the buffet (Schmidt et al., 2018)	OoH, schools	DE, several schools	+	+	–	–	+	–	–	–	(+)	–	–	–
• The business case for hotels: measure FW, engage staff, rethink the buffet, reduce food overproduction, and repurpose excess food (Clowes et al., 2018b)	OoH, hotels	Global, 42 hotel sites in 15 countries	+	–	–	–	+	+	+	–	+	–	–	–
• The business case for catering: measure FW, engage staff, start small and get creative, reduce overproduction, and repurpose excess food (Clowes et al., 2018a)	OoH, catering	Global, 86 catering sites in 6 countries	+	–	–	–	+	+	+	–	+	–	–	–
• The business case for restaurants: measure FW, engage staff, reduce overproduction, rethink inventory and purchasing practices, and repurpose excess food (Clowes et al., 2019)	OoH, restaurants	Global, 114 restaurants, 12 countries	+	–	–	–	+	+	+	–	+	–	–	–
• Mobile catering in hospitals (Snels and Wassenaar, 2011; Kranert et al., 2012)	OoH, care	NL, 1 hospital	+	–	–	–	+	–	+	–	–	–	–	–

(Continued)

TABLE 1 | Continued

Measure (Source)	LC stage or sector in focus	Location & scale	Effectiveness	Sustainability across three dimensions							Efficiency			
				Environmental			Economic			Social				
				p	d	i	p	d	i		m	fw	e	s
• Trayless system in a buffet-style university dining hall (Thiagarajah and Getty, 2013)	OoH, university dining	US, 1 mensa	+	–	–	–	–	–	–	–	–	–	–	–
• University dining hall: education campaign (Ellison et al., 2017)	OoH, university dining	US, 2 mensas	+	–	–	–	–	–	–	–	–	–	–	–
• Smart scale—Tracking FW with LEANPATH. Case study: Intel's corporate cafeterias (City of Hillsboro, 2010)	OoH, business cafeteria	US, 2 cafeterias	+	+	+	–	+	–	+	–	–	–	–	–
• Smart scale RESOURCE MANAGERFOOD to monitor FW; smaller portions on buffet, changes in buffet refilling, staff awareness (Leverenz et al., 2016)	OoH, hotel	DE, 1 hotel	+	–	–	–	+	–	–	–	–	–	–	–
• Smart scale WINNOW to monitor FW in IKEA (Winnow, 2018a,b)	OoH, restaurant	BE & NL, both 1 business	+	+	?	–	+	–	–	–	–	–	–	–
• Nudges: reduce plate size and put signs at buffet (Kallbekken and Sælen, 2013)	OoH, hotels	NO, 14 hotels (7 per nudge) + 38 hotels in control group	+	–	–	–	–	–	–	–	–	–	–	–
• Nudges: smaller plate size at buffet (Wansink and van Ittersum, 2013)	OoH, restaurant	US, 43 guests in 1 restaurant	+	–	–	–	–	–	–	–	–	–	–	–
• Use of disposable vs. permanent plates (Williamson et al., 2016)	OoH, lab test + school & university buffet	USA, 2 lab tests + 3 field tests (buffet lunch at school and university)	+	–	–	–	–	–	–	–	–	–	–	–
• Informational and normative prompts in restaurants (related to leftover take-away; Stöckli et al., 2018a)	OoH, restaurant	SWI, business	+	–	–	–	–	–	–	–	–	–	–	–
◦ Reduce plate waste by bread on demand, bulk meal delivery, choice of portion size, menu options or quicker status update (Dias-Ferreira et al., 2015)	OoH, hospital	PT, 1 hospital (8,000 meals)	+	+	+	–	+	+	–	–	–	–	–	–
• Improved meal presentation (Navarro et al., 2016)	OoH, hospital	IL, 1 hospital, 206 patients (1/2 control group)	+	–	–	–	–	–	–	–	–	–	–	–
• Redistribution of food to charity (Cicatiello et al., 2016)	retail	IT, 1 supermarket	+	+	–	–	+	–	+	+	+	–	–	–
◦ REFED roadmap with 12 avoidance measures (each of them evaluated separately). Example measures: consumer education, waste tracking, trayless dining, packaging adjustments, cold chain management (ReFED, 2016a,b)	Entire food chain	US, society and business	+	+	+	–	+	–	+	–	+	+	–	–
◦ REFED roadmap with 7 redistribution measures (each of them evaluated separately). Example measures: donation transportation, donation tax incentives (ReFED, 2016a,b)	Entire food chain	US, society and business	+	+	+	–	+	–	+	+	+	+	–	–

(Continued)

TABLE 1 | Continued

Measure (Source)	LC stage or sector in focus	Location & scale	Effectiveness	Sustainability across three dimensions							Efficiency			
				Environmental			Economic			Social				
				p	d	i	p	d	i		m	fw	e	s
• HaFs Hospitality and Food service Agreement—Voluntary agreement with combined measures. Example measures: setting of clear prevention and waste management targets; define baseline and set up implementation plan; staff awareness, FW monitoring, changes in amounts of food prepared/served; better menu planning; maximize ingredient use (WRAP, 2014, 2017)	OoH	UK, sector	+	+	–	–	+	+	–	–	–	–	–	–

"+" considered, "–" not considered, "?" not clear, "(+)" considered to a limited extent, "n.a." not applicable.
For the environmental and economic assessment, a differentiation is made into the consideration of avoided embodied or product-related impacts/costs (p), avoided disposal impacts/costs (d), and implementation impacts/costs (i).
*For efficiency calculations, a differentiation is made into economic or monetary (m), food waste (fw), ecological (e) or social (s) efficiency. The non-exhaustive table contains both implemented measures (•) as well as proposed measures with projected outcomes (○), with a focus on Out of Home (OoH) sector. Full details on the applied methodologies as found in literature, as well as the results, are provided for in **Supplementary Table S2**.*

the analysis they count as 19 separate measures with different projected outcomes.

Effectiveness

For 47 out of 48 (combined) measures listed in **Table 1**, an assessment was made of the effectiveness of an intervention, thereby quantifying (projected) food waste reductions. The only measure for which no actual data on food waste reductions was given (even though it seems it was monitored), is the implemented measure using a so-called "Bin-Cam" which captures and shares images of waste on an online platform (Thieme et al., 2012; Comber and Thieme, 2013). Focus of this measure was assessing impacts on awareness and self-reflection, as well as analyzing social influences rather than actual food waste accounting.

Sustainability Across Three Dimensions

Environmental dimension

Figures 4, **5** show the number of single and combined measures for which environmental aspects are considered during the evaluation. **Figure 4** hereby focusses on each sub-criterion on itself, whereas **Figure 5** focusses on the combination of sub-criteria assessed simultaneously.

The literature search has shown that for 16 out of 25 (combined) implemented measures, and for 1 out of 23 proposed measures, no environmental assessment whatsoever was conducted. The (expected) embodied impacts of the food that no longer goes wasted was calculated for the other 9 implemented and 22 proposed measures. For four implemented measures, the environmental savings related to avoided disposal were also taken into account, next to the embodied impacts. For the proposed measures, this was the case for 20 measures.

Only four cases consider environmental impacts directly or indirectly resulting from the implementation of measures. In three cases, implementation impacts related to electricity use from fridges or freezers were considered next to the embodied emissions of food no longer wasted. This concerns foreseen changes in electricity use from reducing storage temperature of refrigerated items and placing additional items in household fridges (WRAP, 2013b, 2015; Brown et al., 2014b), foreseen changes from freezing food by households to be consumed later on (Brown et al., 2014a), or changes in electricity use from reducing storage temperature at retail level (Eriksson et al., 2016). Avoided disposal was not assessed in these cases.

Only one case, the "Fruta Feia" co-op in Lisbon (Portugal) which buys "ugly" produce form farmers and sells it to consumers, takes into account all three impact elements. The implementation impacts hereby consider additional transport for bringing the ugly produce from the farm to a consumer delivery point, as well as the production of bags and baskets used for distribution (Ribeiro et al., 2018).

Economic costs or benefits

The literature search has shown that 9 out of 25 implemented measures did not take into account any economic aspect in their evaluation; the proposed measures with projected outcomes all performed some kind of economic evaluation (**Figure 6**).

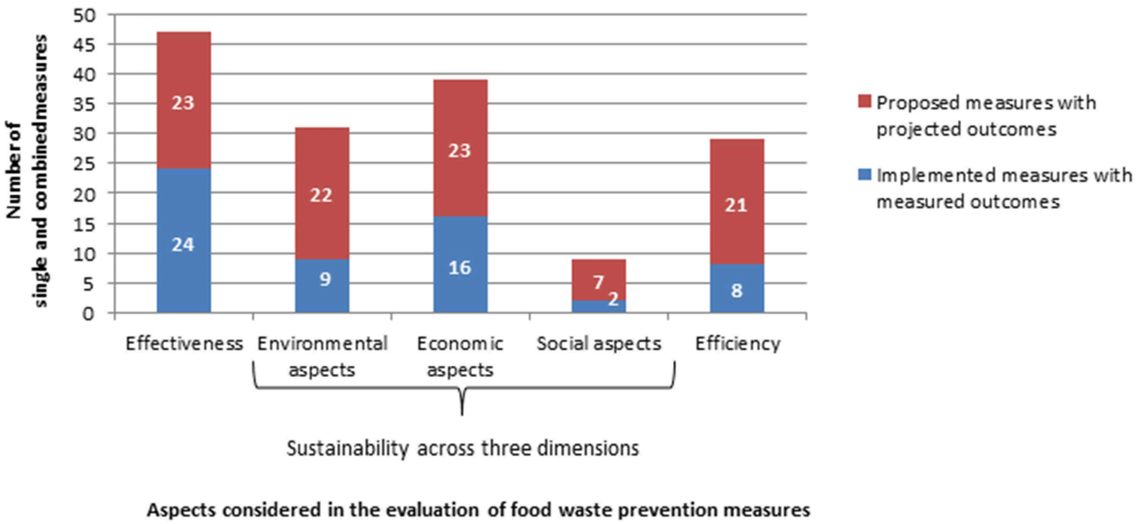

FIGURE 3 | Number of (combined) measures for which effectiveness, sustainability across the three dimensions and efficiency has been evaluated. Overall, 25 implemented single and combined measures, and 23 single proposed measures with projected outcomes are assessed.

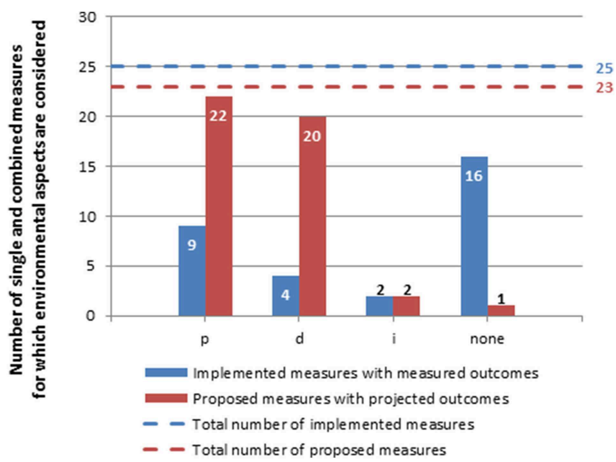

FIGURE 4 | Consideration of environmental aspects in the evaluation of food waste prevention measures: number of single and combined measures for which avoided embodied or product-related impacts (p), avoided disposal impacts (d), and implementation impacts (i) are assessed.

In 37 of the (combined) implemented and proposed measures, the cost or value of the food that no longer ends up in the bin has been calculated. This is mainly done based on market prices at producer or retail level; the exception being the proposed donation solution from the ReFED Roadmap for which the expected value of saved and donated food is based on data from the US food banks network "Feeding America."

For six implemented (combined) measures and one proposed measure with projected outcomes, the (expected) avoided costs for waste disposal were also taken into account next to avoided embodied costs (**Figure 7**). Note that the ReFED roadmap only considers expected avoided disposal costs for recycling/recovery solutions, not for avoidance or donation measures (ReFED, 2016a); hence the "–" in **Table 1**.

Costs or benefits directly or indirectly resulting from the implementation of measures have been considered in in total 33 (combined) measures. These refer to investments in logistics, website and computer hardware and recurring costs for transport and personnel (Ribeiro et al., 2018); (expected) additional costs for electricity use from better use of fridges at household (WRAP, 2013b, 2015; Brown et al., 2014b) or retail level (Eriksson et al., 2016); expected additional costs for electricity resulting from freezing food in households to be consumed later on (Brown et al., 2014a); campaign costs for the "Love Food Hate Waste" campaign in the UK (WRAP, 2015; Hanson and Mitchell, 2017) and for the "Food: Too Good to Waste" campaign in the US (EPA, 2016); expected packaging costs for novel portion packs for fresh meat (WRAP, 2015); time spent for trimming second grade vegetables in commercial kitchens (Lynnerup, 2016); time spent for weighting food waste using a smart scale in a business cafeteria (City of Hillsboro, 2010); cost for using smart scales for measuring food waste in restaurants, hotels and catering businesses, as well as other equipment costs, costs for staff training and consulting, and costs associated with menu redesign (Clowes et al., 2018a,b, 2019); personnel savings from mobile catering in hospitals (Snels and Wassenaar, 2011); costs for recovery of food fit for consumption from supermarkets and redistribution to charity (Cicatiello et al., 2016); and projected initial capital expenditures and annual operating expenses throughout the US society and businesses for all 19 prevention interventions proposed within the ReFED Roadmap (ReFED, 2016a).

Only in a limited number of cases all three cost elements of a (combined) measure were considered. This is the case for the evaluation of the UK "Love Food Hate Waste" campaign (WRAP, 2015; Hanson and Mitchell, 2017) and the three Champions

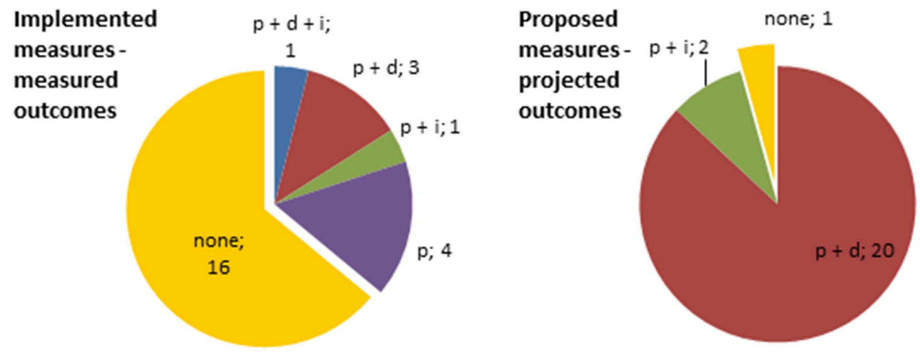

FIGURE 5 | Consideration of environmental aspects in the evaluation of food waste prevention measures: number of single and combined measures for which avoided embodied or product-related impacts (p), avoided disposal impacts (d), and implementation impacts (i) are simultaneously assessed.

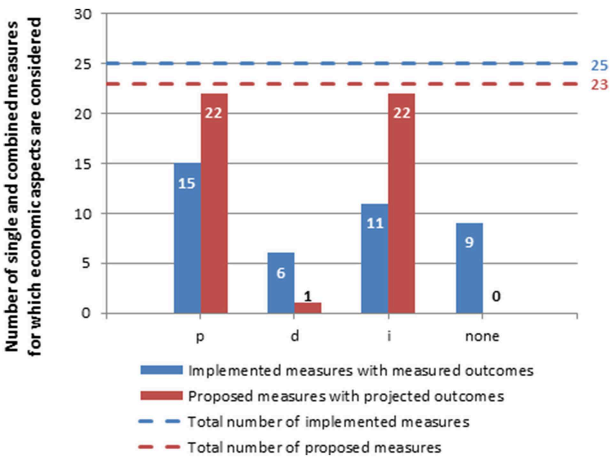

FIGURE 6 | Consideration of economic aspects in the evaluation of food waste prevention measures: number of single and combined measures for which avoided embodied or product-related costs (p), avoided disposal costs (d), and implementation costs (i) are assessed.

12.3 publications entailing various measures and stressing the financial business case for reducing food waste and losses in restaurants, catering, and hotels (Clowes et al., 2018a,b, 2019).

Social impacts

Social effects have been considered in only nine cases.

When it comes to implemented measures, a social life cycle assessment was performed for the Portuguese "Fruta Feia" project that commercializes imperfect produce. The assessment includes the project's contribution to local employment and community engagement, revenue for local farmers, staff working hours, and the possibility for consumers to buy produce at low prices. Finally, its awareness raising effect is mentioned, resulting in project replication in other regions (Ribeiro et al., 2018). Cicatiello et al. (2016) recovered food waste in supermarkets by redistributing food that is still perfectly fit for consumption to charity. Based on the amounts of food recovered, the authors calculated the number of full meals and dessert and bread portions that could be prepared on a daily basis.

When it comes to proposed measures with projected outcomes, the ReFED roadmap calculates the projected number of meals to be recovered for each of the seven donation measures proposed in the roadmap. Additionally, the Roadmap lists the expected number of jobs that will be created for three out of seven donation measures (ReFED, 2016a).

Efficiency

Efficiency calculations were only performed for 8 out of 25 implemented (combined) measures (**Figure 8**), even though in some cases the data needed to perform such calculations was available. For proposed measures with projected outcomes, efficiency was calculated in all but two cases.

Economic or monetary efficiency

The investment pay-back period for the Portuguese "Fruta feia" project has been calculated, and this for two scenarios, namely in case of one or three consumer delivery points (Ribeiro et al., 2018). Additionally, the authors calculated the Social Return on Investment (SROI) to assess the project's contribution to society by monetizing the economic, environmental and social value created. Carbon emissions were hereby assigned a value of €52.7 per ton CO_2. The SROI was found to be positive at all times. Thus, for every €1 invested, the social value generation is higher than €1.

Net (expected) benefits resulting from the value of foods no longer being wasted and additional costs from electricity use by fridges or freezers were calculated at household (WRAP, 2013b, 2015; Brown et al., 2014a,b) and retail level (Eriksson et al., 2016). Net benefits were further also calculated for use of second grade vegetables in commercial kitchens, based on the price of the raw products and the time spent for trimming these second grade vegetables (Lynnerup, 2016).

The benefit-cost ratio was applied for evaluating the Love Food Hate Waste (LFHW) campaign in the UK (WRAP, 2015; Hanson and Mitchell, 2017). Benefits hereby referred to avoided disposal costs for local authorities and savings for households in terms of avoiding throwing away food (embodied

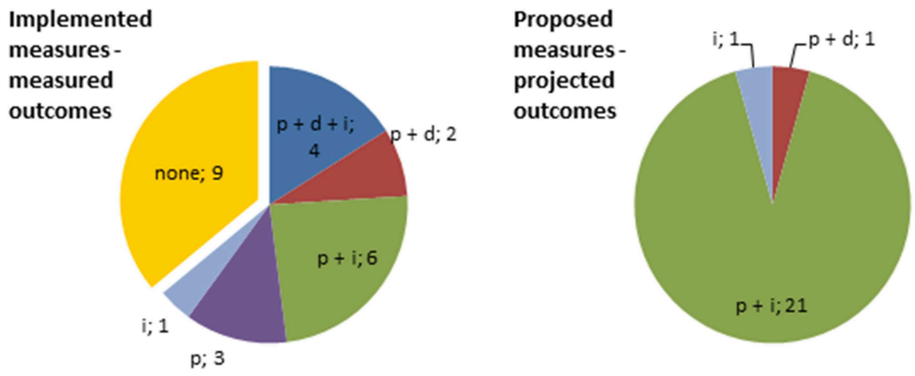

FIGURE 7 | Consideration of economic aspects in the evaluation of food waste prevention measures: number of single and combined measures for which avoided embodied or product-related costs (p), avoided disposal costs (d), and implementation costs (i) are simultaneously assessed.

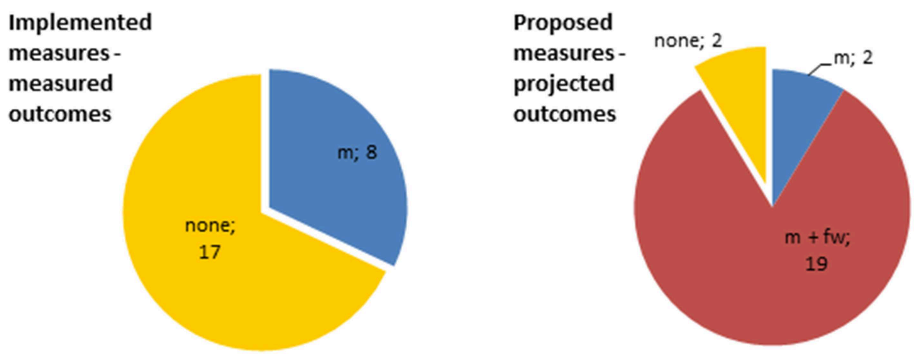

FIGURE 8 | Consideration of efficiency in the evaluation of food waste prevention measures: number of single and combined measures for which economic or monetary (m), food waste (fw), ecological (e) or social (s) efficiency are simultaneously assessed.

economic retail value of food that is no longer wasted). Costs on the other hand, referred to the costs of the campaign itself, namely all expenditures by WRAP, local authorities, Courtauld Commitment signatories, and community groups. Based on this approach, they concluded that every £1 spent by the public and private sector contributed to over £250 of savings. Ecological efficiency was not calculated even though environmental impact savings calculations were made.

The benefit-cost ratio was also applied in the Champions 12.3 publications on the business case for reducing food waste and loss by hotels, catering and restaurants (Clowes et al., 2018a,b, 2019). On average, every $1 spent in hotels and restaurants, realized a return of $7. In the catering business, the average return was found to be $6. Based on these data, the Return on Investment (ROI) was calculated as well as the investment payback period. Within 2 years, 95% of the hotels, 80% of the catering companies and 89% of the restaurants had their investments paid back. Since the ecological savings brought about by the food waste measures were not calculated in the first place, no linkage could be made to the ecological efficiency of the measures in each sector.

In its case study to recover food waste from an Italian supermarket and redistribute it to charity, Cicatiello et al. (2016) calculated the efficiency of the intervention by putting the investment costs against the value of the food recovered. For each € 1 invested in the project, about € 4.6 worth of food could be donated.

Based on the upfront and operating expenses (costs) and the cost savings and revenues (benefits) associated with each solution, ReFED (2016a) calculated the expected annual net economic value associated with each of the 19 proposed avoidance and donation solutions put forward. Combining these 19 prevention solutions with the 8 proposed recycling/recovery solutions, ReFED states that with a $18 billion investment, the Roadmap is expected to yield $100 billion in societal Economic Value over a decade (ReFED, 2016a).

Food waste efficiency, ecological efficiency, and social efficiency

Specific calculations indicating food waste efficiency in terms of costs per kilogram of food waste prevented tend to be missing even though the needed data was often available. The only exception is the ReFED roadmap which, based on per unit costs, visualizes the waste diversion potential of all solutions under study (including recycling/recovery solutions) using a MAC curve. The curve "ranks all 27 solutions based on their cost-effectiveness, or societal Economic Value generated per ton of waste reduced, while also visualizing the total diversion potential of each solution" (ReFED, 2016a).

In none of the cases, ecological efficiency was calculated. Following monetization of the emission savings, the study on the Fruta Feia project did however incorporate ecological impacts into its monetary efficiency calculations (Ribeiro et al., 2018).

Similarly, none of the cases calculated social efficiency even though it is implicitly taken on board by Cicatiello et al. (2016) through its monetary efficiency calculations stating that each euro invested resulted in €4.6 worth of food being donated.

Multi-objective or pareto optimization

Cristóbal et al. (2018) propose a novel methodology, based on LCA and mathematical programming, to visualize efficiency and help decision makers identify the most preferable measure. The model involves multi-objective optimization (or Pareto optimization) of environmental and economic objectives. Taken into consideration are the economic costs associated with each measure, the total budget available for reducing food waste, and the total environmental impacts that can be avoided by implementing the measure (and thus by reducing food waste). The model aims at maximizing environmental savings while constraining the costs of the measures within the limited budget available. Afterwards, a Pareto front can be obtained whereby each point in the Pareto front or graph corresponds to a different combination of measures that for each budget maximizes the total environmental impact avoided.

Using a selection of the 27 solutions mentioned in the ReFED roadmap, Cristóbal et al. (2018) performed a multi-objective optimization of the total environmental impact avoided (TEIA) by each measure within the constraints of a specific budget. Doing so, the authors identified which actions to prioritize for obtaining the highest TEIA, and this for 16 scenarios with each a specific budget available.

DISCUSSION

Main Findings

The present paper has shown that a wide range of measures and activities is being proposed, both at scientific as well as at practical level, and this for all stages and actors along the food chain. In total, over 200 measures were identified through the first step of the literature search.

The second step of the second literature search showed that only for a limited number of measures, an evaluation was conducted. The measures for which an evaluation was available refer to both single measures (such as monitoring of food waste in a commercial kitchen) as well as combined actions (such as voluntary agreements or large-scale campaigns). Based on the analysis made, it seems that not all measures found during Step 1 of the literature search have been evaluated. However, this paper is based on the rapid review approach as a less time-consuming alternative to a systematic review. This resulted in non-exhaustive lists of proposed and/or evaluated food waste measures which may not capture the full spectrum of measures (and their evaluations) being available in literature. Additionally, due to language restrictions in the literature search, the results are biased toward measures and their evaluations published in English (and German). As such, no statements can be made at this point on the percentage of measures for which an evaluation has been conducted.

Effectiveness or Food Waste Reduction Potential

In total, evaluations were found for 48 (combined) measures with 25 of them referring to implemented measures and 23 to proposed measures with projected outcomes. The collected evaluations all include information on the food waste reductions achieved by the measure applied or proposed, with the exception of one measure for which monitoring of food waste reductions seemed to be present but for which no data was published.

For the purpose of this paper, no analysis was made whether or not targets were set for each (combined) measure and to what extent these targets were (or will be) achieved.

Sustainability: Environmental Dimension

When it comes to environmental evaluation of measures, avoided embodied impacts associated with food waste reductions were considered in 65% of the cases and avoided disposal impacts were calculated in 50% of the cases. Implementation impacts on the other hand were only regarded in 8% of the cases. There are however differences in how implemented and proposed measures are evaluated. In case of implemented measures, avoided embodied impacts are only assessed in 36% of the (combined) measures whereas this percentage goes up to 96% in the case of proposed measures. Similarly, avoided disposal impacts are assessed in 16% of the implemented measures and 87% of the proposed measures. Consideration of implementation impacts is comparable with 8% for implemented measures and 9% for proposed measures.

In total, only four cases considered environmental implementation impacts. We could however expect (minor) changes in environmental impacts for other measures as well in case for example operational parameters such as water and electricity use change, in case more or other packaging is applied to increase shelf life or improve portioning, or in case food is donated to charity requiring additional transport.

The lower share of implemented measures having received an environmental evaluation as compared to the proposed measures may indicate that making projections for foreseen impact reductions is easier than actually measuring and calculating impact savings for implemented measures in practice.

Looking at the combinations of environmental evaluation criteria simultaneously considered and thus at the completeness of the environmental evaluation performed, only one study had a complete environmental evaluation whereby all three environmental impact elements (product-related, avoided disposal and implementation impacts) were assessed. For 30 (combined) measures, only one or two out of the three environmental impact elements were considered (incomplete evaluation), whereas for 17 (combined) measures, the environmental assessment was missing as a whole (evaluation missing).

Sustainability: Economic Dimension

More information was found for economic costs and benefits associated with food waste measures. In 77% of the cases, the economic value of the food that is no longer being thrown away is calculated; avoided disposal costs are calculated in 15% of the cases. Specific costs associated with the implementation of measure(s) are assessed in 69% of the collected (combined) measures. We hereby note that for two of these cases, these were the only costs provided as embodied cost savings or savings from avoided waste disposal were not taken up.

Here as well, discrepancies are found in how implemented measures are evaluated as compared to proposed measures with projected outcomes. For both avoided embodied costs and implementation costs, a lower share of the implemented measures take into account these sub-criteria in their evaluation (respectively 77 and 69% as compared to twice 96% for the proposed measures). The avoided disposal costs on the other hand are more frequently addressed in the evaluation of implemented measures (24% as compared to only 4% for proposed measures) as none of the 19 prevention solutions in the ReFED roadmap takes this into consideration.

Looking at the completeness of each economic evaluation, four implemented measures were evaluated using all three economic cost elements (product-related, avoided disposal, and implementation costs), resulting in a complete evaluation. For 12 implemented and all 23 proposed measures, one or two out of three cost elements were taken into account (incomplete evaluation), whereas for nine implemented measures, the economic evaluation was missing as a whole.

In general, the "implementation costs and impacts" sub-criterion is more frequently considered in the economic evaluation than it is in the environmental evaluation. Unfortunately, our literature search did not allow for drawing conclusions on the reason behind this. One explanation may be that the (expected) environmental impacts associated with the implementation of a specific measure are harder to calculate than the economic ones. It may however also be that practitioners are less aware of the importance of including this factor in their evaluation.

Sustainability: Social Dimension

Only nine measures considered social effects, reporting job creation, number of meals saved through donation, or a combination of both.

Efficiency

Many studies omitted efficiency calculations even though the necessary data was available. Economic or monetary efficiency was calculated in 60% of the collected (combined) measures, mostly by calculating net benefits or the benefit-cost ratio. Again, the share of implemented measures for which monetary efficiency was calculated (32%) was lower than the share of proposed measures (91%).

None of the studies under research calculated ecological or social efficiency.

Food waste efficiency on the other hand was calculated in the ReFED roadmap, with results for all solutions being visualized in a MAC curve. This results in 40% of all measures considering this criterion, or 83% of the proposed measures (and 0% of the implemented measures).

One study provided for a novel approach in optimizing avoided environmental impacts and measure implementation costs within budget constraints using Pareto optimization.

Framework for Evaluating Food Waste Actions and Selection of Evaluation Criteria

Quantitative Criteria

The evaluation criteria considered in the present paper are limited to quantitative criteria such as effectiveness, sustainability across three dimensions, and efficiency. Both effectiveness and sustainability across three dimensions are also taken up in the JRC reporting template for evaluating food waste prevention measures under the overarching heading of the evaluation criterion "efficiency" (EC-JRC, 2018a,b). It is not clear if specific efficiency calculations as considered within the context of the present paper are also to be reported within the JRC reporting template. The JRC template further includes the additional aspect of "outreach impact" as one of the sub-criteria for assessing efficiency of measures (EC-JRC, 2018a,b).

Qualitative Evaluation Criteria Complementing Quantitative Criteria

The JRC reporting template further includes the following qualitative and descriptive criteria: quality of the action design (problem identification; setting of aims, objectives, and key performance indicators; implementation plan), sustainability over time (continuity of the action; long term strategic plans), transferability and scalability (ability to be transferred from one place/situation to another; ability to grow or to be made larger), and inter-sectorial cooperation (EC-JRC, 2018a,b, 2019).

The assessment performed in the context of this paper focussed on quantitative criteria for evaluating food waste prevention measures. Some evaluations found in literature however also included qualitative aspects complementing or replacing quantitative data. In their evaluation of measures addressing food waste in schools for example, Schmidt et al. (2018) indicated the estimated time, labor, and costs that go with a selection of measures as well as staff willingness to implement these measures. Expenses, costs, or willingness to implement the measure are hereby expressed as "low," "average," or "high." In 2018, ReFED published a food waste action guide specifically targeted to the restaurant sector (ReFED, 2018). The guide includes a "Restaurant Solution Matrix" helping restaurants prioritize solutions based on a combination of profit potential and feasibility of each measure. Profit potential refers to the net annual business benefits and/or cost savings of a given solution, thereby excluding initial investments. Feasibility combines the level of effort (e.g., the behavior, systems, and process changes required) with the initial financial capital needed to implement a solution (ReFED, 2018). The resulting feasibility matrix thus links quantitative data to qualitative data.

Such qualitative data sheds light on existing barriers for implementation and thus provides valuable information for transferring and upscaling measures addressing food waste.

Singling Out Effects

The evaluation of food waste measures is often hampered by the fact that it can be hard to single out the effects of one specific measure, as also pointed out in literature (Stöckli et al., 2018a,b). Multiple interventions are often ongoing at the same time, making it hard to say how much of the food waste reduction is attributable to each specific measure. This paper also identified various combined measures (with some of them being implemented together as a package), for which evaluations were done for all measures together as a whole.

The 19 promising prevention measures proposed within the ReFED Roadmap are evaluated on an individual basis, and projected outcomes are given for each measure. In practice however, it may be harder to isolate the effects of each individual measure as other (possibly less promising) measures may be applied at the same time.

Additionally, there might be societal influences. For its evaluation of the Love Food Hate Waste (LFHW) campaign for example, WRAP (2015) stressed that, next to the campaign, also deep recession and rapidly rising food prices contributed to lowering food waste during the period of evaluation.

Rebound Effect and Market Feedback Links

Next to the direct impacts and costs, some less visible or indirect feedback mechanisms take place when implementing food waste prevention measures. The first one is "the rebound effect." The prevention of food waste in households for example, might result in less money being spent on purchasing food. The money that becomes available can then be spent on other goods or services. The way it is spent, will greatly affect the environmental benefits from preventing the food ending up as waste. In case the money is spent on more environmentally damaging food and non-food products and/or services, the final benefits from food waste reduction are offset, which is called the rebound effect (Rutten et al., 2013; Bernstad Saraiva Schott and Cánovas, 2015; WRAP, 2015; Martinez-Sanchez et al., 2016; Teuber and Jensen, 2016; Beretta et al., 2017; Salemdeeb et al., 2017; Cristóbal et al., 2018; Wunder et al., 2019).

A second issue relates to market feedback links: as food waste prevention measures affect the demand side for food, also the interactions between demand and supply will be affected, thereby having its repercussions on the entire food market system (Britz et al., 2014). These aspects could also be considered when evaluating measures. The present paper did however not look into whether existing evaluations of food waste measures included rebound effects or market feedback links. The JRC reporting template does not consider these criteria either.

Way Forward

To get an insight in ongoing measures, the EU Platform on Food Losses and Food Waste (see above) asked its members and other relevant stakeholders to provide information on existing food waste prevention activities (EU FLW, 2017). Using its reporting template for evaluating food waste measures, the EU JRC is currently evaluating the collected information (EU FLW, 2017; EC-JRC, 2018a). The present paper complements ongoing work at EU level by providing information on the quantitative evaluation of food waste measures (applied within the EU and beyond) available in literature, and more specifically by providing information on the evaluation methodologies applied hitherto.

This paper concludes that there is a great variety in how measures are evaluated in literature. Additionally, in many cases, economic, environmental, or social assessments are incomplete or missing, and efficiency is only seldom calculated. This hampers practitioners and decision-makers to compare food waste interventions, identify trade-offs and prioritize actions. A more aligned approach on which evaluation criteria to consider and how to calculate the associated indicators would give more insight in which actions are most promising. Moreover, more complete information on the effectiveness and efficiency of measures would make incentives for reducing food waste at various levels along the food chain more visible.

To facilitate the evaluation of food waste measures in the future, it is important to determine essential evaluation criteria and how these should be assessed, ideally before the implementation of a measure. This is exactly what the JRC reporting template is working toward to ensure that, from the early start on, the right data can be gathered at the right time, thereby avoiding data gaps.

A reflection on the various evaluation criteria across the different dimensions (effectiveness, efficiency, scalability…) at the very beginning of the development of food waste actions may create greater awareness by those in charge of defining and implementing measures. This in turn might already result in more effective and efficient measures as practitioners might pursue to perform well in all domains, whereas before, they might have only focused on for example the economic benefits of a measure.

This paper therefore calls for a thorough evaluation of proposed and implemented measures tackling food waste, using a harmonized approach based on an agreed set of evaluation criteria. The authors welcome the developments at EU level, in particular the JRC reporting template, and hope both practitioners and researchers will follow or be inspired by this approach to successfully contribute to a reduction of food waste along the entire chain.

AUTHOR CONTRIBUTIONS

YG performed the literature search and subsequent analysis, and wrote the first draft of the manuscript. AW and TS contributed to conception and design of the study, as well as to redrafting the manuscript during the review process. All authors contributed to manuscript revision, read, and approved the submitted version.

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SUPPLEMENTARY MATERIAL

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Food Waste in Primary Production: Milk Loss With Mitigation Potentials

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Sources and quantities of milk loss in primary production are presented in this paper through an analysis of results from a 2018 survey. Responses from 43 dairy farms in Scotland showed that milk losses occurred due to withdrawal periods for veterinary treatment, parlor infrastructure, and lapses in management routine. A partial life cycle assessment detailed flows of milk from cow to farm gate and captured farm inputs such as imported feeds and fertilizers. Incidence of animal health events such as mastitis, that routinely lead to milk withdrawal were quantified alongside strategies carried out by farmers to reduce milk loss. Treatment for mastitis accounted for 76% of all milk withdrawal days and the remaining 24% stemmed from therapies for health events such as uterine disorders and lameness. Withdrawal periods for mastitis treatments averaged 4.5 days, with a mean incidence of 20% of cows in a herd. Across all farms, an average of 98.2% of total milk produced was sold, 0.66% was purposely retained, 0.55% was rejected due to antibiotic residues, 0.5% was lost from parlor to bulk tank infrastructure and a further 0.09% was rejected by the processor. Carbon footprints found greenhouse gas (GHG) emissions averaged 0.849 kg CO_2e/kg across farms for the milking herd. A scenario of 20% fewer withdrawal days reduced GHG's on average by 0.6%. Additional mitigation was attained by reductions in milk loss from parlor infrastructure and the bulk tank, and this showed a 1% reduction in GHG emissions could be achieved through higher volumes of milk sales. Categorizing responses by management system type highlighted differences in proportional losses between all year round housed and conventional grazing regimes. The most predominant health disorder leading to milk withdrawal was mastitis, however losses due to other health events and parlor infrastructure were not insignificant on Scottish dairy farms.

Keywords: dairy, farm, milk loss, LCA, carbon footprint, antibiotics

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INTRODUCTION

While 821 million people on earth are hungry, 1.3 billion tons of edible food is estimated to be lost or wasted, which equates to one third of all food produced globally (1). These circumstances have propelled an interest in reducing losses and waste along the whole food supply chain (FSC), as a means to improving food security. Food waste in the European Union (EU) is estimated to total 88 million tons, or 173 kg per capita per year (2). Food and drink waste estimates for Scotland in 2013 totaled 1.35 million tons, or 252 kg per capita (3). Neither of these estimates include losses stemming from primary production, because of a lack of sufficient data (3). Studies that consider primary production are limited, and those that are available are considered outdated (1, 4–6). Evidence suggests that losses in primary production are not trivial, further knowledge is required and more specifically, primary production waste estimates for products at a national level be quantified (7).

One reason for a lack of primary production data is that food losses and waste at this stage of the supply chain have proven difficult to define. Until recently this has been an issue across food waste studies in general with a plethora of accounting methods and terminology used, which have impeded the comparability of studies (8). In the last decade however there has been a move to harmonize methodologies and standardize accounting practices (9). Guidelines to quantify food waste totals for EU nations, developed through the FUSIONS project, and the Food Loss and Waste Accounting and Reporting Standard (FLW), used to quantify and attribute food waste globally, adopt different approaches to scope (10). This has resulted in inventory differences and gaps in accounting for waste in primary production (6, 7). Consensus on definition and boundaries applied to studies focusing on primary production is yet to be achieved (7). A system boundary for primary production in dairy farming can be defined from when the milk is drawn from the cow to when the milk is delivered to the processor (7). However, milk that leaves the farm gate can still be rejected at the processor gate and sent for incineration if a tanker delivery fails for reasons such as residue limits being exceeded.

Available estimates of milk loss in the literature differ in scope. Estimates of milk production not actually attained by a cow because of illnesses such as mastitis, are included and added to actual physical losses. The FAO suggests milk not collected and sold due to cow illness and unproduced loss is 3.5%. Studies from Nordic countries which focus on actual milk loss due to disease apply the FUSIONs 0.3% as an estimate of milk waste (11, 12). Small samples of Swedish and Finnish farmers estimated they discarded 0.32 and 0.5% of milk produced, respectively, due to antibiotic residues (13, 14). In France, milk loss stemming from farm production to processing was estimated to range from 5.6 to 8.2%, with 3.2% attributed to primary production losses (4, 15).

Dairy cows receive antibiotic treatments for health disorders such as mastitis and metritis (16). Treatments have consequences for food loss and waste but also for environmental outcomes (17, 18). In the EU the European Medicines Agency (EMA) determines maximum residue limits in milk and farmers required to withdraw milk from sale routinely discard it on the premises. On some farms, and generally for financial or convenience reasons, rejected milk is fed to pre-weaned calves (16, 19). This practice has been shown to increase fecal shedding of antimicrobial resistant bacteria (20, 21) and one study found gut bacteria of calves to have increased resistance after consuming milk containing penicillin (22). In the EU, antimicrobials consumed by food producing animals accounts for 70% of the usage of these substances, more than double the amount for humans (23). Reductions in antibiotic use of 12 and 22% were achieved in the EU and UK, respectively, from 2011 to 2014 (24), and one current reduction target for the UK dairy sector is a 20% decrease in total usage (25).

In terms of environmental outcomes, food production is estimated to be attributed to 10–12% of GHG emissions globally (26) and UK and western EU emissions stemming from milk production are 1.2 and 1.4 kg CO_2 e/kg FPCM, respectively (27, 28). These figures are lower than the global average of 2.5 kg CO_2 e/kg FPCM, nevertheless, measures to decrease milk waste will reduce CO_2 emissions. Decreasing losses in primary production should also exert a positive influence on food security.

This study has two objectives, firstly to provide an assessment of milk loss in primary production on dairy farms in Scotland and secondly to estimate possible reductions in GHG emissions corresponding with (a) a 20% reduction in the use of antibiotics; and (b) an additional 50% reduction in milk losses from infrastructure. Flows of milk, from cow to uplift, to farm and processor gate were gauged by survey responses with all possible losses stemming from health disorders and other causes included, whether the loss was intended or not. Detailed information allowed a comprehensive assessment and identification of possible hotspots where reductions in milk loss could be achieved. A 20% reduction was applied as it is equivalent to current targets for the UK dairy sector (25).

MATERIALS AND METHODS

Data Collection and Analysis

A scoping study was carried out using historical Langhill data (29) combined with investigations on SRUC dairy farms to identify potential areas of milk loss. A survey was designed to enable a partial life cycle assessment (LCA) of milk loss stemming from multiple sources on farm. Survey questions aimed to determine the influence of factors such as incidence and type of disease on amounts of milk rejected by farmers. Data relating to potential sources of farm milk loss, production characteristics, feed and fertilizer use, labor, animal health and behavior were collected predominantly via face to face interviews. A pilot survey was carried out at SRUC's Crichton Farm prior to contacting farmers to assess the ease at which responses could be given. Survey questions are provided for reference as supplementary material.

Social Research Approval was gained from Scottish Government (SG) who supplied contact details of 150 dairy farms across Scotland with a herd size >25 milking cows. Letters were sent to 150 farmers to provide an opportunity to opt out of the process. Farmers who didn't opt out were contacted by telephone. A total of 56 possible respondents opted out giving reasons such as they did not have time, however 10 farms were no longer milking cows. Respondents not included in the SG list were contacted through farmers already participating in the survey and a total of 43 interviews were carried out.

A dataset of the 43 survey responses was compiled and analyzed in Excel to create an inventory of annual dairy farm inputs and outputs, with a focus on quantities and reasons for milk loss. Inventory data included respondent attributes such as gender, age, education, succession plans and farm characteristics, for example herd size, average annual yield, calving pattern, replacement rates, and milking regime. Management systems were described as AYR housed, part summer housed or composite. Cows managed in a composite system are housed in the winter and grazed in the summer. Incidence of mastitis, uterine and other health issues such as lameness with accompanying withdrawal periods per cow were recorded to capture all possible disease types whose treatment can lead to milk withdrawal.

Outputs of milk sold, average annual yield per cow, and fat and protein contents were recorded for each farm alongside hygiene indicators such as somatic cell count. Incidence of disease by type and the number of withdrawal days were provided by respondents. Quantities of milk rejected from sale due to milk withdrawal periods required for veterinary treatment, or milk not sold because of a high somatic cell count were reported for each farm. The destination of milk rejected from sale was provided and included quantities of milk fed to calves. Farmers indicated the types of actions they were taking, or could take, to reduce the incidence of health issues leading to milk withdrawal on farm. Respondents were then asked to rate the effectiveness of any actions implemented. Quantities of milk voluntarily retained for calf feeding or for human consumption on farm were recorded. The method of feeding colostrum was identified as directly, indirectly (from frozen), and sold.

Losses from infrastructure, spillages, accidents and bulk tank rejections with reasons and associated penalties were recorded. Respondents provided losses from the farm bulk tank that had occurred in the last year due to lapses in management routine. Rejection by a processor for reasons such as temperature and antibiotic residue were reported over a 5 year period. This was because bulk tanks rejected by a processor did not occur on all farms and were not generally an annual occurrence. Processor rejections were annualized using bulk tank capacity, corresponding to those respondents reporting losses. A bulk tank rejected due to the presence of antibiotic residues would ordinarily be detected upon delivery of a tanker to a processor.

Inventory

LCA is used to determine environmental or other impacts along a product chain by compiling an inventory which encompasses system inputs. LCA is described by international standard ISO:14040 (30) and follows a specific methodical framework consisting of four phases from scope and boundary setting to inventory analysis and impact assessment. Furthermore, where a system delivers more than one product, an allocation methodology can be applied and attributed to each output (30). A "farm gate" boundary used in this study included inputs and outputs related to milk production on farm and avoided complications that can arise once milk leaves a farm (31). **Figure 1** shows the LCA and farm boundaries alongside inputs, outputs and flows of milk through a typical dairy farm.

Functional units, within an LCA, can be defined as a quantifiable measure of the value of the studied system from which the input and output data can be normalized (30). The primary function of a dairy farm is milk production, thus, to account for milk quality and allow meaningful comparisons, fat and protein corrected milk yield (FPCM) is calculated using the following equation (32).

$$\text{FPCM (kg)} = \text{Production (kg/year)} \times [0.1226 \times \text{Fat (\%)} + 0.0776 \times \text{Protein (\%)} + 0.2534]$$

Impact Assessment and Scenarios for Comparison

Results from the inventory were analyzed and scenarios were established to understand milk loss in terms of environmental impact by classifying and modeling the inputs and outputs for each category in terms of Global Warming Potential (GWP) (30). Emissions attributed to climate change are reported in CO_2 equivalents per kg of FPCM output. Carbon footprints, for each of the surveyed dairy farms were estimated using SAC's AgRECalc v1.4 (33) a carbon foot-printing and resource efficiency tool which utilizes IPCC (34) methodology with a PAS2050 (35) accredited version available online. Tier II emission factors are applied for livestock and manure management and Tier I for fertilizer and crop residue N_2O (36).

Farm footprint input variables comprised of milking cows, dry cows, purchased concentrate, forage crops grown, application of fertilizers, and diesel and electricity consumption. Farm purchased concentrates were assumed to be nutritionally similar, with an emission factor of 200 kg CO_2e/ton and diet digestibility of 74% (37, 38). Fresh weight yields of silage, wheat and barley grown in Scotland were estimated to be 21, 12, and 11.6 t/ha, respectively (39). Electricity use was estimated using milk yield because a proportion of farms surveyed operated a mixed farm type (37). Percentages of time allocated to manure management at pasture, slurry or solid manure were estimated using dairy management system type, replacement rate and calving interval. Six surveys were excluded from the carbon foot-printing exercise, as some input variables were incomplete.

Baseline carbon footprints were calculated for each farm and two scenarios were carried out to estimate mitigation potentials. Scenario 1 corresponded to a 20% reduction in the use of antibiotics and was modeled by a corresponding reduction in withdrawal days being brought about by disease prevention. A 20% decrease in farm antibiotic use is equivalent to current targets for UK dairy farms (25). Scenario 2 added a 50% decrease in losses from parlor infrastructure and bulk tank losses brought about through technology and management practices. Production emissions related to specific types of veterinary pharmaceuticals, and their effects once they have been released to the environment, are not routinely included. The farm gate milk price applied to consider the financial effects of increased milk sales was 29.2 p/liter, which represented average farm gate milk price paid between April 2017 and March 2018 (40). Effects of management system on the incidence of disease and milk withdrawal were investigated.

RESULTS

The first section outlines survey responses and summarizes flows of milk produced on Scottish dairy farms. The second section examines the environmental and financial impacts of scenarios to reduce milk loss on farm.

Survey Response and Analysis

Respondents were located across Scotland from Galloway in the southwest to Orkney in the north. The majority of completed

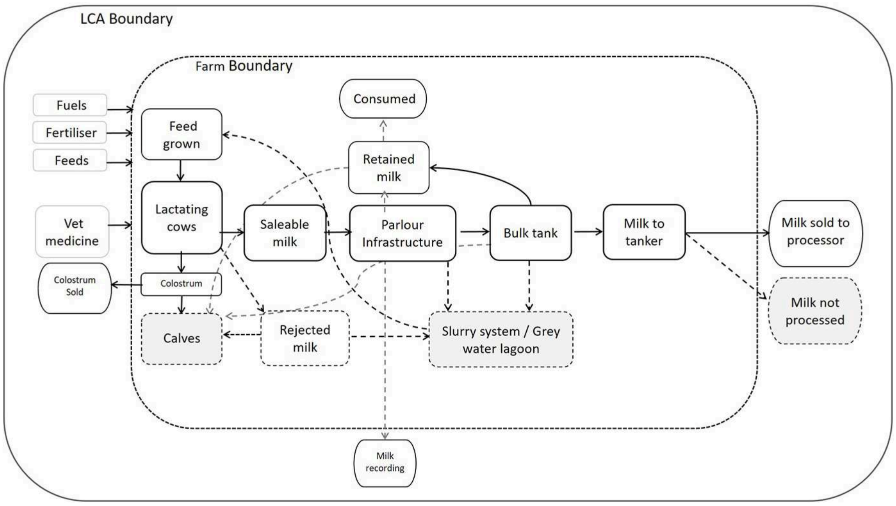

FIGURE 1 | Boundaries considered, and flows of milk through a typical dairy farm.

TABLE 1 | Selected general characteristics of farms participating in the survey.

	Unit	Mean	Standard error	Minimum	Maximum	*n*
Yield	liters	8,315	254	5,000	12,000	43
Fat	%	4.1	0.02	3.9	4.5	43
Protein	%	3.3	0.03	2.9	4.0	43
Lactating cows	n	176	15.5	42	520	43
Dry cows	n	29	2.6	10	80	42
Milking herd	n	205	17.7	56	580	43
Calving interval	days	402	2.9	370	450	38
Farmed land	ha	205	20.0	44	595	43
Grazing	ha	74	9.3	14	200	29
Cut and grazed	ha	93	9.7	25	283	36
Silage /milking cow	kg /day	32	1.6	10	50	41
Silage DM	%	27	0.5	20	35	40
Replacement rate	%	26	1.1	11	46	41
Bulk tank SCC	000's	160	12.5	12	581	43

DM, Dry Matter; SCC, Somatic Cell Count.

surveys arose from areas of higher milk production, such as Dumfries and Galloway and Ayrshire. The forty three completed surveys represent approximately 5% of a total of 902 dairy farms remaining in Scotland (41). Descriptive statistics of selected farm characteristics are shown in **Table 1**. Most survey respondents were male (90%), with only 4 surveys being completed by female dairy farmers. Age groups ranged from under 35 years to over 65 years with over a third of respondents being aged between 45 and 54. Half of all respondents attended education to college level, 12% held university degrees, and 38% did not attend college or university. Three quarters of respondents were owners of their business, while 7% were tenants and 7% were managers. Almost two thirds of respondents inherited their business and half of all respondents had identified a successor.

Holstein Friesian cows were kept by 60% of respondents, and Holstein and Ayrshire cows were the main breeds for 21 and 10% of dairy farmers, respectively. There was a mix of farm types in the sample, with over 30% of responses arising from specialist dairy farms and dairy/beef, dairy/sheep, dairy mixed, comprised 26, 17, and 23%, respectively. Management systems were categorized by farmers as composite (summer grazed winter housed), AYR housed and part summer/high yielder housed and grazing only representing, 49, 28, and 23%, respectively. Mean annual yield per cow averaged across all farms was 8,315 liters. The preferred calving pattern was all year round (AYR), accounting for 93% of respondents and the average calving interval was 402 days (**Table 1**). Some survey questions were not applicable to all respondents, for example, grazing land for cows being housed AYR. Not all respondents recorded measurements such as the dry matter (DM) of forage crops such as silage. No respondents operated with a grazing only management system, this was not surprising, as grass does not grow sufficiently AYR in Scotland.

Milk Loss

Milk was withdrawn from sale due to treatments given to animals for a range of health events. Mastitis, uterine, and lameness and other disorders were attributed to 76, 8, and 16% of all withdrawal days, respectively. Mastitis was the most prevalent disease reported, with a 20% incidence. Withdrawal periods for mastitis were, on average, higher than for other diseases at 5.6 days (**Table 2**). Uterine, lameness and other health disorders requiring milk to be removed from sale accounted for nearly ¼ of total withdrawal days. Dry cow treatment and dry cow teat sealants were given to cows on 98% of farms. These treatments were provided selectively on 49% of farms. Average incidence of high somatic cell count (SCC) was 9% of cows. Twenty three percent of farmers surveyed

TABLE 2 | Disease incidence and associated withdrawal days average and standard deviation.

	Incidence rate of disease			Milk withdrawal (days)	
	Mean	Standard deviation (SD)	Range	Mean	Standard deviation (SD)
Mastitis	0.20	0.02	0.70	5.6	0.33
Uterine disorders	0.07	0.01	0.22	2.8	0.51
Lameness and other	0.07	0.01	0.31	4.3	0.30

TABLE 3 | Descriptive statistics of gross milk production, sales, and proportional loss on farm.

	Mean	Standard error	Minimum	Maximum	Destination
Gross production FPCM (kg)	1,729,892	187,701	233,034	5,882,571	
Sold (%)	98.2	0.002	0.929	0.997	Processor
Retained (%)	0.66	0.002	0	0.047	Consumed on farm
Infrastructure losses (%)	0.46	0.002	0	0.055	Calves / slurry system
Rejected by farmer (%)	0.55	0.001	0	0.022	Calves / slurry system
Bulk tank losses (%)	0.04	0.0002	0	0.007	Slurry system
Rejected by processor (%)	0.09	0.0002	0	0.004	Slurry/waste disposal

FPCM, Fat and protein corrected milk.

reported excluding high SCC milk, for a period averaging 4.5 days.

Milk produced on farm may not be sold for a variety of reasons which can be beneficial or detrimental to the enterprise (**Figure 1**). Total milk production on each farm was calculated by adding the volume of milk sold to quantities of milk retained, milk rejected and milk lost due to infrastructure or other problems. **Table 3** provides descriptive statistics showing average proportions of milk produced, sold, retained, and lost on the sampled dairy farms along with the destination of that milk. Milk voluntarily unsold is retained by the farmer, for human consumption or for calf feeding. Across all surveyed farms, the proportion of milk retained was, on average, 0.7% of total milk production (**Table 3**). However, over 80% of respondents purposely retained milk for consumption. Farmers consumed 1,027 liters per year on average and fed an average of 15,807 liters to calves, which represented 90% of all milk retained.

Quantities of milk rejected because of antibiotic residues arising from veterinary treatment of health disorders were reported by 93% of respondents. Three respondents provided no estimate of amounts of rejected milk even though they had provided disease incidences and withdrawal days for their herds. On average, rejected milk represented 0.6% of total production. Nineteen percent of respondents fed their rejected milk to calves. Total milk rejection on farm averaged 10,750 liters per holding per year, or 43 liters per cow per year and the majority of farmers disposed of rejected milk into the slurry system.

Infrastructure losses of at least one type were reported by 93% of respondents. Total infrastructure losses of all types averaged 3.5 tons per year per farm, or an average of 0.46% of all milk produced. Infrastructure losses were reported to stem from the filter (62%), buffer tank (22%), and from washing through pipes, which was generally carried out after each milking. Losses from spills and accidents were wide ranging. This loss type was reported as never or rarely happening on some farms to happening every 6–8 weeks to daily on others. Zero losses of this type were reported by two respondents, who described feeding all infrastructure and washed through milk to their calves. Respondents indicated that spillages and accidents were generally caused by lapses in management routine and the milk was destined for the slurry system.

Bulk tank losses occurred on 16% of farms and averaged 4,025 liters annually. Farmers indicated that bulk tank losses were caused by lapses in management, such as forgetting to connect pipework or by mistakenly allowing milk containing antibiotic residue to enter the bulk tank. Two farmers who suspected their bulk tank may fail due to antibiotics disposed of their milk in the slurry system to avoid a fine or penalty from the processor. Bulk tank losses were also reported to occur when transferring milk to the tanker, during power cuts, or in extreme winter weather if the tanker could not uplift.

Bulk tank rejections by a processor were reported by 53% of respondents. These rejections were caused by failures of equipment such as a compressor serving the cooling system, or by contamination due to antibiotic residue. Milk rejection because of raised temperature occurred in 35% of bulk tank loss cases and was disposed of into the slurry system before being uplifted. Rejection for antibiotic residue was reported in 65% of cases and usually incurred a penalty in addition to loss of income from milk sales. An annualized average of 2.0 tons of FPCM was estimated to be lost due to antibiotic residue. Penalties can be avoided if a farmer reports a failure to the processor prior to uplift. Frequency of bulk tank rejection ranged from once every 5 years to an annual occurrence. Bulk tank milk containing antibiotic residues would be detected at the processor gate prior to discharging milk from the tanker. A failed tanker would be treated as hazardous waste and disposed of by incineration at a specialist site.

Milk recording was noted by four respondents as a flow of milk from a farm. One respondent reporting a loss of 720 liters/year. Milk recording is carried out on 73% of herds across Scotland, on ∼131,331 cows and each recording requires 35 ml per cow (pers. comm. J. Mathie, Cattle Information Service). Milk recording can be viewed as a voluntary milk retention that aids farm management and herd health. Colostrum was fed directly to the calf by 65% of farmers and was reported to be sold by 1/3 of respondents, for processing into powder.

Impact Assessment

Carbon footprints were carried out to determine the effect on GHG emissions on farm if milk loss could be reduced. Base

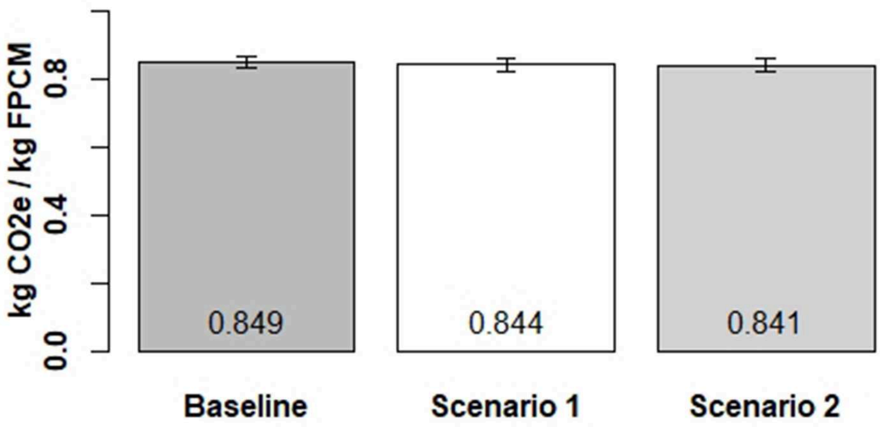

FIGURE 2 | Effect of milk loss reduction on GHG emissions in Scenario 1 and Scenario 2, mean and standard error.

TABLE 4 | Farm indicators by management system type (mean).

	Farms (*n*)	Cows (*n*)	Yield /cow (l)	CM withdrawal (days)	Rejected/cow (l)
Composite	21	158	7,764	5.3	33
AYR Housed	12	289	10,026	6.4	82
Part Summer	10	205	7,420	5.3	29

CM, Clinical mastitis.

TABLE 5 | Descriptive statistics of proportional losses by management system type.

	Composite	Part summer	House AYR
Sold	0.980	0.984	0.986
Retained	0.0092	0.0036	0.0039
Infrastructure losses	0.0051	0.0065	0.0018
Rejected by farmer	0.0048	0.0037	0.0080
Bulk tank losses	0.0002	0.0012	0.0002
Rejected by processor	0.0008	0.0013	0.0004

AYR, All Year Round.

footprints for milking cows on the surveyed farms averaged 0.849 kg FPCM/kg CO_2e (**Figure 2**). In Scenario 1, disease prevention, leading to a 20% reduction in total withdrawal days meant net emissions slightly increased because of the need to cool increased quantities of milk. However, emissions per unit decreased to an average of 0.844 kg in Scenario 1 (**Figure 2**). Reducing withdrawal days by 20% equated to lowering the footprints by 0.6% on average.

In Scenario 2 additional milk sales brought about by fewer infrastructure and bulk tank losses reduced the farm footprints to an average to 0.823 kg (**Figure 2**), a reduction from the baseline of 1%. In Scenario 1, milk sales from farms increased by an average of 1,963 liters, which equated to additional income of £574. In Scenario 2 milk sales increased by 5,330 liters which equated to £1,559 of additional income.

On average, farmers who housed all year round managed larger herd sizes and attained higher yields than those managing composite or part summer housing (**Table 4**). Withdrawal periods for mastitis in AYR housed herds were, on average, 1 day longer and quantities withdrawn greater than in composite or part summer systems. When compared with composite and part summer housed systems, farmers operating AYR housed management regimes sold a greater share of milk because this system type had proportionally fewer losses of milk stemming from infrastructure, and fewer rejections by processors (**Table 5**).

DISCUSSION

This research evaluates causes and amounts of milk loss in primary production on Scottish dairy farms by gathering comprehensive data and conducting a partial LCA. A small proportion of milk is not sold for a variety of reasons, which are ultimately governed by management practices and farm infrastructure. Results captured flows of milk on dairy farms and showed infrastructure and rejected milk influencing losses, which can stem from disease events through to bulk tank failures. Opportunities for improvement were modeled by assessing possible GHG emission reductions corresponding to a 20% decrease in antibiotic use and also by reducing losses further from farm infrastructure. A 20% decrease in antibiotic use is consistent with current targets for reductions in total usage in the dairy sector (25).

Survey results were fairly representative, our sample averages indicated a herd size of 205 and an average annual yield per cow of 8,315 liters, which were close to Scottish averages in 2016 of 199 cows and 7,053 liters (42). Average milk constituents, calving interval, replacement rate and SCC, shown in **Table 3**, are comparable with average key production indicator (KPI) results reported for UK Holstein herds of 4.02% fat, 3.28% protein, 27% replacement, a 400 day calving interval and a 178 herd

SCC (43). Whilst our sample represented only 5% of total farms, the similarity of survey response averages and industry averages suggests that the data gathered is not atypical.

Improving the efficiency of food production can be driven by associations between agricultural management systems and global issues, such as climate change, soil erosion, air pollution, and a loss of biodiversity (44, 45). Carrying out an LCA for agricultural systems may add a layer of complexity because farms utilize multiple inputs, such as natural resources and land and can adopt regionally diverse management practices (46). LCA's of milk production focusing on environmental attributes have been carried out to assess different types of dairy management, such as grazing and housed systems, or to compare organic and conventional regimes (47–50). LCA's can focus on system attributes such as the environmental impact of mastitis (17) or extend the boundary beyond the farm gate to include processing and retail (48, 51). Even though milk loss is accounted for in some studies it is not the focus. As far as we are aware, other figures detailing multiple sources and quantities of milk not sold from dairy farms, are not available.

Where broad data are available, the cause of rejected milk is reported as being mainly due to mastitis, because this disease is the most predominant on dairy farms leading to milk withdrawal (1). Survey results show that milk rejections stemming from treatments for health events such as lameness, uterine and other disorders led to almost a quarter of all withdrawal days on surveyed farms. Red Tractor, a UK food assurance scheme has reformed its standards on the use of antibiotics on dairy farms. Since 2018, Red Tractor requires accurate recording and staff training in the use of medicines, with an annual review of use to qualify for membership (52). Since this survey was carried out, usage of the highest priority, critically important antibiotics on UK dairy farms should now be directed by a veterinary practitioner and must be used as a last resort. One consequence of the restrictions on antibiotic use could be that zero withdrawal critically important antibiotics are substituted with treatments that do require milk rejection. This possible increase in withdrawal days suggest that health events such as metritis and lameness should be included to accurately estimate quantities of milk loss on farm in the future.

In the US a third of dairy farms are thought to feed waste milk to calves, and one UK survey of waste milk feeding practices reported a figure of 83% (16, 53). Our results showed 19% of farmers feeding rejected milk to calves in Scotland. This could be due to awareness of antimicrobial resistant bacteria in feces (20, 21) and pressure from milk buyers to ban the practice. It is possible, however, that pressures could lead to underreporting. Livestock manure applied to soil as a fertilizer provides organic matter, nutrients and microbial populations to grasslands, and is a source of GHG's as organisms decompose and recycle the feces (54, 55). Micro biological and chemical changes to livestock manure as a result of antibiotic treatments have been shown to alter the microbiota of dung beetles, and lead to increased manure methane emissions (56). Further effort should be made to quantify the undesirable consequences of spreading slurry containing waste milk as there could be additional and unforeseen ecological effects.

Further along the FSC, UK pasteurized milk waste stemming from households, shops, transit and processing was estimated to be 7% of all liquid retail sales. Our results indicated 0.55% of milk production was rejected due to antibiotic residue across 5% of the farms surveyed, which averaged over 10,000 liters per farm. If bulk tank rejection and loss amounts were included this would raise the figure further. Information regarding rejection of deliveries at processor gate would improve overall estimates. Greater volumes of milk were found to be rejected in AYR housed systems which had larger herd sizes, although proportionally these farms sold more than composite systems because the amounts of milk intentionally retained and lost from infrastructure were lower. Some farmers reported zero milk losses from infrastructure because washings were used to feed calves. Whilst this practice saves waste, some may argue that the quality and constituents of the feed may be unpredictable.

Product GHG emissions were shown to be reduced by 0.6 and 3.1%, respectively, if losses from rejected milk and from farm infrastructure were decreased. Reducing withdrawal days through prevention and management of disease, spillages, and accidents, could be achieved on farm through a combination of precision technologies and improved management procedures. For example, treatments for mastitis may be unnecessary if an early diagnosis of the disease brought about through technological and management solutions could be achieved. A reduction in losses from infrastructure could be achieved by implementing strict management routines along with up to date technology such as alarms and modern filters in the parlor system. Methods to reduce milk loss in primary production could be targeted by dairy management system type.

Regardless of system type, dairy cows are dried off approximately 8 weeks prior to calving. In the UK until recently, all cows were given routine prophylaxis in the form of antibiotic dry cow treatment and teat sealant. However, widespread use is now being discouraged and non-antibiotic teat sealants are available. If a cow receives prophylaxis at dry off, after calving the colostrum can contain residue for 3 days and Brunton et al. (16) reported that 96% of farms used dry cow antibiotic tubes with 85% of these applying to all cows. Scottish survey results show 98% of respondents utilize dry cow treatment, however only 49% treated all cows, as 49% of farmers used dry cow treatment selectively. Teat sealant was applied to all cows on 63% of farms, whereas it was used selectively on 16% of farms, whilst 21% of farmers did not use teat sealant. A third of respondents used dry cow treatment on all cows, and fed colostrum to calves directly from the cow.

CONCLUSIONS

Survey results demonstrated that milk loss on dairy farms in Scotland stemmed from a range of health disorders and occurred at any stage from parlor to processor due to infrastructure, accidents and spills. Milk loss in primary production was not insignificant and measures should be taken to reduce losses, especially from disease and infrastructure. Progress made to reduce milk loss in primary production will also lower product GHG emissions and should improve food security. Ecological and animal health consequences of milk containing residues from veterinary treatment being fed to calves or entering slurry systems should be further researched.

DATA AVAILABILITY STATEMENT

The datasets generated from survey responses cannot be made available for confidentiality reasons.

ETHICS STATEMENT

The scoping study accessed animal production data and Social Research Approval was obtained from Scottish Government.

AUTHOR CONTRIBUTIONS

MM and MH managed the survey delivery. MM carried out the survey analysis. LT, BT, MM, and MH contributed to concept, methodology, and manuscript preparation.

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An Evaluation of On-Farm Food Loss Accounting in Life-Cycle Assessment (LCA) of Four California Specialty Crops

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The majority of the environmental impacts associated with the agri-food supply chain occur at the production phase. Interests in using life-cycle assessment (LCA) for accounting for agri-food supply chains as well as food losses and waste (FLW) has increased in recent years. Here, for the first time, we estimate production-phase embedded resources and greenhouse gas (GHG) emissions in California specialty crops considering on-farm food losses. We use primary, survey-derived qualitative and quantitative data to consider on-farm food loss prevention and avoided GHG emissions through two different scenarios applied in an illustrative example for processing peach at the production stage. Further, we contribute a mathematical approach for accounting for discrete, unique flows within the net flow of loss in a supply chain, in LCA. Through the detailed LCAs, we identify the hotspots for the four crops as on-farm diesel use, fertilizer application, direct water use, and electricity for irrigation pumping. Impacts from cultivation practices and the additional impacts from on-farm food losses vary significantly by crop. Including the losses in the LCAs resulted in increases in overall resource use and GHG emissions by 4–38% (percent varies depending on the crop type). We used the LCA models and a set of straightforward calculations to evaluate the environmental impacts of a prevention action (a 50% reduction in on-farm food losses) and the secondary use of end-of-life (EOL) biomass from processing peach. The results of this evaluation showed an 11% reduction in GHG emissions compared to the baseline (full harvest). In conclusion, by explicitly including the impacts of on-farm food losses in LCA, we highlight challenges and opportunities to target interventions that simultaneously reduce these losses and the associated environmental impacts in agricultural systems.

Keywords: food loss and waste, prevention, avoided emissions, LCA—life cycle assessment, agricultural production

INTRODUCTION

Life-cycle assessment (LCA) has emerged as a dominant approach to assess the environmental impact of agri-food products (e.g., Corrado et al., 2017; Notarnicola et al., 2017). At the same time, addressing food losses and waste (FLW) is emerging as one of the top priorities in food management for increasing food security and reducing environmental impacts from agricultural production

(Food and Agriculture Organization of the United Nations [FAO], 2013). The importance of FLW on LCA has also been emphasized by researchers (Nemecek et al., 2016; Corrado et al., 2017; Notarnicola et al., 2017; Porter et al., 2018). The studies that include FLW in LCA mostly focus on waste or waste treatment; only two of 222 studies reviewed focus on loss prevention (Laurent et al., 2014). The broader heuristic perspective and a hierarchy preferred management of FLW prioritize prevention (most preferred) while seeking to limit incineration/disposal (least preferred) (e.g., European Union, 2017). The studies that do consider prevention often focus on interventions and impacts at one stage of the food value chain and assume other phases of the supply chain remain the same (Creus et al., 2018).

Different approaches for evaluating FLW in LCA have been proposed, and many analyses utilize consequential LCA, which accounts for the environmental impacts between a baseline scenario and an alternative course of action(s) (e.g., Bernstad and Cánovas, 2015). These approaches recognize that the life-cycle inventories have embedded in them wastes generated along the supply chain, but there is a need to have more explicit, transparent FLW estimations in LCA so FLW interventions can be adequately evaluated (Notarnicola et al., 2017). In turn, this transition in practice needs to be informed by the adoption of more universal frameworks for assessing FLW in LCA consistently along the supply chain (Bernstad et al., 2016; Creus et al., 2018). Creus et al. (2018) present a method based on the (Food and Agriculture Organization of the United Nations [FAO], 2013) calculation that takes into account upstream as well as down-stream stages. The study proposes a standardized calculation that can be applied to any food supply chain to account for the potential impacts of prevention as well as the comparison between prevention actions. In our study, we propose a further modification to the Creus et al. (2018) equation so the net flow (estimated in mass or percentage loss) from the system (as defined by Creus et al., 2018) can be considered on a more granular level for purposes of evaluating multiple flows or products within the net flow of losses at each stage of the supply chain.

Specifically, in this study, we assess biological materials flows from agricultural fields. These losses could be considered as a single mass loss or percentage loss from the system (i.e., as a net flow). However, these biological material losses are inherently diverse in terms of characteristics (composition and constituents) and potential use(s). These material flows are typically composed of both edible and inedible materials. Also, the losses occur at variable times within the season, as well as the lifetime of the production system. For example, on-farm food (fruit) losses in a perennial system like processing peach occur within the year (starting at the point of reproductive maturity) and biomass losses arise both within the year (e.g., due to pruning) and at the end of the orchard life (e.g., through orchard removal).

We focus our work on the production phase. Approximately 71% of the total global carbon impacts and 79% of the overall water impacts that are associated with the food supply chain occur at the point of production (on the farm) as a result of land-use change, soil carbon emissions, and the direct and indirect consumption of fossil fuels to power on-farm operations (Reutter et al., 2017). These global carbon impact and overall water impact estimates do not account for the embedded resources and emissions in on-farm food losses, so they likely underestimate both the environmental impacts and, importantly, the benefits of interventions (Bernstad and Cánovas, 2015).

The significant knowledge gap of annual food losses at the point of production for pre-harvest and harvest phases (Gustafsson et al., 2013; Spang et al., 2019) compels us to fill this information gap as the first step toward improved resource investments in agri-food systems. For the specialty crops included in this study, on-farm loss data collected through semi-structured interviews provide baseline information for the research. It is worth noting available FLW data are generally limited, and it can be challenging to track because of regulatory and reporting requirements, the terminology used to define and categorize FLW, and a range of other reasons (Xue et al., 2017; Porter et al., 2018).

Although we focus on the production phase, food losses occur at all stages of the food supply chain, including pre-harvest and harvest phases, as well as processing, transport, storage, distribution, and disposal. Losses at each of these phases represent not only the physical organic material, but also the embedded water, energy, and material inputs (e.g., fertilizer) and, in some cases, the packaging required to produce, and deliver this food to consumers (Reich and Foley, 2014). For example, Spang and Stevens (2018) explore the water footprint of potato losses at the cultivation stage of the supply chain for seven of the top 10 potato-producing states, based on national level United States Department of Agriculture (USDA) data sets. More detailed regional estimates of on-farm food losses are limited, except for Neff et al. (2018) in Vermont, Johnson et al. (2018) in North Carolina, and Baker et al. (2019) in California. On-farm food loss in northern and central California was further explored with greater emphasis on evaluating the structural drivers leading to losses by Gillman et al. (2019). While providing some useful baseline data for on-farm food losses, none of these studies align their assessment of on-farm food losses for specific foodstuffs with agricultural system LCA. In the following, we provide the first estimation of production-phase embedded energy and materials and greenhouse gas (GHG) emissions in specialty crops in California lost from the supply chain, using primary qualitative and quantitative data. The crops include three annuals (fresh tomato, processing tomato, romaine heads) and a perennial (processing peach). Also, we propose a mathematical approach to account for food loss waste in LCA (described in section Evaluation of On-Farm Food Losses—Calculations and Scenarios).

The study explores the hypothesis that the LCA-based environmental impacts for specialty crops in California vary considerably due to differences in inputs to the cultivation practices as well as the quantity of on-farm food losses. The annual and the perennial crops compared within the study region provide insights on the differences between these crops in terms of impacts from cultivation practices and the additional impacts of on-farm food losses in the region. Also, we evaluate two scenarios for the specialty crops in California using a mathematical approach based on Creus et al. (2018).

Scenario 1 involves on-farm food loss prevention action (a 50% reduction of on-farm losses) applied in an illustrative example for processing peach at the production stage. The second scenario accounts for potentially avoided GHG emissions from end-of-life (EOL) processing peach biomass (a by-product of the system) used for combustion (for energy generation) and incineration (or burning).

Although combustion and incineration (or disposal) are the least preferred options in the FLW hierarchies (e.g., European Union, 2017), it is one of the most likely scenarios for the EOL material for processing peach in California (see section Scenarios 1 and 2 Descriptions), so avoided GHG emissions due to these actions warrant further exploration along with the prevention actions. Also, the on-farm losses from both annuals and perennial systems have a range of potential destinations and secondary uses. We discuss but do not numerically evaluate these options fully due to a lack of data in this area.

Defining Food Loss and Waste

One challenge is the terms "food loss" and "food waste" are inconsistently defined, varying based on multiple factors including cultural practices and food policy and regulations (Evans, 2012). The FAO differentiates food loss from food waste by supply chain segment, with food loss occurring anywhere from the farm through distribution and supply-side retail, and food waste occurring at customer-facing retail and with the consumer (in either home or at foodservice locations) (Gustafsson et al., 2013).

Meanwhile, the USDA applies the term "food loss" to all post-harvest, edible food material that doesn't make it to a consumer, with the subset of "food waste" to signify losses that occur as a result of "human action or inaction" (Buzby and Hyman, 2012). For this paper, we follow the FAO definition and refer to cultivated products left in the field as "losses" rather than as waste. Because these losses occur at the cultivation phase of the supply chain, we see these losses as on-farm food losses. These on-farm food losses are distinguished from post-harvest losses, which may be reported, for example, at a sorting station, in cold storage, or transport. Parfitt et al. (2010), Hebrok and Boks (2017), and Suthar et al. (2019) provide more information on post-harvest losses.

MATERIALS AND METHODS

This research was conducted in the context of a larger project entitled, "Maximizing Farm Resources and Edible Food Rescue" co-funded by the Walmart Foundation and the Foundation for Food and Agricultural Research (FFAR). The goal of the project was to conduct an assessment of on-farm losses for a range of key crops across the United States. The crops evaluated were selected in consultation with our project partners (including the World Wildlife Fund, the Global Cold Chain Alliance, and North Carolina State University) to estimate losses in large-scale cropping systems with different cultivation types (annual and perennial crops) and diverse geography of production. In California, the selected crops represent some of the primary specialty fruit and vegetable crops produced in the state, including fresh and processing tomato, fresh and processing peach, and leafy greens. Complementary studies were conducted in New Jersey (fresh peaches), Florida (processing and fresh tomatoes), Arizona (leafy greens), and Idaho (potatoes). While all of these studies shared the goal of quantifying and understanding on-farm food losses, the California crop study was expanded to include LCAs for the selected crops to directly explore the effect of on-farm food loss on the LCA results and to accurately estimate the environmental impacts of interventions to reduce on-farm food loss and to manage agricultural residues on the farm (in the case of processing peaches).

Goal and Scope Definition

The goal of this LCA study is to characterize the selected California-based cropping systems and the environmental impacts associated with these crops, accounting for on-farm food losses and their management. Based on the evaluation of peer-reviewed literature conducted for purposes of developing this work, we selected the functional unit of 1 kg of cultivated product for ease of comparison with related studies. All resources used and impacts incurred are calculated based on the production of 1 kg of cultivated product. Each production system is accounted for on an annual basis. The perennial system accounts for an 18-years life span but reports the results on a mean annual basis. The packaging is not included in the functional unit. Within specific regions, there is variability in soil conditions and pests (Heller and Keoleian, 2003), weather patterns, and market pressures that can result in on-farm food losses. We do not directly account for these factors in the LCAs as it is beyond the scope of this work.

The system boundary is from the cradle-to-farm gate, including transportation of materials from the manufacturer to farm for all inputs as well as in-field soil emissions from nitrogen (N)-based fertilizers and direct water use (**Figure 1**). The geographic boundary is the growing region within California for each specialty crop.

The total on-farm food losses and life-cycle resources (materials, water, and energy) embedded in these losses are accounted for at the farm gate. Some of these on-farm losses (food, biomass, crop residuals) have secondary uses, e.g., as compost, but may not have established market values within the respective growing regions. Within the LCA methodological framework, if these losses have an established market value, they are accounted for as a co-product. In this study, the on-farm losses are assumed not to have a market value and are considered for as a by-product of the system.

Data Collection

The primary data used to characterize the foreground systems is based on consensus group data collected through the University of California's cost and return studies (e.g., Miyao et al., 2017). These studies define inputs for California processing tomatoes, fresh tomato, romaine heads, and processing peaches for different production years (e.g., 2007, 2011, 2014, & 2017) and regions (Sacramento Valley & Northern Delta, San Joaquin Valley). Also, survey-derived data for tomato (processing and fresh) and in-person communications for processing peach for specific data (e.g., percent use surface water vs. groundwater use) were used,

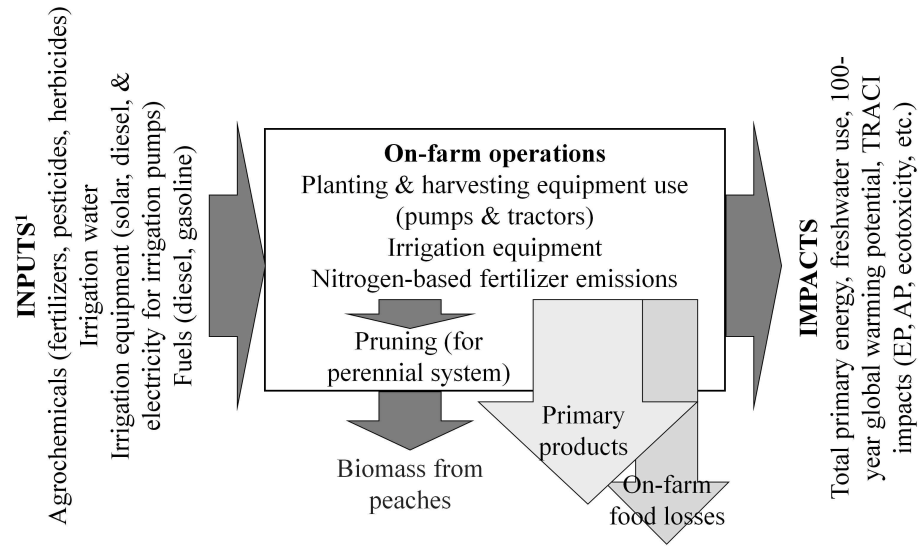

FIGURE 1 | Simplified system boundary. [1]Inputs are accounted for on an annual basis for row crops (processing tomato, fresh tomato, and romaine heads). For the perennial system (processing peach), inputs are accounted for per the 18-years productive lifespan of the orchard and estimated on a mean annual basis. Pruning for the perennial system occurs years 2–18. The Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts (TRACI) baseline characterization factors include eutrophication potential (EP), acidification potential (AP), ecotoxicity, etc.

and extension professionals were consulted for validation and clarification of the data before using this primary data in the LCA models.

Cultivation System Inputs and Transportation

Agrochemical inputs to the cultivation systems are based on the data from the cost and return studies and the California pesticide use reports (PUR) (California Department of Pesticide Regulation (CDPR), 2018) unless specified otherwise. For all relevant input materials, the transport distances are estimated using georeferenced Google map road kilometer data (see **Supplementary Material S1** for more details). The on-farm diesel used in tractors is estimated based on the on-farm equipment use hours (i.e., based on primary data collected for this study) and the manufacturer-based tractor engine testing data (to estimate the fuel consumption in total gallons per hour). This primary data is linked to background data (i.e., secondary LCI data) to account for the emissions for the estimated total on-farm fuel use. The fuel consumption does not account for the load (e.g., heavy load during primary tillage).

Irrigation Water Sources and Pumping Requirements

Surface water and groundwater for irrigation applications must be pumped to lift the water (from groundwater depth) and transport the water for field application, with attendant energy demand subject to significant geographic variability. Irrigation pumping and in-field system pressurization may use diesel-, electric-, or solar-generated pumps. The processing tomato, fresh tomato, and romaine head LCAs use 50:50 breakdown between surface and groundwater use and 40:60 between electric and diesel pumps for irrigation (based on data reported from field staff, n.d.). The processing peach LCA assumes the use of diesel, electric, or solar pumps with a breakdown of 45, 45, and 10%, respectively, and a breakdown of 32% surface water to 68% groundwater use, based on results from the Statewide Water and Agricultural Production Model (Howitt et al., 2010). Accounting for the geospatial relationships of surface water delivery infrastructure and groundwater basins to peach acreage as per Kendall et al. (2015), an area- and source-weighted energy requirement of 299 MJ ha^{-1} (121 MJ ac^{-1}) applied irrigation water is assigned to peach orchards, and 319 MJ ha^{-1} (129 MJ ac^{-1}) for romaine head, and 516 MJ ha^{-1} (209 MJ ac^{-1}) for tomato (fresh and processing).

Cultivation System Outputs

Crop yield data comes from the cost and return studies and the (United States Department of Agricultural/National Agricultural Statistical Service (USDA/NASS), 2017). The IPCC 2006 guidelines are used to estimate direct and indirect emissions associated with N fertilizer application rates using the emission factor for kg nitrous oxide (N_2O) per kg N (1.25%), and the value 0.01 kg N_2O-N per kg ammonium (NH_4-N) based on work by De Klein et al. (2006).

On-Farm Food Losses

The data for the on-farm food losses for processing tomato, fresh tomato, romaine heads, and processing peach were collected through semi-structured interviews with multiple growers conducted by Gillman et al. (2019). Annual and perennial on-farm food losses are reported on an annual percent (%) on-farm food loss basis. The grower-reported values, for annuals and the perennial production systems assessed in this study, indicate a high level of variability in losses from year to year. More accurate numbers can only be obtained through (a) systematic reporting by growers, or; (b) multi-year in-field loss measurements. We did not do a systematic evaluation of the quality or quantity of the grower reported on-farm food losses due to time and other resource constraints.

Secondary Data

Life cycle inventories from the GaBi databases (service pack 32) (Thinkstep, 2017) and Ecoinvent databases (Wernet et al., 2016) are used to characterize the background processes included in the LCA models. The LCI data quantify the total primary energy and material inputs as well as emissions for a variety of materials including fuels and agrochemicals (fertilizers, pesticides, and soil amendments). Inventory data (primary and secondary data) used in the assessments are presented in the **Supplementary Material S2**.

Life Cycle Assessment Model

Process-based life cycle models are used to evaluate the environmental impacts of processing tomato, fresh tomato, romaine heads, and processing peach production in California from raw material extraction through cultivation. The process-based LCA model was developed in Microsoft Excel with VisualBasic Macros to support some data management and calculation processes. Software and modeling tools, including geographic information systems (ArcGIS software), are used for distribution analysis and other spatial models. Where applicable, the LCA methodology put forth by the International Organization for Standardization (ISO) is used to guide life cycle model development and calculations (Organización Internacional de Normalización (ISO), 2006a,b).

Model assumptions include on-farm food loss considered on an annual basis for both the annuals (processing tomato, fresh tomato, and romaine heads) and the perennial (processing peach). Also, the productive lifespan of a California peach orchard is 15–20 years (Hasey et al., 2018a,b). This study assumes 18 years of productive life, followed by an orchard removal process (in the EOL phase). The prunings from trees are removed. These assumptions are based on consensus group data collected through the University of California's cost and return studies.

The results are presented based on the assumption that 100% of the mature crop is harvested (full harvest or $\text{Harvest}_{\text{Total}}$). Using this assumption does not imply that 100% harvest of the on-farm crop is achievable, or even desirable (from the perspective of economic efficiency), but instead serves to provide illustrative boundaries to establish the quantity of material potentially prevented from loss and available for increased harvest or redirection to secondary uses.

The first scenario evaluated in this study assumes a 50% reduction in on-farm food loss at the farm gate (as described in section Evaluation of On-Farm Food Losses—Calculations and Scenarios). In the second scenario included in this study, the on-farm losses from processing peach are redirected for combustion as an energy feedstock (47%), incineration (33%), and spread in-field (20%). In the LCA, system expansion and the displacement of fossil fuel consumption are used to assess impacts due to the use of the EOL peach orchard by-product recovery. This by-product is assumed to offset fossil fuel consumption in the California electricity grid system. In other words, the peach processing system is "credited" with avoidance of fossil fuel use and production of renewable energy. The biogenic carbon dioxide (CO_2) emissions from biomass combustion and decomposition are considered carbon neutral. Pruning and removal and other aspects of biomass management-related material flow, such as tree stakes, ties, and paint, are also assessed in the processing peach LCA.

Life Cycle Impact Assessment

The life cycle impact assessment (LCIA) translates the LCI into indicators of environmental impact. Using the LCIA results, we evaluate the hypothesis that the LCA-based environmental impacts for specialty crops in California will vary considerably due to differences in inputs to the cultivation practices. Based on the evaluation of peer-reviewed literature conducted before developing the LCAs, we selected the following most commonly used impact categories in the studies we reviewed. The impact categories include the 100-years global warming potential (GWP_{100}) without climate-carbon feedbacks reported in kg CO_2 equivalents (kg CO_2e) (Myhre et al., 2013). Also, the Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts (TRACI) baseline characterization factors are used for the following impact categories: ozone creation potential (kg O_3 eq), ozone depletion (kg CFC^{-11} eq), human toxicity (cancerous and non-cancerous) (CTUcancer), human health particulate air ($PM_{2.5}$eq), eutrophication (kg N eq), ecotoxicity (CTUeco), and acidification (kg SO_2 eq) (Bare, 2012). The resource flows reported in this study include total primary energy use from renewable and non-renewable sources (reported in MJ) and total freshwater use. The total freshwater use includes rainwater use, surface water (lakes and rivers), and groundwater use (reported in kg of water). Total water use is modeled to include both upstream water use flows as well as the direct water use (e.g., for irrigation water).

Evaluation of On-Farm Food Losses—Calculations and Scenarios

We use a set of simple calculation steps based on Creus et al. (2018) in combination with an additional step we added for this study to simulate two proposed scenarios. See Equations 1–3 and **Table 1** describes the cases (e.g., Scenario 1) and the crops assessed in each.

Scenarios 1 and 2 Descriptions

For scenarios 1 and 2, we focus on one cropping system, processing peach. Scenario 1 considers the prevention of on-farm food losses through a hypothetical 50% reduction in processing peach food (fruit) losses at the farm gate. We assume that this reduction occurs without the input of additional resources or effort for cultivation or harvesting of the material. Scenario 2 accounts for EOL processing peach biomass treatment focusing on incineration (burning) and combustion (for energy generation).

TABLE 1 | Case, assumption, and crops assessed in each case.

Case	Assumption	Crops
Baseline	100% harvest	All
Baseline+Losses	Including avg. annual on-farm food losses	All
Scenario 1	Baseline+Losses and 50% reduction in on-farm losses	Processing peach
Scenario 2	Baseline+Losses and 50% reduction in on-farm losses plus GHGs and embedded energy and material loss avoided by using EOL biomass	Processing peach

The target of 50% prevention of on-farm food loss accounted for in Scenario 1 is designed to align with the stated national goal of the United States to reduce food loss and waste by 50% by 2030 (US EPA, 2015). In this scenario, we use the model to evaluate loss prevention, which, in turn, leads to the use of more of the food produced on-farm from the same amount of input and then calculates the changes in the resultant GHG emissions and embedded water and energy resources. This approach addresses on-farm resource efficiency, which is apart from traditional efforts to mainly reduce inputs, e.g., to reduce water use through drip irrigation.

Scenario 2 accounts for avoided GHG emissions and embedded material and energy resource loss from the use of processing peach EOL estimated biomass percentage of total harvested material used for the specific destinations (e.g., energy generation). The LCA for processing peach includes this by-product utilization pathway via system expansion using a displacement credit. We calculate the Scenario 2 results in terms of both the prevention action and the avoided GHG emissions as well as embedded material and energy resource loss for EOL processing peach by-product use. Therefore, the results for Scenario 2 show the cumulative effect of the prevention scenario (Scenario 1) plus the avoided GHG emissions (Scenario 2).

The second scenario is selected because, in the context of California's Central Valley growing region, there is a high proportion of biomass energy plants to the orchard cultivation area. There are 34 plants in operation currently, which is a significant reduction from the 66 that were estimated to be in process at the peak of this industry (California Biomass Energy Alliance (CAEB), 2018). This shift in the total number of bioenergy plants is in part due to the heavy restrictions on biomass burning for air quality control in California's Central Valley growing region. Still, the remaining biomass plants create a significant demand for orchard biomass by-products from California's major orchard cropping regions.

Quantification of Full Harvest Including On-Farm Losses

The environmental impact (*EI*) is estimated using nomenclature adapted from Creus et al. (2018), Equation 1, and the averaged % on-farm food loss values reported in **Table 2**.

$$EI_{\mathrm{i}} = \frac{IF_i \times NF_i}{1 - \ \% \text{ on-farm losses}} \tag{1}$$

TABLE 2 | Crop losses (low, high, and averaged) in percentages (%) per respective crop.

Crop type	% of crop loss: Low	% of crop loss: High	Averaged % value	Sample size[c] n =
Processing tomato	2	6	4	5
Fresh Tomato[a]	15	40	28	5
Romaine heads[b]	0	25	13	3
Processing Peaches	2	5	4	3

[a]*There are many different types of fresh tomatoes in this category. For example, cherry tomatoes have much lower loss levels than heirlooms.* [b]*These values explicitly refer to harvest losses, not including the sporadic occurrence of walk-by losses. Crop loss percent (%) values are based on the semi-structured interviews conducted by* Gillman et al. (2019).
[c]*Sample size refers to the number of growers interviewed for each crop type.*

In this case, the EI_i refers to the environmental impact from stage i, the production (or harvest) phase, and includes on-farm food losses. The net flow (*NF*) of the materials is equal to full harvest (or $\text{Harvest}_{\text{Total}}$) at the production stage. The impact factor (IF_i) for stage i for a specific impact category (GWP_{100}) or reported resource flow (e.g., total primary energy) is accounted for at the production stage (i).

Quantification of the Prevention Action (Scenario 1) and Avoided Emissions (Scenario 2)

In Scenario 1, we evaluate the *EI* associated with a prevention action. In this scenario, we evaluate the hypothetical $\text{Harvest}_{\text{Total}}$ and on-farm food loss reduction of 50%. The scenario is applied to the case of processing peach, implying the decrease in on-farm food loss from 4% (annual avg. on-farm food loss) to 2% (50% of the yearly avg. on-farm food loss). So, the calculation is the same as in Equation 1; the only difference is the on-farm loss percentage.

$$E_i^j = \underbrace{\frac{IF_i \times NF_i}{1 - \% \text{ on-farm losses}}}_{\text{Prevention actions}} + \underbrace{IF_{i,j1} \times NF_{i,j1} + IF_{i,j2} \times NF_{i,j2} + IF_{i,j3} \times NF_{i,j3}}_{\text{Avoided emissions}} \tag{2}$$

$$E_i^n = \underbrace{\frac{IF_i \times NF_i}{1 - \ \% \text{ on-farm losses}}}_{\text{Prevention actions}} + \underbrace{\sum\nolimits_j^n (IF_{j,f} \times NF_{j,f})}_{\text{Avoided emissions}} \tag{3}$$

In Equations 2, 3, we add a calculation to the step-wise calculation presented by Creus et al. (2018)—for evaluating discrete, multiple flows within the NF, referred to here as fractions (f). It is worth noting that this calculation step can be added to each stage of the supply chain in the systematic, simplified calculations as well as the EOL calculations presented in Equations 7 and 8 of Creus et al. (2018). In the processing peach example, f refers to percentages of the processing peach EOL biomass with different destinations (e.g., 47% of the biomass is used in bioenergy generation).

In Scenario 2, the avoided emissions include accounting for the *NF* at stage i of material j to a defined destination for secondary use(s) (1, 2, 3,...) and additional impact from the action(s), $IF_{i,j}$. Value from *1* to n, *1* being the first destination for material j, and N being the last one. When $i = 0$, it refers to the flow entering stage 1 (e.g., the pre-harvest stage). In Equation 3, the various materials flows derived from the same NF are accounted for in fractions (f), where each fraction is a defined flow for a designated destination or secondary use (1, 2, 3,...), and j fraction *1* is denoted as j_1.

In this example, the j_1 is EOL processing peach biomass (by-product) to bioenergy generation (47%), j_2 is to incineration (33%), and j_3 is spread in-field (20%). In this case, a mass-based allocation is applied to fractionate flows to defined destinations; however, if these products have established market values, then another allocation approach could be used, such as economic allocation.

RESULTS

The overall LCIA results are presented per kg cultivated product followed by the per crop contribution analysis and comparison with other studies. The main impact category evaluated for the comparison with previous peer-reviewed literature includes GWP_{100}. Total primary energy and water use are also included. TRACI impacts are not as well-reported in the peer-reviewed literature for the crops assessed in this study. Some of the environmental impacts associated with the on-farm food losses are presented in sections Environmental Impacts Associated With the On-Farm Food Losses and Scenario Analysis: Environmental Impacts of the On-Farm Loss Prevention and EOL 398 Biomass Utilization for Processing Peaches.

Life Cycle Impact Assessment (LCIA) Results

Across the supply chain, the top contributors to all impacts for the processing tomato, fresh tomato, romaine heads, and processing peach cultivation systems include diesel use for tractors and irrigation pumps, in-field emissions from N-based fertilizers, direct water use, and electricity generated for irrigation pumps.

Fresh tomatoes have higher impacts per unit product compared to processing tomato in part due to the per-unit input of fertilizer, fuel, and water compared to processing tomato (**Figures 2**, **3**, absolute values in **Table 3**). By comparison, the GWP_{100} impacts and TRACI impacts associated with romaine head have higher impacts compared to the other two annual crops assessed in this study, mainly due to heavier tractor fuel use (**Figures 2**, **3**, **Table 3**). The LCIA results show that the processing peach perennial system impacts are higher than the annual crops, in particular for total primary energy, ecotoxicity, eutrophication, human toxicity (cancer), and ozone depletion (**Figure 3**, **Table 3**).

Contribution Analysis

Diesel use is the main contributor to total primary energy, and GWP_{100}, and all TRACI impact categories except ozone depletion potential and human health particulates (see contribution analysis, **Supplementary Material S3**). The extraction of primary energy sources (crude oil and hard coal) for diesel production contributes to the emissions to air (e.g., radon 222). The combustion of diesel (on-farm) emits CO_2, NOx, particulates, etc. which contribute to the GWP_{100} impacts as well as environmental and human health toxicity impacts. Gypsum and fertilizer production and in-field emissions (from N-based fertilizer application) are the top contributors to the TRACI impact ozone depletion potential and human health particulates.

Direct water use is the primary contributor to total water use (**Supplementary Material S3**). Water use in electricity is the second-highest contribution to overall water use (8–19%), mainly due to the hydro, thermal, and solar thermal processes that make up ∼14% of the total California energy mix (California Energy Commission, 2017; Peck and Smith, 2017).

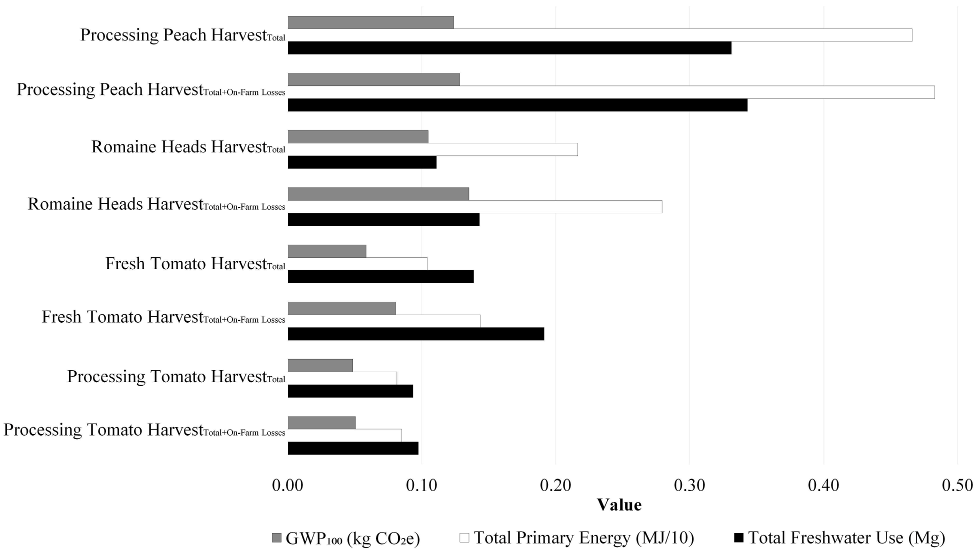

FIGURE 2 | Life cycle impact assessment (LCIA) results for GWP_{100} (kg CO_2e), freshwater use (Mg), and Total Primary Energy (MJ/10) for 1 kg harvested crop for full harvest ($Harvest_{total}$) and including on-farm food losses ($Harvest_{total+On-Farm\ Losses}$). The absolute values for these impacts are provided in **Table 3**.

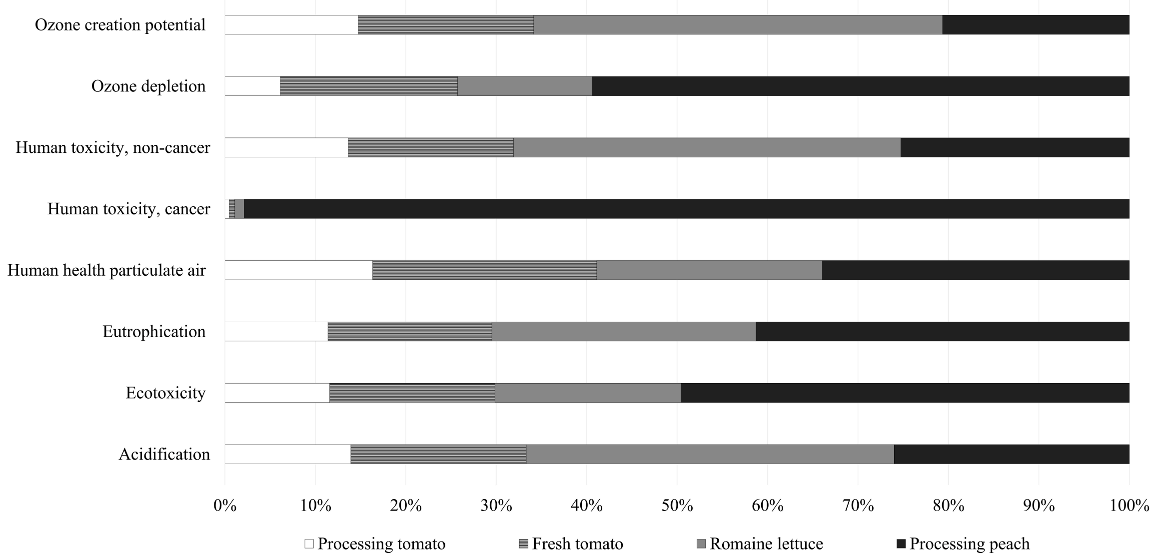

FIGURE 3 | Life cycle impact assessment (LCIA) results for % percent TRACI impacts per 1 kg harvested crop. The absolute values for these impacts are provided in **Table 3**. In the human toxicity, cancer impact category, the processing peach total impacts (6.27E-10 CTUcancer) are relative to other agri-food products assessed in this study (e.g., 6.51E-12 CTUcancer for romaine heads).

TABLE 3 | LCIA results—absolute values.

	Crop			
Impact category	**Processing tomato**	**Fresh tomato**	**Lettuce heads**	**Processing peach**
Total primary energy	8.29E−01	1.07E+00	2.03E+00	4.67E+00
Total fresh water use	9.35E+01	1.39E+02	1.11E+02	3.31E+02
GWP_{100}	4.86E−02	5.84E−02	1.05E−01	1.40E−01
TRACI				
Acidification	3.35E−04	4.67E−04	9.80E−04	6.26E−04
Ecotoxicity	2.43E−04	3.83E−04	4.32E−04	1.04E−03
Eutrophication	2.95E−05	4.70E−05	7.57E−05	1.07E−04
Human health particulate air	3.81E−05	5.78E−05	5.82E−05	7.92E−05
Human toxicity, cancer	2.90E−12	4.09E−12	6.51E−12	6.27E−10
Human toxicity, non-cancer	7.77E−12	1.04E−11	2.44E−11	1.44E−11
Ozone depletion	1.47E−10	4.72E−10	3.58E−10	1.43E−09
Ozone creation potential	9.42E−03	1.24E−02	2.89E−02	1.32E−02

The second highest contributors to impacts include soil N_2O emissions from N-based fertilizers. In general, the soil N_2O emissions are lower in processing peach compared to the annual crops assessed; soil N_2O emission contributes to 17% of the total GWP_{100} impacts in romaine head production and 2.7% of the total processing peach production. In processing peach, pesticides are also a significant contributor to ecotoxicity (14% of the overall ecotoxicity impacts), acidification (10%), eutrophication (50%), and ozone depletion (44%). Material transport contributes to an estimated 25% of the total non-cancer human toxicity impacts and ozone depletion potential impacts (49%). Finally, irrigation system component production contributes to 3% of the total GWP_{100} in processing peach production.

Environmental Impacts Associated With the On-Farm Food Losses

We observed the effects of including on-farm food losses on LCA for the GWP_{100} impact and freshwater use and total primary energy use. The additional results of on-farm food losses vary significantly by crop, depending on the estimated average percent material losses. Including on-farm food losses increased the total GWP_{100} impacts and freshwater and primary energy use for processing peach and processing tomato by 4% (**Figure 2**). Whereas, the overall impacts associated with romaine heads production increased by 29% and by 38% for fresh tomato (**Figure 2**).

Scenario Analysis: Environmental Impacts of the On-Farm Loss Prevention and EOL Biomass Utilization for Processing Peaches

Scenario 1 includes a 50% reduction in the processing peach on-farm food losses, resulting in an overall decrease in total GHG emissions, primary energy use, and water use by 2% (**Figure 4**). When combining both the prevention action and the secondary use of by-products from processing peach as a bioenergy feedstock (Scenario 2), the GWP_{100} emissions reduced by up to 11% compared to the full harvest scenario (**Figure 4**). Total primary energy use reduced by 10% compared to the full harvest scenario, and the aggregate freshwater use in the avoided emissions

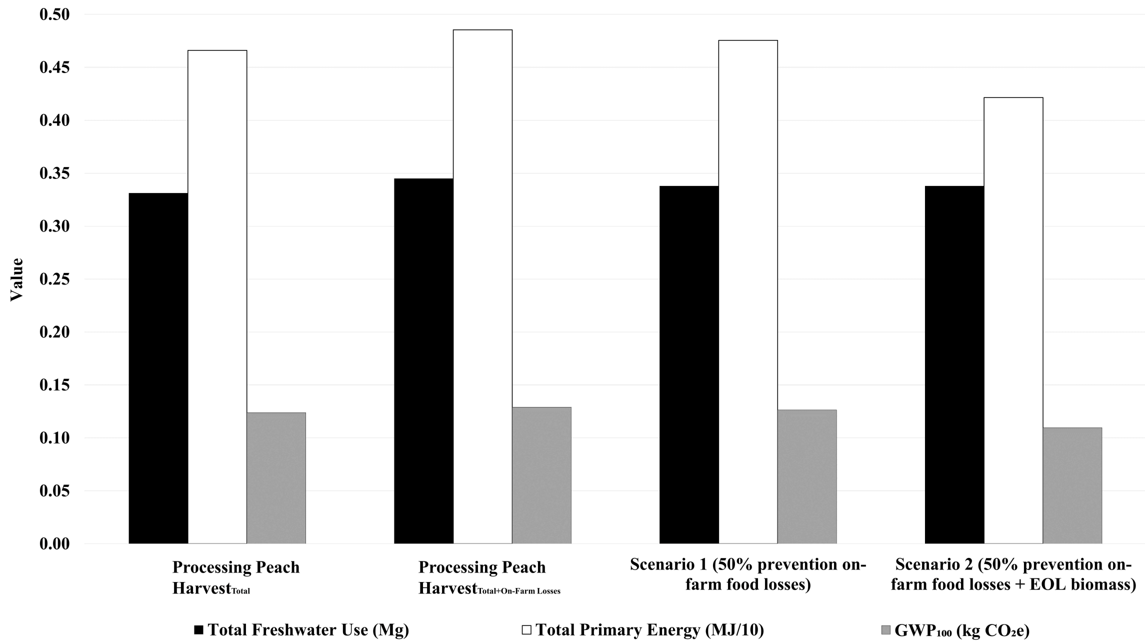

FIGURE 4 | Impacts associated with LCIA results comparing full harvest (or $Harvest_{total}$) and including on-farm food losses ($Harvest_{total+On-FarmLosses}$) with the prevention actions and avoided greenhouse gas emissions due to the use of secondary products for processing peach.

remained unchanged when compared to the prevention action (**Figure 4**).

DISCUSSION

The LCA of tomato (fresh and processing), processing peach, and leafy green cultivation in California show a wide variation in water, energy, and material inputs and the associated emissions and environmental impacts by crop type. We also see a high level of variability in on-farm food losses between the selected crops in this study. Integrating these two components, it is clear that the environmental footprint of on-farm food losses varies by crop type. While this paper adds to the understanding of a few crop types in California, additional studies are needed to gain a baseline assessment of environmental impact and relative loss percentages for a greater variety of agricultural products and with broader geographical diversity to capture inherent complexities within the agricultural systems, such as varying crop-soil relationships. These relationships will be even more critical to enabling consideration of prevention actions and opportunities to valorize on-farm losses, e.g., as a soil amendment (e.g., Cherubin et al., 2018). The implications of these secondary uses of losses on the farm also need to account for current agricultural practices and inputs to agricultural production systems like agrochemicals.

The environmental impact associated with agrochemicals (fertilizer and pesticide) application is limited in terms of in-field and downstream impacts. Ultimately, the upstream impacts need to be balanced with the downstream effects that occur after the field application of the product (Winans et al., 2019), which is beyond the scope of this study. The emissions and environmental and human and animal health impacts associated with fertilizers and pesticides are not only an effect of the agrochemical type and related production practices but also, e.g., the soils to which the agrochemicals are applied (Silva et al., 2019; Winans et al., 2019). In some cases, using more fertilizer can lead to harmful effects on the environment and human health. Thus, the advancement of loss reductions and recovery options that contribute to avoided emissions requires LCA practitioners to increase transparency and comparability of agri-food LCA studies. Clearly stating the agrochemical related assumptions and principles, e.g., for substitution, as well as soil conditions, are required when defining the scope and system boundary (Hanserud et al., 2018).

Comparison With Other Studies

While our assessment focused on four crops in California, the results were broadly comparable to existing studies focusing on the same crops grown in regions with a similar climate. The following sections (Processing Tomato and Fresh Tomato—Processing Peach) compare our results to existing studies. These comparisons include the evaluation of the part of our LCIA results that do not include on-farm food losses compared to peer-reviewed literature studies that conducted LCAs for the same crops and do not account for or include on-farm food losses in their LCIA results.

Processing Tomato and Fresh Tomato

Like the current study, previous studies of processing tomato cultivation show the top contributors to the LCA impacts include fossil fuels (diesel use), electricity use for irrigation, and fertilizer production (Del Borghi et al., 2014; De Marco et al., 2017; Ntinas et al., 2017). An LCA of fresh tomato production also indicates the top contributors to the LCA impacts as fossil fuels (diesel use), electricity use for irrigation, and fertilizer production (Martínez-Blanco et al., 2011). In general, the difference in the results shown in the current study compared to peer-reviewed literature for tomato (processing and fresh) are attributed to differences in diesel use in on-farm equipment and electricity for irrigation. For example, Martínez-Blanco et al. (2011) report nearly double the amount of electricity used for irrigation (0.56 MJ per kg tomato) compared to the current study (0.31 MJ per kg fresh tomato, **Table 3**), contributing to higher GWP_{100} impacts (0.14 kg CO_2e per kg tomato) than in the current study 0.06 kg CO_2e per kg fresh tomato (**Table 3**).

Romaine Heads

An LCA of lettuce (open-field) production in Italy (Bartzas et al., 2015) shows GWP_{100} values amounted to 0.24 kg CO_2e per kg cultivated lettuce, more than twice that found in this study (0.10 kg CO_2e per kg cultivated romaine heads, **Table 3**). The Bartzas et al. (2015) study of lettuce includes emissions associated with compost collection, treatment, transport, and application, and "compost," which accounted for as much as 74% of the total reported GWP impacts. We assume this is the primary source of difference between these two results. The current study does not include compost given the primary data source reports no use of this material on-farm for California romaine head production.

Fertilizer production contributed to 20% of total GWP_{100} impacts in this analysis (**Supplementary Material S3**), similar to the results of Bartzas et al. (2015) (21% of the overall GWP_{100} impacts). This result is expected due to similar input quantities of N, P, and K in nutrient management for the two systems.

Processing Peach

An LCA of a 15-years peach cultivation system in the Catalonia region of Spain indicates that 0.16 kg CO_2e are emitted per kg fresh yield, and 1.62 MJ energy and 201 kg of freshwater are consumed per kg fresh yield (Vinyes et al., 2015, 2017). These results are similar to those observed in the current study: 0.16 kg CO_2e, 4.73 MJ energy, and 331 kg freshwater (**Table 3**). Ingrao et al. (2015), in a case study of a Sicilian farm, found that production of red peach in a 15-years orchard system resulted in 7,380 kg CO_2e and 273,000 MJ of energy use per hectare of orchard, somewhat higher than the mean annual impacts of 5,917 kg CO_2e and 144,270 MJ of energy per hectare for California peach production (**Table 3**). In a study of the peach industry from the south of France, which was more methodologically similar to our analysis of California processing peaches, i.e., the authors also relied on expert opinion and literature rather than individual case studies, Basset-Mens et al. (2016) found that peach production over a 15-years orchard lifespan resulted in 0.17 kg CO_2e and 2.54 MJ non-renewable energy use per kg yield.

Catalonian peach production used about 30% less water, which may be attributable to the use of trees grown on their roots or field-grafted onto the planted rootstock, which may produce more robust root systems and greater water-use efficiency (Hammerschlag and Scorza, 1991). An LCA of Iranian peach orchards found similar results to the current study, resulting in 0.10 kg CO_2e per kg fresh peach (Nikkhah et al., 2017), although the authors did not indicate whether their study accounted for orchard removal or nursery production. In the Nikkhah et al. (2017) study diesel fuel use was found to be the most significant contributor to GWP_{100} impacts, but in general Iranian orchard systems tend to rely less on mechanization and more on hand labor (Talaie and Panahi, 2002; Nikkhah et al., 2017) than California orchards—a possible explanation for the lower GWP_{100} impacts found in their study compared to our results.

LCA Including On-Farm Food Losses, Prevention Actions, and Avoided GWP_{100} Emissions

In this study, the LCIA results show how the cultivation systems differ between crops given the attributes of each system. We observe that the environmental impacts (or footprint) associated with each food is unique. The impacts associated with each food product become more pronounced when we account for the on-farm food losses and their embedded materials, energy, and water. For example, for freshwater use, most of the water use is consumed as direct water use for irrigation. If on-farm food losses are included in the estimated water consumed, the amount of water consumed increases by the same proportion of the observed losses, i.e., ∼30% for fresh tomato and ∼4% for processing tomato.

The prevention action (Scenario 1) of a 50% reduction in on-farm food loss from processing peach directly halved the GHG emissions and embedded energy and materials associated with the on-farm losses (but only had a 2% reduction in GHG emissions per unit product at the farm gate). Combining the prevention intervention with the EOL biomass capture for bioenergy (Scenario 2) decreased the overall GHG emissions by 11% in the processing peach system. We see little to no change in the water use between Scenarios 1 and 2 since embedded water is mostly reduced by the prevention action shared by both scenarios with minimal contribution from the EOL biomass action.

The results underscore how this approach advances capabilities to capture the systemic impacts of both separate and combined strategies for valorizing organic waste flows on the farm. We can evaluate multiple flows from the agricultural production system to assess the interventions of on-farm loss prevention and management of agricultural residues, both separately and as a combined strategy. Because we add a step in the calculations for evaluating unique, discrete flows within mass net flow losses (Equations 2, 3), we can quantitatively observe the potential tradeoffs of management actions (prevention and secondary material use) for these flows that occur at different timestamps within the production system (**Figure 4**).

However, there remain opportunities to improve the model. One component to consider is the ultimate destination of on-farm food losses. Based on interviews with growers, Gillman et al. (2019) determined that the majority of food loss material is tilled back into the field, thereby returning organic matter to the soil. In some interviews, growers also described occasions where the product was used as animal feed. For example, during a year when yields exceeded contracted volumes, one processing tomato grower allowed sheep to graze the unharvested fields. While outside the scope of this study, these final destinations for on-farm loss material do influence the overall LCA for these various crop types. The United States Environmental Protection Agency food recovery hierarchy addresses this topic from a broad heuristic perspective (US EPA, 2019), however detailed quantitative data on the relative economic, environmental, and social costs of food loss material management need to be further developed and specified by food type and stage of supply chain to substantially advance decision-making in the field.

In an attempt to address this issue for the crops assessed in our study, we conducted a review of peer-reviewed literature for the specialty crops to evaluate qualitative (and available quantitative) information about the destinations, benefits, and costs associated with the potential secondary uses of the on-farm losses (see qualitative information available in **Supplementary Material S4**). Through our evaluation of the peer-reviewed literature, we observed a focus on secondary use(s) of on-farm losses for animal feed, composting, and biomass for energy generation. Overall, our findings corroborate previous research findings—the significant data gap in this area implies collecting and consolidating this information on a large scale in the short term is imperative as interest in preventing, recovering, and recycling food loss, and waste continues to increase exponentially (Xue et al., 2017).

Finally, it is also important to consider the on-farm system within the broader food supply chain. For example, as outlined in this study, a successful intervention to reduce losses at the farm would lead to a decrease in inputs per unit of crop products at the farm gate. However, there is potential to ultimately incur higher environmental and economic costs if these recovered losses from the farm are ultimately wasted further down the food supply chain (Gillman et al., 2019). As such, it is maximizing the harvest of all cultivated product is not necessarily an environmentally optimal solution when factoring in the additional downstream environmental impacts and increased risk of wastage, including increased likelihood of disposal in landfill (Scherhaufer et al., 2015; Gillman et al., 2019).

CONCLUSIONS

This study assessed annual cropping systems (processing tomato, fresh tomato, romaine heads), and a perennial system (processing peach) using an LCA approach to characterize the environmental burdens associated with each specialty crop. For the annual crops and the perennial crop assessed in this study, on-farm fuel (diesel) use and irrigation (diesel and electric pump use) are the primary contributors to the impacts associated with production. Considering the LCA in the context of crop losses presented some exciting concepts to explore further concerning the uniqueness of each crop.

First, successful efforts to reduce crop losses in the field have the potential to reduce the environmental burden per unit of product sold at the farm gate. This notion is explored using the example of freshwater use, GWP_{100}, and total primary energy use, and two scenarios. At face value, this relationship might suggest that investments in reducing on-farm food losses would be a practical approach to increase resource use at the cultivation node of the supply chain. However, in discussions with growers, the growers emphasized that the culling of crops at the field level is based mainly on identifying which crops will effectively make it to market in the context of existing quality standards and risk of spoilage (Gillman et al., 2019). Thus, reducing on-farm food losses on the farm only to increase the potential for losses later in the supply chain carries a significant risk of reducing resource use efficiency within the broader system boundary of farm to consumer (or to fork). This concept should be explored more deeply in future research, including an assessment of the economic costs and the relative risks of losses at each stage of the supply chain. Further, evaluating the viability of any alternative to reduce on-farm losses and improving recovery would also require talking with growers about the barriers to recovery.

Second, LCA of crop cultivation must include clear delineation between the production of marketable crops relative to food losses and other crop residues, allowing for multiple flows from net flows that occur at each stage (or node) of the supply chain. In our assessment of processing peaches, EOL woody biomass by-product is assessed as a displacement credit for energy consumption and GHG emissions within the cultivation LCA using system expansion. Along these lines, it is necessary to consider the difference between food losses and other material flows (woody biomass, crop residues) as well as the timing of available material within the life cycle of the production system and potential tradeoffs associated with the various material destinations and utilization pathways.

Finally, accounting for on-farm losses in LCA presents unique challenges and opportunities. There is a wide gap between the existing literature on food losses in agricultural production and actual on-farm practices by crop type and region. Further, any discussion of interventions to either reduce on-farm losses or recover edible product from the field requires more detailed information on costs and benefits of current practices (tilling back into field or diversion to animal feed) relative to the proposed alternative (e.g., animal feed, composting, anaerobic digestion, or collection for donation). We offer a mathematical approach for accounting for discrete, unique flows within the net flow of on-farm food loss in LCA. Not considering the uniqueness of each crop and within a crop, net flows have the potential to result in unaccounted for outcomes, i.e., overestimation or underestimation of economic and environmental costs.

Despite the challenge, there is an excellent potential to advance data and research for improved understanding of the value (economic, environmental, and social) of on-farm losses. While much of the interest in the food loss and waste research community will likely focus on assessing interventions to reduce losses (e.g., through more resilient or consistent crop varietals) or to increase the recovery of edible produce in the field (e.g., through gleaning, development of secondary markets, etc.), studies are also needed to accurately estimate the baseline benefits of existing practices for managing these materials (e.g., tilling into field, diversion to animal feed). Future studies also need to consider the timing and availability of the net biological flow (and multiple potential flows within the net flows) within and through the system to be able to assess interventions and management options on farm accurately. Finally, providing a standardized framework for cross-supply chain analysis, including the application of a consistent vocabulary (or ontology) and associated quantification for different, unique cropping systems and associated material types and destinations is critical for managing agri-food systems and agri-food system losses that are inherently diverse.

DATA AVAILABILITY STATEMENT

All datasets generated for this study are included in the article/**Supplementary Material**.

AUTHOR CONTRIBUTIONS

KW created the processing tomato, fresh tomato, and romaine heads LCAs, the on-farm food loss calculations and models, and contributed to the writing and editing of the manuscript as lead author. EM provided the LCA of the processing peaches and contributed to the writing and editing of the manuscript. AG led the analysis of on-farm losses for all crop types in the study and contributed to the writing and editing of the manuscript. ES served as Principal Investigator for the project and contributed to the writing and editing of the manuscript.

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SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fsufs.2020.00010/full#supplementary-material

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Development and Evaluation of the Eetmaatje Measuring Cup for Rice and Pasta as an Intervention to Reduce Food Waste

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Of all of the stages in the supply chain, more food waste comes from households than any other sector. A Dutch composition analysis showed that the solid food waste (including sauces, fats, and dairy products) from household waste amounted to 48.0 kg per person per year (in 2013), of which 5.0 kg consisted of cooked rice and pasta. These two product groups were numbers 1 and 3 in terms of relative waste: 34% of the purchased quantity of rice and 23% of that of pasta was wasted. Using questionnaires, we discovered that Dutch consumers mainly throw away food because they prepare too much of it. The same is true for rice and pasta because they increase greatly in volume when cooked. The water uptake ratio of rice is 2.5 (2.3–2.8) and that of pasta is 1.8 (1.5–2.3), which increases the chances of consumers overestimating portions. In 2013, more than half of the people surveyed did not measure pasta and rice portions. In view of this, the Netherlands Nutrition Centre developed a measuring cup called the Eetmaatje, which is marked with the recommended volumes for Dutch adults for different types of pasta and rice in terms of dry weight. The theoretical reduction of food waste the Eetmaatje provides is calculated to be ~6% for pasta and 21% for rice, or 12.5% combined. Between 2014 and 2019, more than 1.6 million Eetmaatje cups were distributed for free among Dutch households. Over that period, the measuring of pasta and rice by Dutch households increased. Most people (85–89%) in a panel of consumers who own an Eetmaatje think it is handy or very handy to use. The majority of those in the panel (50–80%) say that they use the Eetmaatje most times when they prepare a meal. Four out of five of those in the panel (77–87%) are convinced that the Eetmaatje helps them waste less pasta and rice. The Eetmaatje functions as a nudge to change cooking behavior and thus food waste behavior. Consumers who measure their pasta using the Eetmaatje self-reported that they produced less total food waste. The measured household waste of cooked rice and pasta seems to show a downward trend since the introduction of the cup. There is strong evidence that the Eetmaatje has increased the number of Dutch households measuring rice and pasta and thereby reducing food waste.

Keywords: household food waste, measuring cup, portion size, intervention, cooking

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INTRODUCTION

The Problem of Waste

The Food and Agriculture Organization estimates that one-third of the world's food production is wasted (1). In the European Union, the annual per capita estimate is 173 kg of food waste per person, which is equivalent to Europeans wasting 20% of the continent's food production (2). Wageningen UR estimated the annual food waste in the Netherlands to be between 1,781 and 2,466 t, which is equivalent to between 105 and 145 kg per person (3). This figure covers all food lost and wasted from after primary production in the food industry to distribution to households. The group contributing the most to food waste is households (52%). According to these numbers, the focus in food waste reduction should be both on households and businesses, but with households prioritized. Consumer behavioral change should therefore be facilitated (4). In view of the above, the focus of this paper is on the reduction of avoidable household food waste. There are also large differences in amounts of food waste among countries (2). European households have the highest food waste numbers as measured in wasted kilocalories: 38% of total kCal (5). Food waste also contributes considerably to greenhouse gas emissions, land use, water use, fossil energy, and other inputs associated with food production (6). According to Tonini et al. (7), "Food preparation, for households and food service sectors, also provided an important contribution to the Global Warming impacts." The United Nations placed food waste prevention on the international political agenda with the introduction of target 12.3 in the UN's Sustainable Development Goal 12 (Ensure sustainable consumption and production patterns): "By 2030, halve per capita global food waste at the retail and consumer levels and reduce food losses along production and supply chains, including post-harvest losses" (8).

Food Waste by Consumers

Consumer-generated food waste is generated by multi-dimensional behavior, influenced by cultural, social, political, economic, and geographic factors, as well as cognitive, motivational, and structural factors, food-related behaviors, and food habits (9–11).

A compositional analysis of Dutch household food waste in 2016 showed that solid food waste (including sauces, fats, and dairy) from household waste amounts to 41.2 kg per person per year, which corresponds to 13% of the amount of food purchased. The annual waste of pasta and rice was measured to be 1.8 kg per person, or 4% of the total annual per capita waste. Rice and pasta are not the most wasted product groups in absolute amounts—they rank numbers 9 and 10, respectively, but in relative waste, they number 1 and 3 per product group: 34% of purchased rice and 23% of purchased pasta are wasted, both adjusted for water absorption during cooking in relation to the percentage of dry product purchased. A remarkable fact is that almost all of the wasted pasta and rice is cooked (12).

The Netherlands Nutrition Centre identified three main behavioral steps that can be taken to reduce consumer food waste: smart buying, smart cooking by using correct quantities, and better storage of food. These goals were defined and selected with the use of intervention mapping (13). Secondi et al. (14) concluded that a more precise measuring of portion sizes could potentially contribute substantially to reducing food waste. The main self-reported reason why Dutch consumers waste food is that they prepare more food than they consume (15, 16). Measuring portions could help reduce food waste in households.

Possible Interventions

Stöckli et al. (17) recently reviewed waste-reduction interventions for consumers published in scientific and non-peer-reviewed reports. Their review concluded that "informational interventions are the most commonly used intervention type even though evidence indicates that this intervention type is relatively ineffective." Interventions with a direct focus on food waste-related behaviors are supposed to be more effective. A four-country study shows that households reporting less waste tend to exhibit five food practices: planning of shopping and planning of meal preparation, exclusion of impulse buying, management of stocks and fridge, cooking the right quantities, and being creative with leftovers (18). A recent review of consumption-stage food waste reduction interventions found no effective interventions described on cooking the right portions or that little or no robust evidence was provided for the described interventions (19). Some effective interventions to promote buying smaller portion sizes in restaurant settings have also been identified, motivated by health reasons and food waste reduction (20). The low number of described interventions is worrying, according to Reynolds et al. (19), especially since most interventions suggested so far appear to be effective at reducing food waste. Nonetheless, most interventions do not focus on cooking and are not proven to be effective or reproducible.

Information to consumers should be tailored to provide knowledge and skills to change particular food waste behaviors, ideally at the point of decision (21). Clear insights into factors related to consumer perceptions and behaviors related to food waste are necessary to reduce food waste in households (18). These factors are given in the consumer food waste model in **Figure 1**: consumer management of food waste related to preparing food is determined by motivation, opportunity, and ability, including skills and knowledge about portions (18). Aschemann-Witzel et al. (9) demonstrated that "consumers' motivation to avoid food waste, their management skills of food provisioning and food handling and their trade-offs between priorities have an extensive influence on their food waste behaviors." Using interventions and experiments, it is possible to implement effective solutions, they concluded. This paper describes in detail the results of an intervention to promote cooking the right portions of pasta and rice.

Aim

The aim of this paper is to perform an intervention on cooking the right amount of pasta and rice by using a measuring cup called the Eetmaatje (**Figure 2**) and to evaluate its contribution to cooking the right portions to reduce food waste in households. The cup reflects the recommended volumes for Dutch adults for different types of pasta and rice in terms of dry weight.

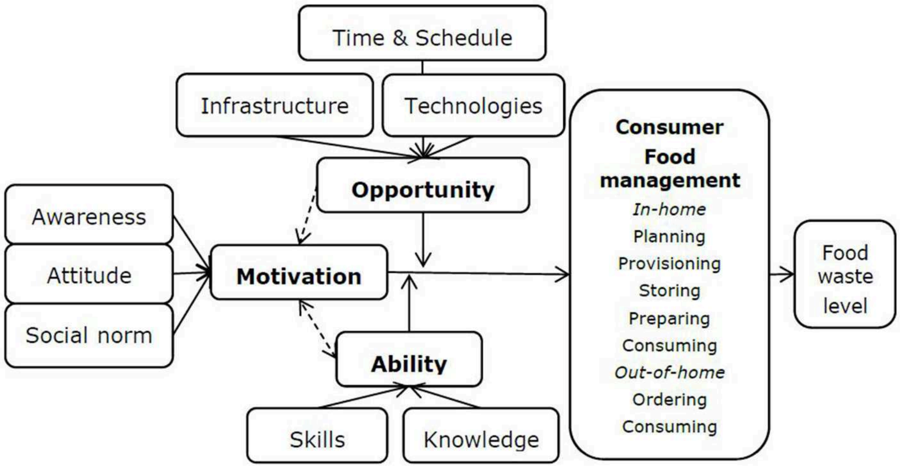

FIGURE 1 | Consumer food waste model including the role of motivation, ability, and opportunity for predicting the level of food waste in households (18).

First, the paper provides a technical description of how to set the right uncooked portion sizes of pasta and rice for Dutch adults. Second, it argues how cooking the nutritionally recommended quantities can theoretically contribute to the reduction of food waste in most target groups. Third, we evaluate the use, satisfaction, and contribution to the reduction of food waste of the measuring cup by consumer research and by measuring actual food waste.

METHODS

This paper focuses exclusively on avoidable household food waste. We define food waste as food intended for human consumption that is not consumed (4, 22). Non-consumed food is split into avoidable and unavoidable food waste (5). Unavoidable food waste consists of the parts of food products that are not intended for consumption, such as shells, peels, stalks, cheese rinds, eggshells, coffee grounds, tea bags, meat bones, and fish bones (23).

Before and after the introduction of the Eetmaatje measuring cup, we conducted several consumer surveys. Most results and conclusions are based on the following four comparative, representative, biannual online questionnaires about food waste behavior in general:

- 2013—An ISO-certified survey with a 72% response rate, performed before the introduction of Eetmaatje by the GfK market research organization, involving a consumer panel of 2,055 adult main shoppers aged 18 or older (15).
- 2015—An ISO-certified survey with a 69% response rate, performed after the introduction of the Eetmaatje by GfK, involving a consumer panel of 2,054 adult main shoppers aged 18 or older (24).
- 2017—An ISO-certified survey with a 58% response rate, performed by GfK, involving a consumer panel of 2,010 main shoppers aged 18 or older (25).
- 2019—An ISO-certified survey with a 60% response rate, performed by Flycatcher Internet Research, involving a consumer panel of 997 main shoppers aged 18 or older out of 1,666 invited (26).

The questionnaires are designed to be comparable with one another (e.g., same question wording and order and same response options and wording). The four samples are stratified and representative of gender, age, region, and income, randomly sampled from a panel of 10,000 consumers. Differences between groups were tested with Chi-square tests, combined with z-tests for percentages and t-tests for averages. Significance was tested with 95% confidence. For averages, the maximum inaccuracy margin in this confidence interval is 3% (where $n = 997$ but lower than $n > 2000$). The Bonferroni method was used to correct multiple testing in order to reduce the possibility of significant differences by chance.

- Supportive evidence is based on a client panel of the Albert Heijn supermarket to evaluate the measuring cup in February 2014 ($n = 336$) and October 2014 ($n = 330$). These clients had the chance to receive an Eetmaatje for free in the supermarket in the winter of 2014. The client panel consisted of clients who were part of the supermarket's loyalty scheme and were randomly invited to take part in consumer research through a maximum of six questionnaires per year. Consumer research for Albert Heijn was carried out by Consumer & Business Insights Albert Heijn, Zaanstad. The two samples are independent.

Additional illustrative insights have been collected from:

- An online Facebook questionnaire among the visitors to the 2018 edition of Huishoudbeurs, a large annual fair for household products in Amsterdam, where 60,000 visitors received an Eetmaatje for free. The questionnaire resulted in $n = 445$ responses, mostly from women of low socio-economic status and therefore not representative of the total population.

TABLE 1 | Dutch recommended daily intakes of carbohydrate-rich products, including wholegrain products such as pasta and rice (29).

	14–18 years old	19–50 years old (M + F)	51–70 years old (M + F)
Recommendation in spoons (cooked)	4–5 spoons (F), 6 spoons (M)	4–5 spoons	3–4 spoons
Recommendation in grams (cooked)	200–250 grams, 300 grams	200–250 grams	150–200 grams

- Professional clients of the Netherlands Nutrition Centre's web shop, such as dietitians and bodyweight coaches, among others, who ordered a package of 10 Eetmaatjes to distribute among their clients ($n = 150$).

Finally, we analyzed changes in household food waste between 2010 and 2019, measured by triennial sorting analyses in a representative sample of 130 Dutch households (23, 27, 28). The methodology and scientific protocol are described in detail in Van Dooren et al. (12).

RESULTS

Development of the Measuring Cup

Setting the Portion Size

The recommended intakes of foods and food groups in the Netherlands were updated and published in 2016 (29). The recommended intakes of carbohydrate-rich products, including wholegrain products, such as pasta and rice, are summarized in **Table 1**. The recommendations are given in cooked serving spoons and in grams. A serving spoon of grain products is set as an average 50 g cooked, although other sources calculate 45 g for pasta and 60 g for rice (30). The portions are in line with earlier recommendations (Wheel of Five, 2004), except for the six spoons recommended for male adolescents. Although the recommendations are the same for adult men and women, we expect that the lower limit of 200 g fits women and people with a small appetite better, while the upper limit, 250 g, fits men and people with more appetite, in line with their metabolic energy needs. According to the Dutch National Food Consumption Survey (31), most pasta and rice is consumed during dinner. Nevertheless, part of the recommended intakes can be consumed on other eating occasions. Therefore, it was decided to apply cooked portions of ∼200 g.

Water Absorption and Volume Ratios

The next step in our research was to translate cooked portions to quantities of dry product. The Netherlands Nutrition Centre recommends 100 g of dry pasta per person or 125 g for persons with a large appetite, which is equivalent to between 200 and 250 g of cooked pasta. The same double portion applies for rice: 75 g of dry rice or 100 g for people with large appetites translates into between 150 and 200 g of cooked rice. These figures are based on assumptions of water uptake of grain products during cooking. The official Dutch measurements and weights table calculates a factor of 2.5 for different types of rice and pasta (30), but the more recent food composition table of the Dutch Food Composition Database (NEVO) applies different factors between different kinds of cooked and uncooked grains: 2.65 for wholegrain pasta, 2.48 for white rice, and 2.72 for brown rice (32) (*personal communication Annette Stafleu, Netherlands Nutrition Centre, 16-7-2018*).

TABLE 2 | Water uptake factors between dry and cooked pasta.

	Portion dry (in cups)	Portion cooked (in cups)	Water uptake factor	Dutch portion of 200 g cooked, calculated as dry (grams)
Tortellini	0.5	1	2.0	100
Farfalle	0.75	1.25	1.7	120
Macaroni	0.5	1.125	2.3	89
Penne small	0.5	1	2.0	100
Penne average	0.66	1.25	1.9	106
Shells	0.75	1.125	1.5	133
Wholegrain penne/shells	0.75	1.125	1.5	133
Average			**1.83**	**112**

Some scientific research looking into the cooking properties of rice and pasta already exists. Thomas et al. (33) found that, for white rice, the water uptake ratio is 2.5 (with a range of 2.33–2.75). Steglich (34) studied the water absorption of spaghetti. The cooking process is characterized by steady water absorption: the longer the time, the more absorption. The best cooking time was 4 min with a 2.25 factor, while in a range of 3–5 min, the uptake ratio varied from 2.0 to 2.5 (34).

The biggest pasta producer in the world, Barilla, is one of the few that provides water absorption ratios for different kinds of pasta (35) (see **Table 2**). Portions of spaghetti are not measured in volume but in circumference, where 2 oz. of spaghetti corresponds to 5.4 cm in circumference (35). Based on these proportions, one 100 g portion of spaghetti for one person is 7.17 cm of spaghetti in circumference, while a two-person serving of 200 g will measure 10.14 cm.

Table 2 demonstrates the water uptake factors for other pasta, ranging between 1.5 for shells and 2.3 for macaroni. The average is 1.83, which is somewhat lower than the 2.0 suggested by different sources. On average, preparing a one-person portion requires 112 g of dry pasta. The selected factor for pasta in the cup is 1.83.

Recipes available online and on the packages of the leading pasta and rice products on the Dutch market mostly use 100 g of dry carbohydrate product per person, as we recommend, but sometimes they use 75 g. Using 100 g dry pasta in recipes, which corresponds to a 2.0 factor, will result in a cooked quantity that is close to the average recommendation of 109 g dry pasta (factor 1.83).

Cup Design and Testing

Based on these factors (2.5 for rice and 1.83 for pasta) and recommendations (∼200 g cooked), the Eetmaatje measuring cup was developed in cooperation with the Dutch Creative

FIGURE 2 | Measuring cup containing macaroni.

Brands Group, a company from Delfgauw, the Netherlands. This company specializes in the development, production, and distribution of innovative houseware products. The company contributed to the design of the cup and the selection of a food-safe, recyclable material (**Figure 2**). The portion sizes in volume for different types of pasta and rice were measured and tested by hand using cardboard molds, which were filled and weighed until the right volumes were calibrated. The company is the owner of the design and is responsible for its production and transport (see https://youtu.be/Hvp2B-jyOqg).

The difference in measured consumed volume between men and women (28, **Table 3**) was addressed by putting a simple message on the package: "This measuring cup indicates uncooked portions. These uncooked portions are based on the daily quantities of wholegrain cereals that the Nutrition Centre uses for an adult Dutch woman." However, the 200 g portions were expected to be also adequate for most men or meet the actual average needs of male and female members of a household, as well as eaters with a small or large appetite.

Theoretical Reduction of Rice and Pasta Waste

In this section, we approximately calculate the theoretical reduction of rice and pasta waste caused by using the measuring cup (**Table 3**). According to the Dutch National Food Consumption Survey 2007–2010 (31) the median consumption of pasta, rice, and other grain products excluding bread is 168–173 g for men and 120–140 g for women on consumption days (rice and pasta were consumed twice a week). The types of pasta and rice are not specified. Those quantities are lower than the recommended intakes. **Table 3** summarizes the consumption of pasta and rice by population subgroups and consumption days. We added the average measured waste percentage to those quantities (27) in scenarios where they consumed only pasta (+23%), only rice (+34%), or half pasta, half rice (+28%). We then compared these amounts with the advised amount on the Eetmaatje measuring cup. The difference between the median cooked quantity and the amount advised on the Eetmaatje cup, which is the actual cooked amount when everyone uses the measuring cup, provides the result for the theoretical reduction of food waste. For the average adult, the approximate result is 6% for pasta and 21% for rice, which is equivalent to 12.5% combined. However, looking into the average for pasta and rice combined, it is theoretically possible that women between 19 and 50 years are still going to waste ∼5–10% more. For all other groups, a reduction in food waste proportional to the result obtained is expected.

The portions used in the cup design were based on recommended and not on actual intakes, so the cup could lead to more food waste among consumers who actually eat less than the recommendations, but, in theory, we expect an overall reduction nonetheless. From a nutritional perspective, it is important for public health bodies to communicate the recommended quantities as part of food-based dietary guidelines (29) instead of promoting low quantities to accommodate people who simply eat less. The lower consumption from women is expected to be compensated for in households of two or three people by an expected higher intake from the other household members, who in most cases, are men. In this sense, the Eetmaatje measuring cup functions as an indicator of the needed quantity. We assume that the measuring cup does not influence the quantities people actually eat, only the amount they use to cook, but this cannot be entirely excluded.

Measuring Portions Before the Introduction of the Cup

According to Temminghoff and Damen (15), almost half of the consumers say that they measure ingredients most times when preparing a meal, but only a fifth do this for every meal. Consumers in general do not know the right portion sizes per person, such as for rice. They randomly rely on intuition to measure pasta for cooking, for example, or they simply prepare an entire package of it at once. Households that do not use any kind of measuring during cooking report that they throw away more food than households that measure (15, 16), however other factors could explain these answers. Before the intervention started in 2014, close to half of Dutch consumers (41%) determined pasta quantities to cook based merely on their intuition or estimation by eye (15). This suggests that at least 41% of the population was likely to cook too much pasta and waste some of it, considering most pasta waste is generated from cooking. According to Temminghoff and Damen (15), a 12% share of consumers said they always cooked an entire package of pasta or rice, regardless of their actual needs or household size. This practice does not necessarily lead to waste if any excess rice

TABLE 3 | Theoretical reduction of rice and pasta waste by using the Eetmaatje measuring cup on consumption days.

	Consumption (g)	Cooked (g)	Advised quantity (g)	Weekly reduction in waste	
Grains mixed	**Median**	**(If 28% wasted)**	**Average rice/pasta**	**(grams)**	**(percentage)**
Men 19–30 y	172	239	185	54	29
Women 19–30 y	120	167	185	−18	−10
Men 31–50 y	172	239	185	54	29
Women 13–50 y	127	176	185	−9	−5
Men 51–70 y	168	233	185	48	26
Women 51–70 y	140	194	185	9	5
Average (unweighted)				**23**	**12**
When only rice		**(If 34% wasted)**	**Rice 75 g × 2.5**		
Men 19–30 y	172	261	188	73	39
Women 19–30 y	120	182	188	−6	−3
Men 31–50 y	172	261	188	73	39
Women 13–50 y	127	192	188	4	2
Men 51–70 y	168	255	188	67	36
Women 51–70 y	140	212	188	24	13
Average (unweighted)				**39**	**21**
When only pasta		**(If 23% wasted)**	**Pasta 100 g × 1.83***		
Men 19–30 y	172	223	183	40	22
Women 19–30 y	120	156	183	−27	−15
Men 31–50 y	172	223	183	40	22
Women 13–50 y	127	165	183	−18	−10
Men 51–70 y	168	218	183	35	19
Women 51–70 y	140	182	183	−1	−1
Average (unweighted)				**12**	**6**

Average water uptake (see **Table 2).*

or pasta cooked is eaten as leftovers at a later date. In families with children and youths aged between 6 and 17, the share of consumers saying they cook entire packages of rice or pasta rises to 16–17% (15). Other consumers already used an instrument to measure dry food quantity to cook before the introduction of the intervention, usually a kitchen scale (21%), a teacup (17%), or a measuring cup (6%) (15).

Evaluation With Consumer Panels

After testing, design, and production, the Eetmaatje was introduced in February 2014. Within 2 weeks, one million items were distributed for free among customers of the biggest retailer in the Netherlands, Albert Heijn. The Dutch Minister of Food and Agriculture received the very first Eetmaatje, generating free publicity and consequently helping with distribution, along with advertisements. Shoppers received one Eetmaatje for free when they bought two packages of pasta or rice on sale, which was done to make sure that regular pasta or rice consumers were the ones receiving the free Eetmaatje cups. In the years that followed, another 0.6 million Eetmaatje cups were distributed through other channels, such as the web shop of the Netherlands Nutrition Centre, other supermarket chains, and the 2018 and 2019 edition of the Huishoudbeurs fair.

The market research company GfK and Flycatcher Internet Research carried out consumer research using independent, representative consumer panels, before introduction (2013) and biannually thereafter, in 2015, 2017, and 2019. The results are summarized in **Table 4**. Before the introduction of the Eetmaatje in 2013, only 6% of the people surveyed said they used some sort of measuring cup to prepare pasta. By 2015, 2 years after the introduction of the cup, this share doubled to 12%. In 2017, more than half of this share (7%) were using the Eetmaatje, as opposed to none in 2013 (25). In 2019, the share of consumers using the Eetmaatje cup was 8%. **Table 4** shows that some consumers (4%) shifted between 2013 and 2019 from a teacup to another type of measuring. Those who used a traditional measuring cup or a teacup did not switch to the Eetmaatje, while using a scale to weigh food quantities actually increased in 2017. The group of people not measuring dry food before cooking decreased from 53% in 2013 to 46% in 2019, showing significant decreases in both groups using random by-eye estimation and those cooking entire packages at once (2017). The research shows that one-person households and families without children under 18 tend to use a measuring cup, a teacup, or a scale to measure dry food to cook more often. Women more frequently weigh dry food amounts (28%), while men use a teacup more often (18%). Among wealthy consumers, the percentage of those who weigh the amount of dry food they cook is higher (32%) (25).

We, together with Albert Heijn, conducted two evaluation surveys among the retailer's client panel, the first in February

TABLE 4 | Consumers who measure and do not measure pasta, including whether they measure dry food using a scale, a teacup, a measuring cup, or the Eetmaatje (before and after the introduction of the Eetmaatje), 2013–2019.

	GfK (15)	GfK (24)	GfK (25)	Flycatcher (26)	
	2013 ($n = 2055$) (%)	**2015 ($n = 2054$) (%)**	**2017 ($n = 2010$) (%)**	**2019 ($n = 997$) (%)**	**Trend**
Quantity estimated by eye	41	37	39	35	Sign. decrease 2019
Whole package cooked	12	13	9	11	Sign. decrease 2017
Total no measuring	**53**	**49**	**48**	**46**	
Weighing with scale (grams)	21	20	23	26	Sign. increase 2017
Measuring by teacup	17	16	15	13	
Measuring by measuring cup	6	12	12	10	Sign. increase 2015
Of which Eetmaatje (no 2015 data)	0	?	7	*8*	Sign. increase 2017
Total measuring	**44**	**47**	**49**	**49**	
Others/unknown	3	4	3	5	
Percentages adjusted for total of 100%	**100**	**100**	**100**	**100**	

?, not measured.

2014, just after the Eetmaatje's introduction ($n = 336$), and the second in October 2014, 8 months after the introduction ($n = 330$). According to the results of these surveys, the Eetmaatje is most commonly used for rice (72%), followed by pasta (50%). The second questionnaire showed that 30% of Albert Heijn's customers know of the cup, among which 59% own one, which is equivalent to 17% of the entire panel. Familiarity with the cup in the panel decreased significantly to 30% from 42% 8 months after the first questionnaire, but ownership remained comparable at 17 vs. 20%, which is not a significant drop.

Among owners, a 26% (15 of 59% owners) share said they always use the cup, 30% (18/59%) use it frequently, and 28% use it sometimes (17/59%). The "always" category increased from 8% (4/48%) in the first questionnaire to 26% (15/59%) in the second, while the "never" category decreased from 27% (13/48%) to 16% (9/59%) (**Figure 3**). Within the total samples, the numbers of frequent users were, respectively, $n = 67$ and $n = 59$ in each survey. Their reported reasons for using the Eetmaatje were always cooking the right portions, generating less food waste, using it being easier than weighing dry food, and eating healthy portions. For the majority of users, the portions of the Eetmaatje are right (66%), but for 15%, they are too small, and for 3%, too big. The most important barriers cited by non-users were that the amounts do not match the desired quantity, a preference for weighing or using a different measuring cup, or forgetting to use the Eetmaatje. A majority of owners in the panel (88%) reported that they were very positive about the Eetmaatje cup, 87% said they are convinced that it helps them cook the right portions, and 77% said they are convinced that it helps them reduce food waste. These results are comparable to the results from the first questionnaire: 85% positive, 89% convinced about the right portions, 83% convinced about food waste reduction [(36), not published]. Albert Heijn is, with a 35% market share, the biggest supermarket chain in the Netherlands. Although their client profile may differ from other chains, the self-reported food waste from Albert Heijn clients does not differ significantly from clients from other chains (37).

A recent questionnaire among visitors to the Huishoudbeurs fair in 2018, which is not representative of the entire Dutch population, confirmed these results. The recent questionnaire shows that 59% always use the Eetmaatje, 28% frequently use it, 5% sometimes use it, and 13% never use it. A share of 87% of the respondents was convinced that the tool helps them reduce their food waste in terms of pasta and rice.

The Eetmaatje was also distributed through the web shop of the Netherlands Nutrition Centre. Dietitians and bodyweight coaches, among other professionals, could order packages of 10 Eetmaatjes to give to their clients for free. In 2017, 150 of those professionals responded to a questionnaire, which provided additional insights: 90% of them recommend the Eetmaatje to overweight clients. Another 53% recommend it to clients with healthy weights and 30% to underweight clients. The Eetmaatje is mainly advised to determine correct portion sizes (89%), but other reasons were also frequently cited, such as losing weight (49%), reducing food waste (46%), and ensuring that the right amount is consumed (43%). For 90% of the professionals surveyed, the Eetmaatje delivers the desired results, meaning accurate portion sizes and eating according to food-based dietary guidelines.

Measuring Actual Household Food Waste

CREM Waste Management measured actual food waste in Dutch households in 2010, 2013, 2016, and 2019 (12, 16, 23, 27, 28). These measurements are longitudinal: every time 130 households from the same 13 districts and streets were sampled. Total food waste showed a significant downward trend from 48 kg to 47.4 kg to 41.2 kg to 34.3 kg. Rice and pasta ranked numbers 9 and 10 on the list of most wasted products in 2016. **Figure 4** shows a downward trend in wasted amounts of rice and pasta before and after the introduction of the Eetmaatje. Before the introduction (2010), the average annual per capita waste of cooked rice and pasta from households was 2.9 kg for rice and 2.1 kg for pasta. Although not statistically confirmed, there seems to have been a decrease in the waste of rice, halving to 1.45 kg, but the decrease of pasta is less clear, fluctuating through the years and ending in 2019 at 1.35 kg. This downward trend cannot be directly attributed to the introduction of the Eetmaatje, since part of the wasted rice is from take-out meals, and the reduction could be the result of other interventions.

Food waste was also measured in 2016 by a self-reporting frequency questionnaire (38). Self-reporting gives an underestimation relative to waste measured by sorting analysis (39). Respondents were asked about their agreement with the statement: "Within our household, we try as much as

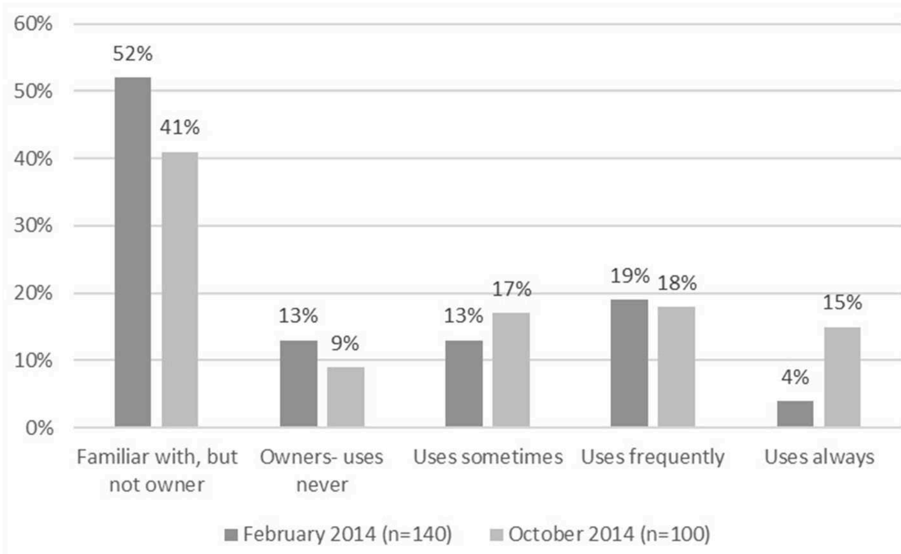

FIGURE 3 | Eetmaatje ownership and frequency of use, February and October 2014 (36).

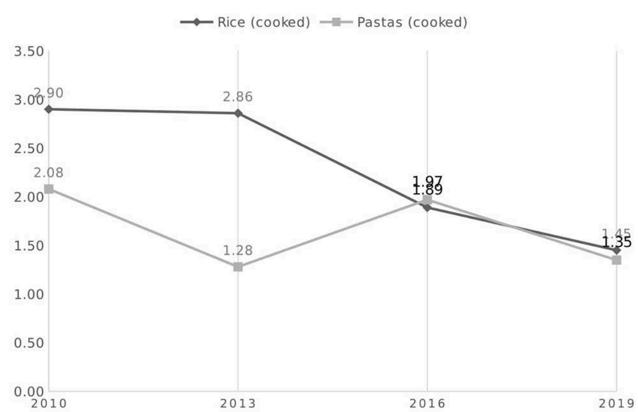

FIGURE 4 | Measured annual waste of cooked rice and pasta in collected household food waste in the Netherlands before 2010 and after the introduction of the measuring cup in 2013, 2016, and 2019, in kg per capita.

possible to weigh/measure ingredients." Answers were related to their reported food waste. Respondents who weigh their ingredients as well as possible wasted less food than respondents who do not. The difference in self-reported food waste between the highest and lowest groups was 16.8 kg less food waste per year. This correlation—of households that weigh food wasting less—does not necessarily mean it is causal, because it could also be explained by an overall awareness about reducing food waste in those households.

DISCUSSION

Ability to Change Behavior

Awareness of the environmental and moral consequences of food waste does not directly correlate with the amount of reported food waste in households (18). This study demonstrates that additional factors stimulate consumers to use a measuring cup:

- Usability and convenience of the measuring cup compared to weighing
- Choosing the right, healthy portions
- Losing weight

In line with the model of Van Geffen et al. (18), convenience and health support consumer motivation. The Eetmaatje cup contributes to the ability of the consumer to cook precise, healthy portions. The health and convenience aspects of using the Eetmaatje meet the consumer's sustainability goals and the common-sense social norm not to waste food.

Most human behaviors are habits, which are less susceptible to rational change. This implies that policies aimed at changing habitual behaviors need to consider the strength of habits and the difficulty of establishing new ones and breaking existing ones. Establishing new habits might include helping people who intentionally want to break the habit, such as through information prompts (40). The Eetmaatje could help to create a new habit, viewed as a prompt to remind the consumer to cook precise portions and reduce waste. From the literature, we know that a higher frequency of cooking is likely to improve skills in, for example, cooking the right portions (41, 42). Using the Eetmaatje measuring cup leads to better matching of individual appetites and circumstances in the household. In practice, food waste reduction is expected, especially in the half of Dutch consumers who have not used measuring instruments or scales so far, proportionally contributing more to rice and pasta waste.

The general feeling of having the ability to change behavior has been examined under the related terms self-efficacy and perceived behavioral control (43). Stancu et al. (44) found perceived behavioral control to have a significant effect on self-reported food waste behavior. In addition to this general feeling of control, the present study has examined the feeling of portion control, i.e., specific abilities to cook precise portions and how they contribute to reducing food waste, in more detail. It is necessary for consumers to be convinced that they can change their own behavior. From earlier research, we can conclude that perceived behavioral control reduces food waste in households (44). The present study underlines that it is essential for interventions to support self-efficacy.

In their review of interventions, Stöckli et al. (17) found that prompts in general were relatively more effective at changing behavior compared to informational interventions. Osbaldiston and Schott (45) defined prompts as "verbal or written messages designed to remind people to perform a target behavior." Nudges are a relatively new phenomenon in the field of reducing food waste (17). Nudges such as changes to plate type and size as well as portion size already demonstrated that they can lead to a reduction in food waste out of the home (46, 47). But there is no evidence that prompts and nudges to reduce food waste are effective in households. Our paper adds evidence to this field. The Eetmaatje could be viewed as a kind of prompt in the kitchen, helping people to cook more precise portions, as well as a nudge to remind the consumer about reducing food waste every time they cook.

Portions in Other Countries

It is interesting to look at the possibilities of implementing the Eetmaatje outside the Netherlands. Other countries most likely have other recommendations for pasta and rice, depending on the culture, food, and energy needs of the population. In Italy, a common portion of cooked pasta is ∼105 g (35). The British Nutrition Foundation recommends cooked medium portion sizes of 180 g for rice, 230 g for pasta or macaroni, and 220 g for spaghetti (48). The US consumption is in the range of 120 to 175 g (49). The Union of Organizations of Manufacturers of Pasta Products of the European Union refers to cooked portion sizes between 180 and 220 g (50). In conclusion, the Eetmaatje could be used in other countries but may require small adjustments in portion sizes.

Possible Improvements

Users (see http://liefdevoorlekkers.nl/2014/02/06/eetmaatje/) suggested that the Eetmaatje is also applicable for other types of grain products that are less frequently used. For example, bulgur and pearl barley seem to have the same water absorption properties as rice and quinoa, while polenta (cornmeal) and buckwheat have the same properties as couscous. Oat and other breakfast cereals would also be possible suggested uses for the Eetmaatje. These are all good possibilities for further improvement of the Eetmaatje, but their inclusion should be further supported by literature or tests. Another user-suggested improvement could be switching the choice of material to compostable or bio-based plastic.

The literature indicates that the water uptake factor of brown rice is higher (2.7–3.9) than that of white rice (2.5) (33). Although the consumption of white rice is currently much higher than that of brown rice (31), food-based dietary guidelines advise an increase in the consumption of brown rice. In the future, a separate measure for brown rice could be added to the Eetmaatje cup.

The Eetmaatje cup is designed for adult portions, but they are also applicable for adolescents between 14 and 18 years old. The development of a version for children could be investigated, as could adding instructions on how to apply adult portions sizes to children, for example, 1 adult portion = 2 children portions (up to a certain age).

Although several studies found statistical correlations between factors and food waste, it is important to understand the theory that explains these correlations (21). Policy-makers who are responsible for consumer-focused interventions and the experts assisting them should therefore strive to identify evidence for causal relationships before they develop, implement, and evaluate interventions for reducing consumer food waste (17, 51). After our study, the REFRESH project published guidance for evaluating interventions preventing household food waste (52). The Eetmaatje intervention is categorized as "prompting people to undertake desired behavior" with a theory-based and an empirical impact evaluation, including measuring outputs, intermediate outcomes, and final outcome. Looking at the recommendations, our intervention could be improved, for instance, by establishing an evaluation plan before the intervention in order to have a better control group and reference measurement.

An estimation of the eventual waste reduction achieved with the use of the Eetmaatje could be done. The theoretical annual waste reduction is ∼6% or 624 g per person for pasta (**Table 3**: 12 g/week) and 21% or 2028 g per person for rice (39 g/week). Based on a distribution of 1.6 million Eetmaatje cups, which are frequently used by at least 50% of receivers who have an average household size of 2.1 persons, the annual waste reduction could be at least 1,050 t of cooked pasta or 580 t uncooked and 3,410 t of rice or 1,360 t uncooked. These are approximate calculations, suggesting that waste reduction could in fact be lower or higher. **Figure 4** shows a downward trend in cooked pasta waste of 0.73 kg per person (12,600 t) and in rice waste of 1.45 kg per person between 2010 and 2019 (25,100 t for the population). The changes appear too large to be attributed to the Eetmaatje alone. The 8% who reported the use of the Eetmaatje in 2019 (**Table 4**) corresponds with half of the maximum of 20% of the 7.9 million households that could own a cup. Many different factors may have affected consumer food waste behavior; in the last decade awareness campaigns on environmental sustainability and other interventions have been performed that may have also influenced this behavior.

CONCLUSIONS

Less than half of Dutch consumers measured the portions of dry pasta and rice for cooking before the Eetmaatje measuring cup was introduced. Measuring portions and use of the Eetmaatje increased in the 6 years after introduction. There is strong evidence that the Eetmaatje has increased the number of Dutch households measuring rice and pasta and thereby reducing food waste. Using recommended portions is expected to reduce waste from cooking pasta and rice. The Eetmaatje cups distributed in our panels remain in use by 50–80% of the consumers who received one, while 85–89% Eetmaatje owners are satisfied with the tool, considering it useful. Approximately 80% of users report that the Eetmaatje cup helps them cook precise, healthy portions and waste less pasta and rice. In addition, consumers who measure pasta before cooking produce less total food waste, according to self-reports. The Eetmaatje measuring cup functions as a nudge toward changing cooking behavior, consequently helping to reduce food waste. In 2019, the measured actual household waste from cooking pasta and rice in the Netherlands showed a downward trend compared to 2013, before the intervention, which does not show that the reduction is directly related to the intervention. In the future, the Eetmaatje tool could be applied to other products and in other countries. Reducing food waste is not the only motivation for consumers to adopt the Eetmaatje measuring cup, but other factors, such as convenience and cooking healthy portions, should also be promoted.

DATA AVAILABILITY STATEMENT

The datasets generated for this study are available on request to the corresponding author.

AUTHOR CONTRIBUTIONS

CD wrote the paper. FM and KE were responsible for the consumer research and questionnaires. MS managed the project. FM, KE, and MS contributed to the content of the paper and gave critical inputs.

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REVIEW
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Valorization of Food Loss and Wastes: Feedstocks for Biofuels and Valuable Chemicals

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Reduction in the amount of food loss and waste requires appropriate quantification method of the amount of food loss annually on the one hand and devising alternative use for foods that would otherwise end up as loss or waste. In this review, food loss and waste (FLW) were classified as avoidable, non-avoidable and possibly avoidable wastes based on inherent composition of several food categories. The current disposal methods of FLW were evaluated for its effectiveness and overall environmental impacts presented by landfills, composting and incineration. Alternative and sustainable alternative for management of food loss and waste include feedstocks for biofuel production, valuable chemicals and coproducts. This approach is renewable, environmentally friendly, improved social status through job creation for local communities and overall improved quality of life.

Keywords: AW, avoidable waste, nonavoidable waste, sustainability, food loss, feedstocks for bio fuel, conversion to valuable chemicals

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INTRODUCTION

A comprehensive evaluation of the quantity or value of food waste or loss is necessary in devising effective strategies for avoiding and/or minimizing such loss. Such measures are aimed at managing the supply and demand in food chain. This is becoming more imperative from the rapidly growing global population which in turn, is demanding more resources to guarantee food security. A delicate balance on increased food production and overall minimal impact on the environment must be established for sustainable development. Sequel to this challenge the United Nations in 2015 (Target 12.3) adopted specified certain objectives in its "Sustainable Development Goals (SDG)" to reduce food loss and waste around the world to "half per capital at both the consumer and distribution points and consequently, food losses along the production chain by 2030." Accomplishing these targets require proper quantification of losses from supply end including production, retail and consumer levels. However, several research and growing body of literature available today differ on common definitional framework and methodological approaches for quantifying FLW (De Laurentiis et al., 2018; Corrado et al., 2019).

Interestingly however, the waste management of food under the auspice of Food and Agricultural Organization (FAO) is actively leading in setting the definitional framework of FLW. It refers to food loss as, "food produced for human consumption but not eaten by human." It went further to define food loss as "the decrease in the amount or value of food," while food waste is considered as a component of food loss which is referred to as "the disposal or non-food use of food that was intended for consumption along the entire food production and distribution chain, that is, from production to consumer l." On the other hand, food waste is a unique and separate part of food loss because the causes of food waste and its preventive strategies are different from those of food losses (FAO, 2013).

The quantity of food loss and waste globally was put "at ∼33% of food intended for consumption" (FAO, 2011). This was further broken down per regions around the world and per capital food waste at consumer level as 98-115 kg/year in the North-America and Europe and "6–11 kg/year in sub-Sahara Africa and South/Southeast Asia" (FAO, 2011). In another research carried out by De Laurentiis et al. (2018), which evaluated food loss and waste attributable to production up to final consumption stage, it was determined that nearly "180 kg per person per annum of food is wasted yearly in the Europe alone" Isah et al., 2019. A great proportion of this loss is attributed to consumer level: "a little over a 100 kg per person per annum is generated at the consumer level of which 76 kg is attributed to individual homes and 25 kg for restaurants and food industry." Thus, consumptions at individual homes are highly implicated in food loss and waste. In China, "organic waste" was highly implicated and narrowed to the consumption of vegetables, nuts and fresh fruits. The implication of this findings is that industrialization and accruing improvement in standard of life may lead to increasing consumption of fruit and vegetable, and thus, "high ratio of organic waste." Similar pattern was observed in Australia with respect to fruits and vegetables where it was implicated as one of the reasons for food loss and waste as high as 286 tons per annum (Zhang et al., 2010; Ghosh et al., 2017). Significant amount of food loss and waste occur at the distribution and point of human consumption.

Measure and Classification of Food Wastes

There is no globally agreed definition of FLW. Most existing quantifications of FLW have varying system boundaries which account for different reported values of FLW across the supply chain. Poorly defined system boundaries in the literature is one major limitation in classification of FLW. The previous research work of Gustavsson et al. (2011), food loss with respect to animal captured "losses rearing stage in the definition of system boundary." In similar work of Barrett et al. (2013), Stenmarck et al. (2016) food loss exclude those losses and the system boundary begins from the point of slaughter of animal. Measure of FLW from production conducted by Hartikainen et al. (2018) defined system boundary as including all agricultural activities (crop production aquaculture and fishing), starting from plants harvest, hatching of fish, animals birth, milk production and when eggs are laid. Boundary system terminates at the point of processing or market distribution.

This lack of uniformity in system boundaries have led to different definitional framework and thus, different values of FLW. The definitional framework of "Food Use For Social Innovation by Optimizing Waste Prevention Strategies" (FUSIONS) focused on the value of food waste recorded within each country European union. On the other hand, the "FLW Accounting and Reporting Standards" (FLW Standard) enables a "different organizations to quantify and report" independently how much waste they generate and determine the point of occurrence. "The Waste and Resource Action Program" (WRAP) proposed classification of waste into "totally-avoidable waste, probably-avoidable waste and non-avoidable waste" (WRAP, 2019). Totally-avoidable waste is defined as food commonly consumed, while probably-avoidable waste as food probably fit for human consumption such as peel and non-avoidable waste as food that is not fit for human consumption such as leaves. These three categories of waste were quantified using "non-avoidable waste intensity" (NWI), "totally-avoidable waste intensity" (TWI) and "Probably-avoidable waste intensity" (PWI) of a product. The NWI, TWI or PWI is defined as the ratio of the weight fraction of non-avoidable/totally-avoidable/probably avoidable waste to the total quantity of food purchased. These are shown on Equations (1–3), respectively, below:

TABLE 1 | Edible and Inedible fractions (%) of some perishable food items (Maletta and Maletta, 2012; Public Health England, 2015).

Food types	Inedible fraction	Edible fraction
Lime oranges	36	37
Peaches & pears	25	17
Pineapples	43	49
Berries & Quinces	21	3
Tangerine & Asparagus	60	70
Artichokes	66	57
Cabbage	16	22
Carrot	18	17
Broccoli	42	20
Cucumber	23	3
Eggplant	8	19

$$NWI\ (\%) = \frac{\text{non} - \text{avoidable waste [Mt]}}{\text{total purchases [Mt]}} \tag{1}$$

$$TWI\ (\%) = \frac{\text{totally} - \text{avoidable waste [Mt]}}{\text{total purchases [Mt]}} \tag{2}$$

$$PWI\ (\%) = \frac{\text{Probably avoidable waste [Mt]}}{\text{total purchases [Mt]}} \tag{3}$$

Whereby NWI, TWI, and PWI of Equations 1, 2, and 3 are the proportion of product that is wasted non-avoidably, totally-avoidably or probably-avoidably, respectively. The "total purchases" in each expression refers to total amount of food acquired. The NWI of food loss or waste is considered equal to the inedible fraction of the food. The varying amounts inedible fractions of food are presented in **Table 1** for perishable food items. Some variables were taken into consideration for differences in the two sets of data. For example, determination of edible asparagus by Public Health England (2015) totally eliminate the base measuring the edible fraction and therefore of inedible fraction is quite lower in comparison with other data.

Characteristics of certain products have been linked the level of generation of avoidable/possibly avoidable wastes. The amount of time it takes for certain food item to perish or considered unfit for human consumption and the commodity price are contributing factors to the values of "totally avoidable" and "probably avoidable" waste intensity. This is based on the fact that the purchase of cheaper commodities might be higher than necessary and as consequence, some of the products are left to spoil in comparison to high end food items. Similarly, certain food prone to high degree of perishability are more likely to be left as waste if stored for long period of time or under abusive storage situation. The perishability of certain commodities is generally linked to its shelf life. The period of time a perishable product becomes "unsuitable for consumption during storage often refers to its shelf-life." Fishes, fresh fruits and nuts are composed of living cells throughout the supply chain up to when they are consumed and the shelf-life are dependent on storage conditions, ripening condition, time of harvest, conditions of growth, and type of packaging of products (Demirel, 2018). Classification of food waste either as totally-avoidable or non-avoidable is an indication of thorough perception of causes of FLW which invariably leads to probable development of appropriate prevention model, and capturing of totally-avoidable waste in the waste-flow analysis.

Definition of food waste in production chain is focused on the flow of food products that were originally designed for human consumption but diverted in the food supply chain (examples include slaughter, wholesale, packaging and retail) and rather were used as feedstocks or diverted for waste treatment facility. The "non-edible" parts of waste /loss such as orange peels and meat bones are not accounted for or deliberately omitted in the definition. FWL under this definition are captured as "side flows" (SF).

Disposal Methods of Food Wastes

The production of food loss and waste often lead large amount of wastewater and solid waste (Valta et al., 2017). These include food peels and seeds, residues from food membranes and non-edible parts of food. Wastewater on the other hand usually consists mainly of liquid waste constituting industrial effluents, wash liquor, cleaning liquid and other industrial solvent system. More often than not, the solid waste fractions are subjected to biological treatment (including anaerobic digestion), incineration, landfills, plowing in fields, dumping into the sea and open burning. Conventional practice ensures that the liquid waste is pretreated, and finally treated in stand-alone ponds in addition with municipal wastewater effluents (Nasr et al., 2014; Valta et al., 2015). Disposal of solid waste arising from food loss and waste have been carried out over time using several biological treatments, amongst which anaerobic digestion has proven to be highly cost-effective because of its inherent "high energy recovery," limited environmental impact and biogas production (Álvarez et al., 2010). The two-phase digestion system is particularly suitable for treating "solid wastes rich in solid matter and source-sorted organic waste of municipal solid wastes" associated with fruits and vegetable wastes such as potato peelings apple, green beans, green salad, and carrots. The process involves several hydrolytic liquefaction digesters for treating each type of solid food waste and ultimately linked to central methanogenetic fixed-bed reactor (Álvarez et al., 2010).

Sometimes, liquid wastes are first pretreated with solution of hydrogen peroxide to oxidize lower oxidation sate of sulfur and thereby adjusting the pH value to neutrality through addition of sodium hydroxide. Following this pre-treatment protocol, the solid biomass is ultimately degraded via oxidation using conventional biological treatment.

Disposal and treatment of food waste and loss via landfills or dumping sites for food waste and pre-treatment (including biological treatment) of waste liquids are not cost effective in addition to the introduction of toxic and harmful chemicals from wastewater treatment (H_2O_2 and NaOH) and CO_2 releases into the environment. Alternative use of these organic biomass such as valorization into biofuel, bio-lubricant and other bio-products is not only economically sound but environmentally compatible alternatives. These feedstocks from waste as source of biofuels and other bioproducts has possesses huge benefits in terms of savings from alternative use of land instead of landfill, electricity generation and savings in the cost of feedstocks for biofuel production.

Incineration of solid wastes arising from food is designed for combustible food waste which is suited in crowded cities where landfills and other disposal methods are not cost-effective. It involves high construction and operational costs. The design includes primary chamber to facilitate rapid desiccation of moist food waste which typically involves the use of a ledge or drying hearth. The secondary chamber is operated at temperatures above 700°C for complete combustion of all unburnt or semi burnt wastes. This practice also is not only costly but unsustainable in terms of energy demand and environmental pollution.

Environmental Impact of Current Disposal Methods

The main driving force for the pursuit of alternative disposal of food loss and waste such as conversion to biofuels as a sustainable alternative is the total contribution of biomass to "climate change." The central theme of climate change hinged upon reduction of greenhouse gas (GHG) emission: gases that trap heat in the atmosphere. The major components of greenhouse gases include the following:

Carbon Dioxide (CO_2)

This gas finds its way into the atmosphere through decomposition of biomass. The good news is CO_2 can also be sequestered or absorbed by plants from the atmosphere during biological photosynthesis. In the United States (US), CO_2 accounts for about 81.6% of the total greenhouse gases in 2016 (U.S. EPA, 2017). Some activities linked to humans are adversely affecting the "carbon cycle" by increasing atmospheric CO_2 °r by altering the effectiveness of natural carbon sinks, like forest to sequester carbon dioxide from the environment. The overall benefits of biofuels in CO_2 reduction requires complete life cycle assessment data for comprehensive determination of natural resource requirements of biofuels and "environmental impacts from the life cycle" of biofuels. This requires a large amount of data and complete network of re-use, recycling, and eventual disposal information (The Royal Society, 2008).

Methane (CH_4)

It accounts for about 10% of total greenhouse gases. Main sources of methane emission include the manufacturing of coal, natural gas, fossil fuels, degradation of biomass in municipal waste and dumpsites and other related agricultural practices. The lifetime of methane in the environment is considerably shorter than CO_2 due to its removal by natural chemical processes in soil and some other atmospheric chemical reactions. Nonetheless, methane is regarded to trap radiation more efficiently than CO_2 that it is now considered as having greater comparative impact, that is, about "25 times greater than CO_2 over a 100-year period" (U.S. EPA, 2017). In general, natural gas and fossil fuels are the largest contributors to CH_4 emission.

Nitrous Oxide (N_2O)

The contribution of nitrous oxide to GHG emission in the US in 2016 was about 6%. Major sources of N_2O include human activities such as agriculture, fuel combustion, municipal waste management (from food loss and waste) and other industrial processes. N_2O stays longer in the atmospheric environment "for ∼114 years before it is eliminated either by sink or degraded through chemical processes" (U.S. EPA, 2017). Thus, comparatively, N_2O impacts on global warming almost "300 times greater than carbon dioxide (IPCC, 2007). Agricultural practices such as application of fertilizer (synthetic or organic) and other farming activities" are highly implicated in N_2O emission system. Contributions from industrial production of nitric acid and combustion of fossil fuels are also significant.

Fluorinated Gases

Some industrial processes emit "fluorinated hydrocarbons (HFCs), perfluorocarbons (PFCs), nitrogen trifluoride (NF_3) and sulfur hexafluoride (SF_6)" which are considered powerful greenhouse gases for their high global warming potential (GWPs). Fluorinated gases found their ways into the environment via several manufacturing processes including aluminum manufacturing and semi-conductor processing. They are considered as long lasting atmospheric global warming gases, lasting thousands of years in the atmosphere. Many fluorinated gases are difficult to remove from the atmosphere unless degraded by some photochemical reactions in the far upper atmosphere. The main source of fluorinated gases is their use as refrigerating gases in cooling systems in homes, offices and vehicles (US Energy Information Administration, 2013, 2018). They were designed as an alternative for chlorofluorocarbon and hydrochlorofluorocarbons which are now being replaced under the Montreal international agreement Protocol. The subsequent amendment Kigali to the Montreal agreement calls for reduction the manufacturing and application of the most harmful hydrofluorocarbons. This led to the recent development of hydrofluoroolefins (HFOs) which are characterized by "shorter lifetimes in the atmosphere and low global warming potentials." The relative contribution of these gases to the overall greenhouse gases are shown in **Figure 1**.

Strategies at minimizing and reduction of food loss and wastes can be viewed from two dimensions of potentially reducing GHG emissions of both regulated and unregulated pollutants and the opportunity to future developments of alternative use of food loss and waste. This include life cycle assessment (LCA) of the total environmental and health impacts.

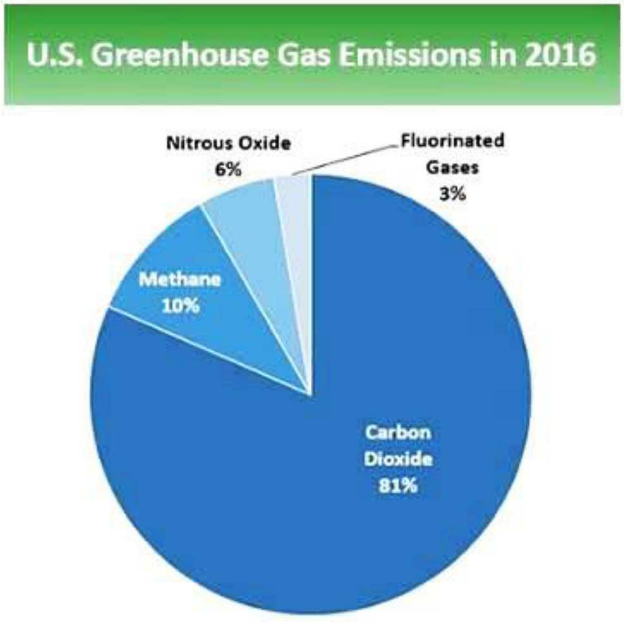

FIGURE 1 | Total greenhouse gas emission in 2016 (6,511 million metric tons) of CO_2 equivalent (US Energy Information Administration, 2018).

At a glance, biofuels can be seen as easily degradable and presents minimal health hazard upon human exposure. However, research has shown that admixture of bioethanol to gasoline distort the natural attenuation of "benzene, toluene, ethylbenzene and xylene" (BTEX) in ground water and soil. There is a potential health risk when one is exposed to these BTEX chemicals (US Energy Information Administration, 2013, 2018).

Similarly, increased farming activities for crop-based biofuels production (corn- based ethanol) could lead to eutrophication with detrimental environmental impacts to the ecosystem and estuarine. The net CO_2 emissions from converting large carbon sinks land for biofuels production is "∼1.5 gigatonnes of cabon per year (GtC/yr)" (Grace, 2004; Baker, 2007). Drainage and bush-burning are some contributing factors to the emission of CCO_2 in largely carbon sink forest as observed in peatland in South East Asian. Such CO_2 emissions from the soil globally is irrespective of the "cause of the land change to the cultivation of crops." Thus, the cause of increase in CO_2 emission cannot be solely attributed to disposal of biomass content of food loss and waste.

Burning of biofuels results in the emission of increased atmospheric pollutants such as CO_2 and other oxides of nitrogen and sulfur in addition to some harmful oxidative hydrocarbon compounds and volatile organic compounds (VOC). Some of these air pollutants increase with biofuels while other gas emission decrease with the use of biofuel that is related on the molecular architecture of the biofuel and feedstock.

TABLE 2 | U.S. bioethanol imports from select countries in caribbean and central America ($1,000) (International Energy Agency, 2016).

Country	2002	2003	2004	2005	2006	2007	2008
Brazil	0	0	2,150	743	10,326	4,495	4,835
Costa Rica	286	350	605	795	855	1,056	872
El Salvador	107	184	136	564	917	1,745	1,667
Jamaica	690	936	871	864	1,590	1,790	2,351
Trinidada & Tobago	0	0	0	238	590	1,017	1,559
Total	1,083	1,450	3,807	3,214	15,555	10,148	12,610

GHG emissions and associated pollutants including CO and oxide of nitrogen from biofuels production are not necessarily less than the emission from conventional fossil fuels from the perspective of comprehensive life cycle analysis. When a thorough look at the entire carbon life cycle including use of land is taken in addition to the emission of "less prevalent but more potent GHG," such as N_2O are considered, the benefits of biofuels as emitting less GHG in earlier studies need to be reexamined. It is even truer when the total GHG emission is considered from combustion of fuel and at every phase of the life cycle of fuel including processing, transportation, and uses as feedstocks for herbicides and fertilizer as well as distribution of biofuels.

Developing alternative use of food loss and waste such as biofuel feedstocks has direct social impacts in the rural communities where the feedstocks are derived. Studies showed that conversion technologies are situated near the source of feedstock, and thereby creating jobs for rural dwellers as well as wealth distribution to rural communities through corporate social responsibilities and social equity (Demirel, 2018). Rural farmers in developing countries who are involved in farming activities are more likely to benefit from higher commodity prices and biofuel inspired development dynamics. There is a need however, to consider the plight of the urban poor who is likely to bear the hardship of increased agricultural food products, unless improvement in quality of life rises across the entire spectrum of the society as whole and sufficient value-addition attributable to biofuel is retained locally (The Royal Society, 2008; Demirel, 2018).

Current U.S. policy on bioethanol import is quite favorable to suppliers from Central American countries including the Caribbean under the "Central American Free Trade Agreement" (CAFTA). This policy has led to importation of up to 7% of US domestic bioethanol demand "without being subject to the usual tariff of $0.54/gal." **Table 2** shows fuel ethanol import from selected Caribbean and Central American countries between 2002 and 2008.

The socio-economic impact and local prosperity of Nampula (Mozambique) and Inhambane (Gaza) from the cultivation and supply chain of bioethanol derived Eucalyptus and Swithcgrass as showed there were positive improvements in all the regions with respect to economic viability, local prosperity, social well-being, food security and land rights (Wicke et al., 2015).

VALORIZATION OF FOOD WASTES

In the past, nearly all petrochemical feedstock for production of valuable chemicals and commodity products were based on fossil fuels such as alkanes (ethane and butane), olefins ("ethylene, propylene and 1,3-butadiene") and aromatics such as BTX which were largely considered platform chemicals. The world is currently experiencing geographical and feedstock shift of platform chemicals for valuable chemical production from fats, oils and greases (FOG) and organic matter comprising of "cellulosic, hemicelluloses, and lignin matter" which are the main composition of food loss and wastes across North America, Europe and Southeast Asia countries. Intensive research in the past few years in synthetic organic chemistry, improvement in catalysts development and biotechnological advancement have recognized the following compounds of plants and animal wastes as potential building blocks for valuable chemicals and consumer products:

- Fatty acids and triacyl glycerides
- Carboxylic acids (acetic, glycolic, oxalic,3-hydroxypropionic, fumaric, succinic, asperic, malic, butyric, levulinic, itaconic, glutamic, adipic, citric, and gluconic acids)
- Olefins (ethylene and unsaturated fatty acids)
- Alcohols (ethanol, glycerol, propane diols, 1,2,4-butane triol, 2,3-butane diol, 1- butanol and sorbitols)
- Enzyme and carboxylic acid production: protease, lipase, cellulose, phytase, amylase, lignisase, xylanase, L-glutaminase, citric acid, lactic acid, gallic acid and gibberellic acid
- Others such as sucrose, furfural, acetone, lysine, antibiotics, poly hydroxyalkanoates, poly gammaglutamate and aromas.

These chemicals and many more are derived primarily from plant and animal sources including fats and oils, cellulose hemicellulose and lignin. Industrial utilization of these feedstocks primarily used as human food and animal feed was slowed due to renewed efforts on renewable fuels (bioethanol and biodiesel) and recent food vs. fuel debate. With the development of second-generation feedstocks (advanced biofuels), it becomes more obvious that biomass can be sufficiently produced for industrial chemical production and renewable fuels "with little negative impact on the supply chain of food products for human consumption" for the ever-growing world population (Biermann et al., 2011). Application of solid-sate fermentation technology have opened another frontier of valuable chemicals, enzymes, antibiotics, surfactants and industrial aromas (Bhargav et al., 2008). Exploring valuable chemicals from biomass is in tandem with the concept of green chemistry which focuses on transforming conventional chemical reactions with the more environmentally benign industrial process. Anastas and Warner (1998) defined green chemistry as the "efficient utilization of renewable feedstocks from plant and animal sources, elimination of waste" and avoidance of "the use of harmful and/or toxic reagents in the production and use of chemical compounds." This led to the 12 principles of green or renewable chemistry:

1. Atom efficiency
2. Waste prevention

3. minimize harmful and/or toxic reagents
4. Innocuous solvents
5. Safer product design
6. Energy efficiency
7. Use of renewable materials
8. Fewer synthetic route
9. Catalysis instead of stoichiometry
10. Biodegradable product design
11. Safer processes
12. Pollution prevention methodologies.

These principles focused on the development of new reaction mechanisms that is environmentally safe, promote health of general population, energy efficiency and increased product selectivity. This is considered more sustainable for the world's growing population and industrial utilization of chemical resources. The emphasis is on renewable raw materials (plant and animal sources) as the preferred platform chemicals for development of valuable chemicals and coproducts. The following sections provide discussions on some valuable chemicals and products derivable from fats and oils, lignin and cellulose/hemicellulose of food waste and loss.

Feedstocks for Biofuel Production

Biofuel can be defined as the energy (work, heat or electrical) derived from biomass and its refined products. Biofuel is classified as solid, liquid, and gaseous biofuels depending on the physical state of the biofuel in-use. These include; bioethanol, biodiesel, bio-kerosene, natural gas (syngas) etc. Biofuel has been used for human activities such as heating of living environment, cooking of food and lighting of our homes since the beginning of human civilization. About "83 billion liters of fuel ethanol is produced annually from farm crops whilst biodiesel from plant and animal oil continue to rise estimated at present capacity of 21,463 million liters per annum" (Guo et al., 2015). It is projected that market growth of biofuels worldwide will be "$\sim$30% of the global energy demand before 2050." Gasoline and other form of energy from fossil reserves are still occupying a significant greater position in our sources of energy today, estimated at greaterthan 80% of the total global energy consumption (US Energy Information Administration, 2013; Guo et al., 2015).

However, fossil reserves are limited and are non-biodegradable. The enormous amounts of GHG emission from fossil fuels is another major concern. This led most developed nations around the world invest heavily in research and development and appropriate technology for application of renewable sources of energy including biofuel and co-products in order to minimize the environmental consequences (IPCC, 2013). Ethanol production from food wastes could be utilized as alternative for fossil fuels to power automobiles engines.

Automobile vehicles traveling the roads worldwide are in millions and "consume nearly 930 million gallons of gasoline per day" (U.S. EIA, 2013). This level of consumption has necessitated some environmental and socioeconomic concerns. Another major concern at the present consumption level is that, "the reserve of fossil fuels will be seriously compromised in another 45 years" (US Energy Information Administration, 2013). Therefore, the need for renewable sources of energy cannot be over emphasized. There may be need to adjust existing fermentation processes in order to generate adequate bio-ethanol from lignocelluloses matter (advanced biofuels) as a separate feedstock for bio-ethanol from food crop.

Adjustment of anaerobic digestion technology of organic wastes is currently in place around the world for the production of syngas (CH_4 $+CO_2$) via the methanogenesis and acetogenesis pathway (Álvarez et al., 2010). This is highly valuable gaseous biofuel. Commercial biogas plants around the world include biogas plant for potato slurry in Belgium with capacity of 150,000 tons/year and co-digestion biogas plant in Voghera, Italy with annual capacity of 27,000 tons/year.

Some species of cellulase (thermostable sp.) were identified and capable of high cellulosic degradation action at $>70\,^{\circ}$C. Application of such enzymes in cellulosic bioethanol production reduces the costs production costs. Similarly, some yeasts have been developed for ethanol fermentation at more efficient manner and effective processes for optimization and commercialization of this technology. Thermo-chemical process is another emerging production technology for bio-ethanol production from cellulose and lignin derived from food wastes. The waste from several food categories including crops, vegetables, and fruits can be pyrolyzed to produce gaseous biofuel (syngas) a mixture of H_2 and CO) which can be subjected to some microbial activities in a special fermenter to produce bio-ethanol of approximate 50% yield.

Solid Biofuel

Biofuel derived from agricultural practices, forest and solid wastes are referred to as solid biofuels. It includes forest debris, woods, coal and other woody materials. Several years Before the discovery and commercialization of gasoline and petrol diesel, woods from forest in the form of pellets or chips were the major sources of energy for home heating, food preparation and light generation. Solid biofuel from different sources including woody types and non-woody can easily be converted to fire (or heat energy) through thermal combustion of organo-carbon contents at high temperatures ($\sim$260°C) using atmospheric oxygen. In 2008, "organic matter from plants and animals became the feedstock of choice for renewable energy, generating around 1,200 million tons of oil equivalent."

Solid biomass are pre-treated to minimize handling costs, storage and transportation and impact improved combustion quality on the final product. Pretreatment methods are usually matched to the chosen combustion technology which can be broadly classified as compacting and heat drying. Compacting or briquetting is designed to improve bioenergy densification of biomass through reduction in the overall volume of the biomass. The compacting method depends on the source of solid biomass. For instance, the squeezing and stabilization of agricultural crop straw is different from compaction of wastepaper or saw dust. The higher the briquetting pressure the denser the fuel becomes (Demirel, 2018).

Sawdust briquettes are obtained experimentally during compacting with screw press and hydraulic piston. Final product

FIGURE 2 | Solid biofuel made from compacted crop straw (Royal Academy of Engineering, 2017).

density as high as 1,400 kg/m^3 and power of 22 kw were obtained after compacting.

The energy density of woody material in general is nearly 15 MJ/ kg which is equivalent to one-half the energy content of fuels from fossil reserve (IPCC, 2013; Guo et al., 2015). Wood trims and chips from trees and branches have been used home heating and power generation. For instance, a boiler installed in Colgate University utilizing woodchips in Hamilton, NY provides about 75% of the heating and hot water requirements via the use of 20,000 tons of wood chips (Guo et al., 2015). Another variant of wood chips is Wood pellets, which is often referred to as refined wood chips. Wood pellets can generate nearly 18 MJ m^{-3} of energy. Biomass from FLW, and other agricultural wastes from food crops and trees can also be efficiently converted into wood chips and pellets or compacted as straw as shown on **Figure 2**.

Wood from mango plant was utilized to generate renewable energy (biofuel) in a typical fuel cell plant (Paul and Kumar, 2016). Other plant materials including orange plant, apple and coconut trees can be transformed to solid biofuels. The energy potential of these plant materials is as high as 19,100,000 MJ/Square kilometer (Winzer et al., 2017). Woods from palm tree (including palm frond) have been reported as efficient feedstock for bioenergy. These solid biofuels are applied for home heating in the form of pellet stove. Some designs allow these stoves to be fed automatically for nearly 80% energy efficiency (U.S. DOE, 2013). The high energy potential of charcoal which is nearly 35% generates an estimated energy content as high as 28–33 MJ $kg^{-1''}$.

Charcoal is renowned to undergo combustion "without generating flame and gaseous smokes at it high heating temperature of ∼2700°C" (Antal and Grønli, 2003). Global production per annum of charcoal is as high as 51 million tons (Van Gerpen, 2005).

Liquid Biofuel

The more predominant energy in the transport sector is liquid form of biofuels. These include bioethanol derived from fermentation, biodiesel from fats, oils and greases as well as renewable hydrocarbon fuels derived from plant and animal sources. The availability of renewable raw materials for bioethanol was first emphasized by Alexander Graham Bell in 1917 which described bioethanol as "any vegetable matter capable of fermentation, crop residues, grasses, farm waste, and city garbage." Bioethanol was experimented as an automobile fuel in 1913 well before the production and commercialization of petrol from fossil reserve. An American inventor named Samuel Morey, "designed and produced an internal combustion engine in 1826 that runs 100 % on bioethanol". Total global production of bioethanol was 23.4 billion gallons in 2013, with contribution from US, Europe, Brazil, Canada and China at roughly 57, 27, 6, 3 and 2% respectively. The united states invested "114 million tons/year representing about 42% of its harvested grains from maize in bioethanol production to meet 10% blending gasoline fuel" (U.S. EIA, 2013). The exponential growth of biofuel production over the las decade with bioethanol contributing the vast majority of this growth which is produced predominantly in the US, Brazil and European Union (US Energy Information Administration, 2012; U.S. EIA, 2014). The world's largest producer of bioethanol is US which began in the early 1980 with a production capacity of 60% of the world production of 1,493,000 bpd in 2011 (Karatzos et al., 2014). The main driver of the US bioethanol production being energy security concerns arising from the fluctuation as well as rapid increases in petroleum prices in the 1970s.

Brazil, as the second largest bioethanol producer launched in 1975 in response to the increased oil prices of 1970s which was named "National Alcohol Program Protocol" designed to make Brazil independent of foreign oil imports and stabilize its growing sugarcane market. During this period the government of Brazil reached an agreement with automobile manufacturers whereby vehicles in Brazil ran on 100% ethanol fuel in 1985.

The term biofuels' is commonly used for liquid biofuels which can be differentiated according to number of key characteristics. Typical characteristics employed include type of feedstocks, conversion technology, and technical specification of the biofuel as well as its end use. Classification according to type of feedstock is one common convention giving rise to the first, second and third generation biofuels (Royal Academy of Engineering, 2017) as shown on **Table 3** which also showed alternative classification as 'conventional, ambiguous or advanced biofuels.

Biodiesel from plant and animal oil is equally important liquid biofuels derived from renewable feedstocks. Petro-diesel is a 'C8^{-C}25' fraction derived from fractional distillation of petroleum at 200–300°C. Energy content of diesel in general is put at ∼38 MJ $L^{-1''}$ which is higher than 34.7 MJ L^{-1} energy content for gasoline. It is recommended for diesel engine transportation vehicles and agricultural vehicles and equipment including tractors, military vehicles, heavy construction vehicles and mining machineries. Other applications of diesel fuels include heating of homes, offices and industries as well as

TABLE 3 | Classification of biofuels according to the type of feedstock, alternative classification and process technology (Royal Academy of Engineering, 2017).

Classification (used in this report)	Alternative classification	Feedstocks	Production	Products
First generation	Conventional biofuels	Sugar crops	Transesterification	Bioethanol
		Starch crops	Fermentation	Biodiesel
		Vegetable oils	Hydrogenation	Methanol
			Fischer-Tropsch	Butanol
Second generation	Ambiguous	Used cooking oil	Gasification	Mixed alcohols
		Animal fats	Pyrolysis	Jet fuels
		Energy crops	Hydrolysis	Vegetable oil
	Advanced biofuels	Agricultural residues		
		Forest residues		
		Sawmill residues		
		Wood wastes		
		Municipal solid wastes		
Third generation		Algae		

electricity generation (U.S. DOE, 2015). Biodiesel is designed to partially or completely replace fossil diesel arising from the shortfall and supply from petroleum sources. Biodiesel is a brownish-yellow liquid derived from plants and animal fats, oils and greases (Van Gerpen, 2005). Chemical composition of biodiesel is more or less mono-alkyl ester (usually fatty acid methyl ester). It is a "catalyzed trans-esterified product of fats, oils and greases" (FOG) and suitable alcohol. The fuel properties of biodiesel depend on the type of feedstock, alcohol and catalyst employed. It includes specific gravity range of 0.87–0.88, lowest temperature of crystallization onset referred to as cloud point (CP) of−4–14°C, flash point (FP) range of 110–190°C, external resistance to flow referred to as kinematic viscosity of 4.8 mm^2 s^{-1}, and centane number of 50–62. Its energy content ∼45 MJ kg^{-1} which is nearly 90% of heating value of diesel derived from fossil reserve (Hoekman et al., 2012).

Pyrolysis bio-oil is also a liquid biofuel which is derived from high temperature (300 – 900°C) pyrolysis of biomass in limited supply of air. Pyrolysis of plant biomass usually lead to three products namely the solid biochar, liquid bio-oil vapor condensate), and gas phase syngas. Almost any biomass may be used to generate bio-oil. Feedstocks include forest trees, crop residues, bagasse, peanuts debris, animal litters or switchgrass. Crude bio-oil is composed of over 300 chemical compounds such as char particulate matter and water molecules.

Other components of crude bio-oils include range of alcohols, carboxylic acids, carbonyl compounds, organic esters, carbohydrates, phenolic, unsaturated compounds, aromatics and nitrogen containing compounds. Unrefined bio-oil is usually unstable and corrosive product. It is highly viscous, insoluble in hydrocarbon fuel with minimal energy value and less flammable (Czernik and Bridgwater, 2004; Ringer et al., 2006; Junming et al., 2008; Vamvuka, 2011).

Refined bio-oil is a substitute for fuel oil either as biodiesel or heating fuel for static machineries including such as boilers, static engines, furnaces and electricity generation. Crude bio-oil is often used directly for heating purpose industrially using such techniques as atomization. In general, bio-oil is an important renewable feedstock for "platform chemicals, bio-lubricants, paints, binders, stabilizer, thickeners and preservatives".

Green biofuels, sometimes referred to as renewable biofuel is also a liquid biofuel with similar chemical and physical properties of existing gasoline. Research is ongoing to meet specifications of gasoline without damaging existing vehicle infrastructures and engines components at high blending ratios. Drop-in biofuel are often considered advanced biofuels or renewable diesel and gasoline derived from lipids and algae or cellulosic materials. They are similar in chemical structure to fossil fuel- based diesel and gasoline. These fuels do not have the compatibility issues with engines or vehicle infrastructure seen with biodiesel and bioethanol, making them ready to displace fossil- derived fuels in no distant future (Araújo et al., 2017).

The molecular oxygen contents of Bioethanol and biodiesel are higher than petrol fuels as well higher dissolution capabilities. When blended at rates >20%, often leads to damage of vehicle infrastructures including vehicle engines and elastomeric components (Araújo et al., 2017).

Suitable feedstocks for green biofuel include biomass, butanol., syngas complex and other suitable monosaccharides/disaccharides. Lignocellulosic sugars can be processed into gasoline using transition metal catalyst such as ruthenium for cyclization and dehydrogenation processes (Dowson et al., 2013; Duan et al., 2013). Research is in progress for commercialization of this process and also for appropriate redesign of existing ethanol plant for transformation to biobutanol. Drop-in biofuels have several advantages over conventional bioethanol or biodiesel. Amongst its superior performance includes its high hydrogen to carbon ratio, high carbon bond saturation and thus greater stability and low solubility in water. Specifically, it is associated with following advantages:

i High octane rating and thus, reduced ignition delayLow sulfur content and reduced sulfur oxide, nitrogen oxide and particulate matter emission
ii. Low aromatic content
iii. Absence of additives or oxygenates and thus, greater stability.

Renewable or drop-in biofuels are obtained from thermochemical, biochemical, hydro-treating and gasification processes. The thermochemical route involves controlled oxygen heating at high temperature, usually above 700°C, whereby biomass is converted to liquid biofuels. Thermochemical process can be carried out as fast pyrolysis (short residence time), slow pyrolysis (long residence time) or under gasification at higher temperature and short residence time. Product spectrum from thermochemical conversion of biomass into drop in biofuel.

Gaseous Biofuel

Gaseous biofuel is another renewable fuel in gaseous state and considered as a replacement for natural gas or liquified natural gas (LPG). The energy value is estimated at 53 MJ kg^{-1} and composed mainly of methane gas at ∼95%, followed by ethane gas estimated 5% and some trace amounts of propane, butane, nitrogen and carbon dioxide. LPG is used as cooking gas, heating, automobile fuels, electricity, and an important energy for industries. Sometimes referred to as biogas, produced by anaerobic degradation of organic biomass and other cellulosic materials. Biogas in its unrefined form is composed "of ∼ 65% methane, 35% CO_2 and little amount of gaseous water, H_2 and H_2S". Usually CO_2H_2S and other impurities are removed to generate biogas as renewable replacement of LPG (Niesner et al., 2013; Radu et al., 2017).

Synthesis gas or simply syngas is also another gaseous biofuel composed of CO, H_2 and CO_2, from high temperature pyrolysis of organic matter. Unrefined syngas consists of about 47% N_2, tar and some H_2S. Application of syngas include generation of electricity and as a renewable feedstock (refined form) for the synthesis of automobile fuel and other valuable chemicals including methane (hydrocarbons) or alcohols such as ethanol or methanol and ether (Fischer-Tropsch process). Existing today are several syngas industrial gasification plants in several countries in the world. This include such commercial plants as 17, 56 and 42 syngas plants in US, China and Europe, respectively, in 2010 with a combined capacity of 71,205 MW th. Although, roughly 0.5% of the syngas was derived from organic biomass, substantially greater proportion comes from coal, pet coke and LPG (Wang et al., 2009; del Alamo et al., 2012). Renewable energy generation from organic biomass via anaerobic digestion often include production of biogas. It is projected that biogas consumption is expected to reach 25% of present global LNG consumption if present process technology is optimized. An example of wood pyrolysis to syngas production and the accompanying chemical reactions were reported by Guo et al. (2015) with a "conversion rate of ∼92%," that is, wood to CO, CO_2, and methane gas.

The thermochemical process (pyrolysis) converts biomass to char and vapor in the absence or limited amount of oxygen to generate a 'mixture of carbon dioxide and carbon monoxide, while the vapor is further pyrolyzed to carbon dioxide and water. Further combustion of char particulates results in the oxidative reaction with carbon dioxide to generate carbon monoxide, or by ^{H_2O} leading to syngas (a mixture of carbon monoxide and hydrogen) as shown above. Syngas has an energy value of nearly 5 MJ n M $^{-3''}$ (Guo et al., 2015). And the fuel can be applied for electrical generation.

Biofuels can be synthesized and utilized in solid biofuel, liquid form or as gaseous fuels. However, specific applications is determined by several factors such as energy density, fuel efficiency and convenience. Solid biofuels in general are often applied at source and quite efficient in energy generation but low in energy density.

Thus, it is restricted to solid fuel burners. On the other hand, liquid biofuels are relatively denser in energy than solid biofuels and finds suitable applications as replacement for gasoline and petrol diesel in almost all stationary and automobile engines. Second generation (advanced) liquid biofuel have several advantages such as low combustion emissions, renewable and simple conversion technology. They are derived from organic biomass and waste which is considered positive environmental impacts. This is intended to mitigate the food vs. fuel debate the first-generation liquid biofuel generate.

Finally, gaseous biofuels is produced from a variety of feedstocks such as organic biomass and residues. Biogas "fits into the existing natural grid," while syngas can be produced existing mature production it also can serve as suitable feedstock for drop-in biofuel and other industrial chemicals.

Renewable Source for Valuable Chemicals and Bio Refinery

Due to sustainable' efforts on more environmentally friendly chemicals, we are witnessing both geographical and feedstock shift of platform chemicals for valuable chemical production from fats, oils and greases (FOG), cellulose, hemicellulose and lignin across North America, Europe and Southeast Asia countries. Research and development in organic chemistry, catalysis and biotechnology have contributed immensely in production of following valuable chemicals and compounds of plants and animal origin as potential building blocks for consumer products and development of bio refinery:

i. Fatty acids and triacyl glycerides from seed oils and nuts
ii. Carboxylic acids (acetic, glycolic, oxalic,3-hydroxypropionic, fumaric, succinic, asperic, malic, butyric, levulinic, itaconic, glutamic, adipic, citric, and gluconic acids) from biomass derived from plants
iii. Olefins (ethylene and unsaturated fatty acids) based on oleochemicals
iv. Alcohols (ethanol, glycerol, propane diols, 1,2,4-butane triol, 2,3-butane diol, 1- butanol and sorbitols)
v. Others (sucrose, furfural, acetone, and lysine).

These chemicals and many more are derived primarily from plants and animals including fats and oils, cellulosic materials as well as hemicellulose and lignin (major components of food wastes and food loss). Industrial utilization of these feedstocks based on food wastes is an avenue for development of biorefinery and production of valuable chemicals and consumer products.

The chemical composition of fats, greases and oils are basically triglycerides of long fatty alkanes and/or alkenes attached to a glycerol backbone (triol). The main functional group remains the triglyceride ester, and most traditional and well-established chemical transformations of these molecules occurs mainly at the ester functional group.

Common chemical reactions of fats and oils include hydrolysis and esterification/transesterification to free acids, alkyl esters or more specifically, fatty acid methyl ester (FAME) which is present day biodiesel. Other common reactions include transformation of fatty acids at the carboxyl functional groups to detergents and soaps, amides, esters, acyl halides and fatty

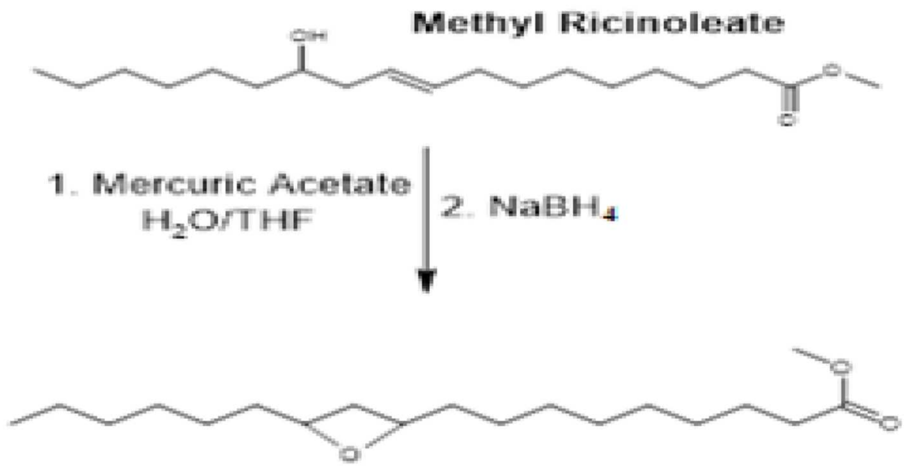

FIGURE 3 | Conversion of methyl recinoleate to cis-10,12epoxy-12-hydroxystearate and its rearrangement product, hydroxy 1,4-epoxides.

alcohols (Biermann et al., 2011). The basic platform chemicals based on fats and oils for transformation to valuable consumer products are:

i. Long chain carboxylic acids (52%)
ii. Esters such as FAME (11%)
iii. Long chain amines (9%) and
iv. Fatty alcohols (25%).

The chemical composition and distributions of these important functional groups abounds in fats and oils (Biermann et al., 2011). These renewable platform chemicals derived from fats and oils are used for production of soaps, surfactants, polyesters, polyamides, lubricants and coatings (Elvers et al., 2011). The production of "1, 2 and 1,3- propanediol, acrylic acid" and epichlorohydrins in large volume was based on glycerol byproduct of FAME production in recent years. This development is rapidly transforming the landscape of bulk chemical production from petrochemical industries to renewable raw materials. The presence of double bonds in some fats and oils allows increased reactivity such as hydrogenation, epoxidation, and oxidative cleavage. These platform chemicals based on fats and oils offer important synthetic applications that will be discussed in the following section.

Oxidation of diene to diacetate and triene can be achieved via anodic oxidation (Biermann et al., 2011). The triene is an important chemical for water resistant vanishes application.

Linoleic acid and conjugated linoleic acids (and their corresponding methyl esters) can simply be hydroxylated with selenium dioxide (SeO_2). While reaction with linoleic acid produce mono-hydroxylated derivatives, when SeO_2 react with conjugated linoleic acids the dehydroxylated derivatives such as "12, 13-dihydroxy-10E-octadecenoic acid, 11,12-dihydroxy-9E-octadecenoic acid and 10,11-dihydro-12E-octadecenoic acid" were produced (Li et al., 2009). These reactions using selenium dioxide were applied to introduce hydroxyl groups in the adjacent carbon to the unsaturated double bond positions in a one-step reaction process (Li et al., 2009).

Abbot and Gunstone (1971) reported the conversions of long-chain fatty acids and their corresponding esters to 1,4epoxides (2.5-disubstituted tetrahydrofurans via acid catalyzed cyclisation of polyhydroxy stearic acids. Other mechanisms include the free radical cyclisation of some hydroxyl esters, oxymercuration-demercuration, and epoxidation of some hydroxy stearates. Methyl ricinoleate, which is a β-hydroxy alkene reacts with m-chloroperbenzoic acid to yield "methyl cis-9,10-epoxy-12-hydroxystearate" which readily rearranges upon treatment with boro trifluoride to give hydroxy 1, 4-epoxide as shown on **Figure 3**.

Several other important chemicals can be obtained from fatty acids. Chemical halogenation be can be carried out via chlorination, bromination and iodination using e.g., monochloride of methyl recinoleate furnish dihalides in addition to halogen-containing cyclic ether (Gunstone and Perera, 1973).

Food wastes are residues of agricultural crops including plants and animals and altogether are described as biomass which are composed primarily of lignin, cellulose and hemicellulose. These characteristics make food waste a superior and renewable source for valuable chemicals, energy and consumer products (Lucas, 2015).

Lignin is derived from plant material as an amorphous polymer acting as an essential glue and giving the plant its structural integrity and the only biomass based on aromatic units: methoxylated phenylpropane structures such as alcohol derivatives of coumaryl, sinapyl alcohol and coniferyl alcohol. The lignin encompasses the celluloses and hemicellulose fractions as a glue holding these units together. On the other hand, the cellulose is a linear polysaccharide consisting of 1,4 glycosidic linkages of D-glucopyronose monomers. The monomer units in plant biomass varies from 10,000 to 15,000 glucopyronose units. Hemicellulose on the other hand is the branched polymeric material of five different sugar units: xylose and arabinose (pentoses) and galactose, glucose and mannose (hexoses). Lignocellulosic food waste can be converted into valuable chemicals (Lucas, 2015).

Effective conversion of these lignocellulosic food wastes into valuable chemicals include depolymerization of lignin, enzymatic and acid hydrolysis of cellulose. Platform chemicals from C2 to C6 compounds are readily accessible from the hexoses and pentoses components of cellulose and hemicellulose while a wide range of valuable aromatic compounds based on benzene, toluene and xylene can be derived from lignin motifs (Holladay et al., 2007).

Platform Chemicals From Cellulose and Hemicellulose

Cellulose and hemicellulose are potential sources of highly valuable chemical can be classified according to the number of carbon content in each molecule as follows:

C2: Acids (acetic, glycolic, oxalic), ethanol, ethylene.

C3: Acids (3-hydroxypropionic, lactic, propionic, acrylic), acetone glycerol, and propane diols.

C4: Acids (fumaric, succinic, asperic, malic, asperic, butyric), 1,2,4-butane triol, 1- butanol, acetoin, and 2,3-butane diol.

C5: Acids (levulinic, itaconic, glutamic), furfural, and sugars (Xylose and arabinose).

C6: Acids (adipic, citric, gluconic), sucrose, sorbitol, 5-hydroxymethyl furfural, and lysine.

Selective depolymerization of lignin can furnish a variety of valuable chemicals that are difficult to make from conventional petrochemical routes in addition to other highly useful products (Holladay et al., 2007). Valorization of food wastes (biomass) for bio refinery is exploring the chemical energy stored in these plants and animal waste for the synthesis of valuable chemicals and biofuels in addition to electricity generation. The "National Renewable Energy Laboratory" (NREL) defined bio refinery as a system for efficient conversion of biomass processes in an integrated sequence to produce bioenergy and valuable chemicals. Thus, several chemicals and co-products could be derived from these food waste if properly channeled into bio refinery.

Valuable commodities and consumer products derivable from these products include antifreeze, thermoplastic fibers, contact lenses, adsorbents phenolic resin and flavoring agents amongst others. Commercial applications of lignin-based products are quite diverse but suffice to list following important uses (Holladay et al., 2007):

1. Lignosulfonate salts is used in cement and concrete industry to enhance plasticity and fluidity to concrete
2. Animal feeds as calcium and sodium salt molasses additives.
3. Provide desirable rheological; properties to oil wells.
4. Polyelectrolyte dispersant and wetting/emulsifying agent
5. Leather treatment agent to prevent rots.
6. Expanders and surface modification agent for lead batteries
7. Manufacture of inks, carbon black and dye pigments.
8. Oxoaminated as Nitrogen fertilizers.

Proper integration of these chemical conversion processes in a biorefinery is required by identifying synergies in individual unit operations. Most of the lignocellulosic components of biomass from fruits and vegetable wastes, cereals, grains and sugar cane is conveniently transformed into suitable chemical products and energy in a biorefinery (Martin and Crossmann, 2013).

Substantial progress in the development of industrial and consumer goods based from biorefineries includes broad based biolubricants base oils containing furan ring and branched chain alkanes from oleic acid, milkweed oil, cotton seed oil, canola oil ricinoleic acid from soybean bean. Chemical and enzymatic modification of these renewable materials have led to commercial production of renewable lubricant base oil, cold flow imoprover additives, "green diesel," surface active agents and rusty and corrosion inhibitors (Adhvaryu et al., 2000; Seo et al., 2012; Yasa et al., 2017; Dunn et al., 2019; Liu et al., 2019).

Biorefinery process pose special challenges including the need to optimize heat of reaction favorable to biological catalyst, deactivation of enzymes by chemical products of reaction (such as high concentration of alcohol and glycerol), requirements for high energy demand and water in distillation columns and the need to minimize overall environmental impacts.

CONCLUSION

Valorization of food wastes and losses through integrated biorefinery conversion to valuable chemicals, energy and consumer products is viable alternative both in terms of economics, sustainability social and environmental impacts. All these are not without important challenges that require systematic and advanced biorefinery process design and optimization to ensure that the chemical conversion processes are energy efficient, economically viable, and capable of employment generation for the rural communities and with minimum environmental impact. This require interdisciplinary approach involving experts in food processing technology including food scientists, chemical engineers, chemists, mechanical engineers and process engineers to find a suitable design with minimum cost and maximum benefit. Suitable R & D in the near term medium/long term need to be put in place to find suitable catalytic production process for transformation of lignocellulosic biomass which are the main composition of food wastes.

AUTHOR CONTRIBUTIONS

SI: developed and organized the manuscript body. GO: supervised the writing, made corrections in every step of the manuscript design and development.

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