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CHAPTER 4

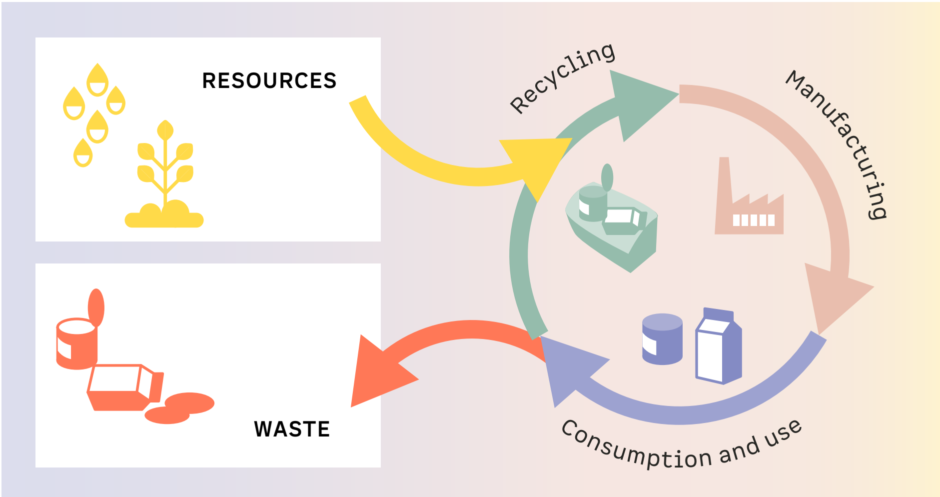
Reconsidering inputs, reducing losses and recycling waste in circular agrifood systems

Losses and waste occur throughout food systems: farm-level practices allow for nutrient depletion, food value chains suffer post-harvest losses, and households and communities generate solid and liquid waste and human excreta. These considerable losses and waste can be lessened if material flows can be shifted towards reducing, reusing and recycling – by transforming linear food systems into more circular ones. In addition, new technologies and biotechnology can advance this transformative shift through novel foods and fertilizers that lead food systems away from fossil fuel dependence.

This chapter explores two broad strategies for making food system resource use more sustainable and efficient. One is training farmers, traders and households in better resource management practices. The other is improving resource use technologies. Both strategies aim to gradually decouple growth from the use of finite resources, arriving at a circular economy that is regenerative by design and uses intensive feedback among food system components to recycle and reduce material losses (**FIGURE 4.1**).

More specifically, the chapter looks at how to promote integrated resource management throughout the food system, how to reduce food losses in agricultural value chains, how to recycle nutrients in production systems (using external inputs more efficiently) and how to use incentives to recover more household waste. Two strategies can engage stakeholders to transform food systems in a more circular direction: first, new technical opportunities – with human investments in training and awareness-raising – and, second, financial incentives to encourage adaptive behaviour.

FIGURE 4.1 CIRCULAR ECONOMY PRINCIPLES FOR TRANSFORMING FOOD SYSTEMS



Source: Nextstep.

The chapter develops five key messages:

1. **Circular principles will make food systems not only more sustainable but also more efficient** – by increasing agricultural yields, by increasing food production and by creating value added in agrifood chains.
2. **Supporting nutrient recycling opportunities at farm, regional and national levels requires specific practices, programmes and policies** – specifically those that enable substantial cost reduction, more diverse and resilient production systems, and more efficient energy and water use.
3. **Interventions to reduce food losses at different stages of the food value chain vary by region, food group and value chain component** – yet they generally combine new technologies, better handling practices and supportive market incentives to improve productivity and food quality while reducing externalities.
4. **Household waste and human excreta can become important sources of nutrients and energy for improving food systems** – and can be recovered with community organization.
5. **Advances in developing a biobased economy are promising** – these, too, can add to circular food systems.

How do we shift food systems towards circular resource use for sustainability and resilience?

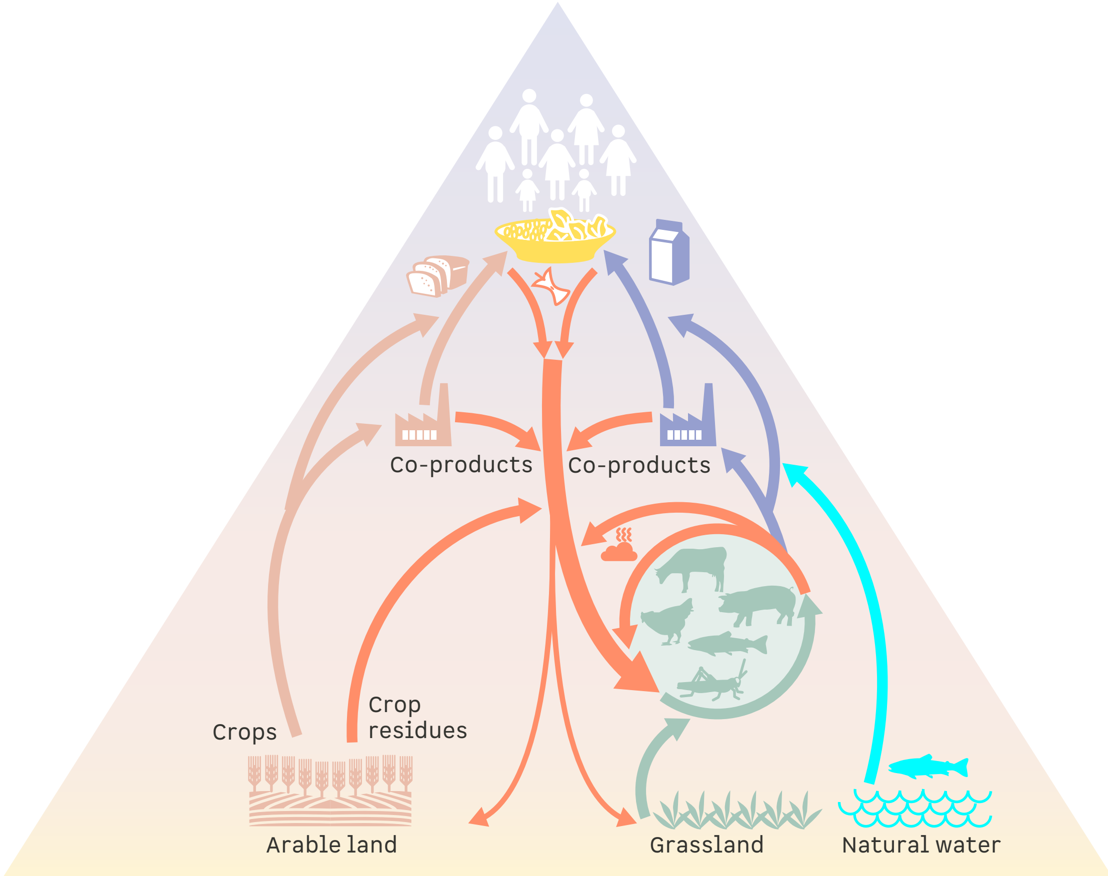
Our society can be greener and more sustainable if we adopt measures aimed at reusing organic material from crops, aquatic biomass and residual flows produced in the agricultural sector. Circular food systems are based on the principle of optimizing all biomass use. The waste streams from one supply chain can be the raw materials for another.

Circularity implies loss prevention, recovery for reuse, remanufacturing and recycling. The concept of circularity originates in industrial ecology, which aims to reduce resource consumption and emissions to the environment by closing the loop of materials and substances (Ghisellini et al., 2016; Jurgilevich et al., 2016). Under this paradigm, losses of materials and substances should be either prevented or recovered for reuse, remanufacturing and recycling.

In the food system, circularity is biophysical (**FIGURE 4.2**), and plant biomass is its basic unit. Farm animals are most effectively used to unlock biomass that is inedible for humans, turning it into valuable food, manure and other ecosystem services. Moving towards biophysical circularity in the food system implies searching for practices and technology that:

- Rely as little as possible on the use of finite resources, such as land and phosphate rock.
- Encourage the use of regenerative resources, such as wind and solar energy.
- Prevent leakage from the food system of natural resources, such as nitrogen and phosphorus.
- Stimulate the reuse or recycling of resources that are inevitably lost – such as those in human excreta – in a way that adds the highest value to the food system (Ghisellini et al., 2016; Jurgilevich et al., 2016).

FIGURE 4.2 BIOPHYSICAL CIRCULARITY IN THE FOOD SYSTEM



Source: van Zanten et al., 2019.

In particular, natural nutrient cycles must be restored to agrifood waste systems. Doing so is necessary for three reasons:

- To reduce the environmental harm that currently results from excess nutrients.
- To conserve valuable resources.
- To safeguard future food security (van der Wiel et al., 2019).

"Hotspots" – such as manure, waste and even human excreta – make good subjects for analysis, if they can be recycled safely and in a way that is acceptable to users. Processing costs have to be low and transportation distance small. Contrasting examples of circular and linear food systems are described in **BOX 4.1** and **BOX 4.2**.

BOX 4.1 LARGELY CIRCULAR: INTEGRATED AGRICULTURE AND AQUACULTURE IN VIET NAM

A high degree of circularity is found in the integrated rice-fish systems of the lower Mekong delta, Viet Nam. At such farms, 30-40 per cent of the farm area is dedicated to trenches for storing water, which helps in dry-season irrigation-water management, and the water area is used for fish production. Depending on the location, such farms can include freshwater shrimp as well as fish. Dissolved run-off fertilizer from the fields enters into the trenches and allows growth of algae and other natural food, the main nutrients for the fish. During the wet season, the fish encroach on the paddy section and the faecal waste released on the flat ground works as fertilizer for the paddy as well. At the end of each culture cycle, the bottom sludge of the trenches is taken out and used in the vegetable beds on the dykes in the farms. When vegetables are harvested, the roots are often mixed with the soil of the flat rice bed by ploughing.

Source: Berg et al., 2012; Bosma et al., 2012.

BOX 4.2 LARGELY LINEAR: SOY MEAL AS ANIMAL FEED FOR EXPORT IN LATIN AMERICA

A largely non-circular system is the global chain of soy meal, grown in Latin America initially to feed animals and subsequently also humans in Europe and Asia. Using nitrogen as a marker reveals five phases in the development of Brazilian soybean systems: forest conversion, soybean cultivation, transport and processing, consumption and waste disposal. The nitrogen that eventually ends up in meat, milk and eggs from soy meal-fed animals is estimated at around 20 per cent of the nitrogen in the freshly crushed soy meal. More than half of the lost nitrogen can potentially be recycled, though mostly far away from soybean production. Recycling these losses can make local and national food systems more circular, but the overall soybean chain is not circular, based as it is on growing animal feed for far-away destinations.

Source: Smaling et al., 2008.

How can smallholder farmers contribute to circular systems?

The circular economy is highly dependent on the management of soils and land to perform four basic functions:

- Producing food and other biomass.
- Storing, filtering and transforming many substances, including water, carbon and nitrogen.
- Providing fresh mineral resources and fossil fuels.
- Remaining a functional platform for nature and human activities (Breure, Lijzen and Maring, 2018).

As the human population grows, the demand for resources increases. Soil and land management are central to the circular economy – to maximize the reuse of resources and products, and to reduce resource depletion to a minimum.

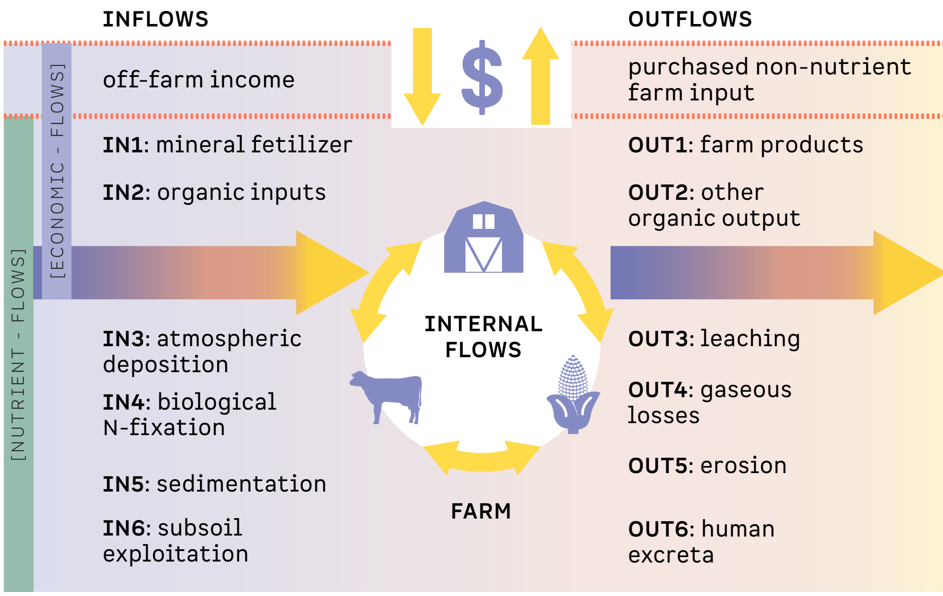
In assessing the circularity of farming systems, soil carbon and nutrient stock and flow analysis can help

To reduce inorganic fertilizer purchases and to control emissions, natural nutrient cycles will have to be restored to agrifood systems. Restoring these cycles implies balancing stocks and flows of carbon and nutrients – nitrogen, phosphorus, potassium – to support circularity and to enhance ecosystem services. Nutrient cycles can be restored at farm scale, subregional scale or national scale. Nutrient balances can be an indicator to determine nutrient-use efficiency of farming systems.

A comprehensive literature review on Africa (Cobo, Dercon and Cadisch, 2010) showed nutrient balances being widely used across the continent. In the 57 peer-reviewed studies surveyed, most balances were calculated at plot and farm scale, and most were generated in East Africa. Data confirmed the expected trend of negative balances in the continent for nitrogen and potassium: fewer than 75 per cent of the selected studies had mean values below zero.

Many approaches follow NUTMON (Smaling and Fresco, 1993), which is based on an analysis of nutrient inputs, outputs and internal flows related to recycling (**FIGURE 4.3**). The analysis of nutrient balances is adopted as a way to assess the degree to which farming systems are circular. Along with the assessment of carbon and nutrient balances, the assessment of stocks – the carbon and nutrients available in soils – is equally important: the combination of the two indicates the rate at which carbon and nutrients decline or accumulate in soils, farms and regions.

FIGURE 4.3 NUTRIENT INPUTS, OUTPUTS AND INTERNAL FLOWS IN A FARMING SYSTEM



Source: Based on Smaling and Fresco, 1993.

Of the nutrient flows commonly considered, four are regarded not only as nutrient flows but also as economic flows, because of their relatively straightforward monetary value: IN1 (mineral fertilizer), IN2 (organic inputs), OUT1 (nutrients in removed crop parts) and OUT2 (nutrients in removed crop residues). The other flows – while contributing to environmental goods and bads – are harder to quantify in monetary terms (see **FIGURE 4.3**).

The NUTMON approach can be used at any spatial scale, as long as the system boundaries are clearly defined. It was first developed for African farming systems, where numerous studies have focused on Kenya (De Jager et al., 1998), Ethiopia (Abegaz, 2005), Uganda and Burkina Faso (Agwe et al., 2007). These studies in sub-Saharan Africa reveal – almost unequivocally – alarming carbon and nutrient depletion rates. NUTMON has also been applied in Asia, with studies focusing on China and Viet Nam (Dang, 2005; Lam et al., 2005; Khai et al., 2007) India (Surendran and Murugappan, 2007) and Thailand (Wijnhoud, 2007).

Studies of high-production irrigated areas in Asia have found that multiple cropping leads to fertilizer use (IN1) and nutrient removal in crops (OUT1) at rates far exceeding those for rainfed agriculture. Irrigated systems bordering the Asian highlands also have free nutrient lunches through IN5. The interaction between livestock, organic manure (IN2) and the fate of crop residues (OUT2) is relevant in determining levels of circularity. Other mechanisms for increasing circularity are reducing atmospheric nitrogen emissions, erosion control and reuse of human excreta (decreasing OUT4, OUT5 and OUT6 in **FIGURE 4.3**).

Farmers rely on composting practices, green manure (cover crops) and household organic waste to improve soil fertility and soil organic matter content, which reduces input purchases and enhances yields

An alternative to manufacturing mineral fertilizers – which is energy intensive and adds to greenhouse gas (GHG) emissions – is to use organic fertilizers. One organic fertilizing method is to include nitrogen-fixing species, such as beans, in farming systems, thus increasing IN4. Another method is to use compost from pits and heaps, or in integrating trees that root deep and bring up "new" nutrients through leaf fall. Yet another organic fertilizing method is manuring, which allows for integrated crop-livestock systems. This can take place at farm scale, where zero-grazing animals feed on crop residues and fodder crops, but it also occurs at larger "system" scale, as in Sahelian West Africa. There, pastoralist cattle often spend the night in rings around villages, fertilizing them with their urine and faeces with nutrients obtained from the bushland farther away (Samaké et al., 2005). After the growing season, abundant sorghum and millet residue from production on these lands is then fed to the animals. More generally, the recycling of crop residues in integrated crop-livestock systems can improve overall system performance, allowing "preferred plot" manuring schemes for high-value crops.

Recycled organic materials can be separated into two categories: those already part of the system – compost, household waste, manure from animals not receiving concentrates – and those entering the system as inputs from outside. In many African countries, commercial livestock clusters are developing at the fringes of cities, yet nearby farms scarcely use the manure generated there. Its value as fertilizer may not be recognized, and legal standards for its use may be lacking. So when researchers work with large amounts of farmyard manure or compost – as they often do – their results may not be realistically applicable to the average African farm (Ejigu et al., 2021).

Much is gained from the combined use of mineral and organic fertilizers (IN1 + IN2). This combination often gives better production results than either fertilizer type by itself. In addition, the combination maintains better soil quality, expressed in pH and organic carbon content. The challenge lies in ensuring that sufficient organic inputs are available at the farm level. But at the same time, conducive policies are needed to take these farming systems to a higher level – that is, to environmental compensation, carbon credits, extension geared towards adopting green technologies, and so on.

And not to be neglected is the reuse of organic waste on farms and beyond for energy. Increasingly, biodigestion is promoted to supply energy for cooking and other purposes, particularly where there is no connection to the electricity grid (Muvhiiwa et al., 2017). The other side of this coin is that carbon and volatile nutrients such as nitrogen and sulphur will be lost from the productive system. Another example of competing use of the same resources is the selling of dung cakes as a source of fuel in Ethiopia, and the widespread practice of using dung to plaster houses. The product serves a clear purpose, but the nutrients are taken out of the system.

How and where can food losses in the food system value chain be reduced?

International attention to food loss and waste (FLW) is clearly affirmed in the 2030 Agenda for Sustainable Development. Awareness began to increase with a few publications that raised the profile of FLW (Parfitt et al., 2010; FAO, 2011). According to rough estimates, a third of all food produced was lost or wasted. These rough estimates are now being replaced by two indices, thanks to efforts by the Food and Agriculture Organization of the United Nations (FAO) and the United Nations Environment Programme to estimate more carefully and precisely how much food is lost in production and in the supply chain before the retail stage (the Food Loss Index) and how much is then wasted by retailers and consumers (the Food Waste Index). Even so, researchers more widely still lack common and agreed definitions of food loss and food waste (**BOX 4.3**).

BOX 4.3 DEFINING FOOD LOSS AND FOOD WASTE

How should food loss and food waste (FLW) be defined? The answer has important implications both for the estimation methodology used to examine FLW and for the interpretation of results. Although the terms "post-harvest losses", "food loss", "food waste" and "food loss and waste" are frequently used interchangeably, they hardly ever refer consistently to the same concept. Two recent definitions of FLW distinguish between loss and waste, but they do so in different terms. FAO defines food loss as unintended loss of food during harvesting, post-harvest handling, processing and distribution, in contrast to food waste, which is food that gets lost at the retail and consumption stages (FAO, 2011). For the World Resources Institute, food loss is "the unintended result of an agricultural process or technical limitation in storage, infrastructure, packaging, or marketing", while food waste is "food that is of good quality and fit for human consumption but that does not get consumed because it is discarded" (Lipinski et al., 2013).

The table below summarizes some issues that arise from different conceptualization and measurement frameworks in assessing various value chain breakdowns (Fabi et al., 2021).

FOOD CHAIN BREAKDOWN IN STAGES UNDER THE MAIN CONCEPTUAL FRAMEWORKS

SDG 12.3		FOOD LOSSES INCLUDING POST-HARVEST LOSSES						FOOD WASTE		
Stages	Pre-harvest	Harvest/ slaughter/ catch	On-farm post-harvest	Storage	Transport	Processing	Wholesale	Retail	Consumption	
SDG 12.3 Food Loss Index	Out of scope	Included at country level	On-farm post-harvest (all activities)	Storage	Transport	Processing and packaging	Wholesale	Out of scope Covered by the Food Waste Index		
African Union	Out of scope	Harvesting		Storage	Transportation	Processing	Packaging and marketing[a]		Out of scope	
EU 2019 directive[b]	Out of scope	Primary production		Out of scope		Processing and manufacturing	Retail and other distribution of food		Restaurants and food services	Household
HLPE	Included	Harvest and initial handling stage (on- and off-farm)		Storage (on- and off-farm)	Transport and logistics	Processing and packaging	Unclear	Retail		Consumption (household)
FLW Protocol[b]	Included	Production		Handling and storage	Processing and packaging		Distribution and market		Consumption	
EU FUSIONS	Can be considered	Primary production ready for post-harvest				Processing and manufacturing	Wholesale	Retail and redistribution	Out of home	In home
FAO 2011	Out of scope	Production		Post-harvest handling and storage (off-farm)		Processing	Distribution (wholesale and wet retail markets, supermarkets)			Consumption

[a] The African Union monitoring and evaluation methodology requires two separate loss percentages for packaging and marketing.
[b] Entities can be classified using ISIC (International Standard Industrial Classification of All Economic Activities) or NACE (Statistical Classification of Economic Activities in the European Community) codes, thus with more detail than the main stages outlined in the conceptual framework.

Note: FUSIONS, Food Use for Social Innovation by Optimising Waste Prevention Strategies; HLPE, High Level Panel of Experts on Food Security and Nutrition; SDG, Sustainable Development Goal.

Source: Authors, based on FAO et al., 2018; HLPE, 2014; WRI, 2016; EU FUSIONS, 2014; EU, 2019; and FAO, 2011.

Food loss and waste estimates still face conceptual challenges, but action is needed

Although FLW reduction is now at the forefront of policy discussions, evidence on the topic is sparse – and the available studies use heterogeneous methods and definitions. A number of publications have started to provide insights that can help in designing protocols (FLW Protocol, 2016) and interventions to reduce FLW (for example, Affognon et al., 2014; Bellemare et al., 2017; FAO et al., 2019; Reynolds et al., 2019; Delgado et al., 2021). Because of estimation difficulties, product seasonality and market sensitivity to food quality, most studies analyse the quantity of food loss in terms of weight reductions (HLPE, 2014; Hodges et al., 2014). Some studies further translate quantity losses into caloric terms (Lipinski et al., 2013; Kummu et al., 2012; Buzby et al., 2014), but these studies still do not capture qualitative dimensions, such as loss of nutritional content and altered physical appearance (Affognon et al., 2014).

While the need to continue monitoring and building an evidence base is clear, policymakers also need current guidance – even if such guidance can be based only on the limited information at hand. Torero Cullen (2021) suggests that four dimensions should drive FLW agendas:

- How much food is lost and wasted, and where and why does this happen?
- What are the underlying reasons or objectives for reducing FLW – do they pertain to efficiency, food security or the environment?
- How effective have interventions on food losses been, and how much can be recycled back into the food system as a result?
- Does evidence exist on interventions and incentives that can help to reduce FLW, and if so do these activities create employment and enhance small and medium-sized enterprise activities?

Food loss and waste can therefore be addressed only with tailored strategies that focus on critical bottlenecks

Reducing food crop losses is critical to sustainably increasing agricultural productivity. Because food loss takes widely varying forms for various types of farmers, products and linkages within the midstream, it can be effectively addressed only by combining different interventions and targeting multiple stakeholders (**BOX 4.4**).

BOX 4.4 REDUCING POST-HARVEST LOSSES IN RWANDA

Rwanda's rural population continues to depend on agricultural activities for income generation. Reducing post-harvest losses is essential to maintaining high sales volumes, but climatic irregularities pose a serious threat to agricultural productivity, with yearly losses estimated at between US$50 million and US$300 million as a result of unpredictable periods of drought and torrential rain.

An IFAD project was implemented to combat climatic irregularities by tackling post-harvest losses at multiple stages of the value chain through several technological interventions. Working with the Government of Rwanda's Strategic Plan for the Transformation of Agriculture, the project assisted in the construction of modern post-harvest infrastructure to support smallholder farmers' productivity. Support was provided through business investments in drying, processing, value addition, storage, and logistics services for smallholder farmers.

The project has supported more than 55,000 members of 277 cooperatives through hub services, training and climate mitigation and information services. Roughly 5,500 farmers have been trained by the Rwanda Meteorology Agency, and an additional 6,000 farmers continue to receive daily text messages on weather forecasting. The completion of research and development of drought- and flood-resistant seed strains has supported farmers' ability to adapt to climate change. Post-harvest losses have come down by 20 per cent, and beneficiary incomes have increased by 10 per cent on average as a result.

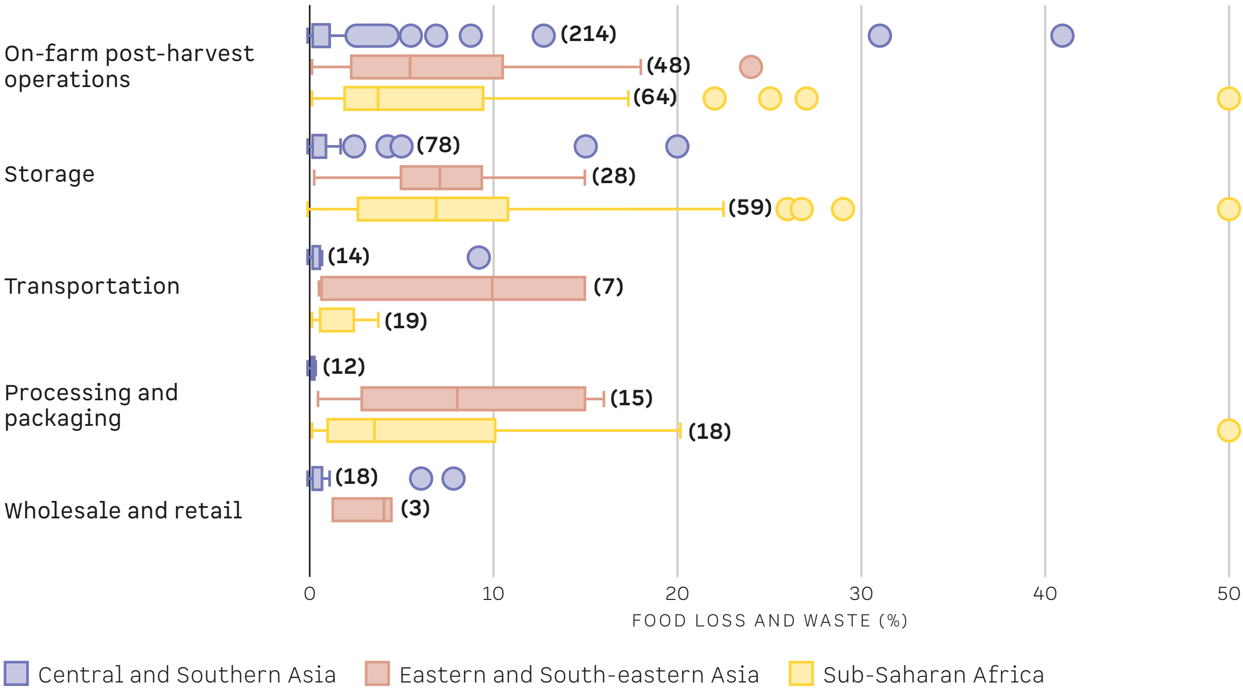
Source: IFAD project completion report.

FAO et al. (2019) reports an average global food loss of 14 per cent. Remarkably, Central and Southern Asia have food losses over 20 per cent, while East and South-East Asia have losses below 10 per cent. Sub-Saharan Africa is close to the global average. On a product group basis, roots, tubers and oil have losses of 25 per cent, fruits and vegetables just over 20 per cent, meat and animal products just over 10 per cent and cereals and pulses just below 10 per cent.

FAO et al. (2019) also offers comparisons by region, product group and stage in the value chain, enhancing insights and entry points for targeted policies. Losses in fruits and vegetables in sub-Saharan Africa are largely in the post-harvest stage and to a lesser extent in storage and wholesale (**FIGURE 4.4**). But in East and South-East Asia, the losses are mainly in storage and in packaging and processing. For meat and animal products, sub-Saharan Africa is the only region having large losses, in the post-harvest/slaughtering and storage stages.

FIGURE 4.4 REPORTED FOOD LOSS AND WASTE PERCENTAGES BY SUPPLY CHAIN STAGE, 2000-2017

A. CEREALS AND PULSES



B. FRUITS AND VEGETABLES

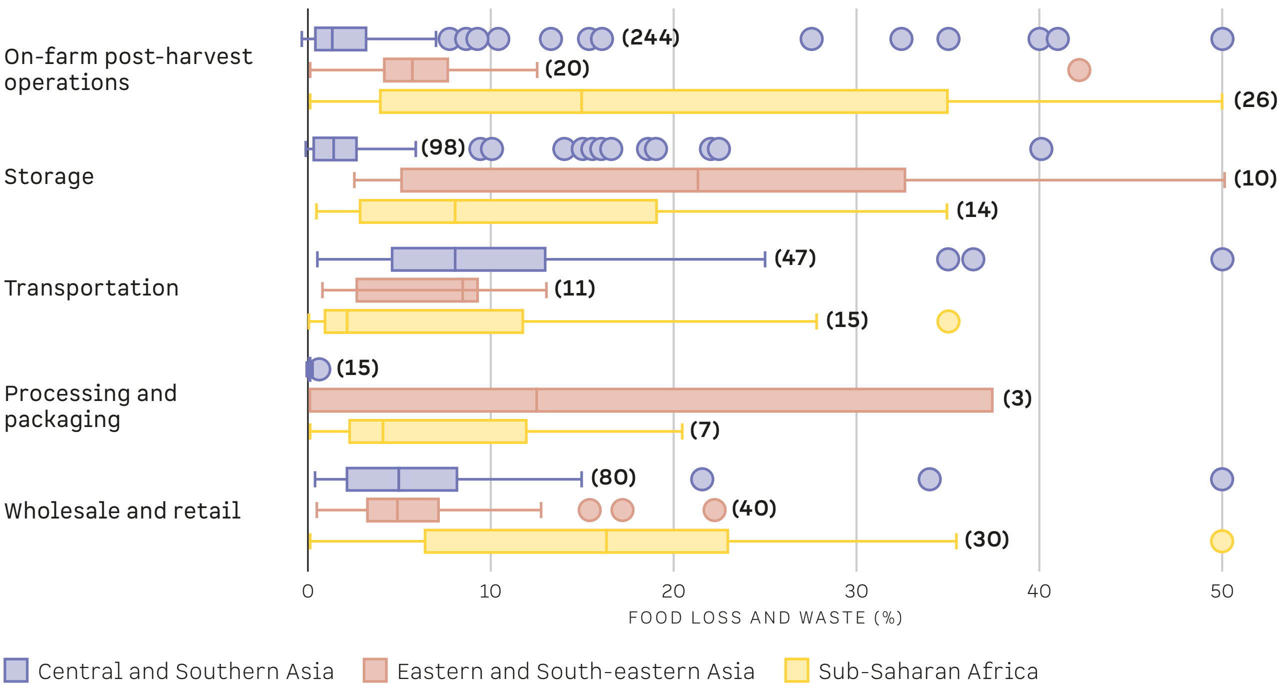
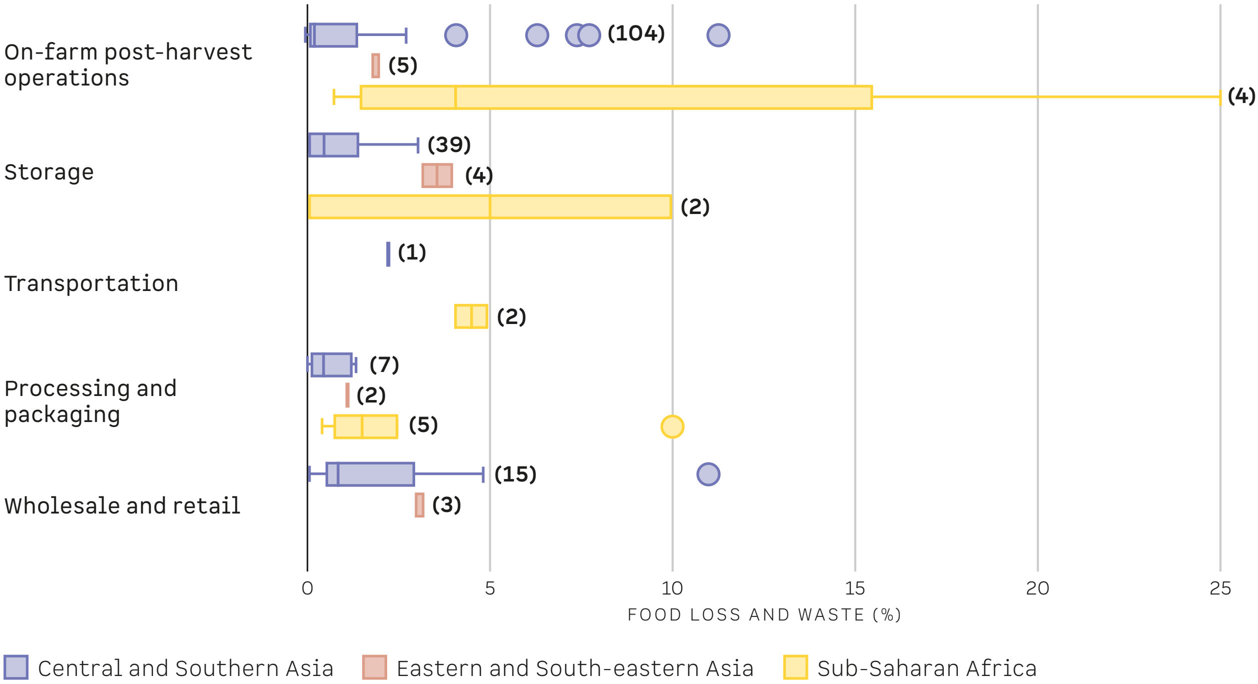


FIGURE 4.4 (CONT.)

C. ANIMAL PRODUCTS (INCLUDING FISH)



Source: FAO et al., 2019.

Using **TABLE 4.1**, priorities can be set for intervention. Torero Cullen (2021) developed an intervention classification, based on median values for region-product-value chain segment losses, with lows, highs and medians as determinants. The first segments to target for intervention are the cells with bold median values: storage and processing/packaging in fruits and vegetables in Central and Southern Asia, and post-harvest losses and wholesale/retail in fruits and vegetables in sub-Saharan Africa. Although no partitioning was possible for meat and animal products, **FIGURE 4.4** suggests that attention to these products should largely focus on slaughter and storage losses in sub-Saharan Africa (**BOX 4.5**).

TABLE 4.1 PRIORITY INTERVENTION AREAS BY REGION, PRODUCT GROUP AND STAGE OF THE VALUE CHAIN

REGION	PRODUCT	ON-FARM POST-HARVEST/ SLAUGHTER	STORAGE	TRANSPORTATION	PROCESSING AND PACKAGING	WHOLESALE AND RETAIL
Central and Southern Asia	Cereals and pulses	Low: 0 Median: 0.4% High: 2.6%	Low: 0 Median: 0.5% High: 2.1%	Low: 0.1% Median: 0.5% High: 0.7%	Low: 0.02% Median: 0.1% High: 0.3%	Low: 0.02% Median: 0.2% High: 1.1%
	Fruits and vegetables	Low: 0 Median: 1.3% High: 7.7%	Low: 0 Median: 1.4% High: 5.9%	Low: 0.4% Median: 8% High: 25%	Low: 0 Median: 0.03% High: 0.25%	Low: 0.3% Median: 5% High: 15%
	Meat and fish	Global average over value chain up to but excluding retail: 12%				
East and South-East Asia	Cereals and pulses	Low: 0.2% Median: 5.5% High: 18%	Low: 0.3% Median: 7.2% High: 15%	Low: 0.5% Median: 10% High: 15%	Low: 0.5% Median: 8% High: 16%	Low: 1.2% Median: 4% High: 4.5%
	Fruits and vegetables	Low: 0 Median:5.7% High: 12.5%	Low: 2.5% **Median: 21.3%** High: 50%	Low: 0.8% Median: 8.4% High: 13%	Low: 0 **Median: 12.5%** High: 37.5%	Low: 0.5 Median: 4.9% High: 12.7%
	Meat and fish	Global average over value chain up to but excluding retail: 12%				
Sub-Saharan Africa	Cereals and pulses	Low: 0.1% Median: 3.7% High: 17.3%	Low: 0 Median: 6.9% High: 22.5%	Low: 0.1% Median: 2.3% High: 3.7%	Low: 0.1% Median: 3.5% High: 20.2%	No data
	Fruits and vegetables	Low: 0 **Median: 15%** High: 50%	Low: 0.5% Median: 8.1% High: 35%	Low: 0.3% Median: 2.1% High: 28%	Low: 0 Median: 4.1% High: 20.5%	Low: 0.2% **Median: 16.3%** High: 35.5%
	Meat and fish	Global average over value chain up to but excluding retail: 12%				

Source: Torero Cullen, 2021.

BOX 4.5 ARTISANAL FISHERIES PROMOTION IN MOZAMBIQUE

Small-scale artisanal fishing constitutes 90 per cent of fishing activity in Mozambique. Fishers in this subgroup commonly lose a portion of their catch due to a lack of processing equipment and the limited availability of ice and storage containers. To ensure minimal post-harvest losses for artisanal fishers, an IFAD project aimed to increase incomes and livelihoods through improved storage techniques and the provision of reliable infrastructure conducive to fish storage.

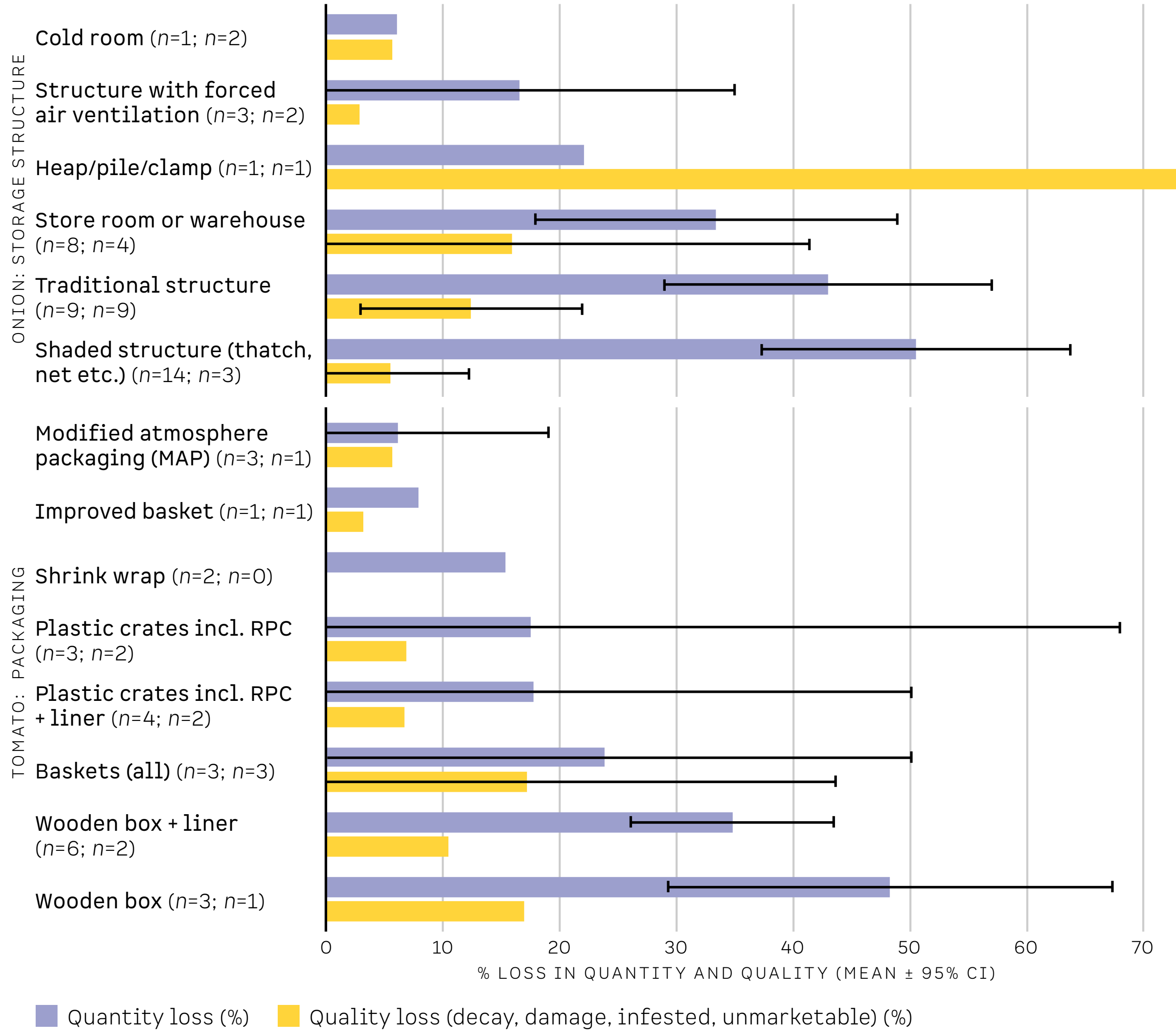
Training was conducted for 13,000 fishers, 16 markets were restored, 15 were constructed, and sanitation stations, water and electricity were provided to fish traders. In addition, 525 kilometres of roads were improved to ensure efficient transfer of goods. Market improvements meant less loss at markets during sales. They also improved the efficiency of markets. Local staff were trained to build and maintain infrastructure for storage facilities and markets to allow for a more sustainable transfer of project responsibilities from IFAD to the host communities.

Source: IFAD project completion report.

Improving on-farm post-harvest operations, storage structures and packaging methods

In many rural areas across the world, rural inhabitants have more food following the harvest period than later in the year. Food losses at the farm level due to poor storage facilities aggravate this see-saw of better and then inadequate nutrition throughout the year. But technologies and handling operations can reduce food losses (Stathers et al., 2020). For maize, using hermetic bags with synthetic protectant reduced losses – in weight and after a storage period of six months – to less than 5 per cent. In contrast, the use of jute sacks without protectant led to losses of almost 30 per cent. For onions (storage structure) and tomatoes (packaging), quantity and quality classifications are both relevant, while the ranges are considerable (**FIGURE 4.5** and **BOX 4.6**).

FIGURE 4.5 QUANTITY AND QUALITY LOSSES ASSOCIATED WITH DIFFERENT STORAGE STRUCTURES (FOR ONIONS) AND DIFFERENT PACKAGING (FOR TOMATOES)



Note: The first *n* indicates the number of examples of quantity loss data for this intervention, and the second *n* refers to examples of the quality loss data. RPC = Returnable plastic crates.
Source: Stathers et al., 2020.

BOX 4.6 FOOD LOSS IN PRACTICE: TWO CASE STUDIES FROM AFRICA

Tomatoes, grown in Burkina Faso, are transported in crates to the market in Kumasi, Ghana. Prevailing weather conditions, estimated using satellite meteorology, and information on the microclimate inside truck trailers were combined with data on the deterioration in tomato quality during transport, expressed by "firmness". A post-harvest loss model built on these estimates as input parameters explained 77 per cent of the variance in observed tomato firmness, with total product losses ranging from 30 per cent to 50 per cent over the entire transportation period. This can help to assess the cost-benefit ratio of various measures to reduce tomato quantity and quality loss – and to illustrate what net gains can be expected if delays along the transport route are reduced, cargo conditions are semi-controlled (for example, by pre-cooling) or a different transport schedule is adopted.

For teff and perishable liquid milk in Ethiopia's growing rural-urban midstream, losses were between 2 per cent and slightly over 4 per cent – a lot lower than commonly assumed. The emerging modern retail sector in Ethiopia has on average half the food losses of the traditional retail sector. This is probably due to more stringent quality requirements in procurement systems, sales of more heavily packaged – and thus better protected – commodities, and better refrigeration, storage and sales facilities.

Source: Venus et al., 2013; Minten, Tamru and Reardon, 2021.

Intervention choices should be linked to desirable outcomes

If the highest or most immediate priority is to change a particular food system outcome, this priority will inform the selection of interventions to reduce FLW (**FIGURE 4.6**).

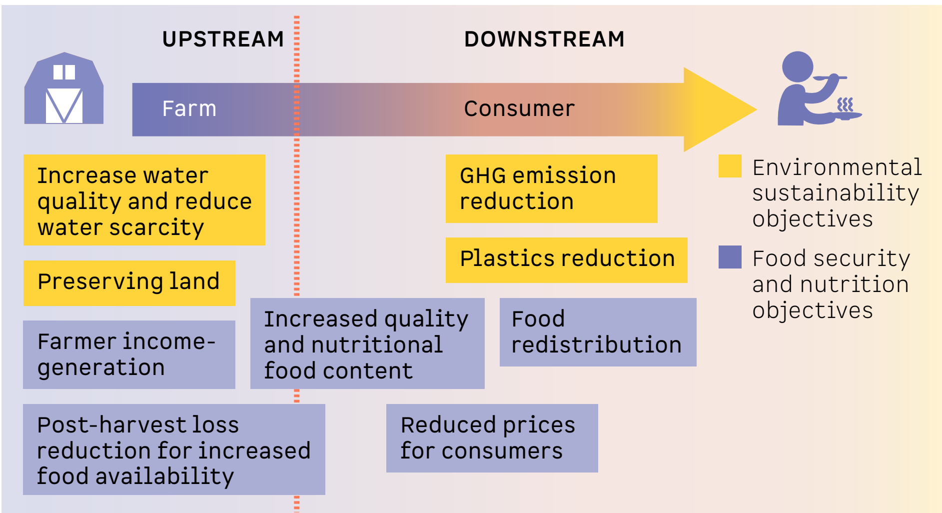
- For environmental outcomes, interventions may reflect the specific objective that is targeted. For example, because GHG emissions accumulate throughout the midstream, the most efficient way to reduce them is to reduce food waste by consumers – that is, the stage with the largest embedded GHG emissions. In contrast, if the objective is to preserve land and water quantity and quality, FLW should be cut in the primary production phase – the phase with the largest environmental footprint.
- For health and nutrition outcomes, the gains from cutting waste are at the farm level – where fewer losses mean increased food availability – and in the processing and retail stages, where food quality can be both increased and decreased.
- For livelihood outcomes, FLW-reduction initiatives should focus on the quantity and quality of production and price levels at points of sale, because these factors bear most directly on farmers' income. Cooling and road infrastructure and other post-harvest facilities are key to success at the market, particularly for perishables (**BOX 4.7** and **BOX 4.8**).

BOX 4.7 INFRASTRUCTURE AND STORAGE AS KEY CONSTRAINTS IN ADDRESSING FOOD LOSS AND WASTE

In the regional consultations among food system experts across IFAD regions, poor infrastructure and the lack of storage facilities were often mentioned as constraining factors in addressing food loss and waste. For example, one civil society respondent from the West and Central Africa region indicated that the quality of rural roads often slows down transport to consumer markets: "Transport from the countryside to the tarmac road, to the cities, where the population is with money, is still an issue. There are still a lot of mangoes, tomatoes and cabbages rotting on the field instead of being brought out." A private-sector respondent from the East and Southern Africa region indicated that the lack of the right storage infrastructure often limits the prevention of food loss and waste: "We are losing a lot before it even gets to the market because we don't have reliable storage. So we need proper storage facilities at the farm gate, we need the electricity so that we can preserve all these different horticultural products."

Source: Regional consultations.

FIGURE 4.6 ALIGNING OBJECTIVES AND INTERVENTION ENTRY POINTS ALONG THE FOOD SUPPLY CHAIN



Source: Torero Cullen, 2020.

As these distinctions imply, the FLW chain involves producer-consumer trade-offs. For example:

- In low-income countries, reducing on-farm losses may have strong positive food security effects for some farmers – but not for all – and for consumers. The loss reduction may especially benefit smallholder subsistence farmers by increasing the availability of food to them. But farmers who market part of their output may see drops in demand and price, with negative implications for their incomes and thus for their food security, as larger volumes cause prices to drop at later points in the supply chain. Such price drops benefit consumers.

BOX 4.8 SOLAR-POWERED MILK COOLERS FOR SMALLHOLDER DAIRY FARMERS IN ETHIOPIA

Researchers and private firms developed a small solar-powered milk cooler for smallholder dairy farmers to store their milk in 40-litre metal containers. Prototypes of this solar-powered milk cooler have spread to other countries in Africa, ranging from Tunisia to Uganda.

SOLAR-POWERED MILK COOLER IN ETHIOPIA

Photo source: Olga van der Valk, WUR/BOPinc. 3P4PPI Program.

- Reducing food waste by consumers is likely to improve food availability and access for the same consumers – yet the resulting reduction in consumer demand may leave farmers, and other supply chain actors, worse off.

Although these arguments provide general indications about which value chains to target for FLW-reduction interventions – given particular environmental, nutritional or livelihood objectives – evidence is lacking to relate FLW interventions to measurable social, economic and environmental outcomes.

Another question, often mentioned but understudied, is how FLW in the quantity and the quality of food crops may affect household food and nutrition security and income. More evidence is needed on the efficacy of FLW-reduction interventions in this area – especially when technical interventions are combined with non-technical interventions, such as changes in training and handling practices. Such evidence is also important to deepen understanding of the combined effects of financial, policy and infrastructure interventions and encourage more participatory learning approaches on nutrition and food security.

Reducing food loss and waste may have benefits and costs – and mixed effects on employment opportunities

Post-harvest loss reduction is not always the most cost-effective route to inclusive and sustainable food system transformation (Sheahan and Barrett, 2017). Quality loss and food safety issues have not been studied as much as quantity losses. Nor is the evidence for venturing into massive food loss-reduction programmes as strong as in the case of urban solid waste in Bangladesh (Ananno et al., 2021) and Africa (Loukil and Rouached, 2020).

In summary, two FLW agenda issues – the extent to which interventions on food losses have been effective and how much can consequently be recycled back into the food system – remain open for discussion (Torero Cullen, 2021). The answers depend greatly on the objective and on which segments of the value chain are addressed, while food loss-reduction activities have winners and losers. Largely unanswered, too, is the question of whether evidence exists for sustainable reductions in FLW and for (gender-sensitive) employment creation through FLW interventions and incentives.

How well can household waste be recycled in food systems?

Household residues consist of solid biological waste, liquid excreta, recyclable materials and non-biodegradable waste (**BOX 4.9**). Household waste and human excreta are important sources of nutrients and energy for improving food systems; loss of these resources can be reduced with appropriate incentives, and lost resources can be recovered with sound community organization.

There is a non-linear relationship between per capita income and the share of food wasted in different parts of the world (Barrera and Hertel, 2020). As a result, household uneaten calories are growing rapidly – especially in emerging economies – and may nearly double by 2050 (**FIGURE 4.7**).[6]

BOX 4.9 HOUSEHOLD RESIDUES

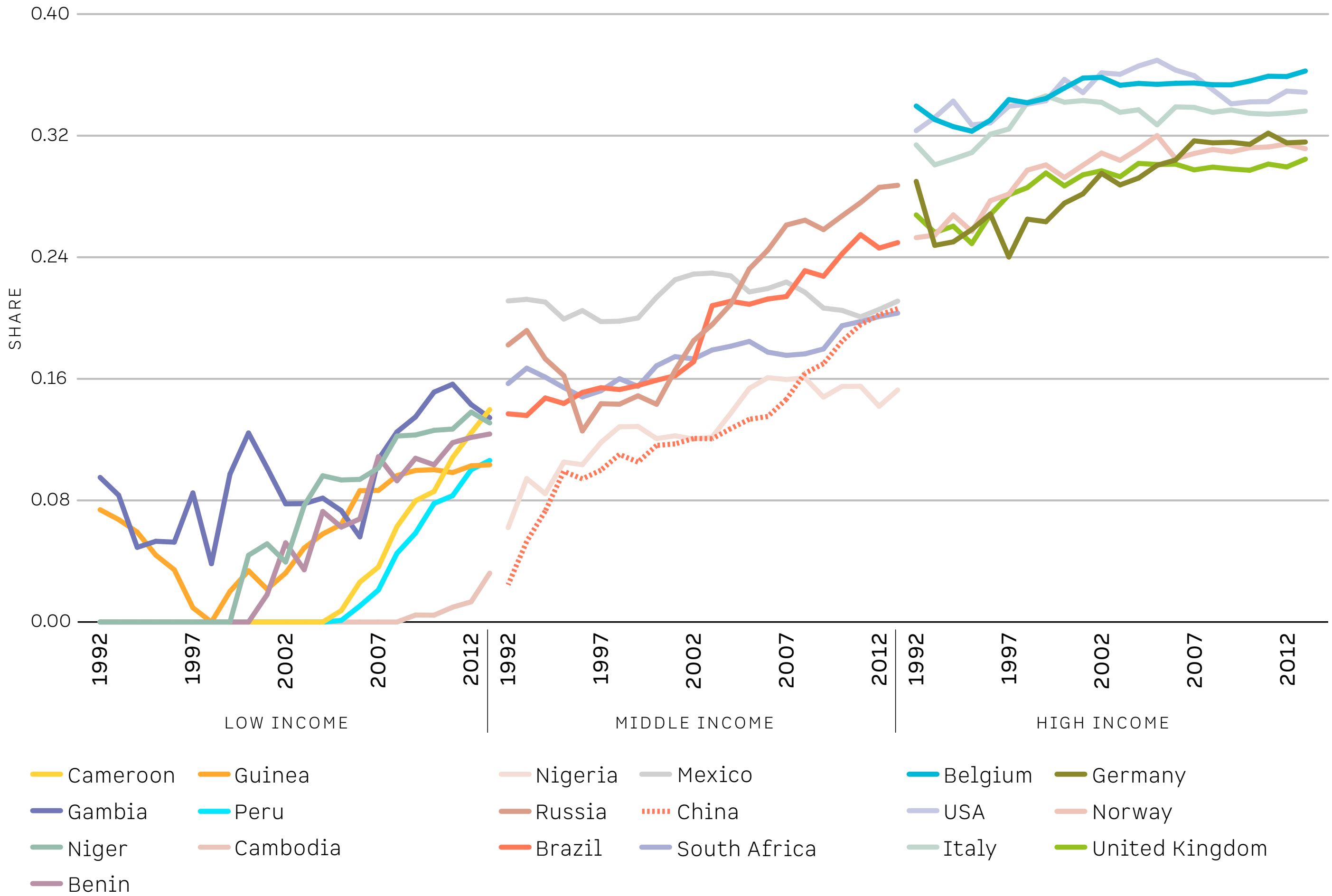
Household residues fall into four types:

- **Solid waste:** food leftovers, waste fruits and vegetables that originate from households and markets. Much of this results from packaging materials (e.g. banana leaves, grasses and potato stalks) used for wrapping fresh foodstuffs, as well as from leftover products that can no longer be sold or consumed.
- **Recyclable material:** includes paper, glass, plastics, metal and textiles. A fraction of this waste can be salvaged and directly recycled for making secondary materials.
- **Non-biodegradable waste:** waste materials that can be harmful or toxic to humans. This includes, for instance, construction and demolition waste.
- **Solid and liquid human excreta:** largely sourced from households, educational institutes and other common facilities that use latrines.

Source: Authors' elaboration based on Gustavsson et al., 2011, and Irani et al., 2018.

6 In sub-Saharan Africa and South and South-East Asia a decade ago, food waste at the consumer level (household and retail) was estimated at 6-11 kilograms per person per year (Gustavsson et al., 2011).

FIGURE 4.7 SHARE OF FOOD WASTE ACROSS THE INCOME SPECTRUM



Note: The share of food waste is calculated as the ratio between calories wasted in relation to calories available.
Source: Barrera and Hertel, 2020.

On the rural-urban continuum, urban residents throw away more food waste than do their peri-urban and rural counterparts – even when they have better cold-storage facilities (Loukil and Rouached, 2020). Low-income households and ethnic minorities are presumed to waste less food than wealthier households (Loukil and Rouached, 2020). Households throw away greater quantities of unprepared food than prepared food and drinks (Chakona and Shackleton, 2017).

Involving households in waste recovery strategies

Household food waste is mainly a result of consumer behaviour related to food preparation and storage. Reducing household food waste requires integrated food management that includes shopping, storing (including cold storage) and appropriate cooking and eating practices. Awareness and educational campaigns can provide incentives for household food waste reduction (van Geffen, van Herpen and van Trijp, 2020).

Dietary transitions typically involve increased consumption of foods with a shorter shelf life – such as dairy, fruits and vegetables – and this shift may increase food waste in the absence of efficient storage options (Lundqvist, de Fraiture and Molden, 2008). About a quarter of household food waste could be reduced with appropriate packaging (Williams et al., 2012).

Residential waste and human excreta are valuable resources for recycling, and their collection and treatment is motivated mainly by environmental and health concerns

Residential waste comprises disposable materials that are generated in day-to-day operations by households and that can be recycled or composted for secondary use. Waste collection, excreta disposal and wastewater sewage are vital for environmental safety and human health. Getting appropriate systems in place for organized waste recovery at scale requires local organization, community collection and treatment services (public or private) and some degree of collective action (Sugihara, 2020).

Sanitation for low-income residential areas relies mostly on pit latrines and bucket latrines. These latrine types enable sludge and night soil to be collected, transported and used for final treatment and disposal. In Asia, cleaners of latrines are often a special social or ethnic group and face dangerous labour conditions and low pay. Along the East African coast, where Islamic influence is strong, people are averse to touching human excreta (Muller, 1997).

Some 4 billion litres of untreated wastewater is created each day in developing countries. Wastewater treatment serves three purposes: improving local health conditions, reducing environmental externalities and recovering nutrients. Untreated wastewater directly contributes to diarrhoeal diseases, such as cholera, typhoid fever and rotavirus, which are annually responsible for 297,000 deaths of children under 5 years old – 800 children every day (The Lancet, 2012). An estimated 80 per cent of wastewater from developing countries flows untreated into the environment (The Conversation, 2021).

The organization of waste recovery and excreta disposal should be undertaken by public, private or community organizations and supported by economic and social motivation mechanisms

A wide range of technological opportunities and innovation strategies are available to better link the producers of waste and excreta in urban and peri-urban households to the potential users of recycled products in rural and urban livelihoods. Waste and excreta are used for different purposes, ranging from energy (cooking and heating) to the organic fertilization of homestead vegetable production.

Recycling and reusing household residues requires efficiently organized collection and treatment processes at the neighbourhood and village level in order to guarantee volume (scale), velocity and safety. Africa currently recycles only 4 per cent of its waste, and more than 90 per cent is disposed of in uncontrolled dumpsites and landfills. In Asia, much of the collection is done by local associations, although in larger agglomerations publicly organized municipal waste services are in charge.

The main strategies for tackling food waste include:

- Sharing information and knowledge among stakeholders.
- Broad legislation for better packaging.
- Circular, rather than linear, solutions, for food waste reduction that rely on multi-stakeholder collaboration – especially public-private partnerships (Irani et al., 2018).

Food waste policies are strongly influenced by non-state actors in communities and households. Yet the decentralization, privatization and devolution of food waste governance to local institutions may be less effective in reducing food waste.

This chapter has focused on rescuing and reusing organic carbon and nutrients in soils, in products, in markets (including informal street markets), in distribution centres for supermarkets and in rural and urban households. The longevity of the product is determined to a great extent by packaging and storage technologies (Stathers et al., 2020). But the more packaging is used, the more materials that will not easily decompose and may burden the environment are used. Bans on plastics through legislation are increasingly common in developed and developing countries alike, and allude to growing circular systems thinking. This is, however, an environmental issue that is far from solved and in need of innovation and investment.

Can biobased foods, feed and plastics replace fossil fuel-based ones?

Recent innovations suggest that feedstocks for biobased products can be produced from renewable raw materials – biomass, waste, CO_2, and so on – rather than from fossil fuels. Such a green shift to biobased products could alleviate economic, ecological and societal problems worldwide.

A visionary path forward would be to achieve full recycling of CO_2 while using other renewable sources, such as waste and biomass. This approach could open a new chapter in the circular economy – using CO_2 from a broad range of sources and offering a variety of biobased platform chemicals and solvents. Yet full CO_2 recycling will require significant research and development, and further investments will be needed to make the technology ready to use (Venkata Mohan et al., 2016).

Knowledge is growing on how biotechnology applications can support circular food and energy systems. Offshore cultivation of seaweed in Denmark provides an innovative feedstock for biobased products (Seghetta et al., 2017). First, the anaerobic digestion of seaweed produces energy, which is converted

BOX 4.10 RENEWABLE ENERGY TECHNOLOGIES

Global energy use dropped nearly 6 per cent in 2020, primarily due to COVID-19, but this reduction and the subsequent drop in CO_2 emissions will not be enough to satisfy the Paris Agreement climate targets. In addition, 770 million people remain without access to electricity, and more than 2.6 billion people continue to rely on the traditional energy sources of solid biomass for cooking – releasing additional CO_2 and causing about 2.5 million deaths annually. Continued investment in renewable energies must accelerate the transition towards low-carbon outputs while simultaneously providing better and more sustainable livelihoods for rural people.

The potential for scaling up and implementing renewable energy technologies is greatest at the household level and provides opportunities for improved processing of agricultural products by domestic enterprises. Through the Adaptation for Smallholder Agriculture Programme, IFAD has supported the expansion of renewable energy technologies through projects in India, Kyrgyzstan, Mozambique and Rwanda through cooking stoves, biogas digesters and solar-powered pumping systems. Pay-as-you-go and energy-as-a-service models have helped people in Madagascar and Rwanda improve their quality of life and conduct business in an efficient, environmentally friendly manner.

Source: IEA, 2020; IFAD 2020.

For more information, see https://www.iea.org/articles/global-energy-review-co2-emissions-in-2020, https://www.iea.org/reports/sdg7-data-and-projections/access-to-electricity; https://www.iea.org/reports/sdg7-data-and-projections/access-to-clean-cooking; https://www.ifad.org/en/renewable-energy; and https://www.ifad.org/documents/38714170/40306309/REF_LL_web.pdf/e533399b-3f1d-4da3-82ca-16321d0bc38d.

into biogas for electricity and heat production – along with digestate, which can be used as fertilizer. Second, the seaweed produces proteins through the use of seaweed hydrolysate as a substrate for cultivating heterotrophic microalgae. Positive results include a reduction in GHG emissions and mitigation of coastal water eutrophication. But the technology also entails a risk: bringing seawater arsenic into the food cycle.

In another biotechnology development, conventional petroleum-based polymers can be replaced with algae-based biopolymers. The benefits of microalgae biopolymer over other feedstock include its autotrophic complex (reducing GHG emissions), its ability to compost (providing GHG credits) and its rapid growth and adaptability to diverse environments (Devadas et al., 2021).

Plant-based materials also play a part in transitioning to a circular economy. Bioplastics, though a growing industry, account for less than 1 per cent of all plastic production. Cellulose and starch are abundant, widely available plant polymers used extensively for paper, packaging, food service items, bags and biofuels. The growing use of plant-based materials will have environmental benefits: reducing waste, lowering GHG emissions, promoting rural investment, reducing the volume of harmful pollutants, conserving ecosystems and biodiversity, and supporting the transition to a circular economy (Shogren et al., 2019).

The promise of biobased solutions lies in:

- Replacing fossil fuel-driven production with circular systems based on biological sources, leading to vast environmental benefits and employment opportunities.
- Introducing untapped resources into the food chain, relieving pressure on existing food systems.
- Producing materials that, being biodegradable, will never be "wasted" for environmental use.

Policy priorities for circular agrifood systems

To shape circular agrifood systems and support the biobased economy outlined in this chapter, policymakers must focus on developing and promoting technologies, resource use practices and policy incentives that enable stakeholders to reduce, reuse and recycle food losses, waste and residues in order to enhance the efficiency, sustainability and diversity of food systems.

Specifically, policymakers should:

1. **Facilitate the transition from linear to circular food systems** through a basket-of-options approach.
2. **Support nutrient recycling in production and food systems with knowledge development**, innovation programmes and market-support measures.
3. **Reduce food losses based on the objective of doing so**, and on product group and value chain segment, by combining focused technical interventions with increased services for agrologistics, finance and training, bearing in mind that the evidence base is still shaky.
4. **Enable waste recovery from food and excreta in households and neighbourhoods** through a combination of awareness-raising, public or private collection services and behaviour change incentives, within the boundaries of food safety and public health.

Simulation 4 in annex 1 illustrates how halving farm gate food losses, against a business-as-usual baseline, has mixed prospects for inclusiveness, improves nutrition and has modest effects on sustainability.

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