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REVIEW ARTICLE

Challenges and opportunities for improved postharvest loss measurements in plant-based food crops

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ABSTRACT

In the last decade, the topic of food loss and waste (FLW) has acquired global attention. The Food and Agriculture Organisation (FAO) and other national and international organisations have estimated that about one-third of all the food produced and nearly half of all fruit and vegetables (F&V) are lost or wasted between harvest and consumption. Presently, abundant literature is available on the causes of postharvest losses and the technologies and practices required to manage them. However, measurements of postharvest losses of food crops are affected negatively by the use of differing definitions, scopes and ad-hoc data collection methods. Comparatively, very few studies are available on standardized measurement techniques of postharvest loss for plant-based food crops. The present review sheds light on different approaches utilized for postharvest food loss assessments and discusses existing and the opportunities available for improving food loss assessment methodologies, measurements and reporting. Detailed, standardized, high-quality information is required on the types and amount of losses at specific value chain or food supply chain points, as well as the information on the causes and sources of those losses.

Keywords: Postharvest losses, Food loss assessment, Measurement methodologies, Gaps

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INTRODUCTION

The rapid rise expected in the global population will go hand in hand with an increase in the food demand. The ability of the world to provide sufficient and safe food to a growing population is becoming vulnerable due to environmental degradation and climate changes. In the past few years, postharvest loss reduction has achieved high importance and is increasingly being quoted as a sustainable means to reduce global hunger and malnutrition and reduce carbon emissions (HLPE, 2014, Lipinski et al., 2013, Kitinoja, 2016). Since the World Bank report on “Missing Food” in Africa (World Bank, 2011) and the “Global Food Losses and Food Waste” report (FAO, 2011) estimated that one-third of all foods were being lost, many new reports have been published on this topic. The FAO sponsored desk study, conducted by the Swedish Institute for Food and Biotechnology (SIK), reported on FLW in terms of weight loss, which results in higher losses being reported for high water content foods such as vegetables than relatively dry cereals crops. The report was followed up by reanalysis of the same findings by the World Resources Institute (WRI) in 2013. Using the FAO Food Balance Sheets, WRI converted SIK’s loss and waste estimates into calories. Measured this way, global food loss and waste equates to approximately 24% of all the fo od produced indicating that

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one-quarter of the food calories produced for humans are not being consumed (Lipinski et al., 2013). In response to calls for action, several postharvest food loss and waste assessment methodologies were implemented by different organizations around the globe, however, the quality of the information available has not been adequate to systematically identify appropriate solutions for reducing losses, the adoption of cost-effective changes in the existing practices or profitable postharvest agri-business investments. The present work is an overview of the different approaches of loss assessment, along with comparisons between the major methods in current use and identification of opportunities for making improvements.

DEFINITIONS AND BOUNDARIES

Research studies have been carried out employing differing terms, scopes and definitions of postharvest losses. Among these are "post-harvest loss and waste" (PHL/W), "food loss and waste" (FLW), "postharvest loss" (PHL) and "postharvest food loss" (PHFL). A recent review entitled "Food Losses and Waste: Navigating the Inconsistencies" provides an overview of the many ways of categorizing loss and waste in terms of timing, scope, terminology, criterion, perspective and type undertaken by different agencies (Chaboud and Davrion, 2017) and argues for more consistency in future data collection efforts.

For the purposes of this review, "postharvest losses" includes losses that take place during the harvest of food crops and all the steps of the value chain to the final buyer, including on-farm handling, packing and storage, processing, distribution, transport, wholesale and retail marketing. Both postharvest loss (harvest to market, including storage) and postharvest waste (mainly occurring during distribution and marketing) are covered in the reviews, but pre-harvest losses (due to lost yield or loss of potential food) and consumer waste (at home and in food service) are not included in these reviews since they have been well covered in past reviews (FAO, 2011, HLPE, 2014, Xue et al., 2017). Including production-related harvesting losses as part of "postharvest losses" is important because it captures measurable losses of unharvested crops and the losses that can occur during the harvest itself.

The most recent evaluation of food loss assessment methodologies in 'Missing Food, Missing Data' (Xue et al., 2017) covered the entire food supply chain (FSC) grouped into three larger categories: on-farm losses (production and harvesting), postharvest losses (handling, packing, processing, transport, storage, wholesale and retail marketing) and consumer losses (home and food service). The reviews undertaken by Xue et al. (2017) examined 202 publications which reported FLW data for 84 countries and 52 individual years from 1933 to 2014, and found that while the number of publications per year is increasing, most existing publications had been conducted on food waste at the retail marketing and consumer levels, primarily for a few industrialized countries (e.g., the United Kingdom and the United States). Over half of the studies are based only on secondary data.

Many of the documents reviewed for this study used unique definitions of food losses and postharvest loss. For example, "postharvest handling" sometimes included harvesting, the FSC stages sometimes included pre-harvest activities, and the PHLs sometimes included food wasted by consumers. The definitions and boundaries of stages of the FSC that researchers have used for their studies varied widely. A few researchers have been arguing for completely new categories or definitions of food losses (Schuster and Torero, 2016; Bellemare et al., 2017).

Many studies use the categories and definitions put forth in 2011 by the FAO-sponsored review published at *InterPack*. These five categories of the FSC are production/harvest, postharvest handling/storage, processing/packaging, distribution/marketing, and consumption (FAO, 2011). Examples of alternative categories include production, post-production, processing,

distribution and consumption (used for International Food Policy Research Institute (IFPRI) studies); the categories of producer, middlemen and wholesaler (Delgado et al., 2017); categories used by World Vegetable Center (previously known Asian Vegetable Research and Development Center) studies on vegetable crops, where researchers typically measured losses for four value chain actors (farm, collector/trader, wholesale, retail); and World Food Logistics Organisation (WFLO) studies that measured at 3 or 4 FSC stages depending on the type of crop and whether or not it was stored before sale (farm, storage, wholesale, retail) (WFLO, 2010). Other studies use different definitions and alternative combinations of a farmer, trader, postharvest handling, packinghouse, transporter, storage, processing, and/or marketing.

Even within one category of an FSC stage, definitions and boundaries can vary within a single study, making comparisons between studies more difficult. An example from IFPRI surveys uses definitions that vary by crop and their FSC stage of "processing" also includes storage (Ambler et al., 2017). In fact, processing activities varied slightly by crop and were defined as follows:

- maize—removing husks, drying, shelling, cleaning, chemical application and packaging, storage related to processing;
- groundnuts—plucking, drying, shelling, cleaning, chemical application and packaging, storage related to processing;
- soy—drying, threshing, cleaning, chemical application and packaging, storage related to processing.

POSTHARVEST FOOD LOSS ASSESSMENT APPROACHES

Among the current postharvest food loss assessment methodologies in wide use, most are indirect, including ad hoc surveys, single-use data collection instruments, written questionnaires, formal or informal interviews and focus group discussions. Direct measurements are used less often and involve a wide range of different methods for making loss measurements.

(a) Indirect measurements

Indirect measurements of postharvest losses are often made using ad hoc methods. "Ad hoc" refers to the absence of a systematic approach or uniformity in scope or definitions. In this case, each researcher has developed their own data collection instruments for different target populations and has inquired about postharvest losses in terms of percentage or volume, generally reported as estimates or ranges. For example, FAO has conducted a series of rapid PHL assessments and policy briefs for different countries in Africa, Central Asia and South Asia, reporting mostly on general topics and estimated PHLs. Kitinoja and Kader (2015) presented an evaluation of methods used for the measurement of fruit and vegetable postharvest losses in developing countries, conducting literature reviews using a wide range of databases, journals and other published and unpublished sources spanning 25 years (1990-2015) and a long list of postharvest horticulture related keywords. As of 2015, only 63 documents were identified that drew on primary data to report on fruit or vegetable crop studies, and these were estimates most often based on ad hoc surveys and interview generated data rather than direct measurements of losses (Kitinoja and Kader, 2015).

A major problem with the use of ad hoc surveys and interviews is that they are developed by researchers who may or may not be experts in postharvest loss assessment and food loss reduction, and so may miss key steps of the FSC or not include known postharvest issues for the crop. Another problem is that written surveys and interviews typically require people to try to recall or remember what happened in the past, sometimes weeks, months or even a season before the collection of the information, and so are generally considered to be less accurate than making direct measurements in the field.

(b) Sampling or direct measurements

Direct measurements are usually considered to be more accurate, but are much more time-consuming and costly, and may not be highly reliable. This is because when postharvest loss measurements have been made in the field, often there is little or no information provided regarding important variables such as harvest indices (i.e. what the maturity of the crop was at the time of harvesting), how much time has passed since harvesting, the temperatures of the produce and ambient air, relative humidity in the ambient air or storage environment, or the type of packaging or containers used (Kitinoja and Kader 2015). Each of these factors predictably affects PHLs, which tend to increase over time and when the crop experiences any damage or is exposed to high temperatures. For example, the time of harvest could be hours, days or weeks before the sampling is done, but this information is generally unknown to the data collector who is measuring in a marketplace or storage facility, while both qualitative and quantitative losses continue to occur and accumulate in the period following harvest. While any measurement may be accurately made, due to the lack of context (e.g. How old was the produce at the time? What were the temperatures experienced during transport or storage?) the data may not reliably capture the full extent or causes of losses.

The complexity of how people handle and store food crops on the farm when they are intended for home consumption can make measuring postharvest losses even more difficult. For example, it is common to remove a certain portion of stored grains and dried legumes to cook and eat at regular intervals during the storage period, so measuring volume changes or weight losses in storage over time must take these withdrawals into account (Affognon et al., 2015). Another complicating factor for perishable indeterminate crops such as vegetables, tomatoes and root crops is that harvesting usually takes place more than once during the season, and in some cases several times per week during the productive life of the crop, making it very difficult to measure what is left behind in the field (as either unharvested or discarded produce).

Even when direct measurements are made, some studies report on PHL percentages, others report ranges, and still others on cumulative PHL percentages (IMechE, 2014, Kitinoja and Kader, 2015). Various PHL studies have taken each of these with different approaches to report. Lack of standardization of calculations for percentages and ranges can, therefore, lead to under-reporting or over-reporting of postharvest losses.

IMPROVEMENTS IN POSTHARVEST LOSS MEASUREMENT METHODS

In addition to the review articles mentioned in the introduction, there have been many reports and meta-analyses of postharvest loss measurement methods.

Table 1 provides a summary of key articles and published reports.

Table 1: Recent review articles and reports on methods used for measuring postharvest losses (PHLs)

S. No.	Review article/ report	Authors (date)	Key findings	Key recommendations
1.	Missing Foods (grains in SSA)	WB, NRI and FAO (2011) also referred to as World Bank (2011) and/or Zorya et al., 2011 in the literature	Past efforts to reduce PHLs have been sporadic, much of the available PHL data is from older studies. Loss figures for grains have been expressed in different ways, and rarely do these include all steps in the postharvest chain.	Need to improve reporting, including qualitative losses, economic losses and cost/benefit information for any potential PHTs proposed as solutions. Need to establish baseline PHL data and indicators.
2.	Global Food Losses and Food Waste (all	FAO (2011) also referred to as	Reported on generally high levels of FLW, based on available 2007-2009	Need to gather additional FLW data for

	foods)	Gustavsson et al., 2011 in the literature	data and a wide range of assumptions.	the regions and crops with data gaps.
3.	High-Level Panel of Experts on food loss and waste (all foods)	HLPE, 2014, also referred to as CFS, 2014 in the literature	UN CFS led the effort to gather all available resources on FLW, provide guidance for future studies. Defined FLW causes as a macro, meso and micro, often with one level affecting the next.	Need to agree on a standard definition and scope for FLW studies. Need to improve the collection, transparency and sharing of data, experiences and good practices on FLW at all stages of food chains.
4.	Phase 1 report on PHLs in SSA (grains, legumes, roots/tubers, fruits, vegetables)	AGRA (2013)	95% of reports on PHLs for 11 key crops in 11 countries did not provide data on FSC stage of losses	Need to employ methods to measure losses at each of the priority FSC stages for the crops.
5.	Food loss analysis (all foods)	FAO (2014), updated in 2015 and 2016.	Most methods in use do not provide adequate information on quantity and quality PHL levels, symptoms, causes for PHLs along an FSC.	Need for a systematic, mixed methods approach. Provides guidance on planning an assessment, interviews, observations, measurements and reporting templates.
6.	Unpacking PHLs in SSA (grains, legumes, roots/tubers, fruits, vegetables)	Affognon et al. (2015)	Many reports were unpublished (gray literature); very few used vetted methods. Most studies focused on storage losses. Few included qualitative assessments or economic data on PHLs.	Need to use more appropriate methods to measure the quantity and quality PHLs, including economic losses. Identified data gaps in 6 countries (Kenya, Tanzania, Benin, Ghana, Malawi, Mozambique). Need to improve reporting, including qualitative losses, economic losses and cost/benefit information for any potential PHTs proposed as solutions.
7.	Measuring PHLs in fruits and vegetables in developing countries (roots/tubers, fruits, vegetables)	Kitinoja and Kader (2015)	Most of the 63 studies reporting on findings based on primary data collection have used ad hoc surveys, interviews.	Need to develop standardized data collection methods and measurement practices. Identified major data gaps in several regions (Latin America, Caribbean, South Pacific). Need to improve reporting, including qualitative losses, economic losses and cost/benefit information for any potential PHTs proposed as solutions
8.	Global food loss and waste (FLW) measurement protocol (all foods)	WRI (2016a)	Global experts network to develop a systematic approach to reporting on PHLs and food waste destinations	Published a reporting standard, recommend use for keeping track of progress on FLW. Provides detailed guidance on FLW measurements but allows each study to measure using ad hoc methods.
9.	Missing Food, Missing Data (grains, legumes, roots/tubers, fruits, vegetables)	Xue et al. (2017)	More than half of FLW reports were based on secondary data, estimates, indirect measures. The majority focused on retail and consumer food waste.	Calls for "more consistent, in-depth, and primary-data-based studies, especially for emerging economies" in order "to better inform relevant policy on FLW reduction and environmental impacts mitigation".
10.	Gaps analysis: Improved methods for assessing PHLs (grains, legumes)	Kebe (2017)	UN FAO sponsored global statistics office review finds methods gaps and data quality issues	Need to better define the scope of PHL studies, use standard methods, improved data collection practices. Provides examples and case studies. The office is exploring the use of modelling to develop a "Global Food Loss Index".
11.	FLW: Navigating the	Chaboud and	Varying definitions, scopes and purposes for measuring food	Calls for more consistent definitions and measurements, for including any

	inconsistencies	Daviron (2017)	loss/waste lead to inconsistent results	non-food uses of discarded or 'lost" food, taking value chain interactions into account (e.g. how one actor's efforts to reduce losses can cause more losses for the next actor in the chain).

As table 1 shows, there have been many calls for the use of improved data collection methods in recent years Some of these call for more comprehensive coverage and further expansion of the scope of postharvest loss assessment studies. Recent reviews have evidenced the limitations in data collected to date. Alliance for a Green Revolution in Africa (AGRA) reviewed PHL literature for 11 crops in 11 countries of SSA and found missing or limited data for most crops (AGRA 2013). For the data that was available for review, only 5% of the studies identified PHLs at different stages along a value chain or food supply chain (AGRA, 2013). Affognon et al. (2015) reviewed hundreds of PHL reports generated in six African countries, systematically screened the reports based on a set of criteria developed to identify unreliable studies or secondary data and found that most of the studies had to be eliminated because they provided unreliable data. Both of these major reviews found that most of the published and unpublished reports had focused on assessments of PHLs during storage of staple crops. Affognon et al. (2015) found most of the available historical data was focused on storage weight losses for maize and recommended expanding future PHL studies to include more crops, the entire value chain, and using more appropriate methods to measure the quantity and quality PHLs, including economic losses.

Since then, Mvumi et al. (2017) has expressed a need to have a standard methodology of loss measurements, with standardization of the use of measuring tools within the same methodology, Xue et al. (2017) called for the use of improved methods to fill in missing PHL data, and the UN statistics division convened a meeting on the topic and published a working paper focused on improving grain loss assessment methods gaps (Kebe, 2017).

There is no shortage of information on recommended "best practices" for measuring food losses, some of which date back to the 1970s and 1980s. Table 2 provides a summary list of resource documents and key references.

Table 2: Summary of sources for best practices and recommendations for improved PHL measurements

S. No.	Document	Focus crops	Citation
1.	Measurements of postharvest loss	Grains	Harris and Lindblad, 1976
2.	Tropical Products Institute loss assessment methods	Grains	Boxall et al., 1986
3.	Commodity Systems Assessment	Horticultural crops	La Gra, 1990
4.	Losses due to pests	Maize	Compton and Sherington, 1999
5.	Value chain analysis	All crops	UNIDO, 2009; UNIDO, 2016
6.	PHL economic analysis	Maize	Basappa et al., 2005
7.	Measuring food grain losses	Grains	Gupta et al., 1999
8.	PHL estimations	Staples and perishables	Aulakh and Regmi, 2013
9.	APHLIS loss manual revised	Grains and legumes	Hodges, 2013

10.	FUSIONS food waste reporting methodology and practice	All foods	FUSIONS, 2014
11.	WRI guidance on quantification methods for measuring FLW	All foods	WRI, 2016b
12.	Global Office Data gaps report	Grains and legumes	Kebe, 2017

RECENT EXAMPLES OF IMPROVED PHL MEASUREMENTS AND METHODOLOGIES

With each passing year from 2006 through 2017, as a larger number of PHL studies were being carried out, and as researchers began implementing recommendations on methods, several improved methodologies emerged. Early cases of improved methodologies were published by the Inter-American Institute for Cooperation on Agriculture (IICA) on Commodity Systems Assessment, and the Food and Agriculture Organization of the United Nations (FAO) based on early fish loss studies using a combination of methods. All the improved methodologies use combined or mixed methods (ad hoc and sampling) and attempt to standardize data collection (by providing questionnaires, checklists and/or worksheets) and reporting (by providing blank tables, figures and worksheets).

(i) Commodity Systems Assessment Methodology (CSAM)

CSAM was developed by LaGra (1990) working with the Postharvest Institute for Perishables and the Inter-American Institute for Cooperation on Agriculture (IICA). A modified CSAM (LaGra et al., 2016) based on improvements over 20 years of fieldwork, mainly conducted during field studies implemented by WFLO and The Postharvest Education Foundation (PEF), shortens the time required for planning and implementing a PHL study by using a simplified list of standardized summary questions and observational checklists. CSAM measures losses in the field (on 10 farms at harvest time, for 10 storage sites, 10 wholesale market vendors and 10 retailers) with 3 replications of measurements for each site) and provides a standard outline for reporting. CSAM results in a description of 26 components encompassing the entire FSC for the crop, identification of the causes and sources of postharvest losses, measurements of % discards and quality characteristics at key points along the FSC, and identification of research needs, extension/training needs and advocacy issues. The CSAM manual is available via IICA (http://repiica.iica.int/docs/B4232i/B4232i.pdf)

The weakness of this methodology is the fact that it draws its findings and conclusions from a relatively small number of sites where samples are collected. The rapid assessment and small sample size does not allow for fully assessing a wide variation of site locations or seasonal differences. For example, a CSAM study might focus only on small farms (rather than including a range of farm sizes) or on one key wholesale market. However, depending on the availability of resources, additional sites could be added to address this issue.

(ii) FAO field case studies for food loss analysis

A new methodology being developed, and field tested by the SAVE FOOD Initiative (FAO, 2016) uses mixed methods referred to as screening, survey, load tracking and synthesis/solution finding, concluding with a draft report and a validation workshop. Early studies in Kenya on maize and bananas in 2013-14 followed the generalized PHL assessment process but did not capture the full methodology (FAO, 2014). Since then, FAO has provided workshops for training local field teams in Uganda, the West Indies, Burkina Faso, DR Congo, Lebanon and more, on applying the methodology and load tracking, cost/benefit analysis, reporting and policy development. The latest Food Loss Analysis (FLA) reports are on rice, chickpeas and mangoes

in India (FAO, 2017a, b and c) and FAO is planning to publish a total of more than 80 studies based upon the methodology manual (http://www.fao.org/3/a-az568e.pdf). In 2018 a free e-course in English and French focused on cereals and pulses, was launched for those who wish to learn to use the methodology (future e-courses will focus on fruits/vegetables and roots/tuber crops). http://www.fao.org/food-loss-reduction/resources/flaelearning/en/

The weaknesses of this methodology include 1) the extensive time required to conduct, analyse, validate and publish the results of the assessments (typically 1 to 2 years), 2) its complex nature, 3) its reliance on users developing their own ad hoc surveys and measurement protocols and 4) its focus on only a few specific critical loss points, leaving out other sites along the FSC where losses may be occurring.

(iii) Potential food loss and waste (PFLW)

IFPRI has developed a new methodology for quantifying "Potential food loss and waste" (PFLW), which incorporates measures of potential production or lost yield. Potential production is sometimes based on so-called productivity or yield improvement. Lost yield is already well covered since most agricultural research focuses heavily on production issues, where pre-harvest losses can be due to weather events, pest attacks, lack of irrigation, poor fertilization, etc. IFPRI is providing training workshops and webinars, and there is a plan in the works to develop a mobile platform for entering data for immediate analysis and sharing. Schuster and Torero (2016) used the FSC categories production, post-production, processing, distribution and consumption in their publication on this method. In their model, "production" includes harvesting, but the word "postharvest" is not mentioned in any of the definitions.

Ambler et al. (2017) employed IFPRI's methodology in their PFLW study in Malawi, using existing data collected at the national level during 2011-14 plus local survey questionnaires in 2015 to inquire about farm-level food losses (both discarded food and food that is used for secondary purposes). The researchers created their own new FSC categories by asking farmers "to self-report whether losses occurred during three particular activities between harvest and sale into the value chain: harvest and transport from the field to home, processing, and post-processing storage." The most recent publication based on this PFLW method does not include measures of lost yield or food waste but focuses only on producers, middlemen and wholesalers (Delgado et al., 2017).

The weaknesses of this methodology include 1) the short time since its inception, with protocols still being worked out in the field, 2) use of ad hoc measurement protocols and 3) allowing each research team to select its own boundaries and definitions of the stages of the food supply chain.

(iv) Value Chain Analysis (VCA)

Value chain assessments have been used since the early 2000s as part of agricultural projects and programs. A manual by FAO (2013b) provides policymakers with methodological guidelines for VCAs. UNIDO has published a VCA practice manual with clearly described steps and activities (https://www.unido.org/fileadmin/user_media/Publications/Pub_free/Agro_value_chain_analysis_and_development.pdf).

Many USAID project reports have used VCAs to develop baseline surveys data, including surveys on tomatoes in Bangladesh (USAID 2014) and in Cambodia (Kula et al., 2015). A recent VCA study in Zanzibar focused on small fruit and vegetable farmers and their experiences with marketing (VSO ICS, 2015). International Fund for Agricultural Development (IFAD)

employs a value chain approach for most of its postharvest and market-oriented projects, including recent projects in Rwanda, Tanzania and East Timor. An updated United Nations Industrial Development Organization value chain analysis manual is available for use by those interested in learning more about this methodology (UNIDO, 2016). The weaknesses of this methodology include 1) its ad hoc approach to interviews, data observation and analysis, and 2) the lack of quantitative measurements.

(v) Life Cycle Assessment (LCA)

Life cycle assessment is a standardized procedure used to determine the environmental impacts of products, services or goods. The standardized procedure can be described by a four-part framework as outlined by the 14044 ISO standard, which includes: 1) Goal and scope definition, 2) Life cycle inventory, 3) Life cycle impact assessment and 4) Interpretation. Examining a product from origination of materials, to use and disposal provides a more holistic analysis of systems that can identify where environmental impacts originate and guide efforts in reducing these impacts (Daystar, 2017). Examples of LCA studies include tomatoes in Rwanda (Daystar, 2017) and Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) studies on maize and cassava (GIZ, 2013) and rice (GIZ, 2014) in Nigeria. GIZ reports are available online via https://www.giz.de/fachexpertise/downloads/giz2014-en-post-harvest-losses-of-rice-in-nigeria-and-their-ecological-footprint.pdf

The World Resources Institute (WRI) provides greenhouse gas (GHG) calculation guidance (https://ghgprotocol.org/calculation-tools). The Farm Carbon Calculator, developed in the U.K. by the organization Climate Friendly Food, is available for free download, via a simple interface http://www.cffcarboncalculator.org.uk/. The weakness of the LCA methodology is its dependence on accurate and reliable data collected using one of the other food loss assessment methods.

(vi) Food Wastage Footprint

The environmental footprint of food wastage is assessed through four different model components - carbon footprint, water footprint, land occupation/degradation impact and potential biodiversity impact – complemented by an economic quantification component (FAO 2013a and 2015), based on UN food balance sheets and LCA data. An example of an early attempt at calculating food loss/waste effects on natural resources can be found in Kummu et al. (2012) and the FAO (2013a) report: http://www.fao.org/docrep/018/i3347e/i3347e.pdf

The major weaknesses of this model are its reliance on data collected using ad hoc methods and difficult to quantify parameters.

(vii) Global Food Loss and Waste Protocol (FLW Protocol)

The FLW Protocol was developed as a global standard for reporting on the amounts and destinations for food losses and waste. The World Resources Institute (WRI) FLW reporting protocol (WRI, 2016a) contains an appendix on data collection methods but allows each user to select their own data collection methods and develop their own protocols, with examples provided in a lengthy appendix (http://flwprotocol.org/flw-standard/tools-resources/). The reporting protocol itself is focused mainly on the destination of quantitative losses (the reported weight of discarded foods) and does not capture qualitative or economic losses due to weight loss if food is eaten or sold. While it is intended to simply serve as a reporting protocol, the

weaknesses of this method are that 1) it allows the use of ad hoc measurement methods, and 2) includes only quantitative data.

(viii) Re-evaluation methods, modelling and data mining

Affognon et al (2015) reanalyzed PHL and PHT studies to identify those with adequate or good quality methods, and those that reported on PHLs as well as economic losses related to PHLs, along with cost/benefit information for postharvest technologies. Van Dijk et al. (2016) published a Smart Adaptive Sustainable Horticulture (SMART) report which used previously published data and added field observations to verify and update reported findings. The SMART study revaluated WFLO (2010) PHL data on tomatoes in Rwanda and conducted updated economic analyses, including 4A adoption analysis (e.g. awareness, advantage, affordable, accessible). Shastri et al. (2015) are developing a model for minimizing total cost and postharvest losses for wheat in India, which includes decision variables from the farm to storage to market. Data mining is a relatively new but promising method in the postharvest field of study (Yethiraj, 2012), in which existing databases are examined for data that can explain relationships (e.g. temperature and deterioration rate for perishables) and predict outcomes (e.g. quality changes and shelf life). The major weakness of these methods is their reliance on existing data, which may have been collected using ad hoc or non-systematic methodologies.

(ix) Mixed methods

Use of mixed methodologies can help data collectors avoid many of the weaknesses of commonly used PHL assessment methods. Nanda et al. (2012) measured PHLs in India for 47 crops, using a combination of farmer and key informant surveys, observations and crop sampling during one full season. Their report for the Indian Council of Agricultural Research (ICAR) used a pooling method to calculate average losses (% and standard deviation (SD)) at the farm level, storage level and overall national level PHLs for each crop. Nanda et al. (2012) used a time-consuming, a costly set of mixed methodologies. CSAM and the FAO field case studies methodologies both use a combination of many different data collection methods, intended to gather both quantitative and qualitative data on losses. The GIZ rapid appraisal tool was the chosen methodology for potato value chains in Kenya, based on a five-step approach following that of the FAO field case studies: 1. Screening of food losses including rapid appraisal. 2. Survey on food loss assessment. 3. Load-tracking assessment. 4. Data analysis, verification workshop and reporting. 5. Synthesis: recommendations and solution finding. Recent studies in Rwanda have used mixed methods in a hybrid rapid assessment, adding CSAM and LCA to VCA, in order to better measure PHLs along the value chain and calculate the economic costs and environmental impacts for tomatoes and green chillies (Christie et al 2017). The Market Infrastructure, Value Addition and Rural Finance (MIVARF) project in Tanzania used a combined VCA and CSAM for their PHL studies in 9 districts (personal communication, 2017), upon which they selected sites and focus crops for designing value addition training centres.

Both the CSAM and FAO field case studies methodologies begin with literature reviews to provide background information on the crop but begin food loss measurements at the time of harvest. FAO field case studies can be very complex and require a lot of time and resources, often including travel expenses for returning to the same site several times. Both the CSAM and FAO field case studies methodologies include key informant interviews (KII), observational checklists and measurements of quantity and quality losses at various points along the food supply chain. The updated CSAM manual provides standardized worksheets for collecting loss and quality data on the farm at harvest, during packing/collection, storage, wholesale and retail, with a slightly different set of worksheets provided for each type of crop. FAO's methodology begins with identifying the FSC,

and the critical loss points (CLPs) for an FSC, after which the field team determines how they want to measure PHL at these points. The field case studies methodology also uses "load tracking", which measures weight and/or quality for the same load at two different times and holds validation workshops in the community to vet PHL findings and the feasibility of any potential solutions.

A brief comparison of improved methods is provided in table 3. For each major methodology, its characteristics, and FCS or VCA steps are described. Additionally, examples of PHL reports with all the methodological details are provided for each.

Table 3: Comparison of PHL assessment methods and measurements

Methodology	Characteristics	FSC or VC stages assessed	Examples
Surveys and questionnaires	Questionnaires designed to inquire into PHL quantity, quality, market value losses	Ad hoc, each survey, questionnaire or interview schedule is different	Maize / Uganda, Tanzania, Malawi (Kaminski and Christiaensen, 2014); Plums/ Pakistan (Shahzad et al., 2013); Tomato/ Pakistan (Rehman et al., 2007)
FAO Field case studies	Mixed methods: screening literature, interviews, observational checklists, load tracking, sampling to measure quantity and quality losses. Validation workshops	Harvest to market, Critical Loss Points and Low Loss Points, specifics vary with each assessment	Mangoes/ India (FAO, 2017b) Rice / India (FAO, 2017c) Maize, bananas / Kenya (FAO, 2014)
IFPRI Potential Food Losses and Waste studies	Mixed methods: existing national database (household surveys), ad hoc survey of farmers asks to self-report their estimates of PHLs, quantity and quality for the past season.	Three activities between harvest and sale into the value chain: 1) harvest and transport from the field to home, 2) processing and 3) postprocessing storage.	Maize, soybeans, groundnuts / Malawi (Ambler et al., 2017)
		Focuses on producers, middlemen and wholesalers (compares self-reported estimates with 3 other PHL assessment methods) and finds all 4 methods provide similar results	Potatoes (Ecuador and Peru); Maize (Guatemala and Honduras); Beans (Guatemala); *Teff* (Ethiopia) (Delgado et al., 2017)
IICA/PEF Commodity Systems Assessment	Mixed methods: literature review, interviews, observations, standardized questions list and standardized measurements of quantity and quality losses at 10 sites per FSC stage	Rapid assessment of 26 components of the commodity system from farm to markets, standardized questions and measurements at 3 to 5 FSC stages: a farm at harvest, packing (if any), storage (if any), wholesale market and retail market (3 reps per site). A full set of data is 90 or more measurements per variable.	Tomatoes / Rwanda (Chahine-Tsouvalakis et al., 2017) Cooking bananas / Rwanda (Rwubatse and Kitinoja, 2017)
Value Chain Analysis	Mixed methods: surveys, interviews, measurements (staples, root/tuber crops)	Value chain from farm to market, grouped as 4 categories: Farm, Trader/Transport, Processing, Retail/Consumption	Cassava in Ghana, Nigeria, Thailand and Vietnam (Naziri et al., 2014)
	Mixed methods: surveys and measurements of quality (perishables)	Value chain actors: Farmer, Collector, Wholesale, Retail	Tomatoes/Ethiopia (Emana et al., 2017) Tomatoes/Bangladesh (USAID, 2014)

Life Cycle Assessment	Standardized methods, usually based on an existing survey or PHL study, measures GHG, water use, energy use associated with production (and in some cases food losses)	Depends on the survey or study used as the basis for the LCA, uses 1 MT of produce as a functional unit for calculations	Tomatoes and Green chilli peppers/Rwanda (Daystar, 2017) Rice/Nigeria (GIZ, 2014)
WRI Food Loss and Waste Protocol	Reporting protocol for food loss or waste, the destination of losses	Can be used for any FSC stage or for the entire FSC, can be used for local or national level reporting, single crops or mixed foods varies widely by case	Case studies on dairy (Pakistan) and retail (USA). http://flwprotocol.org/case-studies/

SOME PUBLISHED WORKS ON PHL MEASUREMENT AND ASSESSMENT METHODS

Several publications can be found that describe some of the methods proposed for measuring PHL and assessing food losses.

i. WRI - annexe on quantifying food loss and waste. This annexe includes a long list of data collection methods that can be used to measure quantitative losses. This publication can be found at http://flwprotocol.org/wp-content/uploads/2016/05/FLW_Protocol_Guidance_on_FLW_Quantification_Methods.pdf

ii. AfricaRice protocol. This protocol is used for measuring physical grain loss (PGL) and grain quality loss (GQL) from harvest to storage. The Africa Rice Center has been working with its partner National Agricultural Research Institutes (NARIS) within the Africa-wide Processing and Value-Addition Task Force (APVATF) in 11 countries, including Benin, Cameroon, Ghana, The Gambia, Mali, Nigeria, Senegal, Cote d'Ivoire and Uganda (Ndindeng et al., 2015).

iii. ADM Institute for Prevention of Postharvest Loss - Postharvest Investment Tool. This macro-enabled worksheet is a practice-based tool that produces estimates of the value of postharvest loss based on known practices and expected loss percentages at supply chain stages. The tool provides baseline information on the extent of loss in terms of both quantity and quality. It also analyses the influence of a change in practices on the extent of loss and the associated value. The analysis can be conducted for a single practice or at a regional scale, which considers all practices at each supply chain stage (http://postharvest.org/ADMI_PostharvestInvestmentTool_Intro.pdf).

iv. UNIDO – The "Agro-Value Chain Analysis and Development" manual (UNIDO, 2009) and Value Chain Analyses (UNIDO, 2016) provides recommendations for selecting and prioritizing a value chain for study, mapping the value chain, analyzing technical capabilities, economic performance and external competitiveness.

v. World Food Programme (WFP) - grain loss manual (Hodges and Stathers, 2012). A comprehensive, step-by-step manual for the postharvest handling, drying, packaging and warehousing of grains, including the assessment of quantitative and qualitative losses.

vi. UN Global Office working paper entitled "Gaps analysis and improved methods for assessing post-harvest losses" (Kebe, 2017) provide recommendations, plus annexes with case studies as examples. The first case study was done for Ghana, and the second was for Malawi.

vii. APHLIS – the African Post-Harvest Loss Information System (APHLIS) was developed as part of the European Commission's Joint Research Centre research programme by the Natural Resources Institute (UK) and the German Ministry of Food (BLE). To make loss estimations, APHLIS needs three types of data. These are: 1) cereal production by province, by season and where possible by smallholder or larger-scale producer - these can usually be obtained on request from Ministries of Agriculture, 2) losses that occur at each link in the postharvest chain - obtained by resource-demanding field survey work (this is why APHLIS has to rely mostly on loss data from the scientific

literature), and 3) factors that affect the severity of losses, between seasons and between years - obtained by field survey interviews or interviews with experienced extension workers. Those who wish to participate in APHLIS data collection should refer to the APHLIS loss assessment manual http://www.aphlis.net/downloads/APHLIS%20Losses%20Manual%2013%20Dec%2013%20revised.pdf

viii. Hodges for APHLIS: measuring qualitative losses in grains (Hodges, 2012a) and measuring quantitative losses in grains (Hodges, 2012b). APHLIS has also published a "grain losses interview form" to standardize data collection for PHL studies. APHLIS depends upon published data on PHLs to populate their model and predict current losses for grains and legume crops.

ix. APHLIS is currently being updated and expanded under the APHLIS+ project via a grant from the Bill and Melinda Gates Foundation. The APHLIS+ project will run from 2015 – 2020. Without good quality PHL data, APHLIS must continue to use older data and may be unable to include all crops or locations in their modelling. APHLIS+ is adding more crops (roots/tubers and bananas) and will need access to more quality information and new studies on these crops in order to provide reliable PHL data for Sub-Saharan Africa (SSA). The APHLIS+ team is currently working on developing enhanced data collection protocols for the new crops.

x. The WRI (2016a) FLW reporting protocol is focused mainly on the destination of quantitative losses (the reported weight of discarded foods) and does not capture qualitative losses or economic losses due to weight loss if food is eaten or sold. The WRI guidance document is a very detailed manual (WRI, 2016b) that is free to access via http://flwprotocol.org/flw-standard/tools-resources/

CONCLUSIONS AND RECOMMENDATIONS

This review has identified food loss studies which use different definitions of PHLs, different categories for FSC stages, different types of measurements (quantitative or qualitative) and different reporting formats. Some studies have used mixed methods and provide practical examples of reporting on key quantitative PHLs (Kamrul Hassan et al., 2010, FAO, 2017a) and qualitative PHLs (Emana et al., 2017). The number and definitions for FSC stages or VC actors vary from study to study, making it very difficult to compare the results of the estimates or measurements. Often there were only a few stages presented (i.e. farmer, trader, a retailer for perishables; or farm, storage, a processor for grains/legumes). Ad hoc methods for PHL assessment can result in variable quality data, depending on the level of expertise of the researchers who develop the surveys.

Established PHL assessment methods can provide high or low-quality data as well, depending on their application. When methods are very complex or time-consuming, people tend to cut corners and skip steps. If methods are too simple (for example, asking a farmer to estimate the quantity or value of postharvest losses at different FSC stages for the last season), a lot of data can be collected in a short time, but the quality of the data will be suspect. What farmer can estimate or remember the quantity of lost grain at harvest or during threshing? What producer can accurately tell us the percentage or market value of these losses? What storage operator can tell us the volume or value of produce lost during 3 months of storage? Who can recall why they experienced these losses? These are questions that require observations during the harvest, threshing, and/or storage period when it is possible to make direct measurements.

A summary of the challenges related to direct measurements includes:

- Use of standardized data collection protocols

- Time between harvest and measurement
- Repeated or multiple harvests in indeterminate crops
- Food storage and consumption patterns
- Little to no information on underpinning variables, particularly in the field

The FAO field case study methodology provides an important foundation for standardizing the PHL assessment process, with a series of training manuals under development, along with a set of e-courses focused on different types of food crops. FAO has been training field teams via workshops in Uganda, Burkina Faso, the Democratic Republic of Congo, Trinidad and Tobago, Ethiopia and Rwanda, and has recently provided financial support via various donors for multiple field case studies. The FAO methodology is still under development, and each successive study and report has improved the data collection methods and further standardized the reporting. However, the process requires extensive time and data is concentrated on critical loss points (CLPs) rather than measuring postharvest losses along the entire FSC. Understanding what is happening and why at these critical loss points is key to identifying appropriate solutions but measuring PHLs only at specific points in the food supply chain does not allow the researcher to calculate a cumulative PHL level for the FSC.

Hybrid or combined methods were recently used to measure PHLs in a USAID Horticulture Innovation Lab funded project in Rwanda (Gill, 2017). A combined methodology of CSAM, VCA and LCA was used to characterize the levels, causes and sources of PHLs in key crops at various FSC stages, for various value chain actors, and their economic and environmental impacts were calculated. To further develop this hybrid methodology, similar PHL studies have been conducted during 2017 for maize and tomatoes in India, Rwanda and Nigeria as part of a World Bank Group funded pilot project.

Reporting standards are just as important as measurement standards. The researcher's data analyses methods and choices regarding how to report data can lead to confusion. For example, someone estimating 10% losses during harvest and another person in the FSC providing data indicating 10% losses during marketing can sometimes be reported by the researcher as an average of 10% losses for the crop, but in a different PHL study may be reported as 20% losses (the sum of the two measurements made for the crop) and occasionally will be reported as a cumulative amount (10% plus 10% of the remaining 90% = 19% losses). Some studies report on PHL percentages or ranges, others on cumulative PHL percentages (IMechE, 2014). Various PHL studies have taken each of these different approaches to reporting. Lack of standardization of calculations for percentages and ranges can, therefore, lead to under-reporting or over-reporting of postharvest losses.

Measuring and reporting on total PHLs for food crops via ad hoc methods do not provide the kind of information that can be used to generate action plans to reduce losses. Rather detailed, standardized, high-quality information is required on both the types and amount of losses at specific value chain or FSC points, as is information on the causes and sources of those losses. Best practices for measuring postharvest losses include using standard methods for gathering information via survey, taking samples at specific FSC points, measuring PHLs (variables will be crop dependent) and reporting on findings. Most PHL studies have focused on only one or two stages of the postharvest chain, for example on the farm, or in storage, or during marketing. Very few PHL studies have followed a specific load of the crop from harvest and along the FSC chain, measuring losses at each point over time, so it can be very difficult to meaningfully sum PHLs for the entire FSC. Systematically providing information on the number of interviews or samples taken to calculate PHLs for each FSC stage or value chain actor and systematically reporting on a wider range of parameters (quantity losses, quality losses, market value changes, nutritional losses, food safety issues) will allow the identification of appropriate solutions that can lead to the adoption of cost-effective postharvest practice changes, technology options for reducing food losses and profitable postharvest agri-business investments.

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