

Waste prevention for sustainable resource and waste management

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Abstract Although the 2Rs (reduce and reuse) are considered high-priority approaches, there has not been enough quantitative research on effective 2R management. The purpose of this paper is to provide information obtained through the International Workshop in Kyoto, Japan, on 11–13 November 2015, which included invited experts and researchers in several countries who were in charge of 3R policies, and an additional review of 245 previous studies. It was found that, regarding policy development, the decoupling between environmental pressures and economy growth was recognized as an essential step towards a sustainable society. 3R and resource management policies, including waste prevention, will play a crucial role. Approaches using material/substance flow analyses have become sophisticated enough to describe the fate of resources and/or hazardous substances based on human

activity and the environment, including the final sink. Life-cycle assessment has also been developed to evaluate waste prevention activities. Regarding target products for waste prevention, food loss is one of the waste fractions with the highest priority because its countermeasures have significant upstream and downstream effects. Persistent organic pollutants and hazardous compounds should also be taken into account in the situation where recycling activities are globally widespread for the promotion of a material-cycling society.

Keywords Waste prevention · Resource efficiency · Chemical control · Material flow analysis (MFA) · Life-cycle assessment (LCA) · Circular economy · Substance flow analysis (SFA) · Life-cycle cost (LCC) · Review

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Introduction

The 3R (reduce, reuse, and recycle) initiative is being promoted to establish a sound material-cycle society through the effective use of resources for 3R activities, thereby ensuring both environmental conservation and economic growth [1, 2]. Furthermore, it is globally recognized that many 3R initiatives contribute to the reduction of greenhouse gas (GHG) emissions. This has led to discussions on how to realize sustainable resource usage, and how to build economic structures that promote highly efficient resource circulation [1–3]. Also, because there are serious unsolved waste management issues, it is essential to develop integrated policies for waste management, including procedures for the proper control of chemicals.

Two of the 3Rs (2R = Reduce and Reuse) are considered high-priority for development [4]. The definitions of waste prevention, reduce, and reuse vary across countries and regions [4]. For instance, the definition of waste prevention in Directive 2008/98/EC in the European Union (EU) includes the reduction of the quantity of toxic substances in materials and products. In contrast, the definition of reduce in Japan refers to reducing the quantity of waste rather than that of toxic substances. However, it is commonly recognized that successful implementation of reduce and reuse principles will lead to the prevention of waste in a society. Quantitative indicators, such as material flow indicators, have been developed and proposed to monitor and evaluate the progress of the 3Rs, including the 2R policy [5–9]. However, the indicators that are actually employed in the policy are limited for various reasons, including the lack of statistical data [4]. This is because the amount of quantitative research on effective 2R management has been limited. Consequently, the effectiveness of various 2R measures must be determined and analyzed. To promote international comparative research on these topics, we held an International Workshop in Kyoto, Japan, on 11–13 November 2015, which included invited experts and researchers that oversaw 3R policies in several countries. The workshop facilitated information sharing among participants on

various indexes for prevention measures, and the progress status for these approaches in their home countries and regions. The participants were policymakers and researchers from Australia, Canada, China, Denmark, Germany, Italy, Japan, the Republic of Korea, Taiwan, and Vietnam. The purpose of this paper is to provide a summary of the information obtained through the workshop and in an additional review of previous studies that was conducted in June 2016. As listed in Table 1, a total of 245 papers were reviewed. However, due to space limitations, not all can be introduced in this manuscript (see the electronic supplemental materials SII for a detailed list). This study consists of three sections: (1) waste prevention policy, concepts and practices in each country, (2) methodologies for decision-making, and (3) target products and/or materials with higher priority. By reviewing current policies for waste prevention in countries around the world, we have observed that (1) decision-making at a policy level is solely dependent on information obtained through material flow analysis (MFA) and life-cycle assessment (LCA), and (2) waste prevention policies target a wide range of materials, from food loss to packaging waste to persistence chemicals.

Status of waste prevention policies in each country

EU countries

In the EU, the Thematic Strategy on the Prevention and Recycling of Waste was established in 2005 [10]. Since then, the importance of waste prevention has been recognized. In accordance with the revised Waste Framework Directive (2008/98/EC), Member States must establish national waste prevention programs. The directive draws attention to key environmental impacts to account for products and materials from a life-cycle perspective, and to achieve a decoupling between economic growth and the environmental impacts associated with waste generation [11–14]. By the end of 2014, national or regional waste prevention programs had been developed in 27 of the 31 countries in the EU (28 EU member states and 3 European

Table 1 Number of reviewed papers, methods, and waste types considered

Number of reviewed papers	Methods						
	Policy	Review and methodology	LCA, environmental analysis	LCC, cost analysis	MFA, SFA	Field survey	Others
245	57	71	54	22	59	39	30
245	Considered waste type						
	Food waste	Packaging waste	Battery	ELV	E-waste	C&D waste	Persistent chemicals
	62	41	39	35	44	35	43

Regarding “methods” and “considered waste type”, papers were counted more than once

Free Trade Association countries) [15, 16], and seven programs were first adopted during 2014 [17].

On the other hand, the flagship initiative developed under Europe 2020, which is the growth strategy for the EU until 2020, addresses sustainable growth based on a more competitive, low-carbon economy that also protects the environment. [18–21]. The concept of a “circular economy” was developed in the EU. In contrast to a traditional linear economy, a circular economy represents a development strategy that enables economic growth while optimizing the consumption of natural resources. This requires deep transformations in production chains and consumption patterns, as well as the redesign of industrial systems [22, 23]. It is remarkable that a circular economy is intended to achieve economic growth along with sustainable growth. The European Commission (EC) adopted an ambitious circular economy package in 2015, which consisted of an EU action plan and included revised legislative proposals on waste to stimulate the transition towards a circular economy [24]. Plastics, food waste, critical raw materials, construction and demolition waste, and biomass and bio-based products were identified as priority areas of focus in the action plan. The revised legislative proposals on waste set both quantitative and qualitative targets for the reduction of waste, and established an ambitious and credible long-term path for waste management and recycling.

In Germany, as a result of the progress made in each EU member nation regarding waste management regulations, the Circular Economy Act (CEA) [25] was developed in 2012 and included the concepts of waste prevention and extended producer responsibility. According to the Act, the established waste prevention program [26] emphasized the importance of waste prevention against the background of the waste management hierarchy of the CEA, although it was without legal commitments. The program outlined the potential for administrative bodies to prevent waste for the first time in a systematic and comprehensive way. The program also introduced 34 specific waste prevention measures along with an evaluation of their effectiveness. Some of the recommendations were for local authorities to develop waste prevention concepts and plans, to provide information and raise awareness regarding clean product design, and to strengthen the waste prevention aspects of purchase recommendations.

Since the 1990s, waste treatment in Denmark shifted from a landfill focus to incineration [27]. In 2011, 61, 29, and 6% of all waste was recycled, incinerated, and land-filled, respectively. In promoting the subsequent shift from incineration to recycling, Denmark established a resource strategy with the goal to increase the portion of household waste recycled from 22 to 50% by 2022, to collect 65% of all waste electrical and electronic equipment (WEEE), including 55% of all portable batteries sold in the market in

2018, and so on [27]. As for waste prevention in Denmark, efforts are focused on food waste, construction and demolition (C&D) waste, textile waste, WEEE, and packaging waste.

In Italy, the National Programme for Waste Prevention includes prevention targets to be achieved by the year 2020 with respect to 2010 [28]. They include a 5% reduction in the amount of urban and non-hazardous waste generated, and a 10% reduction in that for hazardous waste. Both percentage targets will be calculated per GDP unit to achieve a decoupling between waste generation and economic indicators.

Asia and Pacific countries

The Basic Act on Establishing a Sound Material-Cycle Society was established in Japan in 2000 [29]. The Act was intended to limit the consumption of natural resources and to minimize the associated environmental burden by promoting the 3Rs, including “reduce” (waste prevention), as well as environmentally sound waste management practices. In accordance with the Basic Act, the 1st–3rd Fundamental Plans, which were comprehensive waste management plans that included methods to “reduce” waste, were established in 2003, 2008, and 2013, respectively [1, 30–33]. Of the five key areas in the 3rd Fundamental Plan, the plan defined (1) 2R promotion, and (2) the advanced use of recyclable resources and the promotion of critical metal recovery. Regarding each recycling law, the Law for the Promotion of Recycling and Related Activities for the Treatment of Cyclical Food Resources (enforced in 2001, revised in 2007) [34] set reduction targets (reduction weight per number of sales) for 31 business sectors after August 2015. Furthermore, among local authorities, Kyoto City set a reduction target in the revised action plan 2015 to reduce food loss by half as of 2020, compared with the maximum level registered in 2000 [35].

One of the representative waste management policies in South Korea involves the extended producer responsibility (EPR) system and the volume-based waste fee system. As a consequence of the Waste Deposit Program implemented in 1992, a full-fledged EPR system was introduced in 2003 to impose recycling obligations on producers [36]. The volume-based waste fee system was launched in 1994 in accordance with the polluter pays principle [37–39]. This system is applicable to residential waste from households and businesses, and was recently expanded to cover food waste as part of the comprehensive measures for food waste reduction in 2010. As of June 2014, 142 of 145 local governments were participating in this system [39]. The first fundamental plan for resource circulation was established in 2011, and followed the Waste Control Act (amended in 2015) and the Act on Promotion of Saving and Recycling

of Resources (amended in 2016), which were both based on the principle of resource circulation, [39]. To promote the transition to a resource circulation society, additional measures were launched in 2013 that included: free pickup services for large-scale waste home appliances, securing collection services, transportation and classification of recycling resources, expansion of “waste to energy” facilities, and the creation of a recycling marketplace. The Framework Act on Resource Recirculation was legislated in May, 2016 (to be enforced from January 2018). Like the EU member states and Japan, Korea has also implemented a food waste prevention policy, which envisions an eco-friendly food culture, and an energy-saving low-carbon society with the target of a 20% reduction in the amount of food waste generated by 2012, compared to the 2008 level [40]. The strategy included setting up a system of economic incentives for food waste reduction, introducing practical strategies with steady enforcement, developing suitable strategies for each generation source, and carrying out a national practice campaign. Several measures have been implemented in this regard since 1996. The achievement of these strategies included promoting the policy of the separate collection of food waste, an increased recycling rate, the reduction of food waste generation, and the spread of an eco-friendly food culture.

The initial municipal solid waste (MSW) recycling policy in Taiwan was established in 1990 [41]. Then, the national government established an EPR system in 1997 that required manufacturers to pay recycling fees based on the material, volume, weight, and value to be recycled. Through recycling and reduction activities, such as volume-based collection fees (2000- in Taipei city); plastic bag use restriction program (2003-) with the goal to reduce the annual production and consumption of plastic bags by 20,000 tons; and a food- and garden-waste recycling programme (2000-); the amount of MSW generated dramatically decreased after 1997 [41]. Resource productivity in Taiwan increased by 54.9% between 2007 and 2013. Taiwan is shifting its strategy and priority from waste management to sustainable material management (SMM), under the framework of 6R which includes 5R (3R+energy recovery and land reclamation), and Redesign. It is a comprehensive approach that integrates the economy, resources, and environment through database development, networking, and footprint tracking for the management of supply chains, and intends to create closed material loops from source to sink with counter-measures against global resource scarcities, and plans to establish the Cyclic Resources Use Act. SMM is achieved by reductions across the supply chain, a sustainable circulation system of hazardous and non-hazardous substances, and increases in resource productivity.

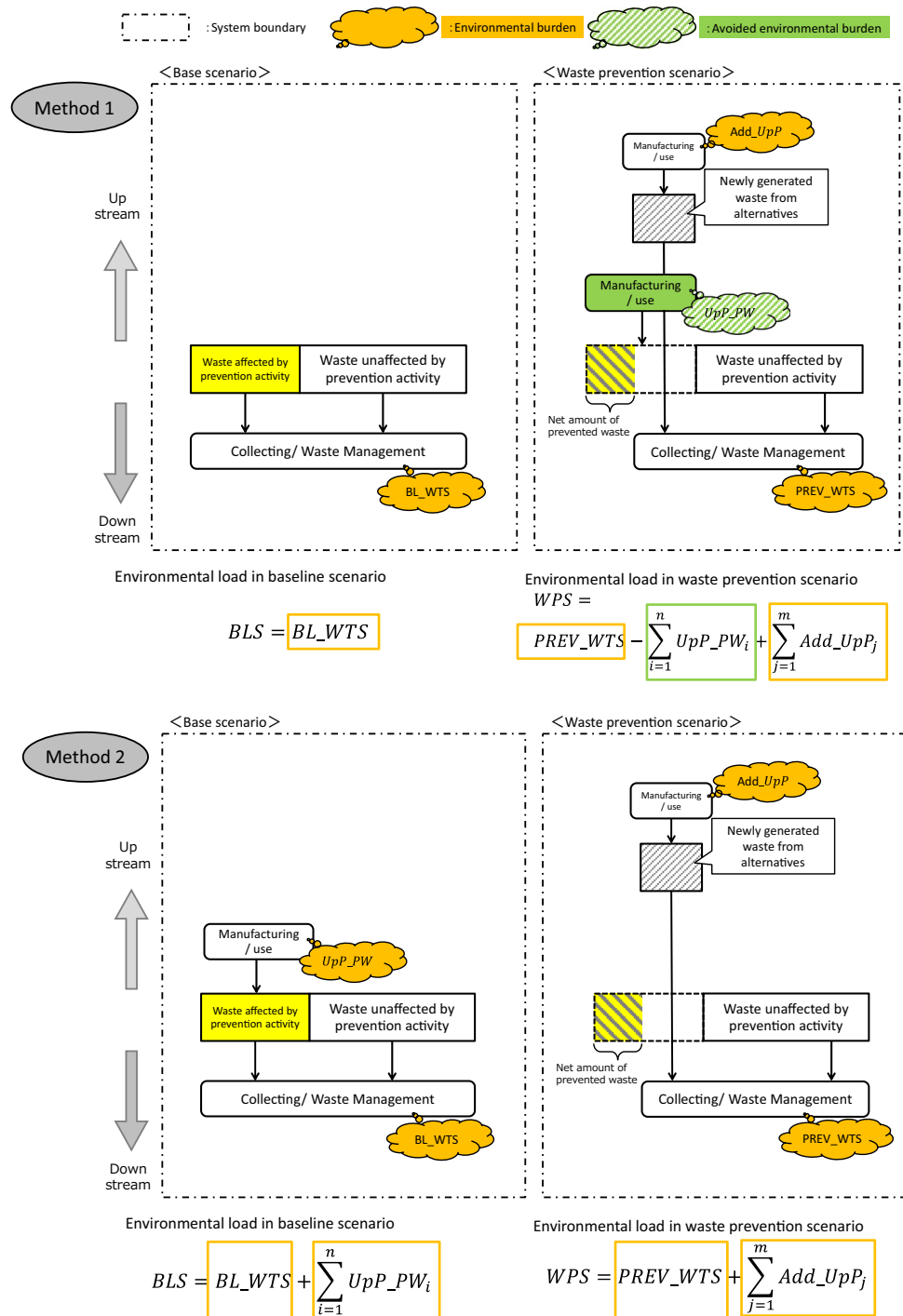
Methodologies for decision-making

Material and substance flow analysis

It is essential to examine the effects of each program or project to identify and implement effective waste prevention policies. Helpful approaches include LCA as well as MFA and substance flow analysis (SFA), which contribute to the visualization of flows, stocks, and balances between various compartments within the system [42–44]. An MFA can also be used for developing indicators to assess resource efficiency and sustainable development [5–9, 44]. These methods are most useful if defined in space and time because they can then be applied to a region, management system, and specific product/treatment methods, such as Ni flow in China [45], Cd flow in MSW in Taiwan [46], Cd flow in Australia [47], Pb flow in end-of-life vehicle (ELV) management systems [48], Au flow in Germany and the USA [49], and Zn flow related to electric-arc-furnace dust management [50]. For instance, a study on Cd flows in Australia during 1998–1999 by Kwonpongsagoon et al. [47] revealed that unintentional sources, such as contamination in phosphate fertilizer, are generally greater sources of Cd than intentional uses, such as NiCd batteries and pigments. It was also found that atmospheric deposition accounted for 52% of the total inputs to agricultural soils.

Although the objective of legislation in the EU and other regions is to increase recycling rates, this type of quantitative approach does not consider the presence of unwanted substances; such as recycling loops that contain both valuable and harmful substances [51, 52]. For instance, copper contamination in steel products leads to down-cycling and lowers the quality of recycled products. Therefore, the concepts of “final sink” and “clean cycle” strategies were proposed along with several indicators [51, 53–57]. Here, “final sinks” are defined as “sinks of immobilized materials with a very long residence time (>10,000 years)” [53, 56]. It has been noted that the characteristics of substance-specific sinks should be determined by the biogeochemical properties of the specific substance, and their application and utilization within the anthroposphere must be considered [57]. Based on the MFA, and considering the availability of final sinks, Brunner determined that three types of residues are generated from processes and systems: (1) “clean” waste products suitable for recycling, (2) “sustainable” emissions that do not overload the global cycles of water and air or the capacities of the available final sinks [53], and (3) waste that meets the final storage quality requirements and can be immobilized for long periods when landfilled. He suggested that if no appropriate final sink could be assigned to a material, then that material should be phased out and replaced.

Fig. 1 Framework of LCA for waste prevention. This figure is made based on Cleary [60], Gentil et al. [61], and Nessi et al. [62]



Life-cycle assessment

Many LCA studies of waste management have been reported globally. Among some 222 published solid waste management studies by Laurent et al. [58], the global distribution of studies was as follows: 33 in Italy, 22 in Spain, 20 in Sweden, and 19 in Denmark. In other

regions, there were 12 studies in the USA, 10 studies in China, 6 studies in Japan, and 8 studies in Australia.

Because it is commonly assumed that waste constitutes no burden until it actually becomes waste (the “zero burden” assumption), the system boundary in the LCA studies of waste management generally starts from waste generation [59]. However, to quantify the effects of 2R activities, improved conceptual models have been proposed [60–62].

Cleary proposed expansion of the system boundary to include the production stages of only the products affected by waste prevention activities [60]. Gentil et al. regarded the size of the reduction (i.e. the amount of waste that was prevented) of MSW as virtual waste that needed no treatment and, therefore, caused no environmental burden [61].

Based on Cleary [60], Gentil et al. [61], and Nessi et al. [62], the framework of LCA for evaluating waste prevention activities is illustrated in Fig. 1. In Method 1, the environmental impacts of the upstream (such as the production and use stages) that are related to the waste affected by the prevention activities (UpP_PW) are subtracted in the waste prevention scenario as avoided impacts. On the other hand, in Method 2, UpP_PW is included in the base scenario. If some additional environmental impacts from the prevention activities are observed, they must be included in the waste prevention scenario. When calculating the net reduction effect ($BLS-WPS$), the same result can be observed. Since the conceptual model has been developed, the number of case studies evaluating the effects of 2R has increased, as will be discussed later in this paper.

Multiple-criteria decision making

In addition to LCA, other decision-making models are also available. Ma reviewed and developed several models to support decision-making in MSW management [63–65]. Multiobjective programming (MOP) has been applied to solve MSW management issues, such as selecting site locations and choosing alternatives and strategies [63–66]. Multi-criteria decision making (MCDM) methods have been applied to choose the best alternative among several choices by considering the number of criteria. There are several MCDM methods available, such as the analytic hierarchy process (AHP) method, the outranking method, and the technique for order preference by similarity to ideal solution (TOPSIS) method. Su et al. applied AHP to evaluate five fly ash management alternatives in Taipei City, Taiwan, while considering the environmental, economic, social, management, and technological aspects [64]. Su et al. also applied the TOPSIS method to evaluate four waste reduction policies in Taoyuan County, Taiwan, while considering environmental, administrative, economic, and social aspects [65].

Target products and/or materials for waste prevention

Some target flows have great potential for preventing the misuse of resources and the environment, such as food waste, batteries, and various parts of end-of-life vehicles. In this section, we consider the products and materials that are now widely investigated around the globe. We also include

materials that we consider it necessary to investigate, and introduce some case studies.

MSW

Gentil et al. [61] conducted an LCA that considered three types of waste prevention in MSW, specifically unsolicited mail, beverage packaging, and food waste, and the weight reduction was assumed to be 60, 20, and 20, respectively. The benefits of prevention were significantly higher in the upstream (production) than that in the downstream (waste management) parts of the life cycle. Of the three prevention measures, food waste prevention showed the highest benefits. Similarly, Cleary conducted an LCA to evaluate five waste prevention activities (WPAs) in Toronto, Canada, which contributed to a 3.6% reduction in the MSW generation in 2008. The five activities were as follows: (1) reduction of unaddressed advertising mail, (2) reuse of disposable carry-out plastic bags, (3) substitution of articles available online, (4) lightweight and refillable wine/spirit glass bottles, and (5) grass cycling [67]. It was revealed that, although the total amount of MSW prevented by the five WPAs was only 3.6%, the endpoint impacts (ecosystem quality, human health, natural resources) in the upstream improved by up to four times. Regarding the life-cycle environmental impacts (midpoint level), the top three impacts reduced by the five WPAs were freshwater eutrophication, ozone depletion, and natural land transformation.

Food loss

Although the definition of food loss differs between countries and regions [4, 68–70], it generally refers to the portion of food waste which can be avoided by careful attention. Food loss is a representative prevention target about which many reports and academic papers have been published. Table 2 summarizes some of the previous studies with quantitative results related to the current situation, and the prevented effects on waste generation, environmental impacts, and economic aspects (see electronic supplemental materials SI2 for detailed list). According to the Food and Agriculture Organization (FAO) of the United Nations, global food waste annually accounts for approximately 1.3 billion tons of waste, and one-third of all food produced is wasted [68]. Munesue et al. estimated that a 50% reduction in food loss and waste in the food industry in developed countries would have accounted for 0.6–9.5% of the domestic regional supply of these products in 2007 [71]. To clarify the current situation in the household, retail and food service sectors, and several specific companies, field surveys such as waste composition analyses and other measurement surveys (e.g. questionnaires and statistics) were conducted [72–75]. For instance, a household waste

Table 2 Summary of previous studies focused on food waste and loss prevention

Authors	Region and sectors	Method	Current situation	Prevention measures	Weight reduction	Environmental impact reduction	Economic benefits
WRI [83]	Global food supply chain (agricultural production, postharvest handling and storage, processing and packaging, distribution and market, consumption)	Review-based estimation Food loss and waste estimated by FAO (2011) converted to calories	Global food waste accounted for 24% of calories produced in 2009 Cereals comprise the largest share (53%)	Food loss reduction opportunities were provided in the table and are introduced in this report	Halving global food loss rate would reduce annual global food demand by 1314 trillion kcal	3300–5600 million t-CO ₂	–
FAO [69]	Global food supply chain (agricultural production, postharvest handling and storage, processing, distribution, consumption)	Review-based estimation Data from FAO statistical yearbook and food balance sheet, and the literature	1.3 billion tons/year of food is wasted (32% of food produced for human consumption in 2009) Food loss during production, postharvest, and processing is 280–300 and 120–170 kg/capita year ⁻¹ in Europe and North America, and sub-Saharan Africa and South/Southeast Asia, respectively Food waste by consumers is 95–115 and 6–11 kg/capita year ⁻¹ in Europe and North America, and sub-Saharan Africa and South/Southeast Asia, respectively	Prevention measures include: Communication and cooperation between farmers Organizing small farmers, diversifying and upscaling production and marketing Developing capacity of food chain operators to apply safe food handling practices Public awareness	–	–	–
Gentil et al. [61]	Household in a typical city (EU)	LCA-based potential	–	–	Assuming potential to prevent 20% of food waste	Prevention of food waste (particularly meat) has greatest benefit. Prevention of 1.0 ton of meat waste in a low-tech waste management system saves 6.4 t-CO ₂ eq	–

Table 2 (continued)

Authors	Region and sectors	Method	Current situation	Prevention measures	Weight reduction	Environmental impact reduction	Economic benefits
Hamilton et al. [78]	Life cycle of food products (trade, plant production, animal husbandry, food processing, human consumption, waste management, biogas production) in Norway	MFA-based potential Data from national statistics, reports, and scientific articles	Avoidable Norwegian food waste accounts for 17% of food sold. Ten percent (92 kilotons (dry)) of avoidable food waste occurs at consumption; industry and retailers account for 7% (63 kilotons (dry))	–	Assuming perfect food utilization, where food demand equals supply	Theoretical potential for system-wide net process energy savings is 16%, with phosphorus savings of 21%	–
Beretta et al. [70]	Whole food value chain (agricultural production, postharvest handling and trade, processing, food service industry, retail, and households) in Switzerland	MFA based potential Twenty-two food categories analyzed Data from 31 companies	Crop production accounts for 165,000 TJ/year: 79% for animal feed, and 21% for plant-based food production. Of the total calories produced, 48% is lost across the value chain: 13% is avoidable and 13% possibly so. Estimated total avoidable losses: 299 kg/capita year ⁻¹	Prevention measures include: Pre-shop planning, avoiding temptation of special offers, and large portions. Reducing plate portions. Optimizing consumption provision, reducing range of perishable products, donating, processing products before consumption date	Theoretical potential for increasing food availability by distribution system optimization from production to consumer is 25% relative to present food energy consumption. If all edible product parts were eaten and appropriate cooking and preparation methods adopted, 25% more calories could be saved for human intake. Fifty percent more food calories could be available from the same amount of agricultural land	–	–

Table 2 (continued)

Authors	Region and sectors	Method	Current situation	Prevention measures	Weight reduction	Environmental impact reduction	Economic benefits
Love et al. [84]	Whole seafood supply chain (fisheries and aquaculture harvests, handling and storage, processing and packaging, distribution and retail, and consumption) in the USA	MFA based potential Data from government website, reports, and peer-reviewed papers	0.82–1.3 million tons/year (1.09–1.27 trillion kcal/year, 2.60–4.21 kg/capita year ⁻¹ , or 40–47% of edible seafood) was wasted in 2009–2013	Potential approaches to reducing seafood waste include: Seafood harvest and aquaculture regulation: limit percentage of bycatch. Distribution: track waste using tools. Consumption: meal planning, including assessment of portion size; use leftovers	If all seafood wasted were instead eaten, it would fill 36% of the gap between USDA-recommended and actual consumption with no increase in production	Wasted seafood could provide the total yearly target quantity of protein for 10.1 million men or 12.4 million women, and EPA and DHA Omega-3 fatty acids, and calories, for 20.1 million and 1.5 million adults, respectively	–
WRAP [73]	UK household	Field survey	In 2012, 4.2 million tons of avoidable food and drink waste was generated. Reasons for disposal (million tons): not used in time (2.0); cooked, prepared or served too much (1.3); personal preference (0.58); accidents (0.17); and other (0.12)	–	–	GHG emissions associated with avoidable food and drink waste were approximately 17 million t-CO ₂ eq	Total cost to households of avoidable food and drink waste was £12.5 billion (food £11.2 billion, drink £1.3 billion), or £470 household ⁻¹ /year

Table 2 (continued)

Authors	Region and sectors	Method	Current situation	Prevention measures	Weight reduction	Environmental impact reduction	Economic benefits
Cicatiello et al. [85]	Supermarket (5300 m ²) in Viterbo, Italy	Field survey Edible items surveyed daily throughout 2012	EU food waste was 90 million tons (180 kg/capita day ⁻¹). The retail sector accounted for 5% (4.4 million tons)	Causes of food waste and prevention measures include: Production: marketing cooperatives and improved market facilities Retail and food service: consumer preference research Household: greater public awareness through education Only recovery for human consumption by donation to charities was monitored	From this supermarket, 23.5 tons/year (4.5 kg/m ² year ⁻¹) of food was recovered; bread accounted for more than 70% Roughly 40,000 tons/year of food waste could be avoided in Italy (approximately 9 million m ² of supermarket sales area)	Overall, 28,000 and 30,000 m ³ of the supermarket's water footprint, and 86,000 and 310,000 m ² of its ecological footprint were avoided through prevention of 17.1 tons of bread and 2.0 tons of meat wastes, respectively	Food waste recovered from this supermarket in 2012 was worth about €46,000 (cost not included)
Eriksson et al. [86]	Supermarket in Uppsala, Sweden	LCA-based potential	-	Donation	Assuming 90% of functional unit (1 kg of supermarket food waste) was donated	Life-cycle GHG emissions -0.12 t-CO ₂ eq/ton of bananas, -0.35 t-CO ₂ eq/ton of chicken, -0.013 t-CO ₂ eq/ton of lettuce, -0.31 t-CO ₂ eq/ton of beef, -0.61 t-CO ₂ eq/ton of bread	-
Matsuda et al. [81]	Household in Kyoto, Japan	LCA-based potential	-	Food waste reduced by food loss prevention Waste reduction via water-draining Food waste reduced by home composting	Assuming 36.8% reduction in food loss Assuming reduction of food waste moisture content from 77 to 73% Assuming 13.4% of food waste is composted	Reduction of 21 500 t-CO ₂ eq/year compared to incineration Reduction of 5200 t-CO ₂ eq/year compared to incineration Reduction of 2600 t-CO ₂ eq/year compared to incineration	-

Table 2 (continued)

Authors	Region and sectors	Method	Current situation	Prevention measures	Weight reduction	Environmental impact reduction	Economic benefits
Katajajuuri et al. [87]	Households, food service sector, industry, and retail sector in Helsinki, Turku, Tampere, and Jyväskylä, Finland	Field surveys Waste composition survey of 380 households Food waste measured in 17 businesses (food service) Data from the Nordic Council's project (food retail) Data from the Finnish food companies and the literature (food industry)	Avoidable food waste Household: 120–160 million kg/year (23 kg/capita year ⁻¹ or 63 kg/household year ⁻¹) Food service sector: 75–85 million kg/year Food industry: 75–140 million kg/year Total: 335–460 million kg/year	–	Assuming all avoidable food waste prevented	Climate impacts: household 350,000 t-CO ₂ eq/year, entire Finnish food system 1.0 million t-CO ₂ eq/year	Value of food waste is approximately €150–220 per average household. Nationally, Finnish households annually discard food worth €400–550 million

More studies are summarized in the electronic supplemental materials

composition survey in the UK by the Waste and Resources Action Programme (WRAP) revealed that the amount of avoidable food and drink waste generated was 4.2 million tons/year as of 2012, which resulted in the emission of 17 million t-CO₂eq at a cost of 12.5 billion euro [73]. This total included 2.0 million tons/year of avoidable food waste from products not consumed by their respective due dates. Statistical analyses were also performed for retail in Austria [76] and one hospital in Portugal [77]. MFA was employed to describe the flow of the food supply chain [70, 78], and Beretta et al. revealed that 48% of the total calories from foods were lost across the whole food value chain [70]. Of course, there are many LCA studies focused on evaluating the prevention effects, as discussed later.

It has often been pointed out that the environmental impact from the production of animal-based food (such as meat) is greater than that from vegetable food plant production [61, 79, 80, 82]. Therefore, the composition of the food lost should be identified through waste composition surveys to quantify the effects generated from the reduction of food loss. This is also a good idea because the effects from the reduction of food loss differ according to the type of food loss reduced, as do the best ways to reduce it [81].

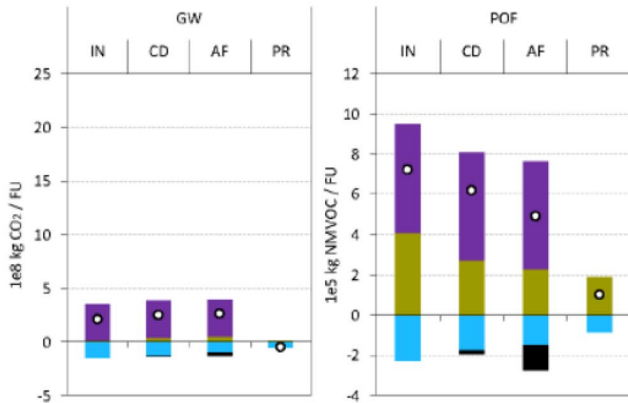
Food waste generation in Germany was 11 million tons/year. Food consumption at home and away from home accounted for 457 kg/capita and 70 kg/capita, respectively [79], of which, 16.6% (76 kg/capita) and 33.5% (23.6 kg/capita), respectively, was wasted. In other words, from the viewpoint of life-cycle GHG emissions, 2,270 kg-CO₂eq was derived from food that was eaten, while 476 kg-CO₂eq was lost to food waste. The amount of agricultural land used globally for German food consumption accounted for 60% of Germany's land area. It was revealed that for 10 impact categories (e.g., global warming, water use, land use, etc.), 13–20% of the environmental impacts of food consumption in Germany were attributable to food loss occurring in the various supply chains.

By way of a scenario analysis in Kyoto, Matsuda et al. [81] estimated the reduction effects of life-cycle GHG emissions by three household food waste prevention activities: preventing edible food loss, draining moisture, and home composting. Their study computed the volume of waste that was prevented, but also noted that the method of prevention significantly affected the results.

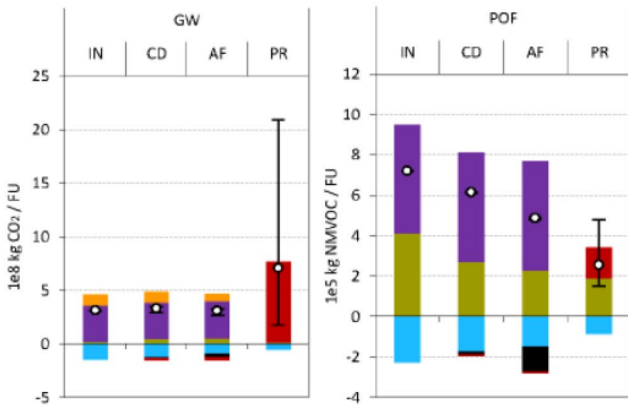
Martinez-Sanchez et al. evaluated the environmental life-cycle costing (E-LCC) and societal life cycle costing (S-LCC) of four food waste management programs including the food waste prevention costs [82]. As shown in Fig. 2, regarding the direct effects, the results of the environmental part of the E-LCC and S-LCC showed that the waste prevention scenario was much lower than those for the scenarios without waste prevention because food production was avoided. On the other hand, while

A Environmental part of E-LCC (LCA)

Direct effects:



Total effects (direct + indirect):



B S-LCC

Direct effects:



Total effects (direct + indirect):



Fig. 2 Results of E-LCC and S-LCC of food waste management by Martinez-Sanchez et al. [82]. *FU* functional unit, *GW* global warming, *POF* photochemical ozone formation, *NMVOC* non-methane volatile organic carbon compound, *IN* incineration as MSW, *CD* co-

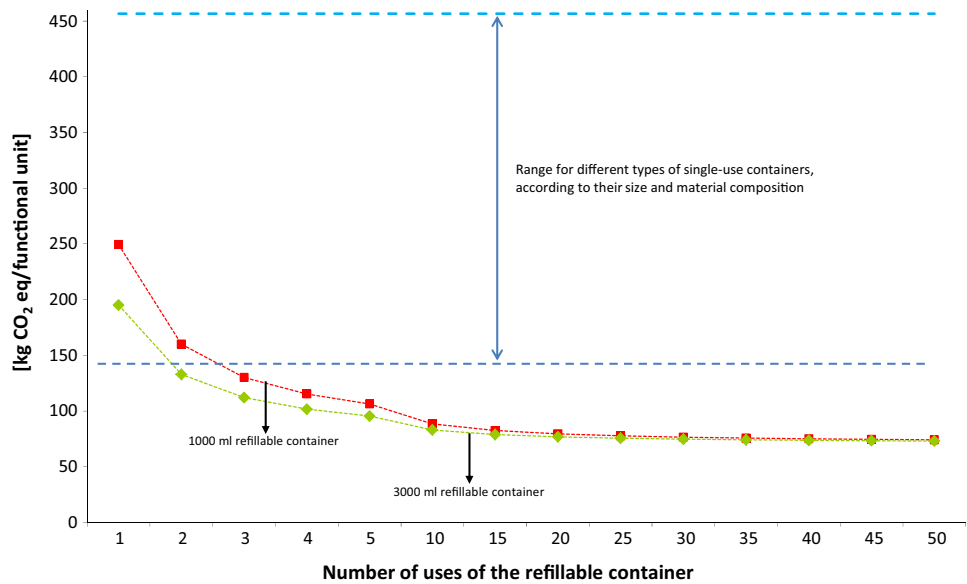
digestion with manure, *AF* animal fodder, *PR* prevention of 100% edible food waste, *WMS* waste management sector, *iLUC* indirect land-use change

considering the indirect effects, the results differed between the E-LCC and S-LCC. The indirect effects considered by Martinez-Sanchez et al. included (1) income effects (also called “rebound effects”) associated with the marginal consumption induced or reduced, and (2) indirect land-use changes induced by the production of food commodities. These results indicated that if the money saved from unpurchased (prevented) food commodities was used to purchase other goods/services, prevention could sometimes appear to be environmentally worse than business as usual.

Packaging waste

A reduction of beverage packaging by 20% was evaluated by Gentil et al. [61] as one of the three prevention measures previously mentioned. Using an LCA, Nessi et al. [88] compared public tap water and refillable bottled water with one-way bottled water as a baseline. They also evaluated the effects of preventing waste generation and reducing environmental impacts through detergent (laundry detergents, fabric softeners and hand dishwashing detergents) distribution (see Fig. 3) [89], and the viability of refillable containers and self-dispensing systems was compared with a single-use scenario (baseline). They showed that five uses of self-dispensing systems allowed lower waste

Fig. 3 Relationship between number of uses of refillable containers and climate change, compared with the range for single-use ones. Case study of laundry detergent by Nessi et al. [89]. Functional unit of the study was the distribution of 1000 litres of detergent nearby a retail outlet of the large-scale retail trade in Italy



generation and environmental impacts than did single-use containers. Then, Nessi et al. evaluated the potential effects of implementing these two packaging waste prevention activities on the overall waste management system in the Lombardia Region of Italy as of 2020 [90]. It was calculated that 0.66% of MSW generation could be reduced by the adoption of these two prevention activities, and that a much greater reduction of environmental impacts could be achieved. Among 14 impact categories, the improvements ranged from a 4.4% reduction of water resource depletion to a 25.0% reduction of terrestrial eutrophication, compared with the baseline scenario without waste prevention. It was found that half of the impact categories could be reduced by 15–25%, and it was also pointed out that the upstream impacts were greater than the downstream impacts. Of the two prevention activities, the utilization of public tap water showed a higher reduction potential of environmental impacts than did the detergent distribution through self-dispensing systems. A 0.5% reduction of waste from the former activity (tap water utilization) reduced 11 of 14 impact categories by 5–23%. LCA by Dolci et al. [91] compared traditional (single-use) and self-dispensing systems (so called “loose distribution”) of dry food products (pasta, breakfast cereals, and rice) to evaluate the effects on waste generation and environmental impacts by packaging prevention; however, the results significantly differed between the products. For breakfast cereals and rice, the loose distribution system contributed to a reduction in the waste generated as well as most of the environmental impacts. On the other hand, waste generation increased by up to 15% for pasta when compared with single-use polypropylene, while it decreased by 50% compared with single-use carton-board boxes. It was pointed out that the results were dependent on how the traditional and the loose

distributions were implemented. If the size and material of the packages were very similar, the loose distribution system might fail in reducing the waste generated and the environmental impacts thereof.

Battery, E-waste, and ELV

End-of-life primary batteries are a representative example of hazardous waste. Historically, there have been concerns about the environmental pollution derived from the Hg, Cd, and Pb contained in end-of-life batteries. To reduce the generation of end-of-life batteries, it is important to advocate for their replacement with secondary (rechargeable) batteries. On the other hand, without proper management, the increasing number of end-of-life secondary batteries is also causing issues related to the associated environmental risks [92]. Secondary batteries consume scarce metals. For example, NiMH batteries contain Ni and Co, and Li-ion batteries contain Li and Co. Because secondary batteries have been recently introduced for various uses, such as small home appliance products, hybrid electric vehicles (HEVs), electric vehicles (EVs), and photovoltaic power generation systems, the resource management of batteries is becoming a more significant issue.

To provide an understanding of a desirable management system, many SFA and LCA studies have been conducted. For example, Dolci et al. [93] used an LCA to compare the use of disposable alkaline batteries to that of secondary NiMH ones, while specifically considering the AA and AAA sizes. They found that the number of times that rechargeable batteries were used is a key factor when determining their environmental impact and energy performance, and at least 50 charge cycles were required for a robust reduction of impacts. High-consumption devices,

such as digital cameras and electronic toys, are the most appropriate use for rechargeable batteries.

The Bio Intelligence Service compared three secondary types of batteries, namely NiCd, NiMH, and Li-ion (LiFePO₄), used in cordless power tools in a case study [94]. An LCA was conducted to compare the environmental impacts of the three types of batteries and identify the impact hotspot in the life-cycles of the batteries. The result was that there were no clear advantages identified between the types batteries. Regarding natural resources, the NiCd batteries were thought to have a potentially lower metal depletion impact on resources than that for the NiMH and LiFePO₄ batteries in the mid-term; while both the NiMH and LiFePO₄ batteries had a potentially lower abiotic resource depletion impact than that for the NiCd batteries over the long term. These results implied that the pertinent time horizon is another significant factor that should be considered.

It was estimated that 20–50 million tons/year of WEEE are generated globally [95] and this amount has been increasing. For instance, the generation of household WEEE in Europe is projected to grow annually at 2.5–2.7% [96]. Since WEEE contains a variety of both toxic and valuable substances, its management requires significant effort. Chancerel and Rotter [97] estimated that approximately 5000 tons/year and 16,000 tons/year of end-of-life mobile phones were generated as of 2007 in Germany and the USA, respectively. Of the amount of Au contained in this waste (350–500 Kg-Au), less than 5% was recovered, 3% was reused, and 92% was lost. While end-of-life mobile phones and PCs accounted for 0.5% and 17%, respectively, of the total generation of WEEE (categories 2, 3, 4, 6, and 7 defined in the WEEE Directive [98]), they accounted for 40% of all the Au contained in WEEE. Similarly, high percentages of other valuable metals are discarded: 88% of Pd, 89% of Ag, and 89% of Ni [99]. An LCA study by Eygen estimated that recycling desktop and laptop PCs could reduce natural resource consumption by 80 and 87%, respectively, compared with landfilling [100]. Regarding the recovery of metals, the compromise between grade (quality) and recovery (quantity) should be of another concern [101, 102]. Bovea et al. investigated the reusability of WEEE from a collection campaign of households in Castellon de la Plana, Spain [103]. Among the 87.7 kg (96 units) of samples, 67.7 and 2.1% were considered as potentially reusable and directly reusable, respectively. On the other hand, an interview survey of 28 reuse organizations around the world pointed out that (1) the access to sufficient volumes, (2) informal and illegal reuse practices, (3) regulations, standards, and product design, and (4) costs, as barriers for promoting the reuse of WEEE [104].

Worldwide automobile ownership exceeded 1.1 billion vehicles in 2010 [105], and it has been estimated that

end-of-life vehicles (ELVs) accounted for 4% of the total ownership, or 40 million vehicles, of which 12.0 million were in the USA, 7.4 million in the EU, 3.5 million in China, and 3.0 million in Japan) [106, 107]. From the viewpoint of hazardous materials, heavy metals contained in ELVs are historically one of the most important issues for ELV management systems, which includes automobile shredder residue (ASR) treatment. In Japan, the Japan Automobile Manufacturers Association, Inc. (JAMA) set a voluntary target to reduce the Pb content in the components of passenger vehicles (except for the lead–acid battery) by more than 90% by 2006, compared to the total content in 1996 of 1850 g-Pb per vehicle [48]. Although the Pb content per vehicle was successfully reduced by up to 100 g-Pb, it was pointed out that it will take some time for this reduction to influence the Pb content in ELVs and ASR [48]. The toxic chemicals, such as brominated flame retardants (BFRs), that are contained in ELVs have also become global concerns [106, 108]. In addition to their levels of toxicity, the need to develop resource recovery methods has become more important because electric devices and next-generation vehicles (such as HEVs and EVs) are becoming increasingly popular. The amount of scarce metals contained in an ELV has been quantified using various approaches, including dismantling surveys [107, 109–115].

Construction and demolition waste

C&D waste is often one of the top three priority waste-prevention areas because it is expected to significantly reduce life-cycle environmental impacts [12, 13, 23]. Several summary reports, guidelines, and reviews related to C&D waste management, best practices, and LCAs have been published [116–123]. Approximately 1 billion tons of C&D waste, one-third of the total waste generation, was annually generated in the EU as of 2006 [116]. C&D waste consists of recyclable materials, such as concrete, bricks, gypsum, wood, glass, and so on. Wang et al. evaluated reconstruction and extension projects for overpasses in Shanghai city, China, through a life-cycle inventory analysis [124], which revealed that using regenerated aggregate could reduce energy consumption and GHG emissions by 45.3 and 43.9%, respectively, compared with using virgin materials. Due to its longer lifespan, life-cycle thinking, including the design stage, is highly relevant [125, 126]. Source segregation is important for promoting recycling and the reduction of environmental impacts [120, 122]. However, when C&D materials are recycled, potential contamination with hazardous compounds may be involved. For example, construction materials are the most common asbestos-containing products [127]. Butera et al. reported that PCBs and PAHs were detected in all 33 C&D waste samples [128]. An LCA revealed that the recycling of C&D waste showed

fewer environmental impacts than did landfilling [122]. On the other hand, it was also pointed out that the fate of Cr in the subsoil greatly influenced the results; therefore, identifying the status of the contaminants emitted (like Cr) in the subsoil was important [129].

Persistent chemicals and hazardous compounds

Despite the development of regulations, persistent chemicals, such as PCBs, BFRs, and hazardous compounds, were and still are contained in different products in use for various purposes [130]. They are released into the environment from various sources and life stages: in the use stage of the product, including in the dust [131–133], in the treatment stage in recycling facilities [134–140], and in landfill sites [141–143]. Mizouchi et al. revealed that BFRs and phosphorus flame retardants (PFRs) were detected in all of the dust samples gathered from elementary schools (18 samples) and domestic houses (10 samples) in Japan in 2009 and 2010. The concentration (ng/g dry weight) ranged from 260 to 9300 for \sum BFRs and 9300–5,500,000 for \sum PFRs. According to the multimedia urban model on the fate of polybrominated diphenyl ether (PBDE) in Toronto, inadvertent ingestion of house dust is the largest exposure pathway for all human life stages except in infants [144].

As the flow of products, materials, and waste has become global due to its legal and illegal transport, the persistent chemicals and hazardous compounds contained within them are also transferred globally. Improper recycling results in negative impacts on the environment and on human health [134–136, 138, 139, 145]. In the case study in Bui Dau [138], northern Vietnam, higher contamination (up to 14,000 ng/g-dry) by flame retardants and some persistent organic pollutants could be observed in surface soils and river sediments near the e-waste recycling workshops or open burning sites, while low concentrations (up to 10 ng/g-dry) were found in the soils from footpaths around rice paddies. The contamination was reduced along the stream in the downstream sediments. As of 2010 and 2011, when comparing human serum from workers at e-waste recycling sites with that from residents in rural areas, the levels of PCB, hydroxylated PCB, PBDE, and bromophenol concentrations in the former were significantly higher due to their occupationally related exposure [139].

Conclusions

This paper provides a summary of the information obtained through the workshop held in Kyoto, Japan, during 11–13 November 2015, which included invited experts and researchers from a number of countries in charge of waste prevention and 3R policies in several

countries, and includes an additional review of 240 previous studies on the topic. The achievements of this study are summarized as follows:

- Regarding policy development, a decoupling between environmental pressures and economic growth was recognized as an essential step towards a sustainable society in each country. It is expected that 3R and resource management policies, including waste prevention, will play a crucial role. Some good practices at the national and regional scales have already been demonstrated.
- Methodologies for decision-making have been developed step by step. Approaches using material/substance flow analysis (MFA and SFA) have become sophisticated enough to describe the fate of resources and/or hazardous substances based on human activity and the environment, including the final sink. An LCA has also been developed to evaluate waste prevention activities. These methodologies can be combined with each other or with other methodologies to consider multiple criteria, such as economic and social aspects.
- To effectively promote waste prevention, target products have been identified with higher priority. Food loss is one of the waste fractions with the highest priority because the corresponding countermeasures have significant upstream and downstream effects. On the other hand, concerns about rebound effects after waste prevention is achieved, have started to be considered. Persistent organic pollutants and hazardous compounds should also be considered in the situation where recycling activities are globally widespread for the promotion of a material-cycling society.

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