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A critical review of on-farm food loss and waste: future research and policy recommendations

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Abstract

On-farm food loss and waste is estimated to be 16% of the total agricultural-related greenhouse gas emissions globally, and reductions in these emissions have the potential to make a significant impact on climate change. There is a plethora of research being undertaken in this area across countries, food supply chains and stakeholders. However, differences in definitions, quantification methods, understanding of drivers and proposed solutions can be difficult to navigate. This narrative review provides a critical overview of the current research landscape of on-farm food loss and waste. The review has two objectives. Firstly, it provides a stock-take of on-farm food loss and waste definitions, quantification methods, causes and management options. Secondly, it provides researchers, policy makers and industry stakeholders with recommendations on opportunities to be pursued.

Background

In 2011, the Food and Agriculture Organisation (FAO) of the United Nations (UN) provided one of the first global estimates of the amount of food that is lost or wasted along the food supply chain, estimating that one-third (∼1.3 billion ton per year) of food intended for human consumption was lost or wasted (Gustavsson *et al.*, 2011). A 2021 report by World Wildlife Fund-United Kingdom (2021) had a higher estimate of 40% (∼2.5 billion tonnes) while the UN food waste index report stated that food waste was twice the amount than previously thought (United Nations Environment Programme, 2021). The contribution of food loss and waste (FLW) emissions to climate change has led to prioritizing the prevention and encouraging the reuse and recycling of food waste. The United Nation's Sustainable Development Goal 12.3 calls for all nations to halve food waste and reduce food loss by 2030 (United Nations Environment Programme, 2021; United Nations, 2022).

The food supply chain consists of several stages. For simplicity, it begins on farm at the production end, and includes processing, transport, retail/food service, and finishes at the consumer end (Mena and Stevens, 2010; World Resources Institute, 2019). More research has been undertaken to estimate the quantity of retail and consumer waste than for the earlier stages of the supply chain (Schanes *et al.*, 2018; Food and Agriculture Organisation, 2020; United Nations Environment Programme, 2021). This prioritization has been justified as these later stages are believed to be significant contributors to total food waste for North America and Oceania (61% of total food waste); Industrialized Asia (46%); Europe (52%); and North Africa, West and Central Asia (34%) (World Resources Institute, 2019). However, the on-farm/production stage has been identified as the second biggest contributor (World Resources Institute, 2019). World Wildlife Fund-United Kingdom (2021) estimated that 15.3% (1.2 billion tons) of food produced was wasted on farms each year. To date, much of the on-farm research has focused on developing definitions of FLW (Spang *et al.*, 2019; Teigiserova *et al.*, 2020), quantification methods (Hanson *et al.*, 2016; Beausang *et al.*, 2017; Kitinoja *et al.*, 2018; McCosker, 2020; Thorsen *et al.*, 2021) and social science theories around why on-farm wastes might occur (Gille, 2012, 2007; Arancon *et al.*, 2017; Kumar Mangla *et al.*, 2021).

As on-farm FLW research is becoming more important globally for researchers, businesses and policy makers, it is a crucial time to provide a comprehensive assessment of our current understanding. This narrative literature review has utilized a mix of published and grey literature to inform the scholarly discourse of FLW on-farm including pastoral farming, livestock farming and horticultural crops. We provide an overview and critical interpretation of the most important aspects of on-farm FLW research that include associated definitions, quantification methods, drivers of on-farm FLW, common management options for farmers and recommendations for researchers, policy makers and industry stakeholders.

Methods

A narrative review rather than a systematic review was employed because it was deemed more suitable for providing readers a broad assessment of our topic of interest (FLW on-farm); a systematic review is better suited to answer specific research questions and requires highly defined inclusion and exclusion criteria. This decision was further justified given that very few papers have been published on this topic and systematic reviews are best suited for reviewing large numbers of papers. In this narrative literature review, searches were conducted in English through databases such as Scopus and Google Scholar using keywords including 'Food loss', 'Food Waste', FLW, 'Post harvest loss', 'On-farm', 'farm', 'farmer', 'food producer' and 'primary production'. Papers were excluded if their focus was on later stages of the food supply chain (e.g., processor, retailer, food service, consumer), were focused solely on aquaculture or marine foods or focused on drivers and management options that are irrelevant or not accessed by farmers. An effort was made to include papers from a range of countries, food types and studies; however, this was limited to those papers available in English. Grey literature was identified through customized Google search engines and targeted websites. Industry reports, information booklets, news articles and websites were included for their intended audience and objectives, relevance to the topics identified in the white literature, and the relevance of the industry/government body affiliation to the topic. A pragmatic approach to deriving the areas of literature reported in this paper (i.e., the themes) combined both inductive and deductive approaches. This approach involved identifying recurring patterns in the farm-level studies under examination and generating themes from the data, as well as considering what themes had been already reported in the wider FLW literature available in other sectors.

Food loss and waste definitions

There are varied interpretations of what constitutes food waste or food loss (Spang *et al*., 2019), including 'food loss', 'food waste', 'FLW' (food loss and waste), 'surplus food', 'side flow' and 'unmet production potential' (Food and Agriculture Organisation, 2014; Östergren, 2014; Hartikainen *et al*., 2018; Teigiserova *et al*., 2020; Oliveira *et al*., 2021; United Nations Environment Programme, 2021). The use of these terms depends on the stage of the food supply chain that food exits. There is some consensus that 'food loss' refers to loss occurring earlier in the food supply chain during the production, post-harvest and processing of foods (Reynolds *et al*., 2020; Cicculllo *et al*., 2021), whereas 'food waste' refers to food prepared for human consumption that exits the food supply chain during the retail and consumption stages (Food and Agriculture Organisation, 2014; Ciccullo *et al*., 2021; United Nations Environment Programme, 2021). Given that currently there is no one accepted definition, researchers should consider three important points when understanding and using these different terms in FLW work.

Firstly, differentiating between 'food loss' and 'food waste' can change interpretation of policies and may impact upon which research is funded and which solutions are implemented (Teigiserova *et al*., 2020). For example, the UN's Sustainable Development Goal 12.3 includes a goal to reduce food waste by 50%, but there is no stated goal for food loss, which suggests that only 'food waste' be prioritized (United Nations, 2022). Separating 'food loss' from 'food waste' implies that the factors causing 'food loss' are external (e.g., climate), or even accidental factors (World Wildlife Fund-United Kingdom, 2021). Therefore, using the term 'food loss' could lead to the assumption that food exiting the food system on-farm can be remedied through technological innovation rather than through social intervention, whereas addressing the human factors and creating solutions through reorganization of systems leading to food loss are ignored (Gille, 2012). Some literature also differentiates 'food surplus' from 'food waste' (Papargyropoulou *et al*., 2014; World Wildlife Fund-United Kingdom, 2021), with arguments that 'food surplus' is that portion of food that is produced but not required to meet daily nutritional needs, that then turns into 'food waste' when it becomes inedible (Papargyropoulou *et al*., 2014). By differentiating in this way, 'food surplus' associates itself with entrenched practices in food systems that support waste to occur. For example, in the United States, it is common for farmers to grow surplus crops in order to mitigate the risk of being unable to fulfil contract quotas known as 'walk-by fields' which remain unharvested (Baker *et al*., 2019). The drivers that lead to this type of waste are therefore different and cannot be easily addressed through improving efficiencies of farming practice alone.

Secondly, some definitions of food waste including those of the Food and Agriculture Organisation (2014), ReFED (2016), United Nations Environment Programme (2021) and World Wildlife Fund-United Kingdom (2021) involve food produced for human consumption. However, these definitions do not include waste associated with food crops that are grown for other purposes such as livestock feed or biofuel (e.g., maize, wheat, barley, soybean) (McBride, 2021). It is also not clear if these conditions would also include crops or animals initially grown for the purposes of human consumption, that have their intended destination changed prior to harvest/slaughter, which can occur due to market price changes, assessments of quality pre-harvest leading to downgrading to other purposes and animal mortality (Ferrazzi *et al*., 2019). Also, the intended market of the food produced can influence whether a component of food is considered a by-product. For example, cow pelts which are considered a meat by-product by many western cultures and usually turned into leather are considered food in some countries including Nigeria, the Caribbean and West Africa (Funke Koleosho, 2015; Yusuf *et al*., 2016).

Thirdly, these definitions do not adequately capture the opportunities for waste prevention on farms. Within farm boundaries, what constitutes food waste is challenging to apply as food shifts categories from 'inedible' to 'edible' owing to factors such as crop maturity or becoming overripe (McCosker, 2020; World Wildlife Fund-United Kingdom, 2021). Unlike many species of plants, animals are theoretically 'harvestable' at any stage in their maturation, with the point of slaughter usually carried out when it is most economical, based on farming practices and market forces (Hartikainen *et al*., 2018; Teigiserova *et al*., 2020). Also, on-farm livestock mortality is largely excluded as FLW because animals that die and are not processed into food products are known as 'pre-harvest/slaughter' and are not recorded (Tostivint *et al*., 2017; Verghese and Lockrey, 2019; World Wildlife Fund-United Kingdom, 2021; O'Connor *et al*., 2022*b*). To avoid confusion and capture the full field of interpretation discussed, this paper

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will continue to use FLW to encompass food and their associated by-products across the food supply chain.

Quantification methods

Food loss and waste accounting and reporting standard

As FLW definitions are variable, there is a need to standardize the quantification methods and enable comparisons of quantities across businesses, industries and countries. The most used methodology is the Global Food Loss and Waste Accounting and Reporting Standard (FLW standard). It was coordinated by the World Resources Institute and developed in a collaborative effort to provide a practical framework for measuring FLW. The FLW standard document (Hanson *et al.*, 2016) also provides easy to follow inclusions and exclusions, for example preharvest/slaughter material is excluded, while food and drink and inedible components of food (e.g., banana peels) are included. The FLW standard implements a framework on the four appropriate data types that are required: timeframe, material type, destination and boundary. To enable comparability across different studies, the standard requires quantities to be reported in weight units (e.g., kilograms, ton, etc.), but suggests that researchers can also express FLW quantities through environmental (e.g., energy use, water use, land use and greenhouse gas emissions), nutritional (e.g., calories, protein, fats) and financial units (Hanson *et al.*, 2016). The FLW standard has become an important constituent in the United Nations Food Loss Waste Index to inform primary data collection of its measurement approach (United Nations Environment Programme, 2021). It has also been used by numerous researchers to quantify waste on farm in various studies such as assessing the dairy supply chain of Nestle Pakistan Ltd from farms to consumers (Tostivint *et al.*, 2017); measuring specialty crop wastes in the USA (Kitinoja *et al.*, 2018); developing Australian FLW baselines (Verghese and Lockrey, 2019) and farmer-led data gathering pilots to inform data collection on-farm of vegetables, fruits and grain (McCosker, 2020). The framework provided by the FLW standard allows for a varied range of approaches to collect data including either secondary data that use previous publications or previously generated data sets or primary data where researchers collect data from farmer estimations and in field measurements.

Secondary data collection

Secondary data refer to data generated for other purposes which can be useful for collating the holistic landscape of waste and assessing entire food supply chains and global and national baselines. The FAO used data obtained from FAO's year book and previously published work to conduct material flow analysis to provide an initial baseline (Gustavsson *et al.*, 2011). At a smaller scale, FLW data have been retrieved to estimate European Union-28 member state wastes (Jensen *et al.*, 2016), and Australian national estimates (Verghese and Lockrey, 2019). However, a weakness in relying solely on secondary data is that many stakeholders in the food industry are not yet familiar with FLW definitions or categorizations (Baker *et al.*, 2019) resulting in data which vary in quality. For example, out of 54 countries with FLW data, only 14 countries were identified to have high confidence data compatible with the Food Waste Index (United Nations Environment Programme, 2021). Further, relying on secondary data does not address the overarching issue which is a lack of primary data of on-farm FLW (Raak *et al.*, 2017; Kitinoja *et al.*, 2018; Food and Agriculture Organisation, 2020; McCosker, 2020; Winans *et al.*, 2020; Ortiz-Gonzalo *et al.*, 2021; Soma *et al.*, 2021; World Wildlife Fund-United Kingdom, 2021; Xue *et al.*, 2021).

Primary data collection

To collect primary data, on-farm researchers employ a mix of social science methods, such as interviews or surveys to obtain farmer estimates, supplemented with sampling in-field (Beausang *et al.*, 2017; Kitinoja *et al.*, 2018; McCosker, 2020; Thorsen *et al.*, 2021). A recurring challenge for researchers approaching the topic of on-farm FLW is the misunderstanding or disagreement of terms and definitions used when corresponding with farmers and relevant stakeholders. This can be attributed to the belief that food waste destinations on farm (tilled into soil, or to animal feed) and not into landfill is an acceptable practice, and isn't considered as 'waste' (Beausang *et al.*, 2017). Kitinoja *et al.* (2018) experienced this view while undertaking quantitative and qualitative methods in researching fruit and vegetable losses on farms in the USA. The researchers were cautioned by advisors and intermediaries against using the term 'food waste' when talking with interviewees. The rationale was that it would likely be received negatively since growers did not consider product left in the field to be waste and may have felt this practice was good stewardship rather than wasteful practice. In England, the organization WRAP (Waste and Resource Action Programme) investigated how to improve farmer engagement measuring FLW occurring in their business with the promise of improving efficiency and productivity. It was found that engagement was difficult to attain and maintain throughout the trial due to farmers not identifying FLW as a priority for them, and the lack of benefits identified for their business through participation (McCosker, 2020). Similar conclusions were made in research across several countries in horticultural production including Scotland (Beausang *et al.*, 2017), Canada (Soma *et al.*, 2021) and the USA (Gillman *et al.*, 2019).

Attaining primary data on-farm is also time-consuming and can be technically difficult to measure in the field. This contributes to the current lack of data. Because of these limitations, most on-farm data collection is based on farmer estimates shared through semi-structured interviews or surveys (Beausang *et al.*, 2017; Tostivint *et al.*, 2017; March *et al.*, 2019; Xue *et al.*, 2021; O'Connor *et al.*, 2022*b*). However, farmers' estimations may be inaccurate. Kitinoja *et al.* (2018) found that tomato and peach farmers estimates of losses (25 and 16%, respectively) were substantially lower than what researchers found from in-field sampling (40 and 37%, respectively). Baker *et al.* (2019) also found farmer estimates were usually significantly less than in-field measurements with the median difference between farmer estimate and measured loss of 157%. These findings suggested bias by farmers toward underestimating quantities due to misunderstanding the definitions of what is considered edible and hence what is FLW (Baker *et al.*, 2019), and a lack of experience accurately estimating wastes (Kitinoja *et al.*, 2018).

Social desirability may also hinder primary data collection. Anecdotally, FLW researchers find that participants consider they have very little or no FLW occurring in their business. The consistent inability of stakeholders to recognize that food is being wasted is an indication that the topic of social desirability and shame associated with food waste should be explored. Society has a unique and complex relationship with food as an essential human need, a cultural heritage, an expression of self-identity and social standing and a commodity (Bradshaw, 2018). Therefore, morality is a big driver for people who are entering and working in the field of FLW with food waste considered to be inherently 'bad'. This can then be extrapolated to 'people who waste food are bad'. This over simplified outlook may explain why some level of information-hiding of waste quantities occurs as people attempt to avoid societal shame. In overcoming the limitations of collecting primary data, other options for data collection on-farm are being explored. For example, WRAP carried out farmer-led data gathering pilots (McCosker, 2020). As FLW research expands, adopting different quantification methods like farmer-led data collection will facilitate quantification and solution finding. However, this approach still needs stakeholders with pre-existing trusting relationships with rural communities to improve uptake and interest in this area.

Drivers

A major component of FLW research is to understand the drivers that lead to FLW occurring on-farm. Information on these drivers has been obtained largely through thematic analysis of interview data with farmers and industry-relevant professionals (Beausang *et al.*, 2017; Kitinoja *et al.*, 2018; Gillman *et al.*, 2019). There are two approaches to identifying and understanding the drivers of FLW. First, the overarching context in which the FLW occurs (Fig. 1). Second, the discrete factors that are identified in case studies on farm (Fig. 1).

Overarching drivers

Low/middle-income vs *high-income nations*

The literature is unclear as to whether low/middle-income (developing) nations waste more than high-income (developed) nations early in food supply chains (World Resources Institute, 2019; Food and Agriculture Organisation, 2020). On one hand, low- and middle-income countries do not have access to the technology and infrastructure of high-income nations. Therefore, they are less efficient and/or unable to store and transport food products as well as high-income nations, which leads to an increase in the amount of avoidable food waste (Hewett, 2013; Papargyropoulou *et al.*, 2014; Nicastro and Carillo, 2021). For example, in low-income countries such as Pakistan and Uganda where some milk suppliers do not have access to automated systems, milk waste has been noticed to occur on-farm due to cows

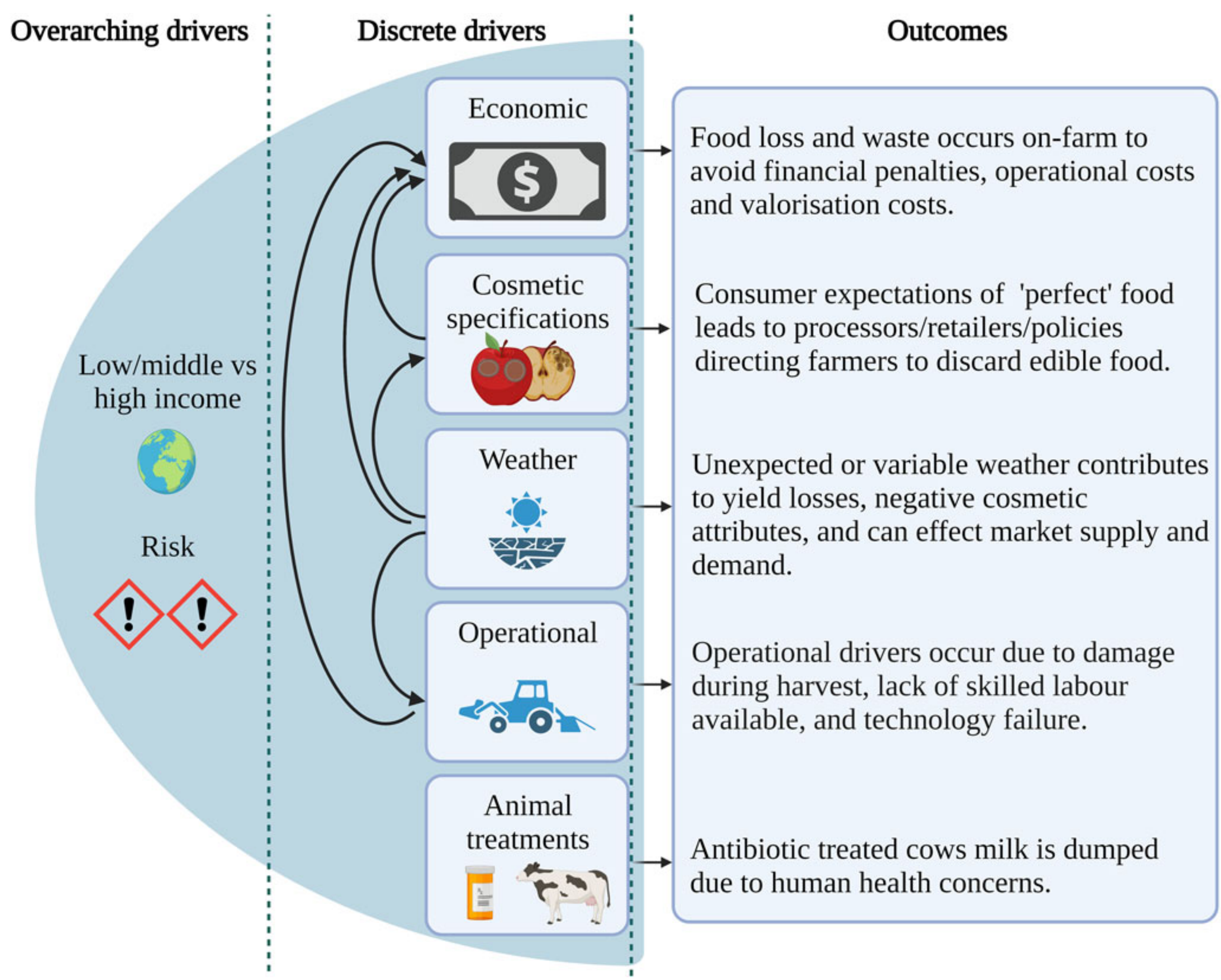

Figure 1. Overarching and discrete drivers of on-farm food loss and waste and their outcomes. Arrows indicate the associations between the discrete drivers. Created with BioRender.com.

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kicking collection buckets during hand milking and spillage during transfer of milk to other vessels (Tostivint *et al.*, 2017; Wesana *et al.*, 2019). In addition, studies on post-harvest tomato losses in the East Shewa zone of Ethiopia found that a significant driver of the 20.45% of tomatoes wasted on-farm was the use of inappropriate packing boxes which damaged harvested fruit, and a lack of access to cool storage facilities resulting in fruit becoming over ripe (Abera *et al.*, 2020). However, other studies have not found significant differences in FLW between high-income and low/middle income-nations (United Nations Environment Programme, 2021). Further, World Wildlife Fund-United Kingdom (2021) estimated that high-income nations actually generate greater proportions of waste during food production. Assuming that low/middle-income nations generate greater waste on-farm has skewed the focus of research in these nations to earlier stages of the food supply chain (on-farm, processor) and technological solutions. Whereas in high-income nations the focus has been on the later stages (retailer, consumer) (Bhattacharya and Fayezi, 2021; Filimonau and Ermolaev, 2021; Ortiz-Gonzalo *et al.*, 2021).

Risk

Another overarching driver is viewing FLW through the theory of the Risk Society, which is 'a systematic way of dealing with hazards and insecurities induced and introduced by modernisation itself' (Beck *et al.*, 1992). Risk is the range of possible occurrences (often specifically negative ones) that may happen given spatial, physical, temporal and social contexts (Mythen, 2004; Rasborg, 2021). The theory of Risk Society first proposed by Beck *et al.* (1992) argues that society is exposed to risks both anthropogenic (e.g., pollution) and external (e.g., natural disasters). Food production, processing and consumption can lead to the uncertainty and risk of negative outcomes associated with nutritional requirements, negative health effects, economic risks, reputational risks and exasperating climate change (Gille, 2012). Related to the Risk Society, is the Food Waste Regime discussed by Gille (2012) which identifies how food waste occurs not only due to technological deficits, but also owing to social relationships and an imbalance in power between farmers, processors, distributors and retailers. Applying this lens to FLW drivers suggests stakeholders in the supply chain are locked into practices that cause FLW to occur, including the avoidance of risks and hedging against uncertainty. This may explain how causes of FLW are not always at the food supply stage in which the food waste occurs (Beausang *et al.*, 2017; Gillman *et al.*, 2019). The greater market power of these actors over farmers leads to the farmer taking on responsibility to discard FLW. This occurs because of the perception that discarding food that won't be sold to consumers is 'better' to take place earlier in the food supply chain as later disposal wastes more money, energy and labor (Kitinoja *et al.*, 2018; Cattaneo *et al.*, 2021). While pushing the onus of FLW onto farmers seems a sensible solution regarding environmental outcomes (Gillman *et al.*, 2019), farmers find themselves taking on risks and uncertainties related to their assumed responsibility to dispose of food (Gille, 2012). These risks include potential health hazards of having high volumes of decaying food on-farm, local ecological damage to farms and waterways owing to high nutrient levels (Dairy NZ, 2012), potential loss of social license to operate due to factors like unpleasant smell, and a societal perception that farmers are shamefully wasteful and poor stewards of the environment.

An example of risk mitigation through pushing the onus onto farmers can be observed in New Zealand, where dairy farmers risk significant financial penalties from the dairy processor they supply if milk specifications or farm practices are unacceptable. These criteria include attributes of the raw milk received from the farmer (temperature, somatic cell count, antibiotic residues), as well as farm practices (e.g., water quality, animal welfare) (Fonterra Co-operative Group Limited, 2016). Various forms of financial penalties are imposed on the farmer for non-compliance which may include monthly penalties, one-off penalty payments or an accumulation of 'demerit' points (a reduction of their payment) (Fonterra Co-operative Group Limited, 2016). These financial penalties are a tool for the dairy processor to incentivize quality standards from milk suppliers and ensure their final products meet consumer needs, overseas market access requirements and government specifications. For example, if milk collected from a farmer has a somatic cell count above 399,999 cells/ml more than once, the farmer will receive a payment deduction (−50%) (Fonterra Co-operative Group Limited, 2016). In these scenarios, the farmer may opt to dump the milk rather than risk the possibility of negative financial and reputational outcomes. In the context of an industrialized nation like New Zealand, the economic penalty of this occurrence for a farmer can be mitigated by purchasing insurance (FMG, 2022). The access to affordable insurance means that their business is less exposed to negative economic consequences should the risk of contamination in their milk occur. However, in avoiding economic consequences and reputational risks (between the farmer and the processor), the tangible outcome of food waste still occurs.

Discrete drivers

Economic

Economic drivers contributing to FLW on-farm can be distilled into three main considerations: the monetary value of the waste (Bonadonna *et al.*, 2018); the overall costs of disposal or prevention of operational costs (Janousek *et al.*, 2018; Thorsen *et al.*, 2021); and the economic penalties of imperfect food from upstream stakeholders (Gillman *et al.*, 2019). Interestingly, while economic benefits are cited by farmers when asked about their options in valorizing waste, the level of farmer concern about economic consequences of generating FLW is varied. Kitinoja *et al.* (2018) found that US fruit and vegetable supply chain stakeholders did not consider greater produce utilization (less FLW) as a metric for success, even with upwards of 25% loss occurring. Conversely, Filimonau and Ermolaev (2021) found greater concern by 22 Russian farmers (pastoral, arable and horticultural) of FLW occurring. Bonadonna *et al.* (2018) also found, in Italy, food loss on farm was rated a moderately high concern (average score 6 where 10 = very concerned) for farmers, again primarily due to perceived economic losses. These varied findings suggest that while profitability is a prominent factor and metric of success in farm businesses, other drivers also influence the occurrence of FLW. One aspect that researchers could address is how farming scale affects the volumes and proportions of loss and waste at production. Janousek *et al.* (2018) found that of the ten organic farms that provided estimates for their study, the larger farms had proportionally greater estimates of FLW compared to smaller-scale food producers. The authors postulated that this difference was due to larger farms selling their products through distributors, whereas small-scale farmers in their study were more likely to sell directly to consumers.

Cosmetic specifications

In on-farm research, product-specific economic penalties imposed on farmers are usually linked to cosmetic specification

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requirements (Beausang *et al.*, 2017; Kitinoja *et al.*, 2018; McCosker, 2020; Thorsen *et al.*, 2021). Often they are implemented by processors and retailers, but they can also be implemented through government policy (Porter *et al.*, 2018). The reason for these specifications can be attributed to two main factors. The first is pragmatic in that cosmetic specifications can help ensure market acceptance after transport (Kitinoja *et al.*, 2018; Gillman *et al.*, 2019). For example, fruit with cosmetic spots, bruises, mechanical damage or non-uniform growth (such as multi-pronged carrots) may be more susceptible to bacteria and fungi infection due to cell rupture and enzymatic activity (Raak *et al.*, 2017), thus shortening their shelf-life. Efforts to utilize imperfect produce should prioritize market access that requires shorter distance transport to utilize food within its shelf-life.

Secondly, consumers expect aesthetically perfect produce, therefore blemishes decrease the purchasing behaviors from the retailer. An early study by Yue *et al.* (2007) identified that consumers were far less willing to purchase imperfect apples, even when informed that the spots were cosmetic and would not affect the fruit quality. It was found that a 9% 'damage' to the apple led to only 11% of consumers claiming they would purchase the apples, even at a discounted price (Yue *et al.*, 2007). Consequently, FLW on-farms is directly influenced by these arbitrary cosmetic standards. For example, in Queensland, Australia, White *et al.* (2011) found that minor blemishes, misshaped, undersized and double/triple bananas accounted for 78% of discarded bananas on-farms, equating to an Australian industry total of 37 thousand tonnes of edible banana waste per year.

Having these strict specifications in place implies that not all consumers will accept imperfect produce. However, surveys have found a wide range of acceptability and perception of edibility across demographics (de Hooge *et al.*, 2017; Nicholes *et al.*, 2019). Consumer acceptance of imperfect produce has been suggested to be a learned behavior and can be altered through growing awareness of imperfect options, public campaigns that target child behaviors and through purchasing decisions based on environmental considerations (de Hooge *et al.*, 2017; Makhal *et al.*, 2021). This can be seen in the marketing strategies assessed by Qi *et al.* (2022). It was found that providing bunches of carrots that consisted of 40% 'ugly' to 60% 'standard' with dual marketing messages of 'naturalness' and social consequences of FLW was the most profitable approach. Some businesses and supermarkets already offer to consumers discounted brands of 'imperfect' or 'ugly' produce. For example, the supermarket Countdown in New Zealand offers a product line called 'The Odd Bunch' which are fruit and vegetables that don't meet cosmetic specifications and are sold as a budget option to their 'standard' counterparts (Countdown, 2022). Allowing imperfect produce to be purchased by consumers through lessening cosmetic standards or offering alternative product lines could lead to greater awareness and acceptance of non-uniform product offerings in turn preventing the biggest driver of FLW on farm.

Weather

Weather is a key driver of FLW and, while outside of the control of farmers, is an important factor that can lead to farmers wasting food. The risk of weather reducing crop yields and quality directly contributes to some farmers growing surplus crops to mitigate against the risks of being unable to fulfil contracts with upstream stakeholders (Baker *et al.*, 2019). All types of weather can create negative outcomes. Weather has also been found to influence market demand and supply. In Scotland, retailers decreased their order volumes from farmers for soft fruit when weekend weather forecasted rain due to an expected downturn in demand by consumers (Beausang *et al.*, 2017). In the USA, a tomato farmer had a 'glut' of 2 weeks' worth of produce supplied to the retailer in 1 week due to hot weather affecting maturation of greenhouse tomatoes (Kitinoja *et al.*, 2018). Extreme weather events can cause one-off FLW events due to infrastructure damage. In New Zealand, floods led to dairy farmers being advised they would need to dump their milk because milk tankers were unable to access farms due to flood damaged roads (Malthus, 2021). While weather is outside human control, better approaches to mitigating the possibility of negative outcomes caused by weather need to be addressed. This may be through creating networks that can redistribute supply 'gluts', or policies that enable better market power to farmers to supply seasonally appropriate foods avoiding seasonal weather risks, or decentralized processing facilities that can bring solutions for reuse and recycling of damaged/inedible food caused by weather to the farm gate.

Operational drivers

Operational drivers on-farm encapsulate the FLW occurring during harvest due to damage (via machine or human), a lack of skilled labor, and failure of technology/machinery (Thorsen *et al.*, 2021). Thorsen *et al.* (2021) found that in glasshouse tomatoes, operational errors let to tomatoes being rejected due to harvest damage or being knocked onto the floor. Operational drivers leading to FLW were highlighted during the Covid-19 pandemic, where widespread disruptions and social distancing requirements led to farmers dumping food despite supermarkets running short on stock, because processors lacked labor to continue normal operations (Khan *et al.*, 2022). For example, during 2020 in the USA, delays to slaughter due to a lack of workers resulted in pigs growing too large to be processed by the automated equipment; this resulted in an estimated 300,000–700,000 hogs euthanized every week (Polansek and Huffstutter, 2020). Understanding operational drivers can be industry and business specific but may also be hindered by knowledge-hiding to be competitive in open markets. More research on the practical limitations and the social contexts in which operational drivers lead to FLW should be undertaken to better understand this driver.

Animal treatments

Compared to crops, a lower incidence of FLW is believed to occur on-farm for milk, meat and egg production (March *et al.*, 2019; McCosker, 2020). Except for eggs (McCosker, 2020), cosmetic imperfections are not a significant cause of wastes occurring on farm for animal products. Rather, animal treatments and their associated withholding periods are a main driver in causing waste (World Wildlife Fund-United Kingdom, 2021). In a survey of 43 Scottish dairy farms, it was found that 76% of milk withdrawal days (produced but not sold on) were due to mastitis-infected cows requiring antibiotic treatment (March *et al.*, 2019). Tostivint *et al.* (2017) also found that antibiotic milk (from mastitis treatments) contaminated 1–5% of the milk produced. What is not discussed in the literature is animal treatments and their effects on FLW for meat. This is due to the categorization of pre-slaughter animals as not 'food' and animals treated with antibiotics are prevented from going to the abattoir until they are out of the withholding period. However, on-farm euthanization is a common practice to dispose of animals that are not responding to treatment, are too sick, pose a risk of infecting other animals, are injured and unlikely to recover, have aged and are no longer productive or are no longer profitable to take to the abattoir. Many of these animals are likely safe and nutritious for human consumption but are not accounted for in current on-farm FLW research.

Common management options

Farmers have limited options for utilization and disposal of FLW. These include allowing access for food rescue organizations to glean unharvested produce (Kitinoja *et al.*, 2018; Kowalczyk *et al.*, 2020), diverting it into feedstock for animals (March *et al.*, 2019), composting (Thorsen *et al.*, 2021), tilling crops back into the soil (McCosker, 2020) and disposal (Matthews, 2014). All these options have benefits and costs which make it difficult for farmers to choose. A specialized food waste hierarchy framework was developed by Papargyropoulou *et al.* (2014) to identify and prioritize these options based on social and environmental impacts. The most favorable options distinguish between food that is fit for human consumption, and food waste that is avoidable or unavoidable; it descends from prevention, re-use, recycle, recovery, to the least preferred option of disposal (Fig. 2) (Papargyropoulou *et al.*, 2014).

Some FLW management options are excluded in this paper as they primarily address FLW at other stages of the food supply chain. These include upcycling, adding value, anaerobic digestion and pyrolysis. Upcycling is food that 'use(s) ingredients that otherwise would not have gone to human consumption, are procured and produced using verifiable supply chains, and have a positive impact on the environment' (Upcycled Food Association, 2020). Upcycling has an added processing step, e.g., waste bread brewed into beer (Citizen Collective, 2022), so is therefore outside the scope of on-farm management options. Another prevention option is through research and development to add value to food preventing waste. However, adding value is usually done by the processor using food that farmers provide them (McCabe *et al.*, 2020; Tsai, 2020; Bioresource Processing Alliance, 2022). Anaerobic digestion is also an option excluded from on-farm FLW. While it is a well-established technology for downstream FLW with over 17,500 anaerobic digesters installed in Europe at the end of 2016 (European Biogas Association, 2019), anaerobic digesters used by farmers are largely for dealing with animal manures rather than FLW (Vanguard Renewables, 2021). Pyrolysis/gasification is also not discussed here as this option has not been observed to be used by farmers for on-farm FLW. These similar processes involve waste (both plastic and biological) being thermally degraded into gas and other by-products (Hicks and Verbeek, 2016, Perrot and Subiantoro, 2018).

Here we discuss on-farm management methods used in the order they appear on the food waste hierarchy (Fig. 2). Starting with prevention practices, such as improving efficiencies and preventing crop damage; gleaning, which redistributes food loss to people; use as animal feed; composting and land application of FLW; and the least desirable option of disposal.

Prevention: technological solutions

On-farm prevention methods can be confused/overlap with farming methods that increase yield potential. These two terms differentiate in their focus. On-farm FLW prevention are actions taken to prevent crops/animals already grown from being lost from the food system, whereas fulfilling yield potential is controlling conditions to enable the genetic potential of a crop or animal to be phenotypically expressed and harvested (Evans and Fisher, 1999). Common on-farm FLW prevention methods include switching to crop cultivars with less losses such as varieties bred with lodging (falling over in the field) resistance (Cui *et al.*, 2022; Li *et al.*, 2022); adoption of mechanical harvesting and threshing (in Nigeria this reduced FLW of small-hold rice farmers by 6.5%) (Castelein *et al.*, 2022); reducing damage by pests and diseases through rodent trapping to minimize post-harvest storage losses (Edoh Ognakossan *et al.*, 2016); and

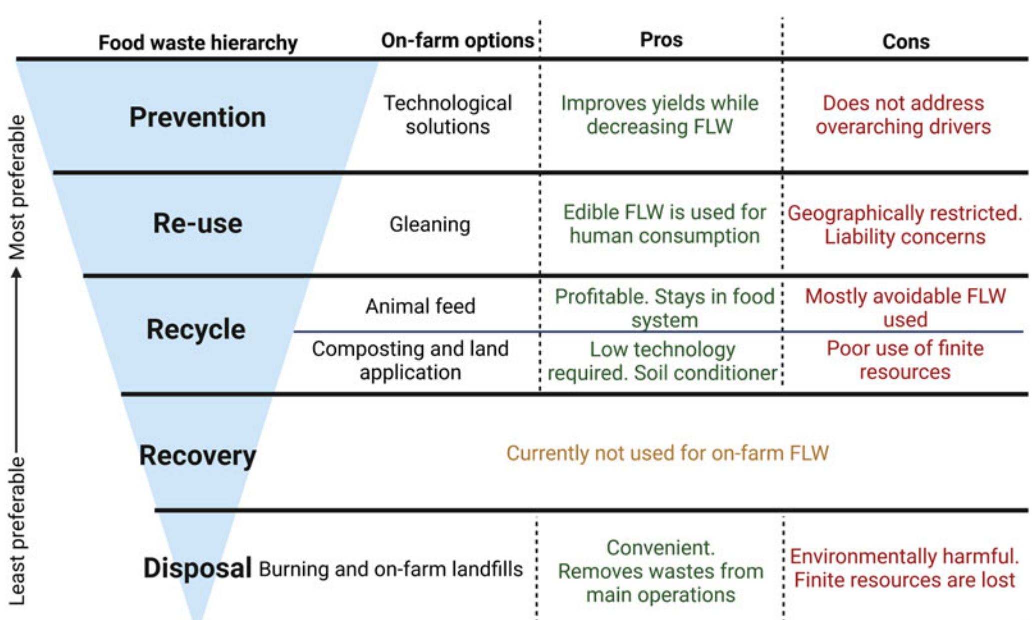

Figure 2. Food waste hierarchy (left), adapted from Papargyropoulou *et al.* (2014) currently available on-farm options, and their identified pros and cons. Created in Biorender.com.

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upgrading post-harvest storage facilities such as installing biomass dryers to decrease mold damage (Magan and Aldred, 2007; Bhadra, 2017). Most prevention methods are technological solutions to address drivers of FLW that do not address systemic, behavioral and social drivers.

Reuse: gleaning

Modern day gleaning is the harvesting of crops, usually by volunteers, to prevent food going to waste due to the crop being surplus to requirements, not meeting aesthetic specifications and/or a lack of labor (Leasure-Earnhardt *et al.*, 2017; Evans and Nagele, 2018). Organizations who provide gleaning service generate two core benefits to their stakeholders. First, it prevents avoidable FLW occurring on farms by providing labor, service, and network support. Secondly, the gleaned food is usually redistributed for use as food for consumers who are food insecure (Leasure-Earnhardt *et al.*, 2017; Walia and Sanders, 2019; Kinach *et al.*, 2020). Although some gleaned produce can also be redistributed through selling to consumers. For example, the social enterprise Perfectly Imperfect (Perfectly Imperfect, 2022) works with growers to glean produce that would have otherwise been wasted. Half of this produce is donated to food banks, the rest is delivered to subscribers who pay for a 'mystery box'. Other organizations provide volunteers for gleaning, and services to sell gleaned or surplus food on behalf of farmers to other businesses (Northeast Organic Farming Association of Vermont, 2022).

One of the limitations of gleaning practices is the liability to farmers of gleaned food that could unintentionally lead to ill health. In some western countries, policies alleviate liability for growers to encourage gleaning activities for food donation. Known as 'Good Samaritan Acts' these policies can be found in several nations including the USA (Evans and Nagele, 2018), New Zealand (New Zealand Government, 2014), Australia (Government of New South Wales, 2005) and Italy (O'Connor *et al.*, 2014). The legal landscape can be confusing for farmers as its application can vary. In the USA, policies that enable farmers to donate food through gleaning (1996 Good Samaritan Act and the 2008 Federal Food Donation Act) have minor deviations of the acts within states (Leasure-Earnhardt *et al.*, 2017; Evans and Nagele, 2018). To help groups of volunteers, social enterprises and beneficiaries/food banks who are involved in food gleaning efforts navigate the legal and logistics of this practice, larger formalized networks of gleaners have been created (Leasure-Earnhardt *et al.*, 2017; Center for Agriculture and Food Systems, 2022; Feedback, 2022). As well as concerns around liability, access to this option is geographically limited to farms that are within a timely commute for volunteers (Kitinoja *et al.*, 2018). Therefore, other solutions should be developed and explored along with expanding the capabilities of gleaning to divert farm FLW into human consumption.

Recycle: animal feed

Using FLW for animal feed is a common practice for both retail, consumer and on-farm FLW (Rajeh *et al.*, 2021). Animal feed is an economically lucrative option for farmers recouping costs (Beausang *et al.*, 2017). FLW diverted to animal feed is considered a recycle option on the food waste hierarchy, and as a preferred option for unavoidable food wastes (Fig. 2) (Papargyropoulou *et al.*, 2014). Production of unavoidable FLW can occur when food produced on-farm is no longer safe for humans to consume. For example, milk from cows treated with antibiotics is commonly used to feed calves (Tostivint *et al.*, 2017; March *et al.*, 2019). Where farmers have concerns around their liability of food that could be hazardous to consumer health, the animal feed option is less risky. However, much of the FLW diverted to animal feed is avoidable and therefore should be used for people to consume. World Wildlife Fund-United Kingdom (2021) argues that by diverting food from 'the food system to the feed system' there is no incentivization to address systematic causes of FLW. They give the example of a case study exploring the UK wheat industry, where on average 40% of crops meet specifications and yet 'loss' rates were reported at 1.3% due to these crops being redirected into animal feed. A lack of incentivization to change to more preferential options in the food waste hierarchy because of the profitability, lower perceived liability and lack of access to other options keeps farmers locked into using animal feed as the main way to deal with on-farm FLW.

Recycle: composting and land application

The next most preferred recycle option is composting (Fig. 2). Composting occurs when material is piled enabling aerobic microbes to decompose biomass into stable organic matter. The resultant gases (CO_2, CH_4 and N_2O) are not captured to generate energy (Barthod *et al.*, 2018; De Corato, 2020). Composting practices vary but usually it requires layering of high lignin material (e.g., straw or woodchip) with nutrient dense and high moisture material to ensure aerobic conditions (Compost NZ, 2007). The resulting compost can then be applied as soil conditioners or mulches to improve soil structure benefiting plant growth (De Corato, 2020). Different methods are used for different feedstock types (Table 1), for example, in-vessel composting is a preferred option for feedstock that contains meat waste, as this prevents rodents and blocks out the negative odors.

Composting is a common option for farmers as it is affordable, can be carried out on farm and can be returned to the soil benefitting future food production (Beausang *et al.*, 2017; De Corato, 2020; Winans *et al.*, 2020). However, the method of composting and the application of subsequent compost substrates is often not specified in FLW research. Farmers may be using the term 'compost' in these studies to refer to the practice of piling FLW on-farm away from their main fields never to be returned to

Table 1. Methods and descriptions of composting adapted from Compost NZ (2007).

Method	Description
Static aerated windrows	Dedicated pipework or sunken covered troughs force air through a pile of organic material to keep the conditions aerobic
Windrow composting	Heaped rows of organic matter, periodically turned to aerate
In-vessel composting	Organic matter is placed in a concrete tunnel or covered windrow
Vermicomposting	Specific worm species are used to create higher quality compost

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the soil. It could be argued this is not composting and instead is akin to landfilling. In some instances, avoiding using compost is necessary to avoid exposure to disease. For example, compost from casualty cows in New Zealand is not used on fields that will be subsequently grazed by the same species due to biosecurity concerns (Dairy NZ, 2022). Further, compost substrates do not return adequate levels of nutrients such as nitrogen and phosphorus to soils and cannot replace fertilizer (De Corato, 2020; Moretti *et al.*, 2020). This is because the aerobic microbial communities consume the nutrients available. In a study on maize yields comparing municipal solid waste compost, mineral fertilizers and a negative control (untreated), Moretti *et al.* (2020) found that maize crops treated with compost alone showed similar yields to the crop that received zero nutrients.

Another option used by farmers is through land application (Beausang *et al.*, 2017; Kitinoja *et al.*, 2018; Winans *et al.*, 2020). Like composting, FLW is returned to the soil, however its benefits are limited. Kitinoja *et al.* (2018) calculated that tilling wasted potatoes (approximately 2.1% of DM is nitrogen) back into soil on-farm did not cover the nutrient needs of the next crop. The widespread use of tilling into the soil and its perception as 'good' farming practice should be reviewed as finite resources (such as phosphorus) are not adequately recovered.

Disposal

The least preferred option in the waste hierarchy is disposal (Papargyropoulou *et al.*, 2014). Disposal on farm is commonly practiced through burning and dumping into landfills (Matthews, 2014). This is the least preferred option because the energy, labor, and nutrients that have been used to create this food is lost from the food system. Disposal methods pose serious environmental risks. Leachate from landfills is identified as pollutants contaminating groundwater and surface water (Vaverková, 2019; O'Connor *et al.*, 2022*a*). Further, FLW disposal has been found to exasperate leachate chemical properties. An assessment of secondary data from 51 countries found that the main factor of increased concentrations of leachate (chemical oxygen demand, biochemical oxygen demand NH_3, K^+ and Cl^-) from landfills was the greater proportion of FLW present (Ma *et al.*, 2022). Disposal of FLW also significantly contributes to anthropogenic greenhouse gas emissions. It is estimated that annual FLW in landfills contributes 16% of total agricultural-related emissions (World Wildlife Fund-United Kingdom, 2021). Therefore, disposal is an unsustainable option for on-farm FLW. Further, it renders this FLW invisible to society and leads to ongoing ignorance of systemic drivers that lead to on-farm FLW occurrence.

Recommendations

Aiming for a global standard definition may be impossible and cause significant volumes of FLW to go unaccounted for. Factors such as intended purpose or intended market, and the subjectivity of whether the FLW is avoidable/unavoidable and edible/inedible are contextual. Using the term 'food loss' and assuming high-income countries have low on-farm FLW ignores preventable and significant quantities of waste occurring on-farm. This view leads to solutions and prevention-based strategies that ignore social, cultural and economic drivers of FLW. Development of technologies that add value to FLW as an end-of-pipe option are attractive for entrepreneurs, owing to their potential to generate both a direct economic return and potentially valuable intellectual property. However, such approaches have so far been unable to provide solutions to the social, cultural and economic causes of FLW.

To identify prevention strategies, more primary data collection for both quantities and drivers is needed across food and farming types. This requires refining quantitative methodologies to be less time consuming or technically difficult such as adopting high-throughput real-time data-collection technologies (e.g., LIDAR) to on-farm FLW reporting purposes. Improving qualitative data collection means revisiting farmer-led methods and improving participation by articulating compelling value propositions for farm businesses to be involved in FLW research. Positive and beneficial relationships around FLW with farmers will enable future research to yield greater transparency of FLW occurrence and management.

Through articulating what risks are being avoided by farmers (and upstream stakeholders) that leads to surplus crops and FLW occurrence, we can investigate alternative ways to mitigate risks and reduce the tangible result of FLW. Solutions in this space should be conscious to not promote the tools of societal and personal shame to drive practice change, as this would likely lead again to social desirability bias, knowledge hiding and avoidance (and is unethical); shame around providing FLW data should be abated. Addressing the social aspects that create FLW will better shape successful research and policy approaches, and lead to impactful entrepreneurship opportunities. These solutions may come through the approach of developing optimized marketing strategies to improve consumer acceptance and understanding of imperfect produce, or the establishment or 'circular economy brokers' connecting farmers with preferential options in the FLW hierarchy available in their geographic location, or government policies that require down-stream stakeholders to have key performance indicators stating the utilization of farmer products that would have otherwise gone to waste. There are many approaches that can be taken to address aspects of this widespread issue and should be viewed as an exciting space for those wanting to create and support positive outcomes in our global food systems.

Conclusions

This paper provides a critical overview of the scholarly discourse on current on-farm FLW research. Most FLW studies are undertaken through utilizing secondary or collecting primary data and are encouraged to use the FLW standard. Secondary data do not provide a high-resolution overview because it is usually retrofitted to the purposes of FLW research. There is not enough primary data collection taking place to give confidence in our knowledge of FLW quantities occurring on-farm although the assumption that lower/middle-income countries have higher FLW on-farm has likely led to a lack of primary data collection in high-income countries. To understand systemic causes of FLW, overarching drivers such as risk should be further investigated. Cosmetic specifications and the lower market power of farmers have been identified as the main reason that on-farm FLW occurs. Farmers are limited and disincentivized on the number of options they have for valorizing their FLW because of physical access to networks and resources, profitability of animal feed options and the invisibility of disposal and composting.

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