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From kitchen scraps to delicacies to food waste

Dietrich Knorr *[a] and Mary Ann Augustin [b]

Food loss and waste occur along the whole food supply chain. The perceptions of food waste and how it is used have changed over time. Prior to and during WWII, household food scraps and leftovers were reused and even upgraded into delicacies which are still valued even today. Currently about one third of food produced for human consumption is wasted and this accounts for a carbon and water footprint of 4.4 giga tons of CO_2 equivalents and 250 km^3 of blue water, respectively. In addition, food waste is responsible for significant wastage of land used for agriculture and 3.3 billion tons of greenhouse gas emissions. Consumer food waste is a major source of the current food waste crisis. As consumer behavior is a key driver of food waste, strategies for reduction and avoidance of waste should appeal to consumers' individual values. Ways to prevent food waste, reuse and upscale recycling and recovery are reviewed. The potential of using waste for future food preparation, food waste avoidance tools and technologies are presented. Urgent action is needed for implementation of waste reduction interventions and more efficient food redistribution systems to improve food security and sustainability.

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Sustainability spotlight

Sustainable food systems are critical to food and nutrition security. Food loss and waste decrease the sustainability of food systems and contribute to environmental degradation and increased climate risk. Waste reduction interventions along the whole supply chain are urgently needed to improve the efficiency of food redistribution systems and to limit wastage of high-quality foods.

1. Introduction

"Food is part of our identity".[1]

Food loss and waste occur along the whole food supply chain.[2] The food supply chain is a "succession of actions and movements, between different actors, going from farmers producing food, passing by manufacturers, then distributed by retailers to reach the final consumers (*e.g.*, household, hospitality level)".[3] Food wastage is the result of food loss and food waste. There are several uncertainties in various estimates reported for food loss and waste and what is accounted for when assessing food loss and waste. Selected definitions which have been used to describe the various types of food that is wasted are given in Table 1. The various definitions already indicate the lack of standardized definitions and methodologies[3] and the high uncertainties in the global food loss and waste databases and the lack of primary-data-based studies[4]

A third of the food produced is lost or wasted along the food supply chain. This amounts to food loss and waste of approximately 1.3 billion tons.[14,15] Though estimates from various sources (FAO, USDA, McKinsey, Coresight) differ, food waste is a significant problem with 33–40% currently wasted from farm to fork, yet one in nine people do not have enough to eat.[16] Food waste and loss represent a critical ethical issue considering that worldwide 828 million people are still unable to satisfy their most basic needs, while about 735 million people suffered from hunger in 2022.[17] The development and modernization of the food system have implications for the industrialization of the food system, globalization, urbanization, and the growth of the economy and policy, and also affect food wastage.[18]

There is an urgent need for waste reduction interventions along the supply chain and to develop efficient food redistribution systems to limit wastage of high-quality foods. Reducing food loss and waste has the potential to improve nutrition and diet quality, with positive outcomes for public health and the environment.[19,20] The issue of food loss and waste reduction, one of the 17 Sustainable Development Goals, requires the utmost attention. The halving of food loss and waste is Target 12.3 of the Sustainable Development Goals by 2030, but in 2020 the world is not on track to meet this target.[21] Important considerations for developing interventions and policies to reduce food loss and waste are knowing what constitutes food loss and how to measure it, identifying where, how and why food loss and waste occur, and working with all key players from public and private sectors.[2,22] Additionally, with respect to avoidable household food waste by consumers, it is suggested that the knowledge of the composition of food waste will help

[a]*Food Biotechnology and Food Process Engineering, Technische Universität Berlin, Königin Luise Str. 22, D-14195, Berlin, Germany. E-mail: dietrich.knorr@tu-berlin.de*
[b]*School of Agriculture, Food and Wine, University of Adelaide, Waite Campus, Urrbrae, SA 5064, Australia*

Table 1 Definitions relating to food wastage, food loss and food waste

Term	Definition
Food wastage	"Food lost by deterioration or waste. Thus, the term "wastage" encompasses both food loss and food waste"[5]
	"Any food lost by deterioration or waste (encompassing food loss and food waste)"[6]
	"Any food, and inedible parts of food, removed from the food supply chain to be recovered or disposed (including composted, crops ploughed in/not harvested, anaerobic digestion, bio-energy production, co-generation, incineration, disposal to sewer, landfill or discarded to sea)"[7]
Food loss and waste	"Deterioration in food quantity or quality along the food supply chain"[2]
Food loss	"Food supply lost because of various pests such as insects, pathogens, weeds, birds, rodents", and includes pre- and post-harvest losses[8]
	"Occurring along the food supply chain from harvest/slaughter/catch up to, but not including, the retail level"[2]
	"Decrease in edible food mass throughout the part of the supply chain that specifically leads to edible food for consumption"[6]
	"Occurring during primary production (agriculture, fisheries), storage and handling, processing, manufacturing and distribution"[3]
	"Occurs before food reaches the consumer as a result of issues in the production, storage, processing, and distribution phases"[9]
	"Unused product from the agricultural sector, such as unharvested crops"[10]
	"Decrease in mass (dry matter) or nutritional value (quality) of food that was originally intended for human consumption. These losses are mainly caused by inefficiencies in the food supply chains, such as poor infrastructure and logistics, lack of technology, insufficient skills"[7]
Kitchen loss	"All food lost during storage or preparation"[6]
Food waste	"Food and inedible parts of food removed from the food supply chain to be recovered or disposed (including – composted, crops ploughed in/not harvested, anaerobic digestion, bioenergy production, co-generation, incineration, disposal to sewer, landfill or discarded to sea)"[11]
	"Occurs at the retail and consumption level"[2]
	"Any substance or product, whether processed, partially processed or unprocessed, intended to be, or reasonably expected to be ingested by humans which the holder discards or intends or is required to discard"[12]
	"Food which was originally produced for human consumption but then was discarded or was not consumed by humans"[6]
	"Food appropriate for human consumption being discarded, whether or not after it is kept beyond its expiry date or left to spoil. Often this is because food has spoiled but it can be for other reasons such as oversupply due to markets, or individual consumer shopping/eating habits"[7]
	"The use of food meant for consumption by humans for non-consumption purposes, the redirection of food to feed animals, or the disposal of edible food"[13]
	"Food that is fit for consumption but consciously discarded at the retail or consumption phases"[9]
	"Food and inedible parts not ultimately consumed by humans that are discarded or recycled, such as plate waste (*i.e.*, food that has been served but not eaten, spoiled food, or peels and rinds considered inedible")[10]
	"Food originally produced (processed or prepared) for human consumption but was not consumed by humans" (authors' suggestion)
Serving waste	"Food served that did not reach the plates of guests"[6]
Plate waste	"All waste from the plate of guests including plate leftovers and non-food parts"[6]
Food surpluses	"Foods cooked in excess for certain quantities or portions, "unused" food waste"[13]
Leftovers	"Cooked and safely distributed foods that have not been fully consumed by the consumer"[13]
Avoidable food waste	"All food wasted by negligence and poor planning" (authors' suggestion)
Unavoidable food waste	"Mostly non-edible parts of food (*e.g.*, bones, skins, peels, hoofs, claws, shells)" (authors' suggestion)

classify food waste and the development of target interventions.[23]

The food waste issue is gaining increasing attention in the scientific literature. The total number of documents related to food waste scientific research were: 14 984 for the keyword "food waste", 1143 for the combination of "food waste" and "environmental impact", and 616 for the combination of "food waste" and "food security". The number of food waste and loss related papers increased from 48 published in 2002 to 2701 in 2022 with various dimensions of food waste being covered.[3] Understanding food waste requires a multidisciplinary approach as it exists between food production and consumption, and social and environmental sciences,[24] and there are sociodemographic, cultural, economic and political drivers of food waste.

The focus of this review is on food waste. Food waste occurs in retail (poor storage, expiry date, aesthetic standards, and poor packaging), in households (expiry dates, overpreparation, aesthetics, and food preferences) and in hospitality areas (over-preparation, poor storage, large portion size, and over-

Fig. 1 Important considerations for building a future with less food loss and waste.

ordering).[3,13] There are still gaps in our understanding of food waste and food waste prevention. This paper is an attempt to highlight the multi-dimensionality of the food waste issue. It provides a historical perspective on food waste and attempts to clarify sources and definitions for various types of food waste, the evolution of food waste, means of reduction and food waste reuse, and means for approaching zero food waste systems. Fig. 1 depicts the important considerations for building a future with less food loss and waste.

2. A historical perspective

In a recent article on food history, the author alluded to the 1767 recipe for fruit cake,[25] which demonstrated that thrift and frugality were part of household management. Two Austrian cookbooks covering the period from 1889 to 1937 containing over 1000 and 900 recipes, respectively, reveal that edible kitchen waste did not exist at that time.[26,27] Soups were essential parts of the daily diets and were effective means for leftover reuse from stale bread to bones (bone broth).[28] Stadler (1937) devoted a specific section of the book as "leftover kitchen", including meat pudding, meat ragouts or soups containing dumpling, pancake, omelets, or noodle remains. In addition, national delicacies such as "Kaiserschmarrn" (shredded pancake named after Emperor Franz Joseph I), "Salzburger Nockerln" (sweet souffle, "golden dumplings"), "Scheiterhaufen" (pyre food), or "Krautfleckerln" (pastry parts mixed with cabbage) were effective means of leftover upgrading. Ironically, national delicacies from leftovers such as "Scheiterhaufen" would now be considered as "ultra-processed food" according to current definitions for "ultra-processed food". A typical daily diet of the three country region at Lake Constance (Austria, Germany, Switzerland) from 1880 to 1920 has been described[29] as consisting of five meals, namely: (1) first breakfast (between 5 : 00 and 7 : 00): cereal porridge, soup, and water; (2) second breakfast (between 9 : 00 and 11 : 00): bread, cheese, sausage, and cider/beer; (3) lunch (main meal): potato dishes, legume stews, dumplings, noodles, and soups; (4) afternoon snack: similar to second breakfast; (5) dinner: leftovers from lunch or bread with cheese or sausage. Meat (including deer) was usually available once a week with animal offal commonly used in soups. This indicates that food waste was at a minimum and would be used as animal feed.

Non-edible kitchen scraps including peels, extracted bones or eggshells would be fed to animals or composted. The consumer's attitudes changed notably after WWII. The use of an in-sink shredder for "garbage" disposal is a dramatic example of the transition to a mindset being comfortable with an easy way to dispose food leftovers and food waste. In the 1950s, the US Department of Agriculture began to formally study food waste, which was 7–10% of total household calories.[18] Around the same time period the "plastic is phantastic" development took off – including food related plastic waste such as packaging and delivery materials.[30]

In contrast to cultural practices designed to avoid wasting food, the 1950s signaled a decade of significant transition resulting in a new global regime, a regime of excess food. A pre-history of food waste from a sociological perspective[24] called the non-existence of food waste prior to the 1950s the transition from invisibility to visibility. The authors also argued that the relative increasing costs of foods, as consequence of the global food crisis of 2008, has become a matter of consumer and public concern. The authors further noted that the changing roles of technologies for the treatment and management of waste are becoming attractive options to policy makers against the demands of reducing the amount of food being sent to landfills, with the hope of transforming waste into value (*e.g.*, conversion of food waste to energy). Thus, "the idea about being scientifically clever about how to deal with food waste seems out of touch in an era of celebration on massively excess food production".[24]

A well-researched book on popular history of food through the ages[31] deals with the history of foods and storing food surplus, while the traditional art of food preservation has been covered in depth elsewhere.[1] A publication in the early 20th century[32] concentrating on food wasted in New York City mainly during large scale transportation and storage strongly promoted dehydration of foods as a means of conservation for food materials to reduce food waste. Meatless days were introduced in the USA during WWI, leading to an overall 15% reduction in overall household consumption (and thus waste) between 1918 and 1919. The idea of a meatless day (Meatless Monday) was re-introduced in 2003 and has evolved to address health, environment, climate and human and animal welfare.[33] During WWII, "mock" (meaning substitute) appeared in many British recipes with examples such as "Woolton Pie" made entirely of patriotic homegrown root vegetables, or the "Tottenham Pudding", a concentrated pig swill.[1] Norway's war time recipes with substitution of lacking ingredients were called "crisis foods" (*e.g.*, crisis whipped cream and crisis spread) and

US government agencies were busy finding ways to reduce the waste of food resources to a minimum. Herring and potatoes represented the mainstay of the Norwegian crisis diet, and the value of wild plant supplements was promoted (*e.g.*, nettles, dandelions, and goutweed as sources of iron and vitamin C).[34] Reducing waste of food on one hand and finding replacements for scarce resources were used as a rather successful strategy in harsh times.[34]

The industrialization of food production and processing of commodities in the early twentieth century was accompanied by large-scale waste production. The diversion of processing waste into other uses such as animal feed and microbial nutrient medium in industrial applications[35] helped to make the food processing industry more profitable. Estimates of food waste show that more than half of the world's food waste is due to household food waste, highlighting the contribution of changes in lifestyle, work and food consumption patterns on food waste.[36]

3. Food wastage: statistics and impacts

One third of food produced for human consumption (1.3 billion tons) is lost or wasted, with a carbon and water foot print estimated to be 4.4 gigatons (8% of the world's total) of CO_2 equivalent and 250 km^3 of blue water respectively, plus 1.4 billion hectares (28% of world's total) of agricultural land and an economic cost of about 750 million US$, as well as the emission of 3.3 billion tons of greenhouse gas.[4,37] In developed countries (1.4 billion people), 670 megatons (Mt) of food are discarded and less than 630 Mt is discarded in developing countries (6.2 billion people). On average, an estimated 11–23% of food waste occurs at the agricultural stage, 17–19% during industrial processing, 8–17% at the retail stage and more than 50% at final consumption.[38]

There are massive shifts in consumer attitudes and dramatic increases in food waste to more than 1.3 billion tons per year worldwide.[38] This is despite the growing number of people facing hunger due to the pandemic, weather shocks and conflicts (735 million people currently compared to 613 million in 2019).[17] Food waste within the EU is now 127–170 kg per inhabitant per year with 70 kg accumulating in households, 12 kg in restaurants and 9 kg in distribution.[39] With regards to food systems "downstream" stages (canteens, restaurants, hotels, and households), food diaries have been suggested as interesting but a complex option, where food waste would be recorded each time it occurs.[38]

The US total daily per capita food expenditure was US$ 13.27, representing 27% wasted, 14% inedible and 59% consumed. The greatest daily food waste expenditures were observed for meal and seafood purchased for consumption outside of the home and for fruits and vegetables in the home.[40] At the European level the costs of food waste and loss were calculated to be 130 billion Euros per year. An USA family of four generates waste worth US$ 1600 per year, while an average UK family wastes US$ 890 per year.[3] In lower-income countries higher economic losses due to food waste and loss were observed during primary production stages. Sub-Sahara Africa registered 4 billion US$ attributed to post harvest losses out of an annual production value of US$ 27 billion.[3]

The EU food waste amounts to approximately 130 Mt per year (39% at the household level and 9% from the hospitality industry). Globally, 50% of food displayed in buffet services is wasted[37] and for the US, food waste in 2009 accounted for more than a quarter of total freshwater consumption.[41] In terms of nutritional values this represents an annual loss of approximately 520 million MJ, which is useful to satisfy the energy intake (at 2400–3100 MJ $year^{-1}$) of about a third of the current European population.[38] The global average food waste per person per year is 65 kg of food, with 25% through wasted vegetables, 24% cereals and 12% through fruits. The average daily environmental footprints per person food waste are 124 g CO_2 eq., and 58 L freshwater use with cereals, meat and sugar being the major food groups contributing also to environmental impact.[20] Global average nutrient losses for food wasted per capita across various studies were as follows: 54.4–1216.5 kcal energy, 2.61–32.8 g protein, 2.21–57.2 g lipids, 10.58–146.4 g carbohydrates, 0.75–5.9 g fiber, 88–308.1 μg vitamin A, 17.1–35.4 mg vitamin C, 26.7–79.2 μg vitamin K, 0.3–1.5 μg vitamin B12, 0.3–0.6 mg vitamin B6, 22.49–286.1 mg calcium, 37.11–450.3 mg phosphorus, 1.2–3.9 mg zinc, 323–880 mg potassium and 1.8–5.3 mg iron.[19] Energy calculations revealed that energy lost at landfill sites (dumped food waste) is equal to 43% of the delivered energy used for the preparation of food in the USA, 37% of the hydroelectric power generated in Japan and more than 100% of the current annual renewable energy demand of UK industries.[42]

The full cost of food wastage on a global scale has been assessed to be 1 trillion US$ of economic costs per year, in addition to around 700 billion US$ of environmental and 900 billion US$ of social costs.[43] The full cost accounting, an indication of the true magnitude of the economic, environmental, and social costs of food wastage, has been estimated to be 2.6 trillion US$ annually. A detailed listing of particular salient environmental and social annual costs of food wastage from various sources (US$) is as follows: total environmental and social costs (approximately 1600 billion $); greenhouse gas emission (394 billion $); increased water scarcity (164 billion $); soil erosion due to water (35 billion $); risks to biodiversity (32 billion $); increased risk of conflict (due to soil erosion) (396 billion $); loss of livelihoods (due to soil erosion) (33 billion $); adverse health effects (due to pesticide exposure (153 billion $)).[43]

Food waste has wider implications for the sustainability of the planet. Projections are that current diets and agricultural production practices alone could add nearly 1 °C to global warming by 2100. However, improvements in food production practices, eating a healthy diet and reducing food waste can mitigate this risk and avoid 55% of the projected warming.[44] Food waste contributes to water scarcity, which is projected to increase from 933 million in 2016 to 1.67–2.37 billion in 2050.[45] The reduction of food waste in future will require the use of innovative strategies, sustainable agriculture, and a significant

shift in dietary patterns. Food waste in smart cities may be reduced by the development of personalized food products and better food packaging.[46]

Time and effort into publications relating to waste are also a cost. Considering the approximately 15 000 publication published on food waste until 2022 and the average cost of article processing charges (APCs) for open access journals between 2800 and 3000 US$ (36% open access journals), regardless of the cost of generating data and writing those papers on food waste,[47]substantial additional costs of food waste have been accumulated.

4. Drivers of food wastage

Behavioral, personal, product and societal factors affect the generation of waste from food. Different drivers (economic, environmental, social, infrastructure/capabilities and market) influence the extent of food waste generation during both upstream (primary production and post-harvest) and downstream (consumer and retail) activities of the food chain (Table 2).

4.1 Understanding why consumers waste food

Consumer food waste is the outcome of multiple behaviors. The complexity and diversity of food waste behavior contribute to the lack of focus on mechanisms underlying how and why food is wasted.[48,49] Reasons for food waste within households are mainly based on consumer behavior.[50,51] The Household Wasteful Behavior and Restaurant Waste Framework shows that the theoretical drivers of wasteful behavior drawing on the consumer waste management process[52] include planning, provisioning, storing, preparing, consuming, disposal, and the buyer decision process (planning, pre-acquisition, acquisition, preparation, consumption, and disposition). This demonstrates that every phase of the household food waste "journey" may trigger wasteful behavior. Table 3 provides perspectives of food waste generation by consumers.

When asked about the major causes of food waste, an expert group identified that the lack of planning and management of purchase, storage, preparation, reuse of food and meals is at the heart of the problem. Context-specific strategies targeted to the consumer is required to change consumer behavior, with attention to motivational factors to avoid food waste, altering consumer food choices and raising awareness.[54–56] In addition, appearance at the point of purchase, confusion about and misinterpretation of labelling were identified as factors affecting food waste. Others considered food internal factors (sensory and perceptional features), food external factors (information, social environment, and physical environment), personal-state factors (biological features and physiological needs, psychological components, habits and experience), cognitive factors (knowledge and skills, attitude, liking and preferences, anticipated consequences and personal identity) and sociocultural factors (culture, economic, variables, and political elements) as the key determinants of general food choices.[57] Further, "cultivated ignorance" leading to dumping food out of sight[58] or the fact that classifications of edible or inedible foods differ among different societies and cultures[59] in conjunction with the increasing internationalization of our food supply add to the complexity of food waste issues. These few examples among the high diversity of food waste literature demonstrate the magnitude and complexity of the problems, the urgency of actions towards solutions and the necessity of collective, interdisciplinary approaches to deal with the existing food waste pandemic. Taken together, all these reports highlight the muti-dimensionality of the food waste problem, suggesting that the solutions for waste prevention must consider multi-disciplinary approaches and multi-sectoral involvement in food waste prevention.

Another influencing factor is food waste awareness, as the majority of consumers are not conscious of the food they are wasting and see food waste as inevitable and as "a mere fact of life, and in that way unavoidable and therefore acceptable".[60] They also indicated that raising consumer awareness does not sufficiently reduce food waste due to the complexity of feeding the household.[60] Childhood education and awareness raising shape routines and behavioral patterns.[61] Further hunger, environmental, economic, landfill and water shortage concerns represent significant dimensions of consumer social awareness marketing in socially responsible plate food consumption.[62] In a survey assessing USA consumer's reported awareness, attitudes, and behaviors,[63] 42% indicated that they had seen or heard information about wasted food and 16% had sought information to reduce it. The respondents overwhelmingly reported discarding low percentages of food, with 13% reporting they did not discard any food and 56% indicating they

Table 2 Drivers of food waste along the supply chain[a]

Stage of the supply chain	Drivers
Primary production and distribution	• Environmental factors, market conditions
Postharvest (processing to storage)	• Lack of investment capital
Retail and consumer	• Overall economic conditions, infrastructure, consolidation in food systems, food costs, sociocultural identity, health and nutrition, regulatory standards, everyday life, waste management services
Wholesale & retail	• Market standards, sociocultural standards
Restaurants and institutions	• Market standards
Households	• Market and sociocultural standards

[a] Ref. 48.

Table 3 Generation of food waste by consumers

Reasons	Description
Causal pathways – general[49]	
Behavioral	• Planning and organizational, shopping, storing, preparation and serving, and consumption practices
Personal	• Demographic and socioeconomic factors, knowledge and awareness, attitudes and preferences, skills and competences, life experience, lifestyle, and time availability
Product	• Food and packaging properties
Societal	• Economic and sociocultural factors, retail, regulatory, technological, and climatological factors
Motivational and behavioral factors in households[53]	
Cognitive	• Practical knowledge on cooking, food safety knowledge, food label understanding, knowledge on reasonable package
Affective	• Respect of food, food safety risk perception, attitude towards environmental protection, attitude towards food shortage problem
Conative	• Lifestyle, parental over-caring, non-conscious eating, inter-familial communication, food preference system
Socio-demographic	• Background (household size, presence of children, habitation, education level, and division of labor within households)
Underlying reasons for consumer food waste[49–51]	
Understanding and perception of food waste	• Lack of awareness about the amount of food wasted, insufficient concern about food waste, acceptance of wasting as a social norm
Food-related household practices and routines	• Lack of planning of food shopping and meals, lack of food supply at home, time constraints, oversized packages, preference of fresh food, lack of acceptance of imperfect food • Different eating habits of family members • Improper storage practices and over-preparation of food • Preference of convenience foods, eating out, large plate sizes, lack of knowledge about leftover's edibility • Confusion about labels, lack of knowledge about shelf-life of food, concerns about foodborne illnesses and food safety • Lack of management of leftovers • Justification for disposing food waste due to composting, feeding pets, recycling, lack of social acceptance of food sharing

discarded 10% of purchased food. Only 10% said they discarded 30% or more. A survey in 1050 Chinese restaurants found that only 37.3% respondents had a high awareness of food waste recycling.[64] Female owners were reported to have lower awareness as compared to male ones, as well as younger to have higher awareness than older ones.[64] Social perspectives on strategies for food loss reduction can be different although they achieve the same aim. For example, consumption of leftover food many be viewed as a community activity with environmental and social benefits but from an individual consumer behavior perspective, it satisfies hunger though considered a threat to health and social order.[6]

4.2 Reduction and avoidance of food waste by consumers

Strategies for reduction and avoidance of food waste must consider the type of food waste and where it is generated and how accessible the waste is for re-distribution or re-use. Three major categories of food waste have been identified: (1) food waste related to a specific phase of the consumption stage (*e.g.*, kitchen waste, leftovers, overproduction, and service waste), (2) possibly avoidable waste (*e.g.*, foods some people eat and others do not like potato peels and bread crusts), and (3) unavoidable waste (*e.g.*, inedible food under normal circumstances (*e.g.*, bones and shells)).[49] Generally, consumers consider throwing food away as improper behavior and concern about food waste plays an important role in the intention to reduce food waste. Guilt may act as an important motivation underlying the reduction of food waste, and financial concerns are given as stronger motivation to reduce food waste than environmental and social concerns.[51] Emerging economies (especially China and South Asia) are likely to play a key role in determining global food waste by 2050, with global calories wasted at consumer levels estimated to nearly double by 2050.[65]

Careful planning and careful shopping (*e.g.*, avoiding buying oversized packages), systematically storing food products (avoiding overloading of refrigerators, controlling shelf life dates), and freezing foods (*e.g.*, leftovers and excess fresh foods) to avoid accelerated decay have been proposed as means for food waste reduction and avoidance.[51,66] As for cooking, portion size control, reduced plates sizes and cooking strategies based on what food is stored at home have been identified as important issues in aiding reduction of food waste. In relation to public health, key messages to reduce waste in food-based dietary guidelines include better food planning, avoidance of impulse buying, improved storage of food and leftovers, enhanced awareness of shelf life, avoidance of overconsumption/excess purchases, and use of imperfect foods.[19]

Leftover reuse, rescue and upscaling represent one of the most effective strategies of waste reduction and avoidance including a revival of taking home leftover food from out of home dining ("doggy bags").[67] Practical implications provided to reduce leftover food include reducing the amounts of leftovers (*e.g.*, shopping lists, meal planning, managing stocks, and reduction of meal portion sizes), reusing leftovers (proper storage, using technology for reuse, recipes to use up leftovers, "doggy bags" from food service eating, and buffet organization) and educating consumers (educational campaigns on the freshness of foods and transforming leftovers).[68–71] There is a need to rethink how households can be motivated to reduce food waste. Message domains and composition influence the intent to reduce food waste and composite messages are more likely to encourage household food waste recycling behavior.[50]

Fig. 2 summarizes food waste and reuse factors based on increasing importance as related to existing reality.

A value system can guide consumer's food behavior. A literature review[72] on food values and their potential implications for consumers' food decision processes revealed three distinct clusters: (1) credence (environmental impact, origin, and fairness), experience (taste, appearance, convenience, and novelty), and price paid (price), (2) beneficial value (taste, price, nutrition, and appearance), social value (restauration, employment creation, origin, and environment), safety value (food inspection methods), (3) product value (texture, color, and freshness), process value (production and processing practices, environmental impact, naturalness, and animal welfare), location value (setting of food purchase or consumption), and emotional value (feel-good factor, experience, entertainment, indulgence, and consumption of specific foods or brands). Process values are particularly relevant in shaping consumer behavior as they include consumers' ethical concerns about the production processes, fast-changing technological innovations, animal welfare and environmental pollution.[73] This consumer-centered concept of food value proposed[73] also needs to be implemented in future consumer food waste behavior activities. Overall, consumer food value appreciation and CO_2 generation reduction could be also improved *via* local food production including urban agriculture and school/university gardening,[74] application of organic food production principles[75] and using kitchen wastes (*e.g.*, dried and anaerobically digested) as sustainable nitrogen fertilizer sources.[76]

A consensus study report of the US National Academies of Sciences suggests various interventions to alter consumer behavior, including appealing to people's values, providing financial incentives, and advising them about ways to reduce food waste.[77] Specific strategies given for the above interventions are smaller plates, reducing portion sizes in buffet settings, or providing information on environmental harm and costs of food waste. Examples of behavioral interventions to reduce food waste provided[78] include increase of: (1) motivation, with shifting social norms (*e.g.*, public commitment to reduce food waste and messaging to promote social acceptance of imperfect foods), affecting attitudes (*e.g.*, information regarding cost savings from reducing food waste), and to increase consumer awareness (*e.g.*, information on the social and environmental costs of food waste); (2) ability, with increasing knowledge (*e.g.*, instructions of correct food storage, education of food safety and data labels), and skills (*e.g.*, training to repurpose leftovers and training on everyday food preparation and storage); (3) opportunity, including physical environment improvement (*e.g.*, reducing the distance to grocery stores, provision of home food storage solutions, and reducing plate and bowl sizes), time and schedule help (*e.g.*, time saving tips and tools and online grocery shopping), and technology use (*e.g.*, inventory, food sharing and shopping apps, and refrigerator sensors).

Coaching for households, local awareness campaigns and nudges as intervention have been suggested,[79] with behavior change models and frameworks indicating that nudges work when they are tangible, relevant and beneficial to the individual and their lifestyle.[80] This is in line with findings by others[81] showing that consumers would most likely support making food donations easier and taxing food waste the least likely. Thus, considering the 30% food waste generation, it may be the

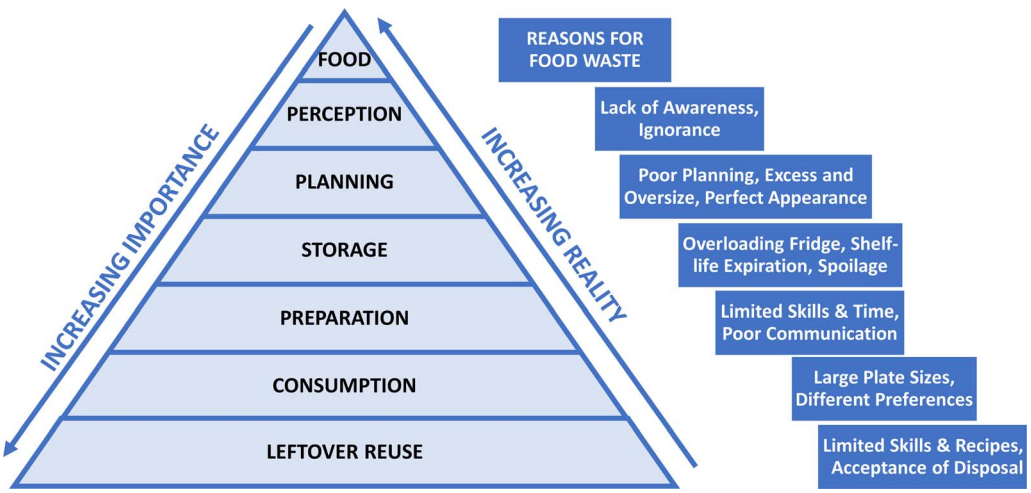

Fig. 2 Factors for food waste and reuse: necessity *versus* reality.

easiest, though not likely, or realistic, to ask consumers to donate 30% of their purchased groceries directly at the store level.

US consumers further considered consumer education campaigns and changes in portion size as effective means to reduce food waste. Based on the results of reviews,[82] information based interventions, school programs, training and building capabilities, food waste prevention governance, new approaches (*e.g.*, use of technology to engage directly with intervention participants), redistribution, and cross cutting recommendations (*e.g.*, knowledge sharing effectiveness) are needed. Amazingly, training and information on the importance and significance of food processing and preservation technologies[83] to aid consumers shopping and storage behavior are missing among the interventions suggested. Despite the vast amount of information available to consumers, previous and current means of consumer information and education regarding food waste behavior and avoidance appear to have failed. It will be useful to have training in the value of food starting at a young age. Teaching manuals and education material targeted at children of various age groups (5–7 years, 8–9 years, 10–13 years and >14 years) have been developed.[84] This might be another means for improvements of the consumers respect of food.

5. Food waste generation and re-use

Fig. 3 provides a graphical presentation of major factors important for waste generation and potential for reuse as food.

5.1 Looking back: learning from the past

There are significant effects of food waste on food security and sustainability. It is essential that the world becomes more accountable for responsible production and consumption of foods that limit food waste to mitigate the negative environmental and social impacts of food waste.[85] For now, there is an estimated 1.4 billion tons of food loss and waste generated annually, accounting for 10% of global greenhouse gas emissions representing over $ 1 trillion in value and equivalent to more than 500 calories per person per day. Assuming that current trends continue, global food waste at the consumer stage is set to double by 2050.[78] Global food waste and loss avoidance could contribute to feeding 939 million adults with a daily caloric intake of 2000 kcal per day per person and 50 g protein per day per person.[86]

For long-term sustainability (2050) across the food supply chain, a classic review[87] recommends locally supported government policies in the developing world and suggests that the greatest potential for the reduction of food waste in the developed world is with retailers, food service and consumers and promotes improved food labeling and food storage as well as innovative technologies in packaging to improve the shelf life of perishable foods and semi-prepared meals. Additionally, the authors see fundamental factors affecting post-consumer food waste "some of which may require solutions that involve direct communication and awareness rising among the consumers of the importance of reducing food waste", government interventions, support and cooperation of the food industry regarding improving food date labeling, advice on storage and ensuring appropriate ranges of package sizes that meet different household needs.[87]

The EAT-Lancet commission proposed to at least halving food loss and waste.[88] However, as an example for the current reality it is projected that there will be an 130.8% increase in worldwide poultry consumption (117.6 to 273.4 million tons per year) between 2019 and 2050.[89] If such projections come true, the worldwide amount of slaughtered poultry[90] of 79.454 billion animals (chicken, geese, turkey, and ducks) in 2021 (1971 data: 12.025 billion) would increase accordingly, and approximately 23.8 billion animals (applying the commonly used 30% food waste figure) would be killed senselessly. It should also be noted within this context that the number of poultry killed worldwide increased 6.6 times in just one human lifespan (1971 to 2021). This human impact was quite clear and plainly put as "…over the past two centuries – barely more than 2 human lifetimes – humans have disrupted living and nonliving systems everywhere" and "one species is compromising Earth's ability to support the living systems that evolved on the planet over millions of years. The systematic reduction in Earth's capacity to support life is thus the most important human-caused environmental impact".[91] Consequently, as also pointed out by various authors, human behavior must be identified as a key driver in food waste.[19,50,51,66,78,92] Within this context, it was demonstrated that a transformation towards more sustainable food production and consumption patterns could support feeding 10.2 billion people, provided that four prerequisites are met. These include spatially redistributed cropland, improved water-nutrient management, food waste reduction and dietary changes.[93] It has been further shown that more nutritious products are often more sustainable,[94] and eating nutrient

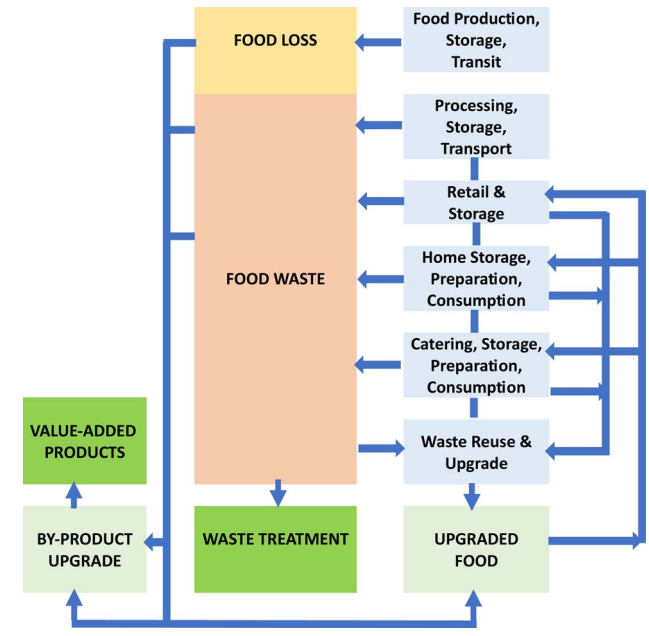

Fig. 3 Key factors important to food wastage generation and reuse.

dense rather than energy dense foods would be in line with recommendations of the EAT-Lancet commission. All this indicates that changing human behavior regarding increased awareness of food values and importance could not only aid the reduction of food waste but also improve human and planetary health. The quote "reason starts in the kitchen" (Friedrich Nietzsche, German philosopher & writer, 1844–1900), which seemed true during the lifetime of Nietzsche, obviously lost its meaning in today's world. These drastic shifts in dietary behavior for a Western European country are likely representative for other countries of the world.

Rationing of food was then the commonsense solution rather than increased taxation to reduce food consumption (and waste). Possible solutions to global warming were to apply carbon taxes or carbon rationing. Based on the WWII experiences governments must convince the public that rationing levels are fair and that the system could be administered transparently and fairly.[92] Taking this in analogy to food waste, implementing waste taxes would not be the most successful policy instrument for changing consumer behavior of food waste. Thus, appealing to individual values, providing incentives and advice on how to reduce food waste as suggested by the US National Academies of Science[77] seems the more promising route to change consumer behavior. In addition to WWI and WWII experiences, the food systems knowledge of indigenous peoples and values and their biocultural "food heritage" needs to be included and implemented in waste food reduction efforts.[95]

5.2 Moving forward: towards a better future state

Scientifically clever and wise management of limited resources can be the only way forward and thus needs to concentrate on preventing, reusing and upscaling food losses and waste.

The global food loss and waste emission was estimated to be 9.3 Gt of CO_2 equivalent from the supply chain and waste management and accounted for half of the global annual greenhouse gas emission from the whole food system.[96] Wasting about one third of our food supply (nutrients, energy, and water) and causing about half of the global greenhouse gas emission make the need for changes in our food value system even more urgent. The most common food waste treatment method in India is dumping/landfills (including illegal dumps and landfills) accounts for over 90% of food waste treatments.[97] Comparing anaerobic digestion, landfill, incineration, composting and heat-moisture treatments showed that landfill contributes most to climate change and is about 10 times larger than the other food waste management methods.[98] Existing and emerging solutions to reduce (packaging, distribution, inventory management, temperature control, increased produce shelf life, consumer campaigns and education, suboptimal food use, food sharing, and portion control), recover (donations, imperfect food redistribution, surplus food recovery networks, and upcycling/remanufacturing) and recycle (animal feed, anaerobic digestion, composting, incineration, disposal, biorefining, and biofuel production) food loss and waste have been summarized previously.[48]

As for food waste prevention the United Nations Environmental Programme (UNEP) suggested thermal preservation (refrigeration and cold chain), biological and biochemical preservation (essential oils and natural extracts in active packaging material), smart phone apps: food planning, shopping, storage, and cooking (guide, track and inform on waste reduction), smart packaging/sensors and data carriers to monitor food quality, smart labelling (data embedded barcodes about food quality), and smart storage and disposal (WIFI connected fridges, bins with cameras and sensors to monitor food quality).[99] For re-use, food waste smart phone apps: food sharing and redistribution (sharing for money, for charity or for community) have been addressed[99] to recycle (animal feed and composting), recovery (unavoidable food waste for energy recovery such as anaerobic digestion) and disposal (unavoidable food waste into engineered landfills as the last option) have been presented. These gadget-oriented approaches[99] do provide ways to mitigate risks. However, the call for rising consumer food value awareness[77] and motivating consumers to act responsibly to reduce waste in the first place could be a more effective strategy as it tackles the root cause of the food waste problem.

Based on Evans and co-authors[24] who stated, when referring to the 1950s, that "the idea about being scientifically clever about how to deal with food waste seems out of touch in an era of celebration on massively excess food production", a new paradigm scheme about being scientifically clever about reducing food waste now is needed. Lessons from WWI and WWII on reducing food waste plus finding replacements for scarce products to ensure food security can be achieved by re-increasing the biodiversity of our food supply.[100] Appealing to consumer individual values in order to reduce food waste as a promising route for changing consumer behavior[77] can be implemented *via* information and training about traditional food values[28] and indigenous food heritage and biocultural values,[95] as well as by providing extensive education about the values, needs and importance of food processing.[83] Environmental messages as well as increasing consumers moral awareness have been shown to be effective approaches as reported about the "love food hate waste" campaign.[60,101] This could be updated and renewed with campaigns like "save the planet save food" or "save the planet hate waste". For waste reduction in food delivery operations, green nudges for consumers proved successful to reduce single-use plastic cutlery which could result in an estimated reduction of 3.26 million tons of plastic waste and saving 5.44 million trees if applied for all of China.[102]

More strategies for prevention of food wastage at the source and upstream are required. A review of the landscape of on-farm food loss and waste[103] highlights the need for a stock-take of waste definitions used for on-farm food loss and waste. Optimizing supply chains is an important strategy for reducing food losses and different solutions may be needed for different supply chain entities and at supply chain network levels.[104] Quoting a figure of >50% food loss on farms, the Consumer Good Forum suggested engagement of growers, suppliers, distributors, and external stakeholders to reduce upstream

loss.[105] A Coalition of Action on Food Waste aims to (1) promote on-farm loss production, as well as training for measurement and reporting of losses, (2) share the best practices among supplier networks, (3) recognize the efforts of suppliers more visibly, and (4) support industry engagements with organized working groups.[105] A recent McKinsey report suggests that an enabler for action is to build transparency into operations by mapping footprint, scope and food loss.[106] Grocers can reduce upstream food loss by collaborating with suppliers to minimize production and processing losses, minimize transit losses by using supply chain infrastructure more effectively, advance procurement approaches to enable value creation and loss reduction and help strengthen that agri-food infrastructure/ecosystem in the country.[106] Other preventative measures include using novel IT and AI solutions (*e.g.*, fine-tuning supply chain and demand projection, models forecasting sales of perishable products, and sensors for decay and spoilage processes), shelf lives (*e.g.*, "test before date" and "use by date"), source reduction by intelligent labeling (*e.g.*, block -chain usage), and intelligent labeling sensors (*e.g.*, time–temperature indicators) have been suggested.[107]

The reuse and upscaling of food loss and waste are gaining more attention. Most food losses upstream are incurred in horticultural produce. Converting biomass that is lost to the food supply chain of fruits and vegetables into value added more shelf stable food products and ingredients (*e.g.*, powders, extruded snacks, and fermented products) is a practical way of reducing loss of harvested produce.[108] Recovery and reuse of bioactive compounds such as polyphenols (*e.g.*, apple pomace, grape skins, and carrots), proteins (*e.g.*, wheat bran, oilseed meal, and animal processing by-products), dietary fiber (*e.g.*, plant peels, skins and stems) and vitamins and minerals (*e.g.*, plant peels, bark, seafood, dairy, and meat by-products) have been summarized.[109] An example for leftover rice recycling and subsequent cracker production with resistant starch formation and thus nutritional improvement generation *via* improvement of glycemic index resulted in no differences in sensory properties between non-heated controls and cracker samples from leftover rice prepared with heat and different acids.[110] The importance of fermentation processes for the generation of valuable compounds such as nutraceuticals, food additives, biosurfactants, single cell proteins and bioplastics has also been demonstrated[109,111,112] as well as the bioconversion of food waste into new food sources such as mushrooms, microalgae and insects.[113] In addition, "dark fermentation" based on chemoautrophy[114] has been suggested for the production of microbial proteins. High voltage electrical treatments (*e.g.*, for electroporation and modification of food molecules) and electro-membrane processes (*e.g.*, electro dialysis and electro-activation) have also been put forward as eco-efficient technologies to convert food waste and by-products to high added value food components.[115]

Table 4 Research needs for reducing food loss and waste

Specific research needs – selected priorities
• Examine the exact amount of food waste at different stages of the food chain
• Study and develop methods to collect and/or concentrate food that would otherwise be wasted
• Develop appropriate/intermediate food processing technologies for intermediate and small-scale waste recycling operations
• Study and develop energy- and cost-effective food waste and water recycling processes
• Investigate toxic and risk factors (*e.g.*, environmental pollutants) and nutrient quality of the recycle products for human and/or animal consumption
• Develop methods to reduce or eliminate risk and toxic factors to increase or preserve nutrient quality during the nutrient recovery process
• Examine and improve functional properties in order to use recycled products as highly functional food or food ingredients
• Investigate and apply innovative food processing techniques for the utilization of recycled nutrients
• Study consumer acceptance of newly developed food products containing recycled nutrients
• Develop definitions and regulatory standards and procedures for these products

6. Conclusions

Food waste is a multi-faceted issue that threatens food security and sustainability. Knowledge of what drives food waste in residential, institutional and commercial sectors and the underlying causes of food waste is needed to underpin the development of strategies and policies for the development of waste prevent programs.[18] Waste hierarchies for efficient use of resources such as the 3R approach (reduce, reuse, and recycle) have been used to guide policy but the strategies have not been systematically applied to reduce food loss and waste. There needs to be greater understanding into the ways in which the various players in the food system view food waste and translate these into actions as they navigate competing waste hierarchy solutions.[116] There have been various recommendations that have been suggested over the years. Some of them such as those given in Table 4 have been suggested more than 40 years ago.[117]

We can no longer afford to waste food or time. The significant effects of food waste on food security and sustainability are an urgent need that requires effective implementation of waste reduction interventions and development of more efficient food redistribution systems to limit wastage of high-quality foods.

Author contributions

Dietrich Knorr: conceptualization. Dietrich Knorr and Mary Ann Augustin: writing and reviewing. All authors have read and approved the final manuscript.

Conflicts of interest

The authors declare no competing interests.

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