THE STATE OF FOOD LOSS ALONG PERISHABLE VEGETABLE SUPPLY CHAINS:

A STUDY OF TOMATOES IN SOUTH INDIA

A Dissertation

Presented to the Faculty of the Graduate School

of Cornell University

In Partial Fulfillment of the Requirements for the Degree of

Doctor of Philosophy

by

Jocelyn Marie Boiteau

August 2021

THE STATE OF FOOD LOSS ALONG PERISHABLE VEGETABLE SUPPLY CHAINS:

A STUDY OF TOMATOES IN SOUTH INDIA

Jocelyn Marie Boiteau

Cornell University 2021

This research was done in the context of tomato supply chains in Chittoor District, Andhra Pradesh and Hyderabad city, Telangana. The study aims were (1) to examine the extent, stages and determinants of food loss along tomato supply chains from farmer to retail; (2) to identify important quality attributes across supply chain actors and the relationships between quality metrics, both subjective and objective; and (3) to critically compare institutional food loss and waste (FL&W) definitional frameworks used with a collective smallholder vegetable farmer definitional framework.

Food loss surveys of were carried out across 75 smallholder farm households, 83 tomato traders, 52 vegetable traders and 50 vegetable retailers from February 2019 to March 2020. Data on tomato production and harvest (at the farm level), post-harvest and marketing, tomato quality, food loss, food quality loss, and demographics were collected. Tomato ascorbic acid concentrations were measured from tomatoes collected at harvest and wholesale market stages, for comparison with survey food quality data. Pile sort group discussions and focus group discussions with farmers contributed valuable insights into farmer decision-making processes with regard to production, harvest, post-harvest and marketing of tomatoes and other perishable vegetables.

Food loss was concentrated at the farmer stage, specifically at the farm-level. Greater post-harvest, farm-level loss was significantly associated with greater pre-harvest quality loss. Harvests during peak harvest season were significantly associated with lower pre-harvest quality loss, post-harvest loss and market-level, pre-auction loss. With regard to quality, farmers make harvesting decisions based on the color/ripeness level of tomatoes. Post-harvest, tomato size and evidence of pest or physical damage become important quality indicators during grading and sorting. All other supply chain actors consider several observable quality attributes to assess tomato quality. Market grades have distinguished quality intensities within and between supply chain actors. The ascorbic acid concentration of tomatoes, a marker of nutrient quality, was significantly associated with quality intensity and tomato ripeness levels. Finally, three major gaps were identified where institutional FL&W definitional frameworks do not align with smallholder farmer frameworks. Some institutional frameworks do not count animal feed as a loss destination, they exclude the pre-harvest stage when produce is market ready from loss estimates, and they do not measure food quality loss. Taken together, findings from this research demonstrate that farm-level supply chain stages, from pre-harvest to post-harvest, are critical points where food loss of tomatoes occurs. Food loss and waste definitional frameworks are the backbone of measurement frameworks. Institutional food loss and waste frameworks that influence global, national and subnational policies should consider the overarching food loss and waste measurement and reduction objectives in the context of specific food groups and supply chain contexts.

BIOGRAPHICAL SKETCH

Jocelyn Boiteau grew up in Ashland, Massachusetts. She attended Cornell University for undergraduate studies, where she worked on a research project reviewing how food security project implementation practices enable programs to integrate agriculture and nutrition to improve child nutrition status in low-income countries. While at Cornell, Jocelyn completed the Didactic Program in Dietetics. In 2012 she received a B.S. in nutritional sciences minoring in global health.

Post-graduation, Jocelyn completed a clinically-focused dietetic internship at Brigham and Women's Hospital in Boston, MA to further build her nutrition background. After passing her qualification exam and becoming a registered dietitian, she sought out opportunities to apply her nutrition background to food and agriculture development settings. Eventually, Jocelyn landed in Jodhpur, Rajasthan, India where she volunteered with a local organization and worked with their agriculturist to modify their home gardening program to become more nutrition-sensitive. Inspired to continue work in the international nutrition field, she joined the Food Aid Quality Review at the Tufts Friedman School of Nutrition Science and Policy, where she worked as a Project Administrator.

Being drawn back to Cornell by the Tata-Cornell Institute for Agriculture and Nutrition, Jocelyn returned to Cornell in 2016 to study International Nutrition, with minors in Food Science and Methods of Social Research.

This document is dedicated to my parents and Berkin.

ACKNOWLEDGEMENTS

This research became a reality with the support of many, many people. First and foremost, I thank the farmers, traders, and retailers who gave their time to participate in our surveys and discussions. Thank you to the staff at APMAS and the World Vegetable Center for their support and assistance in connecting me with farmers and traders along the tomato supply chain in Chittoor district and for their willingness to answer my many questions about tomatoes. Thank you to the staff at ICRISAT, particularly Dr. S Nedumaran, for your support and assistance during my time Hyderabad. Thank you to my entire research team, especially Alphonsa Sony, for your hard work, dedication and trust in the process.

I sincerely thank the members of my committee for their knowledge and guidance. My advisor, Prabhu Pingali, was incredibly influential for my research direction and helped me to see the bigger picture to understand the linkages and pathways between diets, food systems and policies. I am grateful for the generous financial support of the Tata-Cornell Institute and to have had the opportunity to spend extensive time in India; first during formative work to ground my research questions, and later to immerse myself in my research site that provided invaluable insights into the nuances and complexities of food systems. My committee members Dennis Miller, Lori Leonard and Martha Field helped me refine my research direction with their thoughtful feedback. I am grateful to have had a multi-disciplinary committee, which allowed me to explore the many different angles to food loss and waste.

I would like to acknowledge and thank the members of the Tata-Cornell Institute research group for your support and constructive feedback. In particular, thanks to Katy Merckel, Vidya Vemireddy, and Anthony Wenndt for sharing your experiences and lessons learned that made planning a bit less stressful. Thanks to Mathew Abraham for all your guidance regarding food markets, supply chains and field research. I am also grateful to Mary-Catherine French and Brenda Jordan Daniels-Tibke for all your help with planning and getting things organized and in place. A special thanks to Stephen Parry at the Cornell Statistical Consulting Unit for your patience in answering my many statistics questions – I learned a lot! Thanks to my DNS peers: Amy Fothergill, Bonnie Patchen, Camille Jones, Heather Guetterman, Ibukun Owoputi, Jenna Golan, Katie Delaney, Kendra Tiani and Wing Zhong, for all your love, camaraderie, and care. And thanks to Priyakshi Buragohain for your friendship and encouragement during fieldwork in Madanapalle and Hyderabad.

Finally, this research would not have been possible without my parents, Anne and Maurice, and their unconditional love, encouragement and voices of reason. From spending weekends at the soccer field to driving to Ithaca in the middle of the night to help their daughter move out of an apartment during a pandemic, they always made their children a priority, and I am forever grateful. Thanks to my brother, Rene, who continues to be a supportive role model, and my sister-in-law, Kelsey, for her kindness. Thank you to my parents-in-law, Gül and Uğur, who always greeted me during layovers in Istanbul on my way to/from India. Last, but not least, many thanks to my husband, Berkin, for your endless supply of support and care. You are an irreplaceable part of my life and I look forward to our life together.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

CHAPTER 1

APPROACHING FOOD LOSS AND WASTE FROM A FOOD AND NUTRITION SECURTY LENS

The triple burden of malnutrition

The triple burden of malnutrition describes the co-existence of undernutrition, overnutrition and micronutrient deficiencies within a given population (e.g., household, community, national, etc.) that takes the form of insufficient macro or micronutrients, or excess intake of energy. Dietary energy and nutrient intake affects child growth and communicable disease resistance, as well as micronutrient-deficiency derived health problems and non-communicable diseases related to overweight and obesity (Pinstrup-Andersen; P.; Watson II; D.D., 2011). Childhood stunting is a risk factor for increased mortality and impaired cognitive and motor development (Gillespie & Haddad, 2003). The triple burden of malnutrition highlights the need to assess diet quality and account for nutrient adequacy, not just energy (calorie) adequacy.

Poverty reduction through agriculture investment is associated with decreased prevalence of stunting, which is more prominent in rural areas. At the same time, there is an association of poverty reduction with increased prevalence in overweight and obesity in both urban and rural settings (Webb & Block, 2012). From a life cycle perspective, undernutrition and overnutrition can have lasting consequences within an individual and across generations (Benson, 2004). With regard to overnutrition, overweight and obesity accumulating in infancy and childhood increases the likelihood of overweight and obesity in adulthood (Guo, Wu, Chumlea, & Roche, 2002). Further, overweight and obese mothers are at greater risk of obstetric outcomes such as gestational diabetes, cesarean delivery and macrosomia and may have challenges with breastfeeding (Leonard & Rasmussen, 2011; Nommsen-Rivers, Chantry, Peerson, Cohen, & Dewey, 2010; Ryan, 2007; Schummers, Hutcheon, Bodnar, Lieberman, & Himes, 2015). Micronutrient malnutrition is a form of undernutrition that can co-exist with insufficient or excessive energy intake. Addressing micronutrient deficiencies with food-based strategies should encourage dietary diversity with a focus on micronutrient-rich foods (Tontisirin, Nantel, & Bhattacharjee, 2002). However, foods rich in micronutrients are not accessible to poor consumers because they are either physically unavailable or, when available, they are unaffordable (Miller & Welch, 2013). In the 2019 Global Burden of

Disease study, several nutrition and diet-related risk factors are among the top 10 risks for loss of years of full health, globally; child and maternal malnutrition is ranked first (IHME, 2019).

The triple burden of malnutrition in India

Over the past decade, the triple burden phenomenon in India has become increasingly apparent as the prevalence of child stunting (< 5 years of age) has decreased by 13 percentage points (pp) and the prevalence of underweight men and woman has also decreased by 13 pp and 15 pp, respectively (Pingali, Aiyar, Abraham, & Rahman, 2019). At the same time, the prevalence of adult overweight adults has increased by more than 50 pp (Pingali et al., 2019). With regard to micronutrient deficiencies, the Hidden Hunger Index for India decreased from Alarmingly High (≥40.0) in 1995 to Severe (25.0-39.9) in 2000, but has remained at severe since 2011 scores (Ruel-Bergeron et al., 2015).

Diet challenges of modern food systems

The nutrition transition and diet changes

The Green Revolution in the 1970s was a success in terms of achieving calorie sufficiency in food systems, yet was ineffective in addressing issues of dietary quality and micronutrient malnutrition (Pingali, Mittra, & Rahman, 2017). The diet transformation in Asia involved initial diet diversification and later diet globalization and westernization (Pingali, 2006). In the first stage, diets shifted towards more diverse and higher value foods as incomes increased. Diets then shifted away from traditional towards globalized diets that include more processed foods, resulting in diets that are higher in fat and protein (Pingali, 2006). The diet transformation improves diet quality in terms of food variety and diversity but may not necessarily improve nutritional diversity. Rising incomes, alone, without reductions in the price of nutrient-rich, non-staples are not sufficient to increase nutritional diet quality (Herforth & Ahmed, 2015).

Fruits and vegetables are sources of micronutrients essential for human health. Several current diet recommendations converge on fruit and vegetable consumption recommendations (HSPH, 2011; USDA, 2020; Willett et al., 2019). Similarly, the World Health Organization recommends individuals consume 400g of fruit and vegetables per day (WHO, 2020). A major barrier for populations to meet these diet recommendations lies with the fact that the current supply of fruits and vegetables is not sufficient to meet recommended intake, both globally and within India (Bahadur KC et al., 2018; Mason-D'Croz et al., 2019; Siegel, Ali, Srinivasiah, Nugent, & Narayan, 2014). Despite India being the world's largest fruit and second largest vegetable producer (Kusuma & Basavraja, 2014; Vanitha, Kumari, & Singh, 2014), average fruit and vegetable consumption in India is 149-152 g/day/person, well below the World Health Organization recommendation (Thow et al., 2018).

Food supply chain transitions

Alongside the nutrition transition, food supply chains are shifting from traditional to modern supply chains. Traditional supply chains are characterized by smallholder farmers selling their products to traders who then sell to consumers or other traders in wet, often local, markets (Gómez & Ricketts, 2013). Traditional markets have variable pricing, product volumes and quality grades that can impact food availability and affordability to consumers, as well as the price received by the primary producer. While traditional supply chains may have lower-priced fruits and vegetables in rural and poor urban areas, issues of seasonality and distribution infrastructure can limit the degree to which traditional markets can offer year-round access to micronutrient-rich foods (Gómez & Ricketts, 2013).

In contrast, traditional-to-modern supply chains connect smallholder farmers and traders to supermarkets and food manufacturers (Gómez & Ricketts, 2013). In a modern food supply chains, high value crop producers, such as fruit and vegetable producers, and traders may experience greater income opportunities. In turn, as net-food buyers, producers may then be able to afford more diverse diets as their income rises. However, asset-poor, smallholder farmers may miss out on these income opportunities (Gómez & Ricketts, 2013). Policies and schemes to protect farmers from exploitation and increase transaction transparency have created complex market structures (Thow et al., 2018).

Shifting to sustainable food systems that promote nutrition

Aligning health and planetary boundaries in food systems

In addition to nutrition and health, food systems are inherently linked with environmental sustainability. Major drivers of food system transformations include income growth, infrastructure investments, policy liberalization, urbanization and diet transitions (Thomas Reardon et al., 2018). Food supply chain transitions and diet transitions have had negative environmental impacts (Intergovernmental Panel on Climate Change, 2019). In 2019, the EAT-*Lancet* Commission reviewed the current evidence and detailed the EAT-*Lancet* diet, a global reference diet that meets sustainability goals for both human health and planetary health (Willett et al., 2019). Several studies have looked into the cost and affordability of the EAT-*Lancet* diet, concluding the diet is unaffordable for many people in low- and middle-income countries, including many low-income households in India (Gupta, Vemireddy, Singh, & Pingali, 2021; Hirvonen, Bai, Headey, & Masters, 2020; Raghunathan, Headey, & Herforth, 2021). The EAT-Lancet commission calls for a "Great Food Transformation" to make the reference diet feasible (Willett et al., 2019). Reducing food loss and waste (FL&W) is among the proposed strategies to achieving a sustainable food system transformation (Willett et al., 2019). This strategy aligns with Sustainable Development Goal target 12.3 broadly aims to halve food waste and reduce food loss by 2030, as part of SDG 12 on sustainable consumption and production.

In comparison to staple grains, fruits and vegetables are more perishable. Among different food groups, the proportion by weight of fruits and vegetables that are diverted away from human consumption is highest (FAO, 2011). Food loss and waste further widens existing fruit and vegetable supply gaps (Siegel et al., 2014). High perishability also contributes to quality losses such as decreases in nutritional value or economic value. The degree of fruit and vegetable deterioration and loss partly depends on the producer and the type of value chain the product enters (HLPE, 2014). Fresh fruits and vegetables that enter traditional supply chains are at risk of loss due to resource scarcity and lack of infrastructure, such as storage and cold chains. In modern supply chains, fruits and vegetables may be discarded if they do not meet the more stringent food quality standards. Product handling, distribution, processing and distance to markets can impact both the farmers' decisions to produce a perishable, nutrient-rich foods as well as the food quality along the supply chain (Birthal, Roy, & Negi, 2015; Gulati, Ganesh-Kumar, Shreedhar, & Nandakumar, 2012).

Gaps in FL&W measurement

Food loss and waste estimates are plagued by the lack of standard measurement frameworks and a heavy reliance on secondary data and indirect measurements (Fabi, Cachia, Conforti, English, & Rosero Moncayo, 2021; Xue et al., 2017). Measurement method limitations are compounded by the fact that there is no harmonized FL&W definition, leading to differences in supply chain stages evaluated and different final destinations considered as loss destinations (Chaboud & Daviron, 2017; Fabi et al., 2021; HLPE, 2014). Several definitional frameworks exist that influence public and private FL&W measurement and reduction efforts (Chaboud & Daviron, 2017; Craig Hanson et al., 2016; Fabi & English, 2019; FAO, 2014; UNEP, 2021). Fresh fruit and vegetable FL&W estimates vary widely, but simplified estimates may be misleading due to differences between supply chain contexts and factors across product groups and seasons (FAO, 2019; Hodges, Buzby, & Bennett, 2011).

Experts have proposed to organize FL&W causes into "micro-level", "meso-level", and "macro-level" reflecting causes at the same stage, between stages, and systemic issues, respectively (HLPE, 2014). While quantity loss remains the priority indicator, most often expressed as a percentage of product mass or volume, food quality losses are emerging as an important component of FL&W. When FL&W is expressed in terms of calories, FL&W are biased towards higher estimates for energy-dense foods (HLPE, 2014). Estimates of overall FL&W along the value chain at the macro-level consider only quantity losses and cannot be used to identify the value chain stages where losses occur because they are not representative of smaller regional units. Estimates at the micro-level assess losses of specific value chain stakeholders to understand losses at each particular stage of the value chain (e.g. farm, transport, retail), and allow for the estimate of quality losses (Delgado, Schuster, & Torero, 2017). Food quality loss (e.g. nutritional, sensory or other attribute) is related to FL&W; when food has lost quality below an acceptable threshold, it may be entirely removed from the food chain (HLPE, 2014). Minimum quality standards are important to protect consumers from low quality foods that are unsafe to eat (A. A. Kader, 2010). Quality standards in high-income countries may over-emphasize appearance attributes, leading to the removal of food that could have been safely consumed (HLPE, 2014; A. A. Kader, 2010). Several recent studies have been carried out using the micro-approach for specific food products; only one study (Delgado et al., 2017) considers food quality (measured as price) loss as well (Chaboud, 2017; Delgado et al., 2017; Global Strategy to improve Agricultural and Rural Statistics (GSARS), 2017; Macheka, Spelt, Bakker, van der Vorst, & Luning, 2018; McKenzie, Singh-Peterson, & Underhill, 2017; Minten, Reardon, Gupta, Hu, & Murshid, 2016).

Exploring FL&W along tomato supply chains in South India

Study introduction

To contribute to the growing body of evidence on FL&W, we carried out a case study along tomatoes supply chains from farm to retails stages in South India to estimate and understand food loss and food quality loss among fresh, perishable vegetables. Based on existing agriculture production data and formative fieldwork, we determined that tomato supply chains would make a suitable study vegetable. Tomatoes are grown year-round in India, most often consumed fresh, and are highly perishable. Fresh tomato supply chains from rural farms to urban retail outlets are very short, often reaching urban consumers as early as one day after harvest and as late as one week. Smallholder farmers, tomato traders, urban vegetable traders, and urban vegetable retailers were identified as major supply chain actors along the tomato supply chain. Findings from this study provide important insights into the extent and determinants of food loss and food quality loss, as well as food loss measurement methods and definitional frameworks in the context of perishable vegetables, which can be used to inform FL&W monitoring and reduction strategies.

Brief overview of vegetable supply chains in India

Within India, vegetable production is done primarily by smallholder farmers. Farmers most often sell vegetables to local aggregators, through public, state-run *mandis* (wholesale markets), or directly to consumers at local markets. Urban vegetable wholesale markets link outside wholesale markets to urban consumers via vegetable traders, vegetable retailers and supermarkets. Emerging supermarkets in India were quick to sell fresh produce in addition to shelf-stable food items (Nuthalapati, Sutradhar, Reardon, & Qaim, 2020). While supermarket chains in India have quickly spread since the 2000s (Thomas Reardon & Minten, 2011), fresh vegetables in India are still mostly sold to consumers by traditional retailers (Trebbin, 2014). Recent efforts in India to modernize the food supply chain include the promotion of aggregation models, including producer organizations and cooperative, as well as investments in market infrastructure, including online trading platforms and storage facilities (Pingali et al., 2019).

Study overview

This study was conducted across tomato supply chains in Chittoor district, Andhra Pradesh and Hyderabad city, Telangana. We collected data from smallholder farmers, tomato traders, urban vegetable traders and urban vegetable retailers at farm-level, wholesale market and retail stages. Chittoor district is a major tomato-producing region in Andhra Pradesh. Peak tomato harvest occurs during April to July (Subramanian, 2016). Many smallholder tomato farmers in Chittoor district sell their produce at the Madanapalle tomato market, which is the largest tomato wholesale market in Andhra Pradesh, a major tomato trading hub in India (Modekurti, 2016). Tomato traders purchase tomatoes from smallholder farmers during open auctions. Urban vegetable wholesale markets in Hyderabad trade tomatoes sourced from within and outside of Telangana, including from Madanapalle. Urban vegetable retailers typically purchase tomatoes from vegetable wholesale markets and sell them to urban consumers.

Research objectives

Using a supply-chain approach, we sought to explore food loss of a perishable vegetable and identify critical loss stages as well as facilitators and barriers to reducing food loss. The findings from this research will inform future work to refine FL&W definitions, measurement methods and metrics. This study aims to:

1. Examine the extent and stages of food loss along tomato supply chains from farmer to retail; comparing estimates using different final use destinations; and exploring determinants of loss at stages where loss is concentrated

2. Identify important quality attributes across supply chain actors and the relationships between quality metrics, both subjective and objective
3. Critically compare institutional FL&W definitional frameworks with a collective smallholder vegetable farmer definitional framework

Chapter overviews and key findings

Chapter Two provides the detailed study design and methodology. In this chapter, we describe the formative fieldwork and supply chain mapping that informed the supply chain sand study site selection. Additionally, we provide details on participant recruitment and enrollment and data collection methods. Finally, we describe the impact of the COVID-19 pandemic on data collection.

Chapter Three presents findings on the extent, stages and determinants of food loss along the tomato supply chains from farm to retail stages. We find that farmers encounter the most food loss of any supply chain actor, and food loss is concentrated at the farm level, before tomatoes are brought to the market. Peak harvest season is a significant determinant of food loss at several stages including reported pre-harvest quality loss; field-level, post-harvest loss; and market-level, pre-auction loss. Additional determinants of loss, including expected price and grading and sorting, suggest that acceptable quality thresholds at the market may shift depending on the demand for tomatoes.

Chapter Four presents findings on food quality assessment from the perspective of supply chain actors and associations between ascorbic acid and quality intensity and ripeness. We find that supply chain actors assess tomato quality by looking for several quality attributes, nearly all of which are assessed visually. We also find that market grades distinguish different quality tomatoes, based on quality intensity, across supply chain actors. Finally, we find increasing quality intensity is associated with a decrease in ascorbic acid concentration. When considering ripeness level, tomatoes that are less than red ripe are associated with a lower ascorbic acid concentration than red ripe tomatoes, and tomatoes that are more than red ripe are associated with a higher ascorbic acid concentration than red ripe tomatoes.

Chapter Five presents findings on a comparison of institutional FL&W definitional frameworks with a collective definitional framework conceptualized from group discussions with smallholder vegetable farmers, a key stakeholder group. We find three major gaps where institutional FL&W definitional frameworks do not align with smallholder farmer frameworks; some institutional frameworks do not consider animal feed as a loss destination, exclude the pre-harvest stage when produce is market ready from loss estimates, and not measuring food quality loss.

Future directions

Our study findings have salient implications for future work on measuring FL&W of perishable vegetables in South India and globally. First, we find that the frequency and extent of food loss is highest for farmers, specifically at the farm level. Farmers are responsible for investing in activities and inputs from production to harvest, post-harvest and marketing, all of which can prevent or contribute to food loss. Using a micro-approach, we find that pre-harvest quality loss is a significant determinant of post-harvest food loss, possibly due to price fluctuations during peak season and the impact of market price on acceptable quality thresholds. Based on group discussions with vegetable farmers, we find that pre-harvest losses of market-ready vegetables are also likely critical stage for food loss, though difficult to measure. Importantly, the Global Food Loss Index (GFLI), the indicator used to monitor food loss under SDG target 12.3, excludes the pre-harvest stage. Lack of FL&W data at the pre-harvest stage may underestimate on-farm losses for perishable fruit and vegetable groups.

We also contribute to the ongoing debate in FL&W definitional frameworks with regard to loss destinations. We find significant differences in food loss estimates at the farm and retail levels when we compare estimates using different food loss destinations (non-food and non-productive uses). Our qualitative findings reveal that vegetable farmer's take an economic perspective when defining FL&W, and consider any non-food use, including animal feed, as a loss destination. The definitional framework used to monitor SDG target 12.3, again, does not align with the farmer framework in our study, as it considers only non-food, non-productive destinations as loss destinations.

The findings from our study also contribute to the evidence on supply chain actor perceptions along tomato supply chains in South India. While we find all supply chain actors considered observable search quality attributes, future work is needed to elucidate the relative importance of individual search attributes more clearly to product marketability and food safety. Finally, we find associations between ascorbic acid concentration and quality intensity and ripeness. We were not able to follow tomatoes the length of the supply chain from Madanapalle to Hyderabad in order to explore transportation and handling factors on nutrient quality loss. Future studies should explore changes in nutrient content, under real-world conditions, as fresh produce move along the supply chain. Because food quality loss consistently precedes quantitative food loss, accounting for qualitative losses in FL&W definitional frameworks remains important for identifying loss reduction opportunities particularly for fresh, perishable produce.

CHAPTER 2

STUDY DESIGN AND METHODS

Background and objectives

Basic study design and rationale

This study was carried out in Chittoor district, Andhra Pradesh and Hyderabad city, Telangana from 2019-2020. We used a micro-level approach to explore food losses and food quality losses of major supply chain actors to understand losses at across a perishable vegetable supply chain (Delgado et al., 2017). Based on existing agriculture production data and formative fieldwork, we determined that tomato supply chains would make a suitable study vegetable. Tomatoes are grown year-round in India, most often consumed fresh, and are highly perishable, thus at risk for food loss. We collected data from smallholder farmers and tomato traders in Chittoor district, and vegetable traders and vegetable retailers in Hyderabad.

Study objectives and questions

Using a supply-chain approach, we examined the extent, stages, and determinants of food loss along tomato supply chains from farm to retail. In addition to exploring food loss, we aimed to identify important quality attributes that supply chain actors use to assess product quality and relationships between different quality metrics. Finally, we sought to elucidate vegetable farmers' perspectives and experience related to perishable vegetable food loss in order to compare their collective frameworks with institutional food loss and waste (FL&W) definitional frameworks. The major questions for this study are:

1. What is the extent of food loss across major supply chain stages of fresh tomato supply chains in South India from farm to urban retail?
2. What are the determinants of loss at supply chain stages where losses are concentrated?
3. How does each supply chain actor assess quality, and what are important quality attributes?
4. How do observable quality metrics compare to commonly used market grades?
5. What are the associations between observable quality attributes and ascorbic acid content?

6. How do vegetable farmers perceive the food loss pathways and what are their motivations for food loss reduction?
7. How does the vegetable farmers' collective FL&W definitional framework compare to institutional FL&W definitional frameworks?

Formative work

Supply chain selection

The study supply chain was selected based on formative work conducted from June - July 2018 in Delhi; Lucknow, Uttar Pradesh; Hyderabad, Telangana; Madanapalle, Andhra Pradesh; and Kolar, Karnataka. At each location, key informant interviews were held with supply chain actors and NGO representatives involved in food supply chains. Additionally, direct observations were done at the farm, wholesale, and retail levels.

The criteria used to evaluate an appropriate study food included a highly perishable fruit or vegetable that is harvested year-round and is commonly consumed throughout India and globally. To evaluate perishability, we use a classification of relative perishability of fresh horticultural crops (Adel A. Kader, 1992). Informants regularly reported that, in India, the three most important vegetables are potato, onion and tomato. This list holds true when considering vegetable and tuber production quantities in India (FAOSTAT, 2018). Unlike potatoes and onions, tomatoes are highly/very highly perishable, even at near-optimal temperature and relative humidity conditions (Adel A. Kader, 1992). Based on interviews and direct observation of farms, wholesale markets and retail outlets, modified storage conditions for fresh tomatoes are not used.

Tomatoes are produced and consumed globally. In low- and middle-income countries, tomatoes are the fourth most economically-valuable food crop produced (Schreinemachers, Simmons, & Wopereis, 2018). India is ranks second in tomato production, behind China (FAOSTAT, 2020). Tomatoes are produced year-round in India and are widely consumed across the different regions.

Mapping the tomato supply chain

Major channels through which tomatoes are bought and sold are through state-run *mandis* (wholesale markets). In the wholesale markets, smallholder farmers sell their tomatoes to major traders. In the vegetable markets, traders source various vegetables from the wholesale market before selling to other wholesalers and retailers. Therefore, the supply chain actors along these major channels include smallholder farmers, tomato traders, vegetable traders and vegetable retailers.

In 2017-2018, Andhra Pradesh produced the most tomatoes of any Indian state and was the most productive (GOI, 2019b). Within Andhra Pradesh, Chittoor district is a major tomato producing district (Government of Andhra Pradesh, 2018c). Located about 550 km north of Chittoor district, Hyderabad, Telangana is the sixth most populous metropolis in India (GOI, 2011b), is among the many cities that imports tomatoes from Chittoor district.

Farmers growing tomatoes in Chittoor district are smallholders, with average operating land areas of 2.13 acres (Government of Andhra Pradesh, 2018a). Most people in Chittoor district are involved in agriculture where 22.5% percent of people work as cultivators and 38.7% of people work as agricultural laborers (GOI, 2011a). Peak tomato harvest in Chittoor district occurs during April to July, which is an off-season in much of India (Subramanian, 2016) (Reddy, 2019). Farmers harvest tomatoes from the same plot multiple times during a harvest period. During formative work, farmers indicated they usually harvest tomatoes eight times, each about 5 days apart. Among key informants interviewed were agriculture specialists from APMAS and the World Vegetable Center who lead programs to engage with tomato farmers on improved production practices and market linkages in Chittoor district.

The Madanapalle tomato market in the Madanapalle sub-district of Chittoor district is the largest tomato market in Andhra Pradesh, and is among the major tomato trading hubs in India (Modekurti, 2016). Open auctions are held mid-morning and coordinated by a commission agent. Farmers organize their tomatoes into lots based on the market quality grade (e.g., 1st, 2nd, etc.). Each farmer sells their tomatoes through only one marketing agent, and tomato traders buy from more than one agent. Once sold, the tomatoes are repacked and loaded for transport out of the market. Often, tomatoes are repacked into plastic crates and transported via large, commercial trucks. Weighing tomato crates was never observed nor reported. Key informants reported that tomato crates generally come in two sizes, 15 kg and 25-30 kg.

Vegetable wholesale markets in Hyderabad import tomatoes from outside of Telangana, including from the Madanapalle tomato wholesale market. Vegetables arrive to the wholesale market very early in the morning, before sunrise. Trading is usually finished by late morning or early afternoon, depending on the market. Vegetable retailers selling tomatoes include modern and traditional retail outlets and purchase their tomatoes from the vegetable wholesale markets.

Key informants listed quality attributes: ripeness, color uniformity, size, and evidence of pest or disease damage. Grading and sorting is first done at the farm level and may be done at the wholesale and retailer levels, depending on the trader or vendor. Therefore, this study considers fresh tomatoes only, as opposed to processing tomatoes, because the important quality attributes for fresh tomatoes (e.g. taste, appearance, handling characteristics) are different from important attributes of processing tomatoes (e.g. viscosity and solids) (Shuch & Bird, 1994).

Data collection methods

Chittoor district: village selection

Of the 66 sub-districts in Chittoor district, we purposively selected Madanapalle and, neighboring, Nimmanapalle sub-district as study sites due to their close proximity to the Madanapalle tomato wholesale market. Since the Madanapalle tomato market is a major tomato trading hub, we assumed tomato farmers in these sub-districts would likely bring their tomatoes to this market. Of the 15 panchayats (collection of villages) in Madanapalle and 10 panchayats in Nimmanapalle, we selected four panchayats from each sub-district using stratified random sampling. Panchayats were stratified based on the coverage area of the World Vegetable Center and/or APMAS programs on tomato production and marketing. Panchayats were randomly selected using the random number function in Microsoft Excel and selecting the lowest numbers within each stratum. Finally, using horticulture farmer data from the previous year (Government of Andhra Pradesh, 2018b), we identified villages with ≥20 farmers that grew tomatoes and randomly selected one village per study panchayat. During visits with panchayat leaders, two villages were reported to have no households that were growing tomatoes in the coming season. We therefore selected the next village listed on the randomized list for a total of eight villages. To enroll additional households after the 2019 peak season, we used village rosters to enroll households in Regadagollapalle and Venkappakota, and door-to-door recruitment in E. Machireddigari Palle, since no village roster was available. During the course of the study, after the 2019 peak tomato-harvest season, less than one third of enrolled farmers from three *panchayats* harvested tomatoes. From late-July to early-September 2019 we expanded the study coverage area and recruited and enrolled farmers from three additional villages across the three *panchayats*. In CTM and Kondamarri Palle *panchayats*, we selected the villages from randomized lists used in the initial enrollment. In the case of Rachevetivari Palle *panchayat*, there were no other villages from the horticulture farmer data that had ≥20 farmers growing tomatoes. Therefore, we went we recruited participants from the village adjacent to the study village, and screened farmers for eligibility by going to every other door. Based on our interactions with this community, the two villages were essentially the same village, separated by caste.

Chittoor district: participants

Tomato farming households were enrolled into the study in February 2019. Using a roster of households that grew tomatoes the previous year in study villages, we randomly ordered households to screen for eligibility and aimed to enroll 15 households per village. Households were eligible to participate if they reported tomatoes are one of their major vegetable crops produced, by weight, and if they planned to grow tomatoes during the survey period. Tomato traders at the Madanapalle tomato wholesale market were invited to participate if they purchased a lot of tomatoes from a participating farm household at auction on the same day the farm household was surveyed at the wholesale market. Tomato traders were consented at the time of their first survey. At any follow-up surveys, a traders' consent was verified using the phone number they provided at enrollment.

Hyderabad district: market selection

Three Agricultural Produce Market Committees (APMCs) operate in Hyderabad district. We selected one wholesale market per APMC for the study. Bowenpally and Gudimalkapur market committees each oversee one market that trades tomatoes. The Hyderabad APMC oversees two wholesale markets that trade tomatoes, Madannapeta and Meeralamandi. We purposively chose Madannapeta because it deals with larger volumes of tomatoes. We used snowball sampling to select retail outlets in Hyderabad that sold tomatoes.

Hyderabad district: participants

Across the three APMC vegetable markets, we carried out a census of vegetable traders in April 2019 to assess study eligibility. We invited vegetable traders to participate in the study if they planned to trade tomatoes during the study period and tomatoes were one of their three main vegetables traded. At the time of enrollment, we asked participants to refer vegetable retailers who sell tomatoes. Some vegetable traders were reluctant to refer retailers at the time of enrollment. After building rapport with the traders during the survey period, traders were more willing to refer retailers. When tomato traders provided only a specific location of the retailer, without their name, we went to that location or market and enrolled eligible retailers selling tomatoes. Vegetable retailers were eligible if they planned to sell tomatoes during the study period, and were recruited over a period of three months, from April-July 2019.

Pile sort group discussions

We conducted pile sort group discussions with tomato farmers and tomato traders to identify important sensory attributes, quality categories and marketability of tomatoes. During this activity, participants sat in a circle and were each given a basket of tomatoes. We aimed for four to six participants per discussion and did not separate people based on gender. The tomatoes used in the pile sort were sourced from farms in a different village than the discussion village and harvested on the day of the group discussion. The tomatoes had not been graded or sorted. For the pile sort activity, we asked each participant to think about how they determine tomato quality, and group tomatoes into piles so that similar tomatoes in the same pile (Weller & Romney, 2011). We did not constrain the number of piles participants could make. Participants were given one opportunity to sort items before we began the group discussion.

Once participants were finished grouping their tomatoes, we placed markers on each tomato group to indicate the participant number and pile (e.g., 1-1 for participant 1, pile 1). The markers were only used to facilitate the discussion as the group referred to the different piles. The Project Coordinator led the group discussions in Telugu, which were audio recorded. The semi-structured discussions asked participants to explain why they grouped tomatoes as they did. We asked probing question on quality attributes, destinations or uses for tomatoes, and marketability.

Following the first two pile sort discussions, we took photos of each pile to use as reference photos in supply chain actor surveys. For each photograph we placed tomatoes on a black cloth and out of direct light. We placed 1, 2 and 5 rupee coins, one each, next to the pile as a size reference. Twenty photos were purposively selected to use throughout the surveys. At each survey, the tablet would random generate a number between 1-20 for the participant to answer quality attribute-related questions.

Development and delivery of supply chain actor surveys

Survey questionnaires were developed for each supply chain actor: farmers, tomato traders, vegetable traders and vegetable retailers. We aimed to capture information on quantity and quality loss, activities and inputs, and expected selling price. The recall period for each survey was the specific survey day, except for some retailer questions that referred to tomato sales on the previous day. We used this short recall period to reduce potential recall bias . Surveys were carried out from February to December 2019 in Chittoor district, and from April 2019 to March 2020 in Hyderabad. Surveys were conducted in-person in Telugu by trained enumerators using the Android-based application Open Data Kit (http://www.opendatakit.org/).

In each supply chain actor survey, we aimed to capture information on food loss using subjective and objective measures. Questions on self-reported quantity and quality loss at the different supply chain stages were adapted from Delgado et al. (Delgado et al., 2017). We used crate counting as an objective measure of quantity loss where participants reported the quality grade and destinations for each group of crates. Potential destinations that would count as food loss destinations included animal feed, compost and trash. Crate counts were only used during surveys with farmers and retailers due to logistical limitations. Tomato traders and vegetable traders deal in large quantities of tomatoes and, in the case of vegetable traders, trades occurred before sunrise. Therefore, we were not able to observe all crates that passed through these traders.

Surveys captured information on tomato quality using several approaches. Supply chain actors reported the tomato quality grade(s) as well as important tomato quality attributes. Additionally, we collected information on perceived ripeness levels using a color classification chart (United Fresh Fruit and Vegtable Association & USDA Agricultural Marketing Service Fruit and Vegetable Division, 1975). While piloting the original six-level color classification chart, respondents reported ripeness levels above sixth "red" category and referred to this more intense red color as "super-red". Therefore, we included one additional ripeness level in the final chart, similar to Suslow & Cantwell (Suslow & Cantwell, 1997). Finally, we aimed to capture overall perceived quality and asked supply chain actors to market the tomato quality intensity along a line with labeled endpoints "low quality" and "high quality" (Lawless & Heymann, 2010).

To compare perceptions of quality across supply chain actors, we showed photographs of tomatoes to survey respondents and captured information on quality grades, intensity, price and destination. The photographs used were taken during pile sort group discussions, described in detail later in this chapter. Among 20 different photos, 2-3 photos were randomly selected using a random number generator programmed into the survey constrained to the 20 photos. We aimed to include the photograph-referenced questions across all surveys.

In Chittoor district, we conducted surveys the farm-level and market-level. At the farm-level, we surveyed farmers on the day they harvested tomatoes from the vine. We aimed to survey three harvests from the same plot and harvest period. This farm-level survey captured information on the quantity and quality of harvested tomatoes, production activities and inputs, post-harvest activities, and on-farm quantity and quality loss. The day after harvest, we surveyed the farmers and tomato traders at the Madanapalle tomato wholesale market. At market-level, information was collected on pre-auction activities and quantity and quality loss, auction quantities and prices, post-auction activities and quantity and quality losses. In Hyderabad, vegetable traders and vegetable retailers were surveyed monthly at the wholesale market and retail outlet, respectively.

The 2019 Indian general election began mid-April 2019. We were unable to travel to farm field during the month leading up to the election due to local concerns of voting interference. From March 14 – April 13, 2019, we conducted farm level surveys at the Madanapalle wholesale market. Therefore, farm level surveys conducted during this time were limited to households that brought their harvest to the Madanapalle tomato market and excluded households that harvested and brought their harvest to another wholesale market. Additionally, the recall period for the farm-level survey was the previous day rather than same-day, and we were unable to observe a crate count.

Changes to surveys after data collection began

We made several changes to our surveys once data collection began. Due to time limitations expressed by tomato traders and vegetable retailers, we only included photograph-referenced questions for in farmer and vegetable retailer surveys. Due to timing of market activities at the tomato wholesale market, we added survey questions to capture the timing of our survey and market activities. For example, tomatoes were sometimes already repacked and loaded onto trucks before tomato traders gave a survey. We also added questions to note when tomato traders often mixed crates from different auctions during the repacking phase.

Vegetable traders, in particular, were the most sensitive to responding to the survey, often expressing concerns related to the survey length, questions of food loss, and sharing of information with the marketing committees. In response to these concerns, we shortened the survey, removing questions about market activities, specific tomato quality groups and their destinations. With regard to concerns of sharing information, we met with concerned traders and revisited the consent form, again explaining the confidentiality of their responses and how the data would be used. After building rapport with vegetable traders over several survey months, traders were willing to respond to questions directly asking about food loss, and we reintroduced these questions into the survey.

Cost of production and information sources

Due to low numbers of tomato harvests planned for January and February 2020 among our participants, we developed an additional survey to capture specific tomato production activities and inputs during the farmers' most recent harvest, including detailed costs, as well as information sources and decision-making processes related to production and marketing. The aim of this survey was to better understand the costs farmers incur during the production stage as well as information sources that might influence harvest and postharvest decisions and, ultimately, food loss. This survey was conducted in February 2020 with farm households already participating in the main food loss survey.

Tomato ascorbic acid

Ascorbic acid in tomatoes was measured by reflectometer. Ascorbic acid was measured in sampled tomatoes on the same day that tomatoes were collected. 100 mg samples of tomato flesh were sampled from tomatoes using a 16 gauge, angle-cut tipped syringe needle (Tang & Lee, 2016). We sampled from three regions of each tomato based on evidence that the amount of ascorbic acid may change with sunlight exposure during production (Lee & Kader, 2000). Each sample was mixed with 200 μl extracting solution (0.01 M oxalic acid and 5% acetic acid) and 2 mg polyvinylpolypyrrolidone (Divergent, Millipore). The mixture was homogenized with an electric motor and pellet pestle for one minute and then spun in a mini centrifuge (Fischer Scientific) for one to two minutes, until a pellet formed, and the supernatant appeared clear and colorless. The ascorbic acid concentration was measured with an RQflex plus 10 Reflectoquant (Millipore) using ascorbic acid analytical test strips (25-450 mg, Millipore). After the lamp in the RQflex plus 10 broke, we replaced the machine with an RQflex 20 Reflectoquant (Millipore), using the same analytical test strips. All testing in 2020 was then conducted using the RQflex 20. Each test strip was saturated with the supernatant and transferred into the RQflex plus adapter for the measurement result. Values below the 25mg/L detection limit were treated as missing values. A stock solution of ascorbic acid was prepared by dissolving 25 mg of L-ascorbic acid (Avantor Rankem) with 10 ml of the extractant solution. Aliquots of ascorbic acid were diluted with the extractant solution to provide standards used to construct a standard curve from 25 to 400 mg/L. The standard curve was used to calculate the ascorbic acid measured value (mg/L). The ascorbic acid concentration in each sample was expressed in mg/100g fresh weight and calculated using the equations provided by Millipore (Millipore Sigma, 2021a, 2021b). Since tomatoes are approximately 94% water (Longvah, Ananthan, Bhaskarachary, & Venkaiah, 2017), we accounted for this additional water and calculated the total volume of extractant solution as the sum of the volume of oxalic acid/acetic acid and the volume of water coming from the tomato sample. Finally, we calculated the mean ascorbic acid concentration for each tomato.

$$Ascorbic\ acid\ (mg/100\ g\ fresh\ weight)\ =\ 100\ x\ \frac{Measured\ value\ (mg/L)\ x\ Vol.extractant\ solution\ (L)}{Weight\ of\ sample\ (g)}$$

In Madanapalle, ascorbic acid analysis was carried out by two trained project staff in the project office. Because room temperatures could reach as high as 38°C, we used an air conditioning unit to maintain consistent room temperature between 25-26°C on ascorbic acid measurement days. In Hyderabad, ascorbic acid analysis was carried out by a trained ICRISAT lab technician and a trained project staff member at an ICRISAT lab facility. Both sites followed the same protocol.

We planned to sample tomatoes from the same harvest as they traveled from the field to a wholesale market in Hyderabad by way of Madanapalle. Ascorbic acid measurement was done on fresh tomatoes, the same day they were sampled. We sampled tomatoes at the farm level from study farmers on the day of their harvest. For the same farmer and harvest, we sampled tomatoes again the next day at the Madanapalle tomato market, prior to auction. To sample the tomatoes from the same harvest after transport to Hyderabad, we connected with a vegetable trader in Bowenpally market with the help of a tomato trader in the Madanapalle market. A sample crate of tomatoes from the harvest being tested was packed, labeled and included in the truck shipment from the Madanapalle tomato market to the vegetable trader in Bowenpally market, in Hyderabad. A project enumerator in Hyderabad picked up the labels crate in Bowenpally market and randomly sampled tomatoes throughout the crate to fill a secondary (smaller) basket that they transported to the lab at ICRISAT. The three day sampling schedule is summarized: **Day 1**: Farm-level, harvest day; **Day 2**: Madanapalle auction day; **Day 3**: Hyderabad wholesale market day. Ascorbic acid analysis in Chittoor district was carried out May 2019 through October 2019. One tomato testing day was completed in Hyderabad (from tomatoes from a Madanapalle harvest chain) late August 2019.

Focus group discussions

Focus group discussions took place within villages where we were conducting a quantitative survey. We used snowball sampling to recruit focus group participants by reaching out to study participants. Focus group discussions were scheduled based on participant availability to make sure participants had enough time for the discussion. At the time of the focus group discussion, the project coordinator provided each farmer with additional details about the study and the objective of the focus group discussion and obtained informed consent. We provided refreshments, snacks and cold drinks to participants.

The trained project coordinator led all focus group discussions using a semi-structured discussion guide with 13 questions organized in an hourglass design (Hennink & Leavy, 2014). After reviewing the informed consent and discussion procedures, we opened the discussion with “ice breaker” questions, to make them feel comfortable contributing to the discussion (Hennink & Leavy, 2014). These were simple questions about vegetable production, including how long they have been a producer and the types of vegetables they grow. The main discussion focused on reasons for growing perishable vegetables and the production and post-harvest activities they are involved in. Key questions outlined several scenarios where food loss may occur, such as leaving market-ready vegetables in the field, not bringing harvested vegetables to the market, and not selling vegetables that they had brought to the market. We asked specific questions regarding quantity food loss and food quality loss, describing each term based on their experiences and if/how it affects their decision-making. We closed the discussion with questions on strategies farmers use to reduce losses and thoughts on growing vegetables in the future. Discussions were conducted in Telugu. The audio recordings were translated and transcribed into English.

Impact of COVID-19 on data collection

Survey data collection was permanently suspended in March 2020 due to the COVID-19 pandemic and concern for participant and staff safety. This suspension had implications particularly for data collection from farm households that were enrolled after the 2019 peak season. We were not able to survey these late-households during the 2020 peak season, resulting in an imbalance of data collected across the study panchayats. Based on phone calls with some participant farm households we were informed that farmers were not harvesting or planting tomatoes as of early June 2020. Lack of labor was given as one reason. Another reason was the intermittent closure of the Madanapalle tomato market.

Access to the Madanapalle tomato market had also been restricted to only those carrying out business: farmers, laborers and tomato traders. Truck drivers and truck laborers were not allowed to get out of the vehicle at the market to limit the number of people exposed to one another. Periodic cases were found at the market, resulting in intermittent market shutdowns. Sporadic restrictions and lockdowns in Madanapalle combined with increasing cases hampered any effort to restart survey data collection.

In Hyderabad, enumerators rely on public transportation and autos for meeting at different wholesale markets and traveling around the city to retail outlets. Given the density of an urban area where social distance would be challenging, data collection also remained suspended. Unfortunately, the surveys in Hyderabad started in April 2019 and took several months to build trust with vegetable traders to respond to the survey and refer vegetable retailers.

We also suspended ascorbic acid analysis in Madanapalle and Hyderabad. In Hyderabad we were unable to restart this activity due to the same challenges affecting the survey. In Madanapalle, we were able to collect tomato samples and measure the ascorbic acid when restrictions in Madanapalle were eased and the office neighborhood was not under a restricted zone.

Due to time to set up the logistics of sending tomatoes to Hyderabad and testing the same harvest in Madanapalle and Hyderabad, there was only one round of tomatoes that was sampled for ascorbic acid analysis across the supply chain. Therefore, there is sufficient data only to consider ascorbic acid concentration and tomato quality attributes.

Ethical approval

This study was approved by the Cornell University Institutional Review Board (protocol ID 1810008329).

CHAPTER 3

EXTENT, STAGES AND DETERMINANTS OF FOOD LOSS ALONG TOMATO SUPPLY CHAINS IN SOUTH INDIA

Introduction

The current global food system continues to struggle to provide healthy diets in the setting of increasing environmental changes. The United Nations recognizes the interconnected relationship between food security and sustainable food production systems in Sustainable Development Goal 2, zero hunger. Shifting diets towards healthier, environmentally sustainable dietary patterns will require reduced consumption of unhealthy foods and increased consumption of healthy foods, such as fruits and vegetables, as well as improved food production practices and food loss and waste (FL&W) reductions (Willett et al., 2019). In many global regions, there are already deficits in the availability of fruits and vegetables to meet dietary intake recommendations, particularly in sub-Saharan Africa and South Asia (Bahadur KC et al., 2018; Mason-D'Croz et al., 2019; Siegel et al., 2014). Persistent fruit and vegetable inadequacy will slow progress towards achieving SDG target 2.1, to ensure food security for all.

The food supply in any given region is a function of food production, imports, exports and losses. Fruits and vegetables are among the more perishable food groups and are more at risk of FL&W. Sustainable Development Goal target 12.3 broadly aims to halve food waste and reduce food loss by 2030, as part of SDG 12 on sustainable consumption and production. Reliable FL&W estimates along the supply chain are unavailable, partly due to the lack of standard measurement frameworks and heavy reliance on indirect measurement and secondary data (Fabi et al., 2021; Xue et al., 2017). Simplified FL&W figures may be misleading because the extent of FL&W differs between supply chain contexts and factors across food groups and seasons (Hodges et al., 2011). Further complicating the reliability and comparison of FL&W estimates is the lack of a harmonized FL&W definition, often differing in terms of the supply chain stages considered and the perspective of final use adopted, when to count unconsumed food as FL&W (Chaboud & Daviron, 2017; Fabi et al., 2021; HLPE, 2014).

As such, FL&W estimates for fresh fruits and vegetables vary widely between and within supply chain stages and global regions (FAO, 2019).

Several recent studies have used different methods for collecting region- and supply chain-specific data to estimate food loss of several perishable foods. Delgado et al. (2020) compared four measurement methodologies (self-report, category, attribute and price methods) to measure quantity loss and quality loss from pre-harvest to distribution of seven staple foods across five countries, including potatoes in Ecuador and Peru (Delgado, Schuster, & Torero, 2020). The authors find that producer self-reported food loss is significantly lower, between 10 and 15 percentage points, than loss figures estimated by the three other measurement methodologies. All four measurement methods combine quantity loss and quality degradation. Therefore, loss estimates do not distinguish between the extent of food loss, food that has been removed from the supply chain; and quality loss, food remaining in the supply chain that has quality deterioration. Distinguishing between food loss and food quality loss is important, particularly from a food security perspective where food may be removed from the supply chain based on an over-emphasis of appearance quality standards, despite the product being safe to consume (A. A. Kader, 2010).

Minten et al. (2016) surveyed supply chain actors along potato value chains form farm to retail in three Asian countries: China, India and Bangladesh (Minten et al., 2016). Using comparable methodologies across countries to estimate quantity losses based on self-report, the authors estimated the total loss of potatoes in India in the harvest period and off-season, 3.2% and 3.3%, respectively. In Bangladesh, total losses were estimated to be 5.2% and 6.4% in each period, respectively. Both India and Bangladesh reported having cold storage capacity, in contrast to China where total potato loss was 9.9% in the harvest period, and no data were available for off-season losses (Minten et al., 2016).

Using semi-structured questionnaires, Chaboud (2017) estimated food loss along a traditional tomato supply chain in Cali, Colombia from self-reported data by farmers, traders and retailers (Chaboud, 2017). In addition to post-harvest losses at the farmer level, the author estimated food loss at the harvest stage, the proportion of tomatoes left unharvested out of total available tomatoes. The recall period for farmers was the last complete tomato crop cycle, whereas the recall period for traders and retailers was the week before the survey.

Losses were highest at the farm level; 7.5% of tomatoes that were ready for harvest were left on the field, and 13.6% of harvested tomatoes were not sold. At all stages, most food loss was diverted to garbage, as opposed to animal feed, compost, or donation/home-consumption (Chaboud, 2017).

Several studies have used the *FLW Accounting and Reporting Standard* (Craig Hanson et al., 2016) to determine quantity food loss along the supply change using direct measurement. In a case study of two commercial domestic tomato supply chains in Australia, McKenzie et al. (2017) quantified food loss from farm to retail by weight, using direct measurement, and by volume, using crate counts (McKenzie et al., 2017). Data collection was carried out over a short duration from November to December 2014. The percent of loss as a fraction of potential harvest was 40% and 56% for each supply chain. In both supply chains, the majority of loss occurred at the field level, where tomatoes left in the field unharvested. Wholesale market prices were the major reason for leaving product unharvested (McKenzie et al., 2017). Macheka et al. (2018) also used crate counting, recorded by the study participants, to quantify food loss along tomato supply chains in Zimbabwe, from harvest to transportation stages. Using snowball sampling, the researchers recruited small-scale subsistence farmers, small-scale commercial farmers, and large-scale commercial farmers to participate in the study. The authors found that commercial farmers lost 1% ± 0.9 of their harvest, whereas the group consisting of mostly subsistence farmers lost 4.9% ± 2.1 of their harvest. Deciding on the tomato maturity to harvest, moment to harvest and storage practices were significantly associated with food loss (Macheka et al., 2018).

In this current study, we examined the extent, stages and determinants of food loss using primary data collected along a perishable vegetable supply chain in South India. The stage and extent of food loss depends, partly, on the underlying food supply chain and marketing structure. Most perishable vegetables are harvested progressively; several harvests occur in the same plot over a single season, when only the part that is at proper maturity is harvested. Post-harvest, under near-ideal conditions, vegetables have a wide storage life range, from 16 to less than two weeks for low to very high perishability, respectively (Adel A. Kader, 1992). However, controlled storage conditions are typically not available in India for most fresh vegetables (Minten, Reardon, Singh, & Sutradhar, 2014). Under these circumstances, fresh vegetables must quickly reach the market, and any delay can lead to loss. A number of factors can exacerbate food loss between farm and retail, including pre-harvest damage in which defects emerge prior to harvest, post-harvest practices and handling, and market conditions and prices (HLPE, 2014; Adel A. Kader & Rolle, 2004). We estimate food loss across several supply chain actors from farm to retail stages, at peak-harvest and off-peak seasons. Unique to this study, we compare food loss estimates after applying different final use definitions to classify food loss and better understand the impact of food loss definition criterion on estimates. Finally, we explore activities and factors that are associated with food loss at supply chain stages where food loss is found to be concentrated.

Methods

Case study supply chain and location

Tomatoes are an important horticultural crop in India. Along with onion and potato, tomato is among the top three vegetables and tubers produced (FAOSTAT, 2018). India ranks second in global tomato production, behind China (FAOSTAT, 2020). An estimated 13 kg/person of fresh tomatoes and tomato products were available in 2018 (FAOSTAT, 28 DEC 2020). Less than one percent of tomatoes produced in India are processed (Subramanian, 2016).

Smallholder farmers are primarily responsible for tomato production in India. Farmers usually sell tomatoes to local aggregators or through public, state-run *mandis* (wholesale markets). In urban vegetable wholesale markets, traders source a variety of vegetables, including tomatoes, from wholesale markets and sell to other urban traders and retailers. Controlled atmosphere storage is not typically used in fresh tomato supply chains; most cold storage facilities in India are used for potato storage (Minten et al., 2014). Since fresh tomatoes are highly/very highly perishable vegetables (Adel A. Kader, 1992), tomatoes reach final consumers within one week from harvest. The majority of fresh vegetables in India are sold by traditional retailers as opposed to modern retail outlets (Trebbin, 2014).

We carried out this study in Chittoor district, Andhra Pradesh and Hyderabad city, Telangana. Andhra Pradesh produced the most tomatoes of any Indian state in 2017-2018 (GOI, 2019b), and Chittoor district is a major producing district in Andhra Pradesh (Government of Andhra Pradesh, 2018c). Located about 550 km north of Chittoor district, Hyderabad is the sixth most populous metropolis in India (GOI, 2011b), and is among the many cities that import tomatoes from Chittoor district.

Farmers growing tomatoes in Chittoor district are smallholders, with average operating land areas of 2.1 acres (Government of Andhra Pradesh, 2018a). Most people in Chittoor district are involved in agriculture either as cultivators or agricultural laborers, 23% and 39% of the population, respectively (GOI, 2011a). Peak tomato harvest occurs during April to July (Subramanian, 2016). The Madanapalle tomato market in Chittoor district is the largest tomato wholesale market in Andhra Pradesh, and is among the major tomato trading hubs in India (Modekurti, 2016). Commission agents coordinate auctions where farmers sell their tomatoes through one marketing agent to tomato traders. In reality, commissions agents are also tomato traders themselves. After the auctions are complete, tomatoes are repacked and transported via large, commercial trucks.

Vegetable wholesale markets in Hyderabad import tomatoes from within and outside of Telangana, including from the Madanapalle tomato wholesale market. Three Agricultural Produce Market Committees (APMCs) operate a total of four vegetable wholesale markets that traded tomatoes in Hyderabad district. Vegetables arrive to the wholesale market very early in the morning, before sunrise. Trading is usually finished by late morning or early afternoon. Vegetable retailers, both traditional and modern outlets, typically purchase tomatoes from vegetable wholesale markets.

Participant recruitment

Among the 66 sub-districts in Chittoor district, we purposively selected Madanapalle and Nimmanapalle sub-districts for the study due to their close proximity to the Madanapalle tomato wholesale market. To recruit farm households, we used a stratified, multistage sampling design. Of the 15 *panchayats* (collection of villages) in Madanapalle and 10 *panchayats* in Nimmanapalle, we randomly selected four *panchayats* from each sub-district. *Panchayats* were stratified based on the coverage area of a local organization implementing tomato production and marketing programs that were not associated with this study. Using a roster of tomato producing households in each *panchayat* from the horticulture department, we identified villages with ≥20 households that grew tomatoes. We randomly selected one village per *panchayat and* generated a randomized list of farm households to recruit from each village. In February 2019, we recruited households to participate in the study, aiming for 15 households per village. Households were eligible if they planned to harvest tomatoes during the study period. After the 2019 peak tomato-harvest season, less than a third of enrolled farmers from three *panchayats* harvested tomatoes. We therefore expanded the study coverage area and, from July to September 2019, recruited and enrolled farmers from three additional villages across the three *panchayats*.

At the Madanapalle tomato wholesale market, we recruited tomato traders when they purchased a lot of tomatoes from a participating farm household at auction on the same day the farm household was surveyed at the wholesale market. Tomato traders were consented at the time of their first survey. At follow-on surveys, we verified study participation based on the phone number provided at enrollment.

In Hyderabad, we selected one wholesale market per APMC. Bowenpally and Gudimalkapur market committees each oversee one market that trades tomatoes. The Hyderabad APMC oversees two wholesale markets that trade tomatoes, Madannapeta and Meeralamandi. We purposively selected Madannapeta because it deals with larger volumes of tomatoes. We carried out a census of vegetable traders in April 2019 to identify those that trade tomatoes as one of their primary products. Using the census questionnaire, we invited all eligible vegetable traders to participate in the study.

We used snowball sampling to recruit vegetable retailers from April to July 2019. At the time of enrollment, we asked vegetable traders to refer vegetable retailers who sell tomatoes. Traders referred retailers over several months because some vegetable traders were initially reluctant to give referrals. We enrolled referred retailers after verifying that they would be selling tomatoes during the study period.

Data collection

We developed several surveys to examine food loss and potential determinants of loss along major supply chain stages from rural producers to urban retailers. Data collection included surveys with smallholder farmers and tomato traders in Chittoor district and urban vegetable traders and retailers in Hyderabad. We aimed to capture information on food loss, food quality, activities and inputs, and expected selling prices. The recall period for each survey was the day of survey, except for retailer questions that referred to tomato sales from the previous day. We used this short recall period to reduce potential recall bias. Surveys were carried out from February to December 2019 in Chittoor district, and from April 2019 to March 2020 in Hyderabad. Surveys were conducted in-person in Telugu by trained enumerators using the Android-based application Open Data Kit.

In each supply chain actor survey, we aimed to capture information on food loss using subjective and objective measures. Questions on self-reported quantity and quality loss at the different supply chain stages were adapted from Delgado et al. (Delgado et al., 2017). We used crate counting as an objective measure of quantity loss where participants reported the quality grade and destinations for each group of crates. Potential destinations that would count as food loss destinations included animal feed, compost and trash. Crate counts were only used during surveys with farmers and retailers due to logistical limitations. Tomato traders and vegetable traders deal in large quantities of tomatoes and, in the case of vegetable traders, trades occurred before sunrise. Therefore, we were not able to observe all crates that passed through these traders.

Surveys captured information on tomato quality using several approaches. Supply chain actors reported the market grade(s) as well as important tomato quality attributes. We collected information on perceived ripeness levels using a color classification chart (United Fresh Fruit and Vegtable Association & USDA Agricultural Marketing Service Fruit and Vegetable Division, 1975) modified with an additional ripeness level, similar to Suslow & Cantwell (Suslow & Cantwell, 1997). Supply chain actors reported the price of a given quality grade that they expect to receive, based on evidence that observable product quality is associated with price differences (Fafchamps, Hill, & Minten, 2008). Finally, we captured perceived quality and asked supply chain actors to market the tomato quality intensity along a line with labeled endpoints “low quality” and “high quality” (Lawless & Heymann, 2010).

Food loss estimates

We estimated food loss at supply chain stages across four major supply chain actor groups: farmers, tomato traders, vegetable traders and vegetable retailers. In Chittoor district, we estimated food loss at the farm and tomato market levels. At the farm level, farmers self-reported field loss; pre-harvest quality loss; and post-harvest, farm-level food loss. We defined field loss as harvest-ready tomatoes that are left in the field, either remaining on the plant or picked but left in the field; pre-harvest quality loss as quality deterioration among harvested tomatoes that occurred prior to harvest; and post-harvest, field-level food loss as loss among harvested tomatoes. At the tomato market level, farmers self-reported pre-auction food loss among tomatoes they brought to the market. At both the farm and wholesale market, we also estimated food loss using crate counts and farmer-reported destination(s) for each group of crates. For post-harvest, farm-level and pre-auction, market-level stages, we calculated food loss as the fraction of counted crates (filled with tomatoes) that go to a loss destination. When we were unable to measure crate size, we inferred the crate size was the same as previous harvests based on multiple measurements taken for each farm household and assuming that crate size would be time-invariant. To estimate tomato trader post-repacking loss, we calculated food loss as a fraction of crates that went to a loss destination based on trader-reported crate counts of crates that had been repacked and the trader-reported destinations.

In Hyderabad, we estimated food loss at the vegetable market and vegetable retail levels. At vegetable markets, we estimated food loss using vegetable trader self-reported crate counts of lots received and sold on the survey day. We also estimated loss based on trader-reported quantity of tomatoes removed from their auction lots and the reported destination. At vegetable retail outlets, we estimated food loss from the previous day based on retailer self-reported loss once sales were completed. On the day of survey, we observed crate counts of tomatoes vegetable retailers had at the start of selling and estimated loss based on retailer-reported destination.

We estimated food loss using two different approaches: declared loss and destination loss. We calculated declared loss based on supply chain actor self-reported food loss. As such, declared loss relies on the supply chain actor's own interpretation of food loss. For vegetable traders, we calculated declared loss based on the difference between number of crates received and number of crates sold. We calculated destination loss based on the reported destination use. In the case of farmers and retailers, the number of crates was based on observed crate counts. In the case of tomato traders and vegetable traders, the number of crates was based on self-reported crate counts, since it was not feasible to physically count the crates given the large volumes of tomatoes traded.

We considered destination loss using two different criterion distinguishing food destinations and final use (Bellemare, Çakir, Peterson, Novak, & Rudi, 2017; Craig Hanson et al., 2016; FAO, 2019). "Non-food use" refers to destinations where the food will not be consumed by humans (e.g., animal feed, discard/refuse, trash). "Non-productive use" refers to destinations where the food no longer has a productive use (e.g., discard/refuse, trash). Because supply chain actors reported multiple uses, we included the prefix "any" to non-food use and non-productive use loss estimates when at least one loss category was reported, and the prefix "only" to loss estimates when only loss destinations were reported.

Conceptual framework for determinants of food loss

We explored the associated determinants of food loss at stages where food loss was concentrated: pre-harvest quality loss; post-harvest, farm-level loss; pre-auction, market-level loss; and retail-level loss. To model the determinants of loss, we pulled from FL&W, agriculture and food science literature to create our conceptual framework. At the farmer levels, we considered production, harvest, and post-harvest handling factors. At the retail stage, we considered product source, handling, and target consumer factors.

In farmer loss models, we included caste as a covariate because caste is an indicator for several factors including access to resources (e.g. credit), inclusion or exclusion from extension services, and regional differences in the quality of services and infrastructure (Krishna, Aravalath, & Vikraman, 2019; Kumar, 2013). Broad caste categories Scheduled Tribe (ST), Scheduled Caste (SC), and Other Backward Castes (OBC) were compared, collectively, to Other castes. Additionally, we included a covariate dummy variable indicating if the household fell with the coverage area of a local NGO that operated tomato production and marketing programs at the time of our study.

We included independent variables that are hypothesized to influence food loss outcomes via household characteristics, production, post-harvest, and marketing activities and decisions, and information sources. We organized predictor variables, presented in **Appendix, Table A.1,** into theoretically distinct sets and built regression models within each set to determine the variable relationships.

Regarding household characteristics, longer production experience, higher education levels, and agriculture as a main income source have been found to be significantly associated with decreased food loss at the farmer stages (Delgado et al., 2017). To account for education level, we used the highest education level attained from a surveyed household member, rather than the education level of the household head, because a household head's characteristics may be insufficient to characterize the household and all household decision-makers (Kleinjans, 2013). We assume that surveyed household members responsible for the harvesting and marketing aspects of tomato production are decision-makers.

At the plot-level, production activities and inputs that occurred once per plot applied to all harvests of that plot. Production activities and inputs that occurred at different time-points on the plot were accounted for at the harvest-level. Plot-level activities and inputs included sapling density, growing area, and the tomato breed planted. Harvest-level activities and inputs included types of irrigation, staking and plastic sheeting, and fertilizer and fungicide applications. Production activities, from choice of breed and planting to irrigation practices and fertilizer applications, impact the fruit quality and can reduce product degradation before and after harvest (Adel A. Kader & Rolle, 2004; Kitinoja & Kader, 2002). With regard to harvest number, previous studies have demonstrated that, for each plot, the vegetables from the first or second harvest are the best quality because the plants are young and healthy compared to later on in the season where the plants lose vigor and harvest traffic causes some damage (Dunning, Johnson, & Boys, 2019). Harvest, post-harvest and marketing factors may influence food loss, including harvest timing and tomato quality; harvest and post-harvest labor and handling; and transportation and marketing conditions (A. A. Kader, 2010; Adel A. Kader & Rolle, 2004; Kitinoja & Kader, 2002; Magalhães, Ferreira, & Silva, 2021; Mohammed & Craig, 2018; Rolle, 2006).

In addition to hired and family labor, we accounted for labor gender to understand the involvement of females and males as the main actor in a particular supply chain step (FAO, 2018). Finally, we explored participant-reported production and marketing limitations, as well as loss reduction strategies and information sources. Delgado et al. (2017) find that producers reporting perceived production limitations such as animals, pests and disease increase food loss (Delgado et al., 2017). Inadequate knowledge or information from production to marketing stages may also increase food loss (Rolle, 2006).

In vegetable retailer models, we included caste and gender covariates as both characteristics are associated with access to resources (Kambara, 2015; Munshi, 2019). Similar to the farmer models, we included caste as a dichotomous variable. We included independent variables that are hypothesized to influence food loss outcomes via retailer characteristics, retail sourcing and operations. We organized independent variables, presented in **Appendix**, **Table A.2,** into theoretically distinct sets and build models within each set to determine the variable relationships. We extended principles of product quality and post-harvest factors that influence quality deterioration and food loss to the retail stage, and accounted for retail-type, product source, selling conditions, target buyers, and product quality.

Statistical analysis

We used Wilcoxon-Mann-Whitney and Pearson's χ^2 tests to determine differences between household characteristics among enrolled farm households that never harvested tomatoes during the study period and households that harvested at least once. For each supply chain level with food loss estimates based on loss destinations, we used Kruskal-Wallis ranks test to determine differences in food loss estimates across loss criterion, with a post-hoc Dunn's test and Bonferroni correction indicating where any differences occurred. Significance level was set to $\alpha = 0.05$.

We modeled determinants of food loss to explore the relationship between independent variables selected *a priori* and food loss, the dependent variable. Initially, we planned to model determinants for each supply chain level where food loss was estimated. However, based on the final dataset, average food loss estimates at the tomato trader and vegetable trader levels were <1% and modeling determinants of loss would not provide meaningful interpretation. Therefore, we modeled determinants of loss at supply chain levels involving farm households and vegetable retailers. We used declared food loss estimates as dependent variables for models at the pre-harvest farmer stage and end-of-sale retailer stage. We used destination food loss estimates (any, non-food use) as dependent variables for models at the post-harvest and pre-auction farmer stages and start-of-sale retailer stage.

We used a multi-level mixed-effects approach to account for hierarchical effects where independent variables are measured at the village, household, plot and harvest levels and at the retailer and sale-day levels for farmers and vegetable retailers, respectively (Garson, 2013). Because food loss estimates are skewed right, with a mass point at zero, we used a two-part model approach to model the dependent variable, food loss, using two steps (Belotti, Deb, Manning, & Norton, 2015). We first fit a mixed effects binary logit model for the odds of observing a positive-versus-zero food loss outcome. We exponentiated both sides of the logit model to interpret the coefficients in terms of odds ratios. Next, conditional on a positive food loss outcome, we fit a mixed effects linear model for the positive food loss outcome. We log-transformed the extent of food loss in each linear model using the natural log to control for heteroskedasticity of the error term. We built models within each set of independent variables, as described in the previous section, and constructed final models that included only significant independent from each set in order to reduce risk of overfitting the models. We used Stata, version 15, for all analyses.

The two-part models estimated for each food loss outcome among farmers are:

(1) Mixed effects logit model

$$log[\frac{P_{hpfv}}{1-P_{hpfv}}] = \beta_0 + \beta_1 X_{hpfv} + \beta_2 X_{pfv} + \beta_3 X_{fv} + \beta_4 X_v + \varepsilon_v + \varepsilon_{fv} + \varepsilon_{pfv} + \varepsilon_{hpfv}$$

(2) Mixed effects linear model

$$\ln[Y_{hpfv}|Y_{hpfv} > 0] = \beta_0 + \beta_1 X_{hpfv} + \beta_2 X_{pfv} + \beta_3 X_{fv} + \beta_4 X_v + \varepsilon_v + \varepsilon_{fv} + \varepsilon_{pfv} + \varepsilon_{hpfv}$$

P_{hpfv}	is the probability of a positive food loss outcome at harvest *h*, on plot *p*, of farm household *f*, in village *v*
$Y_{hpfv} \mid Y_{hpfv} > 0$	is the food loss estimate conditional on a positive outcome at harvest *h*, on plot *p*, of farm household *f*, in village *v*
β_0	is the constant
$\beta_1 X_{hpfv}$	are the estimated coefficients of observed characteristics of harvest *h*, on plot *p*, of farm household *f*, in village *v*
$\beta_2 X_{pfv}$	are the estimated coefficients of observed characteristics of plot *p*, of farm household *f*, in village *v*

$\beta_3 X_{fv}$ are the estimated coefficients of observed characteristics of farm household *f*, in village *v*

$\beta_4 X_v$ are the estimated coefficients of observed characteristics of village *v*

ε are the unobserved disturbance terms across village variation, across farm household variation within villages, across plot variation within farm households within villages, and across harvest variation within farm households within villages

The two-part models estimated for each food loss outcome among vegetable retailers are:

(1) Mixed effects logit model

$$log[\frac{P_{dr}}{1 - P_{dr}}] = \beta_0 + \beta_1 \mathrm{X_{dr}} + \beta_2 \mathrm{X_r} + \varepsilon_\mathrm{r} + \varepsilon_\mathrm{dr}$$

(2) Mixed effects linear model

$$\ln[Y_{dr} | Y_{dr} > 0] = \beta_0 + \beta_1 \mathrm{X_{dr}} + \beta_2 \mathrm{X_r} + \varepsilon_\mathrm{r} + \varepsilon_\mathrm{dr}$$

P_{dr} is the probability of a positive food loss outcome on sale-day *d* of retailer *r*

$Y_{dr} | Y_{dr} > 0$ is the food loss estimate conditional on a positive outcome on sale-day *d* of retailer *r*

β_0 is the constant

$\beta_1 X_{dr}$ are the estimated coefficients of observed characteristics of sale-day *d* of retailer *r*

$\beta_2 X_r$ are the estimated coefficients of observed characteristics of retailer *r*

ε are the unobserved disturbance terms across retailer variation and across sale-day variation within retailers

Results

Sample description: Chittoor district

Among the 145 farm households enrolled, 75 (52%) harvested tomatoes during the study period. The remaining 70 households never harvested tomatoes. In **Table 1**, we compare household characteristics between households that never harvested and households with at least one harvest. Households with at least one harvest were more likely to report agriculture as a main source of income ($p = 0.037$). There was no significant difference among households enrolled during the initial enrollment period or later period and harvesting ($p = 0.34$). As discussed in the previous chapter, we were unable to collect data during the 2020 peak harvest season due to COVID-19 restrictions. Food loss surveys taken during peak harvest season were only completed for households that were enrolled during the initial enrollment period since later-enrolled households were not enrolled until the end of the 2019 peak harvest season. Among households without any harvest that were enrolled during the initial enrolment period, the majority, 71%, reported water scarcity as the main reason for not producing or harvesting tomatoes.

Table 1. Enrolled farm household characteristics by households with and without any harvest

	Household with 0 harvest (n=70) Median (IQR) or n (%)	**Household with ≥ 1 harvest** (n=75) Median (IQR) or n (%)	**p-value**
Land, owned (acres)	2.5 (1-3.18)	3 (1.5-5)	0.10[a]
Land, leased (acres)	0 (0-.5)	0 (0-1)	0.28[a]
Experience in tomato production (years)	15 (8-20)	15.5 (10-20)	0.34[b]
Agriculture as a main income source	58 (84%)	71 (95%)	0.037[b]
Farmer Producer Organization member	16 (23%)	24 (32%)	0.24[b]
Covered under NGO programming	36 (51%)	40 (53%)	0.82[b]
Scheduled Caste/Tribe and Backward Caste	46 (70%)	50 (72%)	0.72[b]
Enrolled during initial enrollment period	56 (80%)	55 (73%)	0.34[b]

[a] p-value from Wilcoxon rank-sum test

[b] p-value from Pearson's chi-squared

Table 2 summarizes the characteristics of farm households and tomato traders in Chittoor District that were surveyed. We observed an average of 3.8 harvests per study household with at least one harvest. We aimed to survey three harvests per household plot. At both the farm and market levels, there was a median of one respondent per household across surveys meaning that we usually surveyed the same household member at each location. Most farm household respondents were male, 73% and 93% at farm- and market-level surveys, respectively. About half of respondents were the household head, 50% and 56% at farm- and market-level surveys, respectively. Most households, 79%, brought their harvests to the Madanapalle tomato market at least once during the survey period.

We enrolled a total of 83 tomato traders into the study, all of whom were male. The number of surveys given per tomato trader was skewed, averaging mean (SD) of 2.4 (3.3) surveys per trade, and a median of one survey per trader. Tomato traders were enrolled at the time of their first survey after they purchased tomatoes at auction from a study farmer. Tomato traders were only surveyed subsequent times if they, again, purchased tomatoes at auction from a study farmer and agreed to respond to the survey.

Table 2. Descriptive statistics of study sample of tomato supply chain in Chittoor District

	Mean or n (%)	Median	Standard deviation
Farmers			
Households with ≥ 1 harvest	75		
Harvests observed per household	3.8	3.0	2.0
Respondents per household across farm level surveys	1.5	1.0	0.6
Male respondent, farm level survey	80 (73%)		
Farm-level respondent relationship to HH head			
Household head	55 (50%)		
Spouse	19 (17%)		
Child or child-in-law (adult)	33 (31%)		
Other relative	2 (2%)		
Farm-level respondent education level, ≥ grade 8, secondary	56 (51%)		
Households sold harvest at MPL mkt			
Always	51 (68%)		
Sometimes	8 (11%)		
Never	16 (21%)		
Respondents per household across market level surveys	1.2	1.0	0.5
Male respondent, market level survey	68 (93%)		
Market-level respondent relationship to HH head			
Household head	41 (56%)		
Spouse	3 (4%)		
Child or child-in-law (adult)	22 (30%)		
Other relative or other non-relative	7 (10%)		
Market-level respondent education level, ≥ grade 8, secondary	40 (55%)		

Tomato traders			
Number of traders	83		
Number of surveys given by traders	2.4	1.0	3.3
Male trader	83 (100%)		
Education level, ≥ grade 8, secondary	64 (77%)		
Experience in tomato business, years	14.8	15.0	9.3

Food loss estimates: Chittoor District

Table 3 summarizes the food loss estimates across supply chain stages involving farm households and tomato traders in Chittoor District. The distribution of food loss estimates is skewed to the right. Therefore, in addition to reporting the mean, median and standard deviation of food loss across all harvests, we report summary statistics on harvests with food loss >0%. Only at 7% of harvests did farmers report leaving harvest-ready tomatoes on the field. When field loss was reported, a median of 25% of harvest-ready tomatoes were left on the field and not harvested. Reported reasons for field loss included bad harvest technique (20%), low price for tomatoes (20%), lack or costly labor (15%), and shortage of crates (15%). Farmers reported harvesting tomatoes that were damaged at 69% of harvests. Among harvests where damaged tomatoes were harvested, a median of 13% of the harvest was affected by pre-harvest quality loss. Farmers most often report pests/disease/animals as the major cause of pre-harvest loss (56%), followed by too much sun or rain (21%), and lack of rain (9%). Post-harvest loss was common; 64% and 46% of harvests had loss based on declared loss and destination loss methods, respectively. Among harvests with post-harvest loss, median loss was between 9-10% across both estimation methods. Food loss at the market before auction was also common; 58% of tomato lots brought to the market for auction had loss, using either method. When pre-auction loss occurred, the share of tomatoes lost was small with a median loss between 1.5-1.6% across both estimation methods. Farmers most often reported pests/disease/animals as the major cause of both post-harvest and pre-auction loss (73% and 49%, respectively), as well as too much sun (19%) or rain (26%). Farmers experiencing pre-auction loss also reported transportation as a major cause of pre-auction loss (21%).

Food loss estimates from tomato traders are potentially biased towards tomato traders that participated more often due to the skew in the number of responses for tomato traders. Therefore, we collapsed the tomato trader loss estimates, taking the mean of each tomato trader, resulting in 60 observations. Average food loss estimated by tomato trader reported quantities and destinations was <1%. Among tomato traders that did not respond to food loss-related survey questions, 96% were surveyed only one time; either they never purchased tomatoes from a study farmer a second time or they refused to respond again to our survey.

Table 3. Food loss estimates in Chittoor District

	Supply chain actor	Declared loss n	Declared loss Mean or n (%)	Declared loss Median	Declared loss Standard Deviation	Destination loss n	Destination loss Mean or n (%)	Destination loss Median	Destination loss Standard Deviation
Field loss, harvest-ready tomatoes left in field	Farmer								
Frequency of harvests with food loss		275	20 (7%)			-	-	-	-
Among harvests with food loss, share of harvest lost (%)			27.85	25	17.91		-	-	-
Among all harvests, share of harvest lost (%)			2.03	0	8.64		-	-	-
Pre-harvest quality loss	Farmer								
Frequency of harvests with quality loss		261	180 (69%)			-	-	-	-
Among harvests with quality loss, share of harvest damaged (%)			20.19	13.42	19.74		-	-	-
Among all harvests, share of harvest damaged (%)			13.93	6.67	18.87		-	-	-
Post-harvest, farm-level loss	Farmer								
Frequency of harvests with food loss		234	149 (64%)			264	121 (46%)		
Among harvests with food loss, share of harvest lost (%)			11.85	10	11.2		10.76	9.09	9.6
Among all harvests, share of harvest lost (%)			7.55	2.27	10.6		4.93	0	8.42
Pre-auction, market-level loss	Farmer								
Frequency of lots with food loss		190	110 (58%)			190	111 (58%)		
Among lots with food loss, share of harvest lost (%)			2.98	1.52	4.26		2.8	1.64	4.76
Among all lots, share of harvest lost (%)			1.72	0.21	3.56		1.64	0.24	3.88
Post-repacking, market level loss	Tomato trader	-							
Frequency of lots with food loss			-	-	-	60	4 (7%)		
Among lots with food loss, share of harvest lost (%)			-	-	-		0.42	0.25	0.46
Among all lots, share of harvest lost (%)			-	-	-		0.03	0	0.15

Notes
Declared loss refers to loss estimated using participant self-report.
Destination loss refers to loss estimated using participant reported destination of tomatoes. Animal feed and trash/discard are counted as food loss.

Sample description: Hyderabad

We screened 224 vegetable traders for study eligibility in a census across three state-run vegetable markets. Of the 78 (35%) vegetable traders that were eligible, 70 (90%) we enrolled. Eighteen vegetable traders that were enrolled dropped out prior to any study survey. Therefore, a total of 52 (74% of enrolled) vegetable traders participated. **Table 4** summarizes characteristics of enrolled vegetable traders. All vegetable traders were male and most had at least secondary education (90%). We screened 66 vegetable retailers referred by participating vegetable traders for eligibility. Sixty-one (91%) retailers were eligible and 53 (87% of eligible retailers) were enrolled into the study. Characteristics of enrolled retailers are summarized in **Table 4**. Three vegetable retailers dropped out of the study prior to any survey. Therefore, a total of 50 (94% of enrolled) vegetable retailers were included in the study sample. Most tomato retailers were located at daily markets (70%) and most retailers were male (80%).

Table 4. Descriptive statistics of study sample of tomato supply chain in Hyderabad

	Mean or n (%)	Median	Standard deviation
Vegetable trader			
Number of traders	52		
Male traders	52 (100%)		
Education level, ≥ grade 8, secondary	47 (90%)		
Experience in tomato business, years	19.4	19.0	11.5
Surveys given by each trader	7.2	8.0	2.9
Vegetable retailers			
Number of retailers	50		
Retail type			
Daily market	35 (70%)		
Local brick and mortar	7 (14%)		
Weekly market	4 (8%)		
Pushcart/roadside shop	4 (8%)		
Male retailers	40 (80%)		
Education level, ≥ grade 8, secondary	23 (46%)		
Experience in tomato business, years	15.9	15.0	10.2
Surveys given by each retailer	6.6	7.0	2.4

Food loss estimates: Hyderabad

Table 5 summarizes food loss estimates for vegetable traders and vegetable retailers in Hyderabad. Vegetable traders had finished selling tomatoes at 182 of surveys, nearly half (49%) of the total 373 surveys. All vegetable traders declared no food loss at each survey, reporting that the sold the exact number of tomato crates received. After building rapport with vegetable traders, traders were willing to directly report the quantity of tomatoes removed from the traded lots and the intended destination. Using this destination loss method, food loss occurred at 59% of lots. The extent of food loss was small, and a median of <1% of tomatoes in a lot were diverted to loss destinations.

Vegetable retailers reported total losses on the previous day, once sales were completed. Retailers reported losses 88% of the time, with a median loss of 3.6% of tomatoes they had available to sell at the beginning of the day. Estimated food loss based on destination reflected food loss on the survey day from retailers grading and sorting tomatoes at the start of selling. Retailers reported diverting tomatoes to a food loss destination at 26% of survey visits. Among lots with food loss at the start of selling, a median of 2.6% tomatoes were sorted out to loss destinations.

Table 5. Food loss estimates in Hyderabad

	Supply chain actor	Declared loss				Destination loss			
		n	Mean or n (%)	Median	Standard Deviation	n	Mean or n (%)	Median	Standard Deviation
Vegetable market food loss[a]	Vegetable trader								
Frequency of lots with food loss		182	0 (0%)			78	46 (59%)		
For lots with losses, share of lot lost (%)			-	-	-		1.26	0.52	2.96
For all lots, share of lot lost (%)			0	0	0		0.75	0.16	2.35
Vegetable retail food loss[b]	Vegetable retailer								
Frequency of lots with food loss		110	97 (88%)			331	87 (26%)		
For lots with losses, share of lot lost (%)			4.77	3.6	4.95		7.05	2.6	13.21
For all lots, share of lot lost (%)			4.21	2.93	4.89		1.85	0	7.43

Notes

Declared loss refers to loss estimated using participant self-report.

Destination loss refers to loss estimated using participant reported destination of tomatoes. Animal feed and trash/discard are counted as food loss.

[a] Declared loss calculated difference between vegetable trader reported tomato crates received and crates sold on survey day.

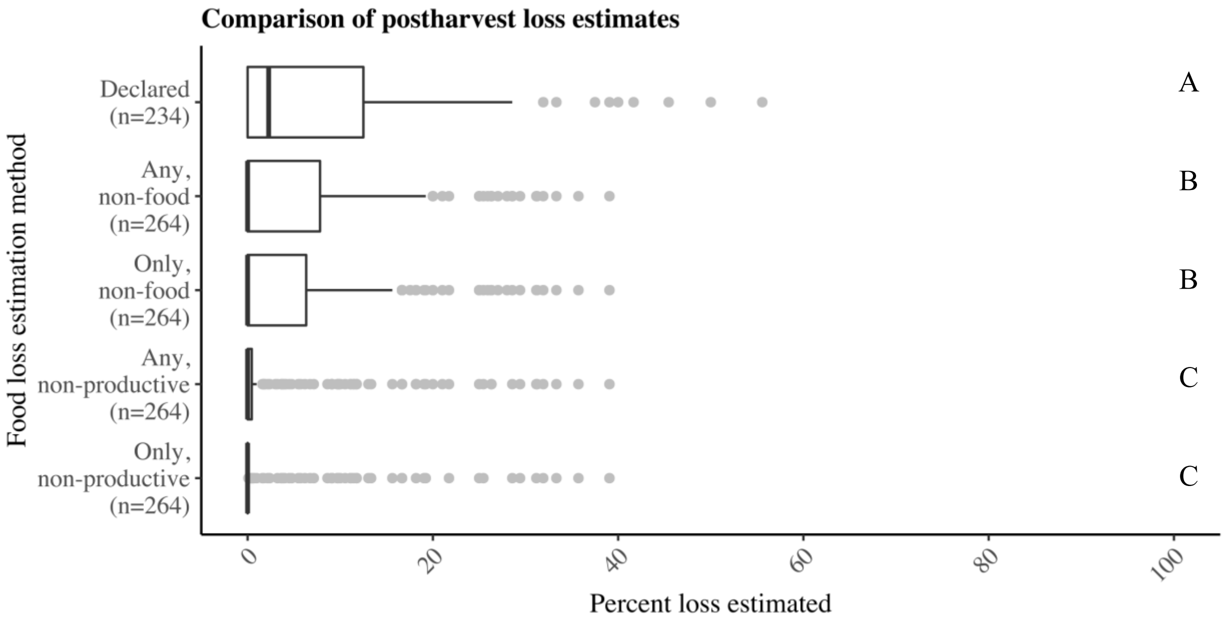
[b] Declared loss from previous day, at the end of selling tomatoes. Destination loss from survey day at start of selling.

Comparison of food loss estimation methods by supply chain actor

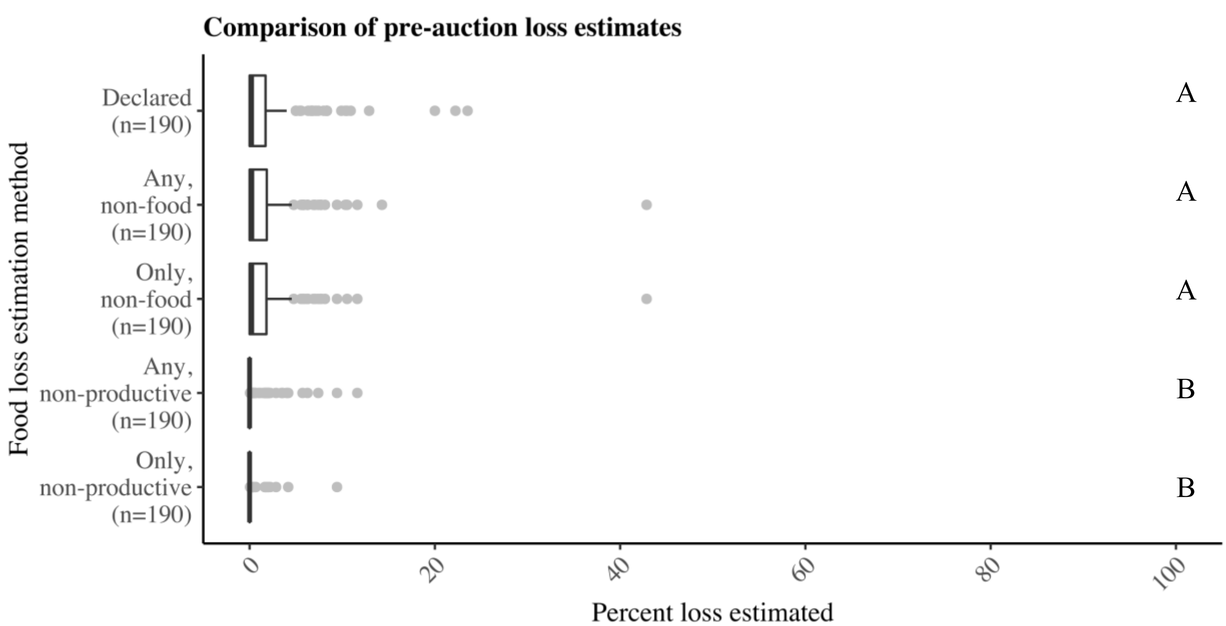
We compare food loss estimates at the post-harvest, pre-auction, post-repacking, vegetable market and vegetable retail stages to determine the differences between estimates at each stage when applying different loss destination criterion to estimate food loss. **Figure 1 (a-e)** summarizes the comparisons of food loss estimates by estimation method and destination criterion at each stage using $p = 0.05$ significance level. We find at the post-harvest stage, declared loss was significantly different than all destination loss estimates, and that food loss estimated by non-food destinations was significantly different than food loss estimated by non-productive destinations. At the tomato market pre-auction stage, declared loss was not significantly different than food loss estimated by non-food destinations. Pre-auction food loss estimated by non-productive destinations was significantly different from both declared loss and non-food destination methods. At both farm and market levels, the median price farmers expected to receive for tomatoes used for animal feed was 0 Rs. (IQR 0, 0; n=58 and n=77 at farm and market, respectively). Post-auction, among tomato traders, median food loss estimated by non-food destinations was significantly different than median food loss estimates using non-productive destinations. There was no significant difference in food loss estimates between non-food and non-productive destinations at the vegetable market (vegetable trader) stage. At the vegetable retail stage, food loss estimated by non-food destinations was significantly different than loss estimated when the only destination was non-productive. Vegetable retailers reported a median expected selling price of 0 Rs. (IQR 0, 0; n=30) for tomatoes reported to go to animal feed.

Figure 1 (a-e). Box and whisker plots comparing food loss estimates by estimation method and loss destination criterion.

Methods sharing the same letter are not significantly (p > 0.05; Kruskal-Wallis/Dunn's test), Bold line, median value; box, 25th and 75th percentiles; thin lines, extreme line.

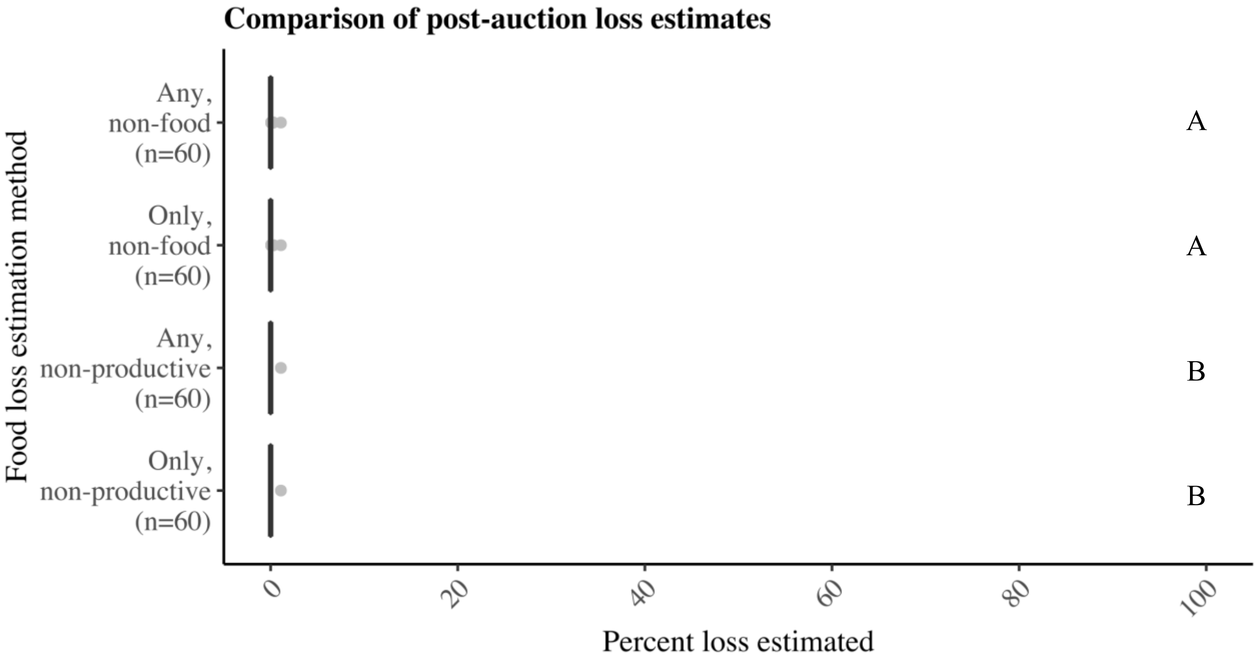


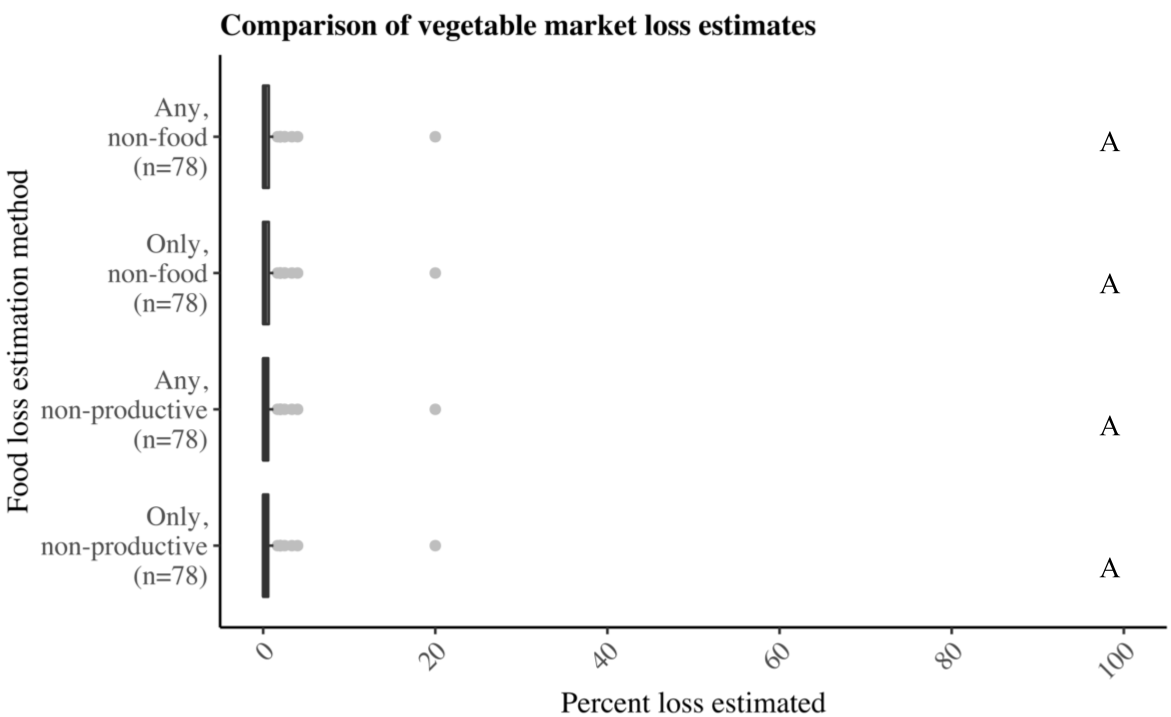
(a)



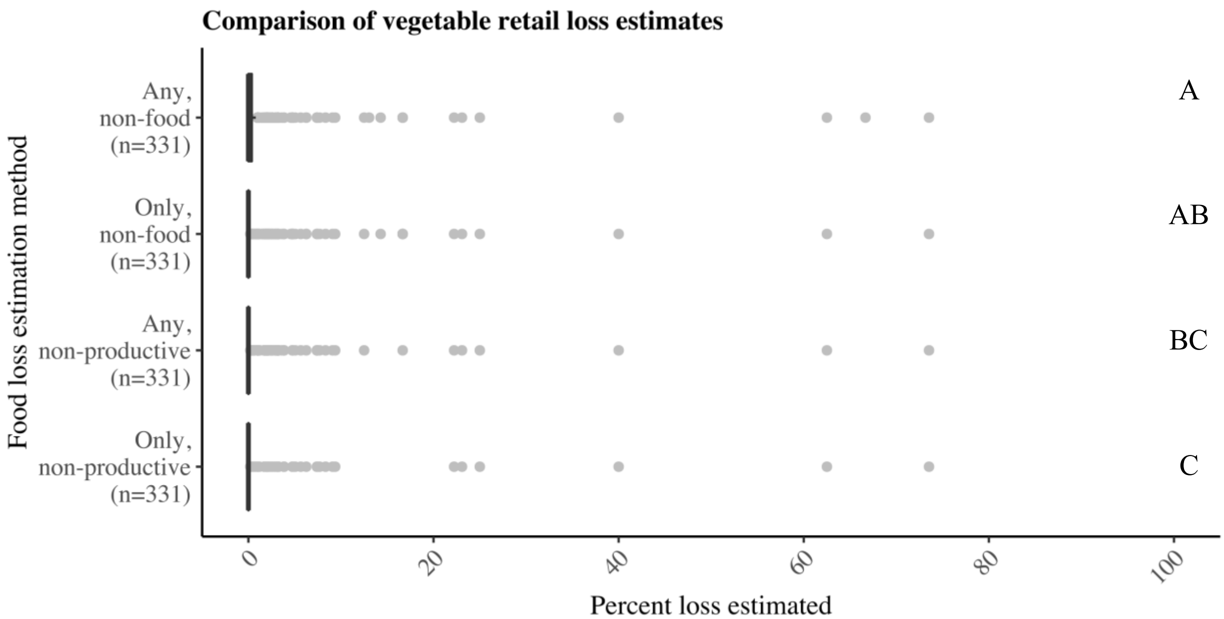
(b)

(c)


Comparison of post-auction loss estimates
Food loss estimation method
Any, non-food (n=60)
Only, non-food (n=60)
Any, non-productive (n=60)
Only, non-productive (n=60)
A
A
B
B
0
20
40
60
80
100
Percent loss estimated


Comparison of vegetable market loss estimates
Food loss estimation method
Any, non-food (n=78)
Only, non-food (n=78)
Any, non-productive (n=78)
Only, non-productive (n=78)
A
A
A
A
0
20
40
60
80
100
Percent loss estimated

(d)



(e)

Determinants of food loss

Results from the two-part models to examine determinants of food loss at stages involving farmers are presented in **Table 6-Table 8**. At pre-harvest, harvest number and harvest during peak season are significantly associated with a reduced odds of pre-harvest quality loss, and expected price of tomatoes is significantly associated with the magnitude of pre-harvest quality loss. A one-unit increase in harvest number decreased the odds of pre-harvest quality loss by a factor of 0.807, 95% CI (0.66, 0.98). Harvest during peak season (April-July) decreased the odds of quality loss by a factor of 0.171, 95% CI (0.04, 0.75). Among harvests with positive pre-harvest quality loss, a one-unit (100 Rs./30kg) increase in expected price for tomatoes is associated with 15.04% lower quality loss (SE = 0.04, $p < 0.001$).

At the on-farm, post-harvest stage, a one-unit (30 kg) increase in the quantity of tomatoes harvested increased the odds of post-harvest food loss by a factor of 1.02, 95% CI (1.00, 1.03). Compared to harvesting during the off-peak season, harvesting during peak season was associated with a reduced odds of post-harvest loss, 0.12 times lower, 95% CI (0.05, 0.29). With regard to the extent of post-harvest loss among harvests with loss, harvesting during peak season was associated with 63% lower loss compared to harvests during off-peak season (SE = 0.31, $p < 0.01$). On-farm grading and sorting increased the odds of post-harvest loss by a factor of 7.07, 95% CI (3.31, 15.10). Among harvests with post-harvest loss, harvests where on-farm grading occurred was associated with 51% lower loss than harvests without on-farm grading (SE = 0.30, $p < 0.05$). Finally, pre-harvest damage was associated with post-harvest losses; a one-percentage increase in pre-harvest damage is associated with a 2% greater post-harvest loss (SE = 0.01, $p < 0.01$).

At the Madanapalle wholesale market, the odds of pre-auction loss are associated with farm-level packing and market-level grading. When males from the farm household are involved in farm-level packing, the odds of pre-auction loss are 3.66 times greater than the odds when males from the farm household are not involved in farm-level packing, 95% CI (1.11, 12.03). When hired females are involved in farm-level packing, the odds of pre-auction loss are 4.90 times greater than the odds when hired females are not involved in farm-level packing, 95% CI (1.52, 15.85). When hired females are involved in grading at the market-level, the odds of pre-auction loss are increased 5.17 times than the odds when hired females are not involved, 95% CI (1.65, 16.27). When males from the farm household are involved in market-level grading, the odds of pre-auction loss are 3.41 times greater than the odds when males from the farm household are not involved in market-level grading, 95% CI (1.08, 10.78). Among lots with pre-auction loss, peak season was associated with 72% greater pre-auction loss compared to lots marketed during off-peak season (SE = 0.34, $p < 0.001$).

Results from the two-part models examining determinants of food loss at the vegetable retail stage are presented in **Table 9** and **Table 10**. None of the independent variables included in our models were significantly associated with the odds of end-of-sale food loss. Only caste was associated with the extent of end-of-sale food loss. Retailers that identified as either SC, ST or OBC were associated with a 48% lower end-of-sale loss compared to retailers that identified as other caste (SE = 0.309, $p < 0.05$). At the start-of-sale, the odds of food loss are associated with retail type, expected sale price, and the maximum ripeness of tomatoes. Compared to a retailer at a daily market, the odds of food loss among retailers at brick and mortar shops is lower by a factor of 0.152, 95% CI(0.024, 0.94). A one-unit (10 Rs./kg) increase in the maximum sale price lowers the odds of food loss by a factor of 0.637, 95% CI (0.500, 0.811). Compared to tomatoes with a super red maximum ripeness level, the odds of food loss among tomatoes with a breaker to light red maximum ripeness level are lower by a factor of 0.251, 95% CI (0.069, 0.908), and the odds of food loss among tomatoes with a red maximum ripeness level are lower by a factor of 0.160, 95% CI (0.059, 0.436). When start-of-sale food loss was positive, the range of ripeness levels available and the retailer's gender were associated with the extent of food loss. A one-unit increase in the range of tomato ripeness level was associated with 22% higher loss (SE = 0.085, $p < 0.01$). Compared to male retailers, female retailers were associated with 92% higher loss (SE = 0.648, $p < 0.05$).

Table 6. Estimation results from two-step mixed effects regression models of pre-harvest quality loss. Extent of pre-harvest quality loss is natural log-transformed.

Variables	Pre-harvest quality loss occurs, OR [95% CI]	Extent of pre-harvest quality loss, β coefficient (SE)
Harvest number	0.807*	
	[0.66, 0.98]	
Peak harvest season (Apr-Jul)	0.171*	
	[0.04, 0.75]	
FPO member		0.283
		(0.24)
Highest price expected, farm-level (100 rs. per 30kg)		-0.163***
		(0.04)
Experience in tomato cultivation (years)		-0.00258
		(0.01)
Quality intensity (1-9)		-0.0747
		(0.04)
Loss reduction strategy, Apply pesticides		0.191
		(0.20)
Under local NGO coverage area	1.926	-0.113
	[0.21, 17.72]	(0.26)
SC/ST/OBC (reference = Other Caste)	6.358	0.509
	[0.64, 63.32]	(0.29)
Constant		3.256***
		(0.55)

Random Effects Parameters		
Village Variance	2.615	1.86E-34
	[0.26, 26.33]	(0.00)
Household Variance	1.364	8.27E-36
	[0.02, 80.22]	(0.00)
Plot Variance	246.3	0.463**
	[0.26, 233413.39]	(0.16)
Residual Variance		0.676***
		(0.12)
Observations	244	145
Number of groups	11	10

Abbreviations: CI, confidence interval; OR, odds ratio; SE, standard error

* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

Table 7. Estimation results from two-step mixed effects regression models of post-harvest food loss. Extent of post-harvest food loss is natural log-transformed.

	Post-harvest food loss occurs, OR [95% CI]	Extent of post-harvest food loss, β coefficient (SE)
Peak harvest season (Apr-Jul)	0.122***	-0.989**
	[0.05, 0.29]	(0.31)
Total harvested tomatoes (30 kg)	1.016*	
	[1.00, 1.03]	
Tomatoes kept in shade while harvesting	0.463	
	[0.21, 1.05]	
Field container for harvested tomatoes		
No container	3.021	
	[0.67, 13.54]	
Crate ≤ 20 kg	2.263	
	[0.73, 7.03]	
Crate ≥ 25 kg	Reference	
	-	
On-farm grading/sorting	7.069***	-0.707*
	[3.31, 15.10]	(0.30)
Preharvest damage (% of harvest)	1.006	0.0173**
	[0.99, 1.03]	(0.01)
Harvest container, basket		0.213
		(0.28)

Under local NGO coverage area	1.665	0.747*
	[0.73, 3.82]	(0.33)
Scheduled Caste, Scheduled Tribe or Backwards Caste (reference = Other Caste)	5.388**	1.054**
	[1.81, 16.07]	(0.40)
Constant		0.974*
		(0.44)
Random Effects Parameters		
Village Variance	1	0.0176
	[1.00, 1.00]	(0.12)
Household Variance	1	0.141
	[1.00, 1.00]	(0.45)
Plot Variance	1	0.303
	[1.00, 1.00]	(0.46)
Residual Variance		1.031***
		(0.21)
Observations	231	107
Number of groups	11	11

Abbreviations: CI, confidence interval; OR, odds ratio; SE, standard error

* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

Table 8. Estimation results from two-step mixed effects regression models of pre-auction food loss. Extent of pre-auction food loss is natural log-transformed.

	Pre-auction food loss occurs, OR [95% CI]	Extent of pre-auction food loss, β coefficient (SE)
Peak harvest season (Apr-Jul)	0.974	-1.273***
	[0.39, 2.41]	(0.34)
Production, Drip irrigation		-0.869
		(0.47)
Production, Staking		-0.916
		(0.81)
Production, Chemical fertilizer or NPK applied		-0.791
		(0.58)
Total harvested tomatoes (30 kg)		0.0031
		(0.00)
Farm-level packing, Family, male	3.658*	-0.363
	[1.11, 12.03]	(0.28)
Farm-level packing, Hired, female	4.903**	

	[1.52, 15.85]	
Market-level grading, Hired, female	5.174**	
	[1.65, 16.27]	
Market-level grading, Family, male	3.412*	
	[1.08, 10.78]	
Under local NGO coverage area	3.593	0.576
	[0.65, 20.00]	(0.52)
Scheduled Caste, Scheduled Tribe or Backwards Caste (reference = Other Caste)	3.921	0.542
	[0.68, 22.68]	(0.54)
Constant		2.559*
		(1.11)
Random Effects Parameters		
Village Variance	1.00E+00	5.51E-33
	[1.00, 1.00]	(0.00)
Household Variance	1.54E+00	3.41E-33
	[0.60, 3.93]	(0.00)
Plot Variance	1	0.765**
	[1.00, 1.00]	(0.24)
Residual Variance		0.592***
		(0.13)
Observations	170	98
Number of groups	10	10

Abbreviations: CI, confidence interval; OR, odds ratio; SE, standard error

* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

Table 9. Estimation results from two-step mixed effects regression models of end-of-sale food loss. Extent of end-of-sale food loss is natural log-transformed.

	End-of-sale food loss occurs, OR [95% CI]	Extent of end-of-sale food loss, β coefficient (SE)
Retail type		
Brick and mortar shop/local retail shop		0.167
		(0.346)
Pushcart or roadside shop		0.199
		(0.394)
Vendor at daily market/rythu bazar		Reference
		-
Vendor at weekly market		0.66

		(0.450)
Female (reference = Male)	0.592	0.211
	[0.0349,10.05]	(0.345)
Scheduled Caste, Scheduled Tribe or Backwards Caste (reference = Other Caste)	1.324	-0.653*
	[0.125,14.06]	(0.309)
Constant		1.599***
		(0.318)
Random effects		
Retailer variance	38.08	0.123
	[0.0297,48870.2]	(0.0807)
Residual variance		0.619***
		(0.107)
Observations	110	97
Number of groups	43	41

Abbreviations: CI, confidence interval; OR, odds ratio; SE, standard error

* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

Table 10. Estimation results from two-step mixed effects regression models of start-of-sale food loss. Extent of start-of-sale food loss is natural log-transformed.

	Start-of-sale food loss occurs, OR [95% CI]	Extent of start-of-sale food loss, β coefficient (SE)
Retail type		
Brick and mortar shop/local retail shop	0.152*	
	[0.0244,0.944]	
Pushcart or roadside shop	0.727	
	[0.177,2.985]	
Vendor at daily market/farmer's market	Reference	
	-	
Vendor at weekly market	0.554	
	[0.116,2.633]	
Display cover		
Open air, uncovered	1.132	
	[0.481,2.662]	
Open air, covered	Reference	
	-	
Indoors	0.248	
	[0.0184,3.346]	

Purchasing selection		
Customers choose/handpick tomatoes to purchase	Reference	
	-	
Retailer chooses/handpicks tomatoes for customer	1.933	
	[0.688,5.426]	
Tomatoes are pre-packed for sale	0.155	
	[0.0133,1.794]	
Maximum sale price (10 rs/kg)	0.637***	
	[0.500,0.811]	
Maximum ripeness level		
Breaker to light red	0.251*	0.995
	[0.0694,0.908]	(0.590)
Red	0.160***	0.911
	[0.0589,0.436]	(0.480)
Super red	Reference	Reference
	-	-
Procurement source		
Bowenpally wholesale market		0.177
		(0.286)
Gudimalkapur wholesale market		Reference
		-
Madannapeta wholesale market		-0.4
		(0.356)
Other source		0.989
		(0.523)
Range of ripeness levels (1-7)		-0.254**
		(0.0849)
Female (reference = Male)	1.691	0.648*
	[0.614,4.662]	(0.329)
Scheduled Caste, Scheduled Tribe or Backwards Caste (reference = Other Caste)	0.684	-0.425
	[0.195,2.403]	(0.372)
Constant		1.575***
		(0.387)
Random effects		
Retailer variance	1.748	6.24E-34
	[0.795,3.846]	(1.25e-17)
Residual variance		1.140***
		(0.173)
Observations	330	87

Number of groups	50	33

Abbreviations: CI, confidence interval; OR, odds ratio; SE, standard error
$^{*} p < 0.05$, $^{**} p < 0.01$, $^{***} p < 0.001$

Discussion and conclusions

This paper seeks to elucidate the extent, stages and determinants of food loss along tomato supply chains in South India. Different from previous studies on food loss along perishable vegetable supply chains, we collected intensive food loss data on harvest, trade and sale days. Similar to previous studies on FL&W, we find that food loss estimates are skewed at each supply chain stage (Chaboud & Daviron, 2017; Delgado et al., 2020). Unlike Delgado et al., we do not combine quantity and quality loss estimates, since products that have food quality loss still remain within the supply chain, available for human consumption (Delgado et al., 2020). From our repeated measures on each supply chain actor, we find that there is a wide range of frequency of food loss, 7% at the tomato trader stage compared with 58% at the pre-auction stage, as well as a wide range of the extent food loss when loss is positive, averaging 9% loss at the on-farm, post-harvest stage to <1% loss at trader stages. Our findings demonstrate that summary, single-point estimates may obscure important food loss patterns both between and within supply chain actors.

Nearly half (48%) of our enrolled sample of tomato farmers, who had expressed intent to grow and harvest tomatoes during the study period, did not harvest tomatoes, often citing water scarcity as the major production barrier. In Andhra Pradesh, Chittoor district is among the districts that is most vulnerable to climate change (Rao et al., 2017). Chittoor has been experiencing decreased July rainfall (start of monsoon season) leading to low groundwater availability, which is important for irrigation. Food loss estimates that do not cover pre-harvest and field losses may underestimate the effects of climate change on food loss.

We find that 69% harvests include tomatoes with pre-harvest damage. Among harvests with damage, an average of 13% of tomatoes are damaged. Farmers most often attribute the damage to pests or disease. One pest that is of particular problem is the South American tomato leaf miner, *Tuta absoluta*, an invasive pest that was first reported in tomato fields in Maharashtra, India in 2014 (Shashank, Chandrashekar, Meshram, & Sreedevi, 2015) and has since spread to other states, including Andhra Pradesh

(Buragohain, Saikia, Sotelo-Cardona, & Srinivasan, 2021). Not only affecting the tomato plant during growth, *Tuta absoluta* larvae enter and feed on tomato fruit, causing damage and undesirable product attributes even after tomatoes have been harvested (Desneux et al., 2010).

We also demonstrate that the changes counting unconsumed food as FL&W based on final use significantly changed the food loss estimates at the farmer, tomato trader and vegetable retail stages, but not at the vegetable trader stages. This is likely because vegetable traders report very low food loss (<1%) and are more likely to simply discard unconsumed tomatoes to the trash (non-food and non-productive use) rather than divert to a productive use, such as animal feed. In comparison, livestock are readily available at the farm level as an end use for diverted tomatoes, as well as at the tomato wholesale market where an animal feed side channel exists. Importantly, farmers and retailers do not financially benefit when tomatoes are diverted to animal feed, reporting an average expected price of 0 Rs. At the farm level, food loss estimated by farmer declaration and food loss estimated using the non-food use definition are both significantly greater than food loss estimated by non-productive use, suggesting that farmers consider tomatoes diverted to animal feed as food loss. Some farmers divert tomatoes to feed their own animals. We are unable to differentiate between food diverted to farmers' own animals versus animals owned by others to determine if there is a difference in farmer-perceived benefit. Unlike staple grains where non-food pathways are built into the supply chain, perishable vegetable supply chains are structured differently, and vegetables are grown with the sole intention of being used as food. Therefore, redirecting food towards non-food, but productive use, such as animal feed, is a diversion of important micronutrients sources away from a food system that is already at a deficit.

At pre-harvest, we find that the harvest number and harvesting during peak season are factors associated with decreased odds of preharvest quality loss. Meanwhile, a higher expected market price is associated with decreased proportion of pre-harvest quality loss when reported loss is positive. Given that we did not find quality intensity (measured by a line scale) to be significantly associated with pre-harvest quality loss, these findings suggest that farmers perceive pre-harvest quality loss based on the current acceptable quality thresholds at the market. During peak season when tomato wholesale market prices are higher, lower quality tomatoes are sold at auction. During off-peak season, when prices are lower, tomato traders may only bid on higher quality tomatoes and lower quality tomatoes remain unsold. Therefore, either the quality thresholds become too stringent during the off-peak season, where food that is edible is discarded, or the quality thresholds become too lax during peak season and there might be a food-safety concern regarding food entering the supply chain, or both.

Associations of loss and shifting quality standards are further supported by the fact that harvest peak season was significantly associated with a decreased odds of post-harvest loss and a decreased extent of post-harvest loss. Intuitively, on-farm grading is associated with an increased odds of post-harvest loss, as the purpose of grading and sorting is to remove tomatoes that do not meet quality standards. The extent of post-harvest loss was significantly associated with pre-harvest quality loss, post-harvest loss increases as pre-harvest quality loss increases. These findings suggest that when prices during off-peak season are low and quality standards are shifted upwards, farm-level grading and sorting helps farmers to remove tomatoes that will not sell at the market and reduce transaction costs. Unexpectedly, we find that among harvests with post-harvest food loss, on-farm grading and sorting was associated with a decrease extent of food loss. One possibility is that famers who perform grading and sorting on the farm remove only tomatoes that are found to be below a marketable quality threshold, compared to farmers who do not thoroughly assess quality through grading and sorting, and end up discarding more tomatoes than may be necessary.

At the Madanapalle wholesale market, the odds of pre-auction loss are increased when hired females or males from the from households are involved in farm-level packing, as well as when hired females are involved in grading at the market. This finding reveals the importance of considering not only hired versus family but also gender labor differences. Peak harvest season, when tomato prices tend to be higher, was associated with a lower extent of pre-auction loss among lots with loss. Again, given that quality intensity was not a significant determinant of loss, this suggests there are seasonal changes in acceptable tomato qualities.

We did not find any significant factors associated with loss from the end-of-sale at the vegetable retail stage. Loss on the end-of-sale includes tomatoes that the retailer graded out at the start of selling, as well as tomatoes the retailer discarded at the end of the day that they did not sell to consumers. Start-of sale food loss estimates only account for tomatoes that the retailer graded out at the start of selling and were, therefore, not available to consumers. We argue that this loss falls on the supply side since consumers are not yet involved in the selection process. The odds of start-of sale food loss are decreased when the retailer expected a higher selling price and when the ripeness level of tomatoes is less than super-red. Tomatoes that are not too ripe may be more attractive to consumers, as they are less prone to bruising and may not need to be used the same day.

Study limitations

A major limitation of our study was that nearly half our enrolled farm sample did not harvest tomatoes, leading us to have a reduced sample size than intended. Due to complication with COVID-19, we were unable to survey these additional farm households during the peak harvest season. However, as previously discussed, the reported challenge of water scarcity is not likely to go away in the era of climate change. Therefore, tomato farmers in this area may continue to find it difficult to produce tomatoes. Additionally, we were unable to follow participating farmers to wholesale markets outside of Madanapalle. As such, our pre-auction loss results are biased towards only harvests where farm households traded at the Madanapalle wholesale market.

At the tomato trader and vegetable trader stages, we encountered logistical challenges during data collection due to the timing of activities, market space, and volumes of tomatoes traded. Particularly during peak season at the Madanapalle tomato market, the market is packed with farmers, traders, laborers and trucks to move tomatoes in and out of the market, and tomato traders may not be willing to give their time. At the vegetable wholesale market, transactions start before sunrise, creating a missed opportunity to observe tomato lots in-full, and relying on vegetable trader recall only.

Future directions

In this study we aimed to explore the extent, stage and determinants of food loss along tomato supply chains in South India. Using primary data collected from farmers, tomato traders, and urban vegetable traders and retailers, we find that there is a wide range of incidence of food loss and a smaller range of food loss incurred when food loss is positive. Across the supply chain from farm to retail, food loss is highest at the farm-level. From production to post-harvest, there are many different activities and inputs farmers are responsible for that can prevent or contribute to food loss. In addition to building the evidence on food loss estimates, it is important to continue to build the evidence on determinants of loss, including at the production and pre-harvest stages.

We also find significant differences in food loss estimates at the farm and retail levels when we compare non-food and non-productive uses. Perishable vegetable supply chains are different from staple grain supply chains in that perishable vegetables are produced for human consumption and pathways for redirecting vegetable to productive, non-food uses may not be remunerative. Future work on FL&W estimations should consider the food group(s) of interest and potential supply chain contexts when defining food loss destinations.

Finally, pre-harvest damage and post-harvest loss appear to be closely aligned, possibly due to shifts in price during peak season and the impact of market price on acceptable quality thresholds. The National Agriculture Market (eNAM) electronic trading platform may become a source of information to better quantify the flow of tomatoes to and from wholesale markets. Further, farmers may benefit from using eNAM as a source of accurate price information. Future studies should account for technology shifts that improve price and quality transparency to understand potential linkages with FL&W.

CHAPTER 4

FOOD QUALITY ASSESSMENT ALONG FRESH TOMATO SUPPLY CHAINS IN SOUTH INDIA

Introduction

Food loss and waste (FL&W) has emerged as a priority food systems issue, particularly after the FAO estimated that one-third of all food is lost or wasted (FAO, 2011). Ongoing work to estimate and reduce FL&W along supply chains of different food groups and contexts primarily focuses on the quantity of food that is removed from the supply chain (Craig Hanson et al., 2016; FAO, 2019). Food loss and waste is most often expressed as a percentage of product mass or volume. Several studies have expressed FL&W in terms of calories, leading to greater FL&W estimates for energy-dense foods (HLPE, 2014). Food quality loss and waste refers to the decrease in quality (e.g. nutritional, sensory or other attribute) of food along the food chain without a decrease of dry matter of food (HLPE, 2014). Food quality loss and waste is related to FL&W; when food has lost quality below an acceptable threshold, the food may be removed, entirely, from the food chain and no longer available for human consumption (HLPE, 2014). Therefore, understanding food quality loss along food supply chains is important not only to examine underlying causes of FL&W, but also to examine the quality of food that is reaching consumers. This is particularly true for more perishable foods that are important sources of micronutrients, such as fruits and vegetables.

As a human construct, food quality is not a single attribute, but incorporates different properties including sensory (e.g. appearance, texture, and taste), nutrient content, function and defects (Abbott, 1999). The search, experience, credence (SEC) framework is useful for distinguishing between search attributes, those that are easy to identify before purchase; experience attributes, those that are identified at consumption (Nelson, 1970, 1974); and credence attributes, those that cannot be immediately identified by direct experience (Darby & Karni, 1973). The SEC framework is often used to explore end-consumer preferences and behaviors (Ariyawardana, Ganegodage, & Mortlock, 2017; Kapoor & Kumar, 2015; Uribe et al., 2020). Importantly, there are several consumers along food supply chains; each supply chain actor behaves as a consumer with respect to the previous actor and sets their own acceptability criteria and thresholds that vary by context, personal expectations and preferences (Abbott, 1999).

Conceptually, the main post-harvest objectives for fruits and vegetables are to maintain quality, including appearance, nutritive value and food safety, and to reduce food losses (Kitinoja & Kader, 2002). Quality standards often use search attributes to determine acceptable thresholds (Kyriacou & Rouphael, 2018), below which food is removed from the supply chain. Minimum quality standards serve to protect final consumers from inedible and low quality foods (A. A. Kader, 2010). In contrast to low- and middle-income countries, high-income countries usually have rigorous quality standards that may over-emphasize appearance attributes and remove foods that can be safely consumed (HLPE, 2014; A. A. Kader, 2010). Because credence attributes are unobservable in the marketplace, credence quality attributes, such as nutrient content, can decrease without the food itself being removed from the supply chain. In this paper, we explore search and credence food quality attributes along a perishable vegetable supply chain in South India. Although previous research has explored food quality information transfer and quality loss as a cause of food loss in India (Fafchamps et al., 2008; Sheoran A, 2015), there remains a research gap with regard to supply chain actor quality assessment in the context of food quality loss and food loss of perishable fruits and vegetables in India.

Compared to staple crops, such as grain, the quality of non-staple crops, such as fruits and vegetables, is more variable (Fafchamps et al., 2008). Without adequate cold storage, mature fruits and vegetables quickly deteriorate as bruising, over-ripeness, excessive softening and biological spoilage cause quality loss and post-harvest food loss (Hodges et al., 2011; Kitinoja & Kader, 2002). Compared to rice, Vandeplas and Minten (2015) find that tomatoes with different quality attributes have a significantly higher value relative to the average price (Vandeplas & Minten, 2015). While market channels for low-quality produce may exist, either year-round or seasonal, supply chain actors face financial losses when produce is sold in lower price channels. Among supply chain actors, farmers are often the first to grade and sort produce into groups of marketable and unmarketable tomatoes, relying on sensory evaluation methods.

Compared to sensory evaluation, instrumental measurements are the preferred measurement method because they reduce variation between supply chain actors (Abbott, 1999). Indian fruit and vegetable wholesale market services and infrastructure remain basic, with limited use of modern technology and lack of modern methods to identify and certify quality differences (Fafchamps et al., 2008).

Supply chain actors make decisions on harvest and post-harvest practices with the aim to maximize the period of acceptable product quality (Kyriacou & Rouphael, 2018). Ripening and other physiological processes are usually correlated, such as estimating firmness from ripeness stage (Abbott, 1999). However, production and post-harvest conditions and handling may change plant physiological processes and indirect measurements are no longer correlated with other quality attributes (e.g. a tomato softens without expected color change) (Abbott, 1999). Further, market quality standards are not fixed and change with product supply and demand (Dunning et al., 2019).

Fruits and vegetables are perishable foods that are important source of micronutrients. Nutrient content is a credence attribute that supply chain actors and consumers cannot observe. Pre-harvest, the nutrient content of fruits and vegetables varies by cultivar, season, growing location, and maturity. The maturity stage, indicated by ripeness, at harvest affects the product composition and quality (A. A. Kader, 1986). At harvest, products are separated from their nutrient source. Post-harvest processes, conditions and storage timing can affect vitamin content (Rickman, Barrett, & Bruhn, 2007). Considering these different variables, a research gap remains to fully understand these effects on vitamin retention because few studies follow the same product from harvest to consumer (Rickman, Barrett, et al., 2007).

Ascorbic acid (vitamin C) degradation is often measured as an indicator of overall vitamin degradation. Ascorbic acid is water soluble vitamin, highly sensitive to heat and oxidation. However, ascorbic acid does not accurately indicate the degradation of more stable vitamins such as fat-soluble vitamins A & E and carotenoids (Rickman, Bruhn, & Barrett, 2007). Post-harvest storage conditions and timing affect the temperature and oxidation of the product which affect nutrient retention (Rickman, Barrett, et al., 2007; Rickman, Bruhn, et al., 2007). Importantly, the statistical significance of nutrient retention should be considered in the context of the practical significance to human nutrition and whether or not the examined food is an important dietary source of the examined nutrient requirements (Rickman, Barrett, et al., 2007).

The objective of the current study was to explore supply chain actor perspectives on quality attributes and identify associations between important sensory attributes and ascorbic acid content. Using data collected from tomato supply chain actors in major growing and trading regions in South India, we identified important quality attributes used to assess overall product quality, examined how quality intensity and price relate to market grades within and between actors, and modeled associations of search quality attributes with ascorbic acid, a credence attribute.

Data and methods

Study location & participants

This study was carried out along tomato supply chains in Chittoor district, Andhra Pradesh and Hyderabad city, Telangana. Details on the study sites and participant selection were presented in Chapter 2. In brief, Andhra Pradesh is a major tomato-producing state in India, and Chittoor district is a major tomato producing district in Andhra Pradesh (GOI, 2019b; Government of Andhra Pradesh, 2018c). The Madanapalle tomato market in Chittoor district is among the largest tomato trading hubs in India (Modekurti, 2016). Vegetable wholesale markets in Hyderabad, Telangana import tomatoes from Chittoor district for supply to urban consumers. We used stratified, multistage random sampling to recruit farmer participants from Madanapalle and Nimmanapalle mandals in Chittoor district. Farmers were surveyed on the day of harvest and on the following day, for those that brought their tomatoes to the Madanapalle tomato wholesale market. At the Madanapalle market, we enrolled and surveyed tomato traders who purchased tomatoes from a participating farmer. In Hyderabad, we enrolled vegetable traders that trade tomatoes based on a census carried out across three state-government run vegetable wholesale markets. Using snowball sampling, we recruited vegetable retailers that sell tomatoes based on referrals from vegetable trader participants. Vegetable trader and vegetable retailers were surveyed monthly.

Pile sort focus group discussions

Along the tomato supply chain, farmers are the first actors to assess product quality, and most of the grading and sorting occurs while tomatoes are under the farmer's control, either at the post-harvest, farm-level or at the pre-auction, market-level. To identify important search attributes relative to marketability and market grades, we held pile sort group discussions with tomato farmers. During this activity, four to six tomato farmers sat in a circle and were each given a bowl of tomatoes (weighing approx. 10 kg). Tomatoes were harvested on the same day of the group discussion and had not been graded or sorted. We asked participants to group their tomatoes into piles so that tomatoes of similar quality were in the same pile. Participants were unconstrained in the number of piles they chose to make, and we did not give any reference to specific quality criteria (Weller & Romney, 2011). Participants were given one opportunity to sort items before we began the group discussion. Once all participants finished the pile sort task, we asked participants to describe their sorting processing, probing on quality attributes, use or destination, and marketability. Each participants' piles were numbered to serve as a reference for participants to clearly identify the pile(s) they were referring to throughout the discussion. Group discussions were led by a trained staff member and conducted in Telugu. Discussions were audio-recorded with permission from participants. For participants who wished not to be audio-recorded, the audio recording was paused, and hand-written notes were made to summarize the discussion. Audio recordings were translated and transcribed into English for analysis. At the end of the first two pile sort group discussions, we took photos of the grouped tomatoes set on a black cloth background with rupee coins as size references. We used these photos throughout supply chain actor surveys as reference photos for quality attribute-related questions.

Eleven pile sort focus group discussions were held across 11 study villages. The full interview transcripts were coded using a qualitative analysis software, ATLAS.ti version 8, and analyzed to understand how farmers perceive tomato market grades, quality attributes, use and destinations, and marketability. We used a deductive coding approach where we identified a coding framework *a priori* (Crabtree & Miller, 1999) based on our research question and theoretical framework on tomato quality and marketing (Chaboud &

Moustier, 2020; Fafchamps et al., 2008). Codes within code groups evolved as we reviewed the data. To explore the pile-specific patterns, we created similarity matrices to tabulate the co-occurrence of codes in piles so that the items that are together are counted as being similar (Weller & Romney, 2011).

Quality assessment along the supply chain

Based on formative work carried out from June-July 2018, we observed that market grades (e.g., 1st, 2nd, 3rd grade or A, B, C grade) are frequently used to describe the quality group of tomatoes. At the farm level, farmers may or may not perform grading and sorting. However, once farmers bring their tomatoes to the wholesale market, they perform grading and sorting as they organize tomatoes into auction lots by market quality grade. During surveys with supply chain actors, we asked participants to report important quality attributes to understand priority attributes for assessing tomato quality. Certain quality attributes may be correlated with others. For example, firmness is closely related to the ripeness stage; and color is most commonly used as an indicator of the ripeness stage (A. A. Kader, 1986). We therefore asked supply chain actors to report the overall tomato quality intensity using a line scale with labeled endpoints from 1 to 9, “low quality” and “high quality” (Lawless & Heymann, 2010). In this way, we aimed to avoid presenting participants with the challenge to separate quality attributes that are typically assessed as a group (Diamond & Hausman, 1994). Finally, we considered the reported price supply chain actors expect to receive for their product as a quality indicator, as quality differences have been shown to be associated with price differences along vegetable supply chains in India (Fafchamps et al., 2008). Farmers provided quality assessment at two supply chain stages, farm-level and market-level, since grading and sorting may be done at both locations. Tomato traders, vegetable traders and vegetable retailers provided quality assessment at tomato market, vegetable market and vegetable retail stages, respectively.

Tomato sampling and ascorbic acid analysis

Tomato used for ascorbic acid analysis came from study farmers participating in the main survey. On the day of harvest, we collected harvested tomatoes from the field. Tomatoes were either sorted into market grades or unsorted, depending on the farmer’s postharvest activities. We randomly selected tomatoes from either the top two market grades or, if unsorted, from the general pool of harvested tomatoes. On the following day, we met the same farmer at the Madanapalle tomato wholesale market and collected tomatoes in the same manner. Starting March 2020, due to social distancing limitations related to the COVID-19 pandemic, we were not able to collect quality intensity data, since this required the participant to touch the line scale on the tablet. Data on the tomato ripeness level came from survey data where participants reported the ripeness stage of tomatoes using a six-level color classification chart (United Fresh Fruit and Vegtable Association & USDA Agricultural Marketing Service Fruit and Vegetable Division, 1975). Based on participant feedback during piloting stages, we modified the chart to add a seventh ripeness stage (super red), similar to Suslow & Cantwell (Suslow & Cantwell, 1997).

Several methods exist to measure the ascorbic acid content of prepared food samples. Analysis using redox titration is the AOAC official method (AOAC, 1990). High performance liquid chromatography (HPLC) is another commonly used lab-based analytical method (Bouzari, Holstege, & Barrett, 2015; Rizzolo, Brambilla, Valsecchi, & Eccher-Zerbini, 2002; Tang & Lee, 2016). The British Standards Institution and the National Institute of Nutrition, India use HPLC methods to analyze ascorbic acid in foods (Longvah et al., 2017; Nielsen, 2017). A limitation of using lab-based methods is the distance and timing from sampling a fruit or vegetable at a rural farm to extracting ascorbic acid and analyzing the sample in a lab with adequate facilities and equipment. An alternative method is to measure ascorbic acid in fresh food samples using ascorbic acid test strips and a reflectometer. On the analytical test strip, ascorbic acid reduces yellow molybdophosphoric acid, also known as phosphomolybdic acid, to phosphormolybdenum blue, an unstable dye (Huckle & Lalor, 1955; Lowry & Lopez, 1946). The color change is measured as a reference color determined by a reflectometer. In this reaction, the higher the ascorbic acid concentration, the more rapid the reduction of phosphomolybdic acid (Heinonen & Lahti, 1981). Measurement of ascorbic acid using analytical test strips in a reflectometer has previously been done with tomatoes (Ashebir, Jezik, Weingartemann, & Gretzmacher, 2009), red raspberries (Neocleous & Vasilakakis, 2008), apples

(Drogoudi, Michailidis, & Pantelidis, 2008), and cherries (Yilmaz, Ercisli, Zengin, Sengul, & Kafkas, 2009).

We measured the ascorbic acid in sampled tomatoes on the same day that tomatoes were collected. Using an angle-cut tipped syringe needle (16 gauge), 100 mg samples of tomato flesh were sampled from tomatoes (Tang & Lee, 2016). Because the amount of ascorbic acid may change with sunlight exposure during production (Lee & Kader, 2000), we sampled from three regions of each tomato. Each sample was mixed with 200 µl extracting solution (0.01 M oxalic acid and 5% acetic acid) and 2 mg polyvinylpolypyrrolidone (Divergent, Millipore). The mixture was homogenized with an electric motor and pellet pestle for one minute and then spun in a mini centrifuge (Fischer Scientific) for one to two minutes, until a pellet formed, and the supernatant appeared clear and colorless. The ascorbic acid concentration was measured with an RQflex plus 10 Reflectoquant (Millipore) using ascorbic acid analytical test strips (25-450 mg, Millipore). However, after the lamp in the RQflex plus 10 failed, we replaced the machine with a newer model, RQflex 20 Reflectoquant (Millipore), and used the same analytical test strips. Each test strip was saturated with the supernatant and transferred into the RQflex plus adapter for the measurement result. Values below the 25mg/L detection limit were treated as missing values. A stock solution of ascorbic acid was prepared by dissolving 25 mg of L-ascorbic acid (Avantor Rankem) with 10 ml of the extractant solution. Aliquots of ascorbic acid were diluted with the extractant solution to provide standards used to construct a standard curve from 25 to 400 mg/L. The standard curve was used to calculate the ascorbic acid measured value (mg/L). The ascorbic acid concentration in each sample was expressed in mg/100g fresh weight and calculated using the equations provided by Millipore (Millipore Sigma, 2021a, 2021b). Since tomatoes are approximately 94% water (Longvah et al., 2017), we accounted for this additional water and calculated the total volume of extractant solution as the sum of the volume of oxalic acid/acetic acid and the volume of water coming from the tomato sample. Finally, we calculated the mean ascorbic acid concentration for each tomato.

$$Ascorbic\ acid\ (mg/100\ g\ fresh\ weight) = 100\ x\ \frac{Measured\ value\ (mg/L)\ x\ Vol.extractant\ solution\ (L)}{Weight\ of\ sample\ (g)}$$

Statistical analysis

To determine differences between market grades and quality intensity and price within and between supply chain stages, we used linear regression with random effects at the supply chain actor and harvest/lot levels. We included these random effects to account for the random variability that occurs as each supply chain actor assesses the quality of tomatoes, comparing tomatoes relative to each other in each harvest or lot. To determine which groups differed from each other, either across different market grades or across different supply chain stages, we performed a pairwise comparisons of means with a Bonferroni correction indicating where any differences occurred. Significance level was set to $\alpha = 0.05$.

To explore potential associations of search attributes, quality intensity and ripeness stage, with ascorbic acid concentration, a credence attribute, we fit a linear mixed model with farmer-level random effects. We log-transformed the mean ascorbic acid concentration using the natural log to control for heteroskedasticity of the error term. We included tomato breed, sampling location, and harvest season as covariates, as these have been shown to impact ascorbic acid concentration in tomatoes (Giovanelli, Lavelli, Peri, & Nobili, 1999; A. A. Kader, 1986; Lee & Kader, 2000). We exponentiated the estimated coefficients to interpret the coefficients in terms of percent difference in ascorbic acid concentration. We used Stata, version 15, for all analyses.

Results

Quality attributes: qualitative pile sort FGD & similarity matrix

We conducted one pile sort focus group discussion at each study village for a total of 11 group discussions. In total, participants identified 197 tomato groups. Using a pre-determined framework of grouping domains and categories, we expanded the codes while reviewing the group discussion transcripts. The grouping domains, categories and participant-reported grouping aspects are reported in **Table 11.** While participants most often referred to the quality grades in terms of market grade (n=150), some participants used more general quality group terms such as “high”, “medium” and “low”. The quality attribute grouping domain had the greatest number of grouping categories, indicating that participants consider many different attributes when grouping tomatoes. Many of the quality attributes described were search attributes, such as size, color/ripeness, firmness and damage. Participants distinguished different uses and destinations for each tomato group ranging from destinations where tomatoes would be consumed as food to destinations where tomatoes would be used as either animal feed or discarded as refuse (e.g., leaving on the vine, on the field or at the market). Finally, participants explained which tomato groups could be sold when market rates were high and when market rates were low.

Table 11. Grouping domains, categories and specific aspects reported by participants during pile sort group discussions

Grouping domain	Grouping category	Specific grouping aspects reported by participant
Quality grade	Market grade	1st quality/A grade; 2nd quality; B grade; 3rd quality/C grade; 4th quality/D grade; Damaged
	Quality group	High; good; medium; low; last
Quality attribute	Size	Big; medium; small
	Color/ripeness	Over-ripe; Ripened/red-ripe; semi-ripened; unripe/green; shine; discolored
	Firmness	Firm; soft
	Storage performance	Can be stored; cannot be stored/consume same-day
	Transport performance	Good for transport; not good for transport
	Pest/disease/physical damage	Black spots; oozi; worms; broken; leaking; spoiled/rotten; holes; blisters
Use/destination	Use	Fresh food; processing; animal feed; discard
	Destination	Market; household; leave on vine/field; trash
Marketability	Always sell	Sell at high or low rates
	Sometimes sell	Sell at high rates, cannot sell at low rates
	Never sell	Cannot sell at any rate

Using each grouping category and aspect for each of tomato group identified by market grade, we constructed a similarity matrix to visually describe the relationships of market grades with quality attributes, uses/destinations, and marketability. The results are presented in **Table 12.** Among quality attributes, participants most often used size attributes to describe grouping aspects for tomatoes. First grade tomatoes tended to be big in size, whereas 2nd grade tomatoes were often described as medium or small size. Third and 4th grade tomatoes were mostly described as small in size. Damaged group tomatoes were most often grouped based on the presence of pest, disease or physical damage. Most tomatoes across 1st through 4th grade were reported to be used for food. As the market grade quality decreased, participants more frequently mentioned animal feed and trash destinations. Animal feed and trash destinations were mostly described for damaged tomato groups. Finally, participants most often mentioned that the tomato groups could always be sold for 1st grade tomatoes. Only when tomato groups were described as 4th grade or damaged did participants also mention never selling the tomatoes.

Table 12. Similarity matrix of quality attributes, use or destination, and marketability across market quality grades.
The heat map assigns colors to attributes based on the number of groups reported for that grouping aspect. White boxes indicate that no data are available for that grouping relationship. Each grouping category was standardized by the number of groups in each market grade, so that attributes with fewer observations would not automatically have a lighter color.

	1st grade (n=47)	2nd grade (n=46)	3rd grade (n=31)	4th grade (n=7)	Damaged (n=27)
Quality attribute					
color: discolored	.	.	6%	14%	4%
color: shine	15%	.	.	.	.
color: no shine	.	.	3%	.	.
color/ripeness: over-ripe	.	2%	3%	.	4%
color/ripeness: ripe/red-ripe	13%	11%	3%	14%	.
color/ripeness: semi-ripe	11%	13%	13%	.	.
color/ripeness: unripe/green	.	4%	6%	.	7%
pest/disease/physical damage	.	2%	10%	.	67%
no pest/disease/physical damage	6%	.	.	.	4%
firmness: hard	11%	2%	.	14%	.
firmness: soft	.	.	6%	14%	7%
good to transport	6%	7%	6%	.	.
not good to transport	.	.	6%	14%	.
size: big	47%	2%	.	.	.
size: medium	4%	30%	13%	14%	.
size: small	4%	33%	48%	71%	4%
storable	9%	11%	10%	.	.

not storable	6%	2%	3%	.	4%
Use/destination					
fresh, food	89%	76%	71%	71%	37%
processing, food	11%	17%	19%	29%	15%
animal feed	6%	11%	39%	57%	63%
non-productive use/discard	11%	13%	29%	43%	89%
Marketability					
always sell	74%	48%	39%	43%	7%
sometimes sell	15%	30%	52%	43%	41%
never sell	.	.	.	14%	41%

Quality grading: color, market grade, quality intensity, price

In response to surveys, each supply chain actor reported quality attributes that are important in tomatoes. The results are reported in **Figure 2.** Nearly all of the reported quality attributes are search attributes, those that can be determined prior to consuming the product. Firmness was often reported by supply chain actors involved in stages after the farmgate. In contrast, pest/mold damage was frequently reported among farmers and vegetable retailers, who participate in opposite ends of the supply chain. Over half of all supply chain actors reported size as an important attribute. Color was most often reported by farmers, vegetable traders and vegetable retailers. Out of 276 harvests surveyed, 82% of the time farmers reported deciding to harvest based on the tomato ripeness level. In addition to asking supply chain actors to assess the quality of their product in real-time, we asked participants to assess the quality of tomato photos taken during the pile sort discussion, as described in the previous section. Examples of the tomato photos are shown in **Figure 3**, and the results from farmer-reported ripeness level for these two photos are presented in **Figure 4**. Farmers appeared to be in general agreement when tomatoes were fully ripened, as pictured in Photo A where over 90% of farmers presented with this photo reported the super red ripeness level. When tomatoes were not fully-ripened, farmers reported a wider range of ripeness levels. While 60% of farmers presented with Photo B reported red ripeness stage, between 30-40% of farmers also reported pink, light red and super red levels.

Figure 2. Radar plot of important quality attributes reported by supply chain actors

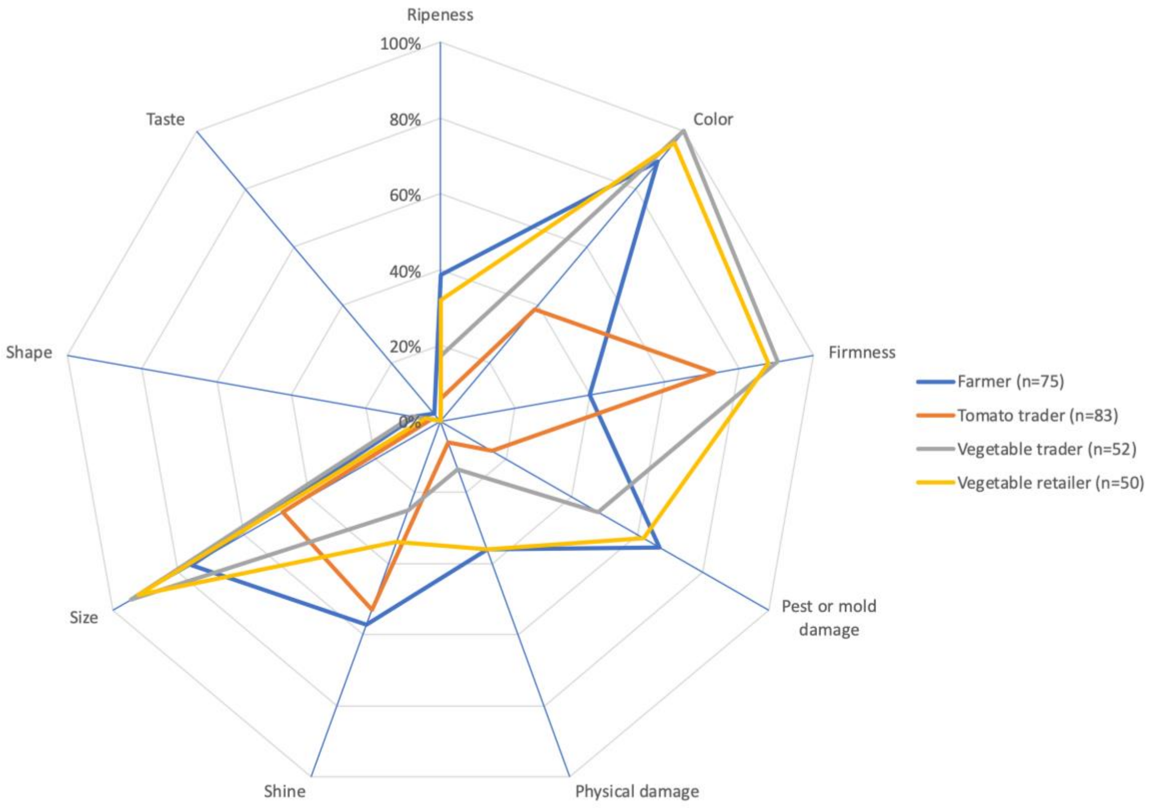


Figure 3. Examples of two tomato photos (Photo A and Photo B) used in supply chain actor surveys. Tomatoes were grouped by quality during farmer pile sort group discussions. 1, 2, and 5 rupee coins serve as size references.

Photo A

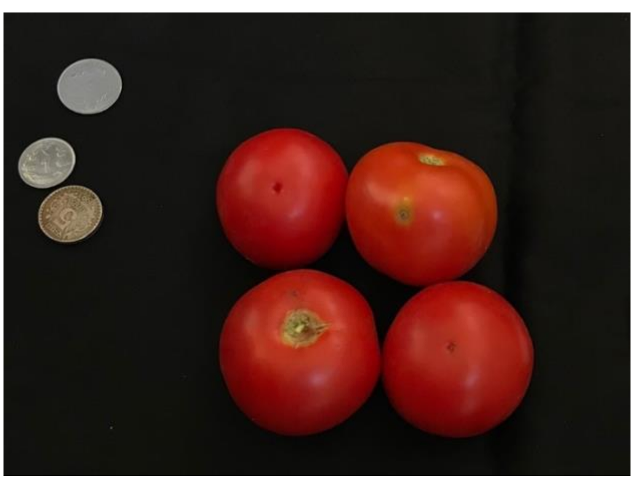
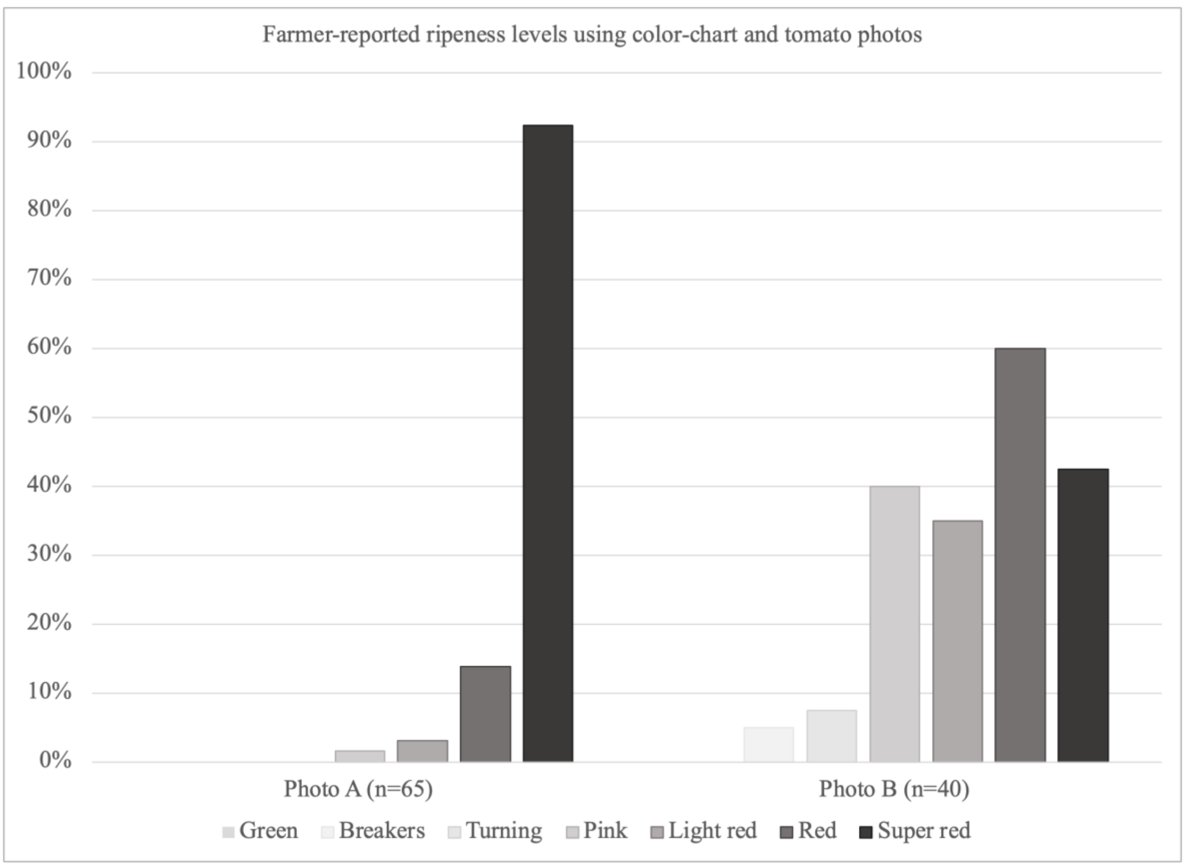


Photo B

Figure 4. Bar chart of farmer-reported ripeness levels for selected tomato photos



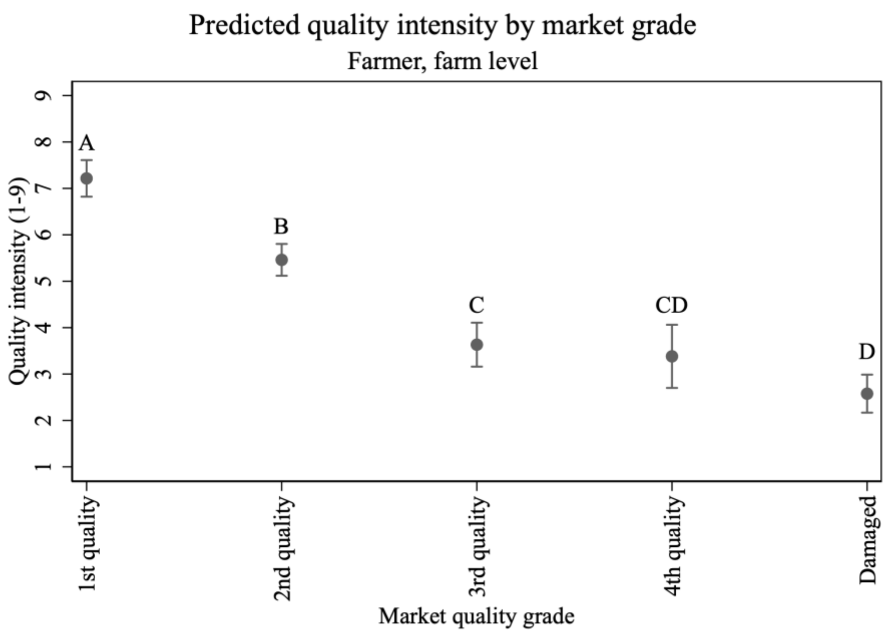
To determine which market quality grades differed from each other at across supply chain stages, we performed pairwise comparisons of means for quality intensity and price. We first examined differences in quality intensity between market grades at a given supply chain stage, with results presented in **Figure 5**. We find that market grades had statistically different quality intensities at 1st quality, 2nd quality, and 3rd quality across all supply chain stages. Third quality tomatoes had statistically different quality intensity than damaged tomatoes at all supply chain stages except for farmer-reported market level. Fourth quality tomatoes were indistinguishable from 3rd quality and damaged tomatoes, except at the vegetable trader stage. This could be due to the low frequency of 4th quality market grade reported at the farm, tomato market and vegetable retail stages. Vegetable traders did not report any damage quality tomatoes.

The results from comparisons exploring differences in quality intensity between supply chain actors at each market grade are presented in **Figure 6**. Supply chain actors did not report significantly different quality intensities at 1st grade, 2nd grade, 4th grade, and damaged tomatoes. Significant differences in quality intensity emerged among 3rd grade tomatoes, where vegetable retailers reported a greater quality intensity than farmers at the tomato market level. We did not find quality intensities reported at the farm level, tomato trader, or vegetable trader level to be significantly different than either the farmer at the market level or vegetable retailer.

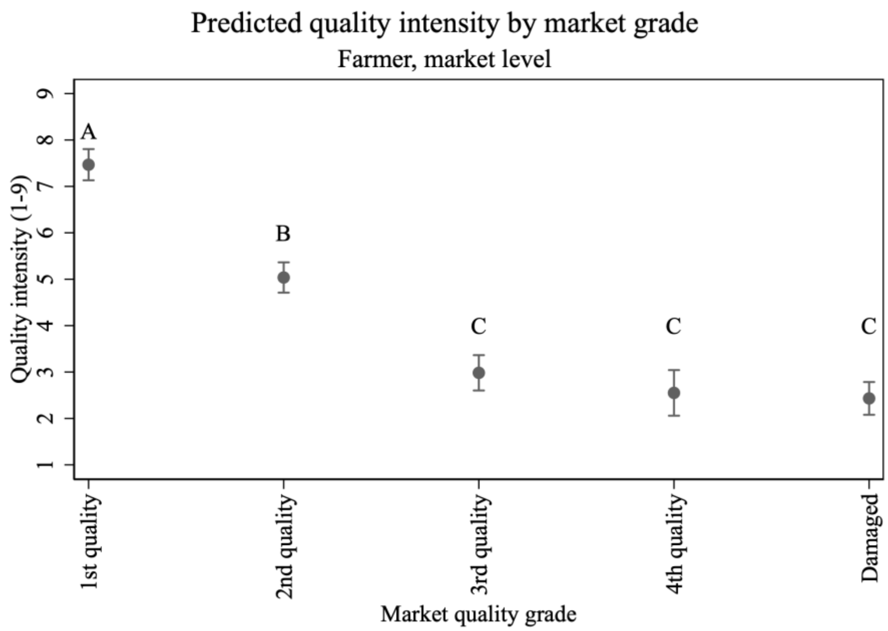
Next, we compared prices supply chain actors expect to receive at each stage with market grade. We first examined the differences between market grades by supply chain stage, and results are presented in **Figure 7**. Farmers and vegetable retailers were consistent in distinguishing market grade by price at the farm and tomato market, and vegetable retail stages, respectively. The expected price descends with lower market grades. Only 3rd and 4th qualities were not significantly distinguished by price. In contrast, only 1st and 2nd grades had significantly greater prices than damaged tomatoes at the tomato trader stage. There was no significant difference in price across 1st through 4th grade tomatoes, as well as no significant difference between 3rd and 4th grade and damaged tomatoes. At the vegetable trader stage, market grade was not significantly distinguished by price across any grade. When comparing results for peak and off-peak season, associations of price and market grade were different from the overall analysis at the pre-auction and vegetable retailer levels, only at off-peak season. At the pre-auction stage, there was no significant difference in price between 3rd and 4th quality, and between 4th quality and damaged. At the vegetable retailer stage, there was no significant difference in price across 2nd, 3rd and 4th market grades during off-peak season; and there was no significant difference in price across 4th and damaged grades during off-peak season.

Finally, we compared price across supply chain stages for each market grade, with results presented in **Figure 8**. At 1st, 2nd and 3rd quality market grades, vegetable retailers consistently reported a significantly greater price than farmers, at farm or market level, and vegetable traders. Other significant differences between supply chain actors were less consistent across each market grade.

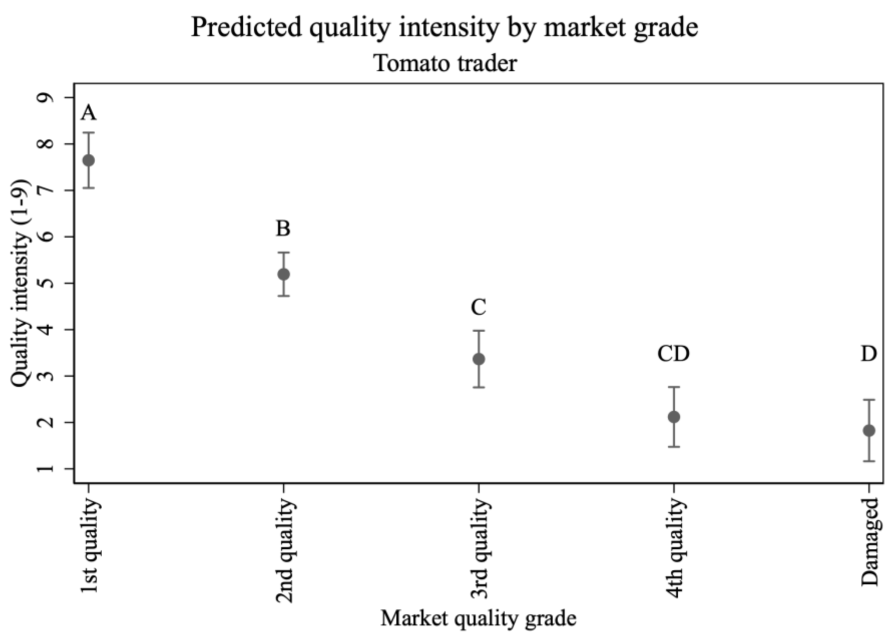
Figure 5. Marginal mean quality intensity by market grade reported across supply chain stages. Error bars denoted 95% CI. Bars sharing a letter are not significantly different at $p < 0.05$: analyzed by pairwise comparison with Bonferroni correction. (a) Farmer at farm; (b) Farmer at tomato market (c) Tomato trader at tomato market; (d) Vegetable trader at vegetable market; (e) Vegetable retailer at vegetable retail



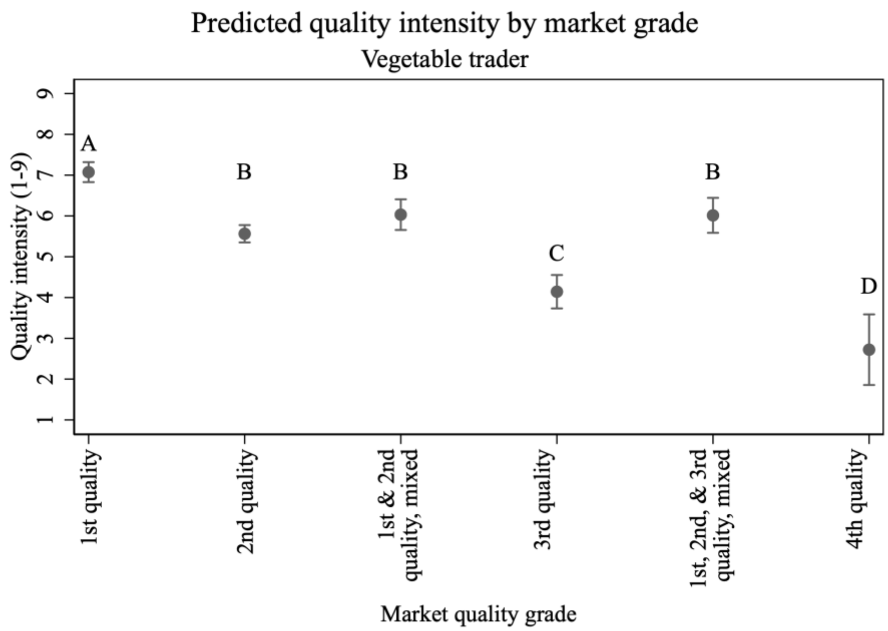
(a)


Predicted quality intensity by market grade
Farmer, market level
Quality intensity (1-9)
1
2
3
4
5
6
7
8
9
A
B
C
C
C
1st quality
2nd quality
3rd quality
4th quality
Damaged
Market quality grade

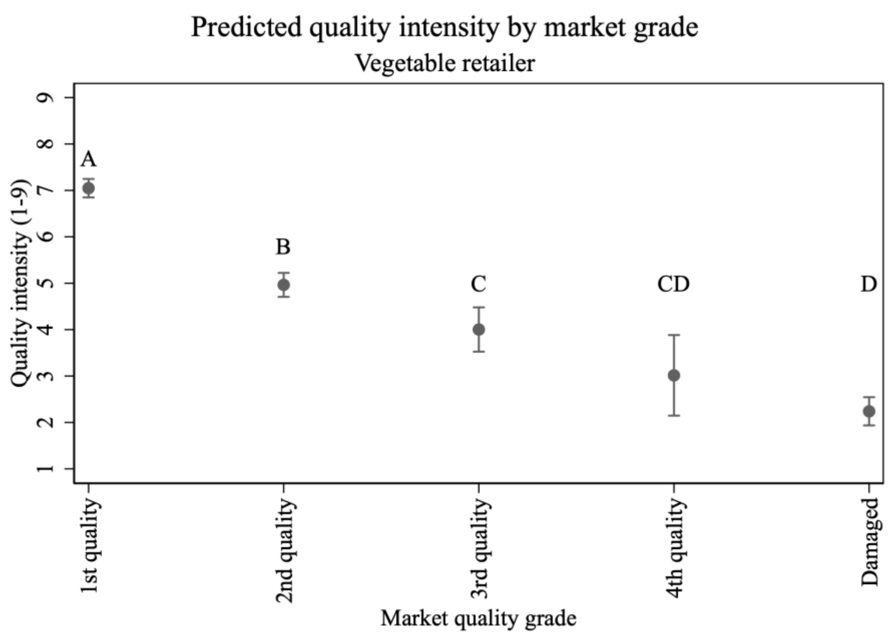
(b)


Predicted quality intensity by market grade
Tomato trader
Quality intensity (1-9)
1
2
3
4
5
6
7
8
9
A
B
C
CD
D
1st quality
2nd quality
3rd quality
4th quality
Damaged
Market quality grade

(c)


Predicted quality intensity by market grade
Vegetable trader
Quality intensity (1-9)
1
2
3
4
5
6
7
8
9
A
B
B
C
B
D
1st quality
2nd quality
1st & 2nd quality, mixed
3rd quality
1st, 2nd, & 3rd quality, mixed
4th quality
Market quality grade

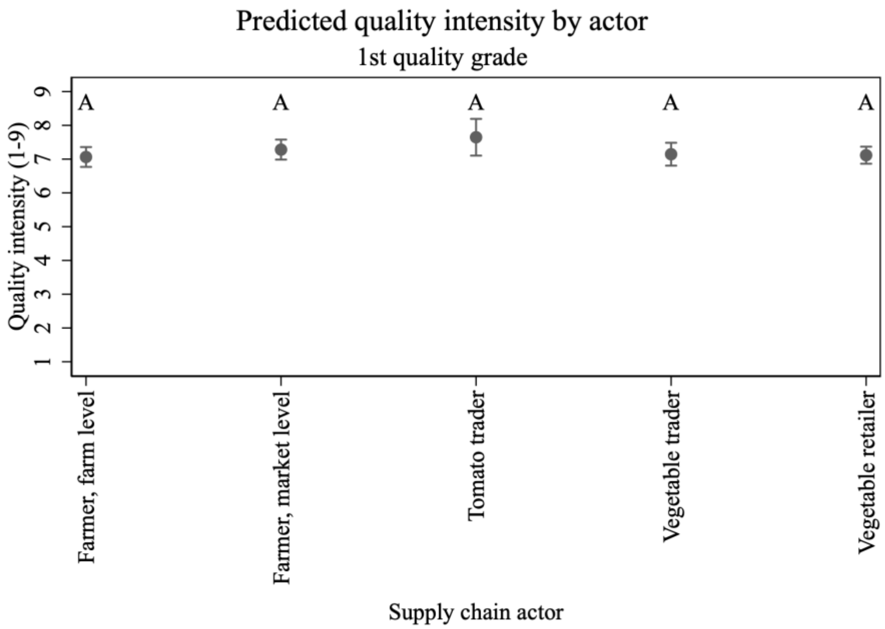
(d)


Predicted quality intensity by market grade
Vegetable retailer
Quality intensity (1-9)
1
2
3
4
5
6
7
8
9
A
B
C
CD
D
1st quality
2nd quality
3rd quality
4th quality
Damaged
Market quality grade

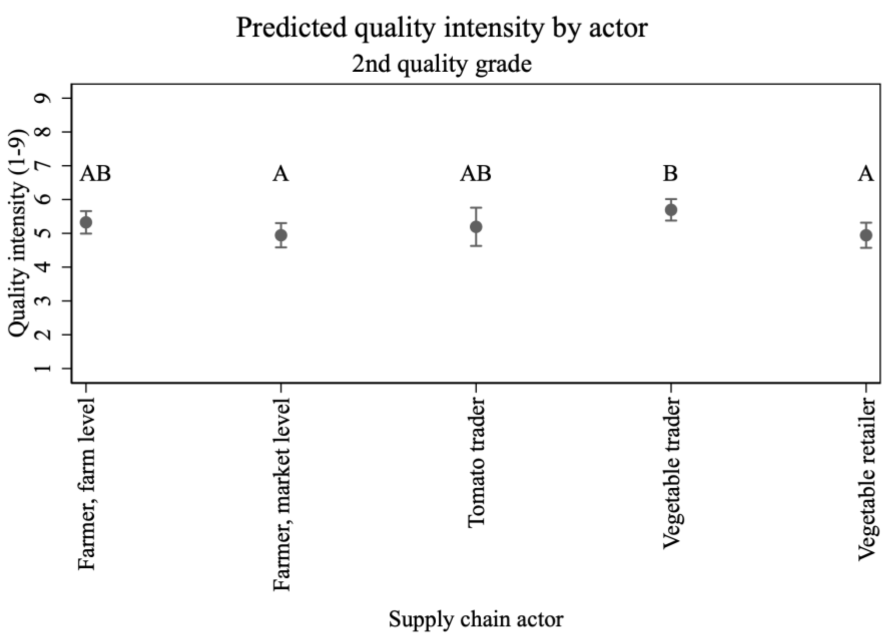
(e)

Figure 6. Marginal mean quality intensity by supply chain stage for individual market grades.

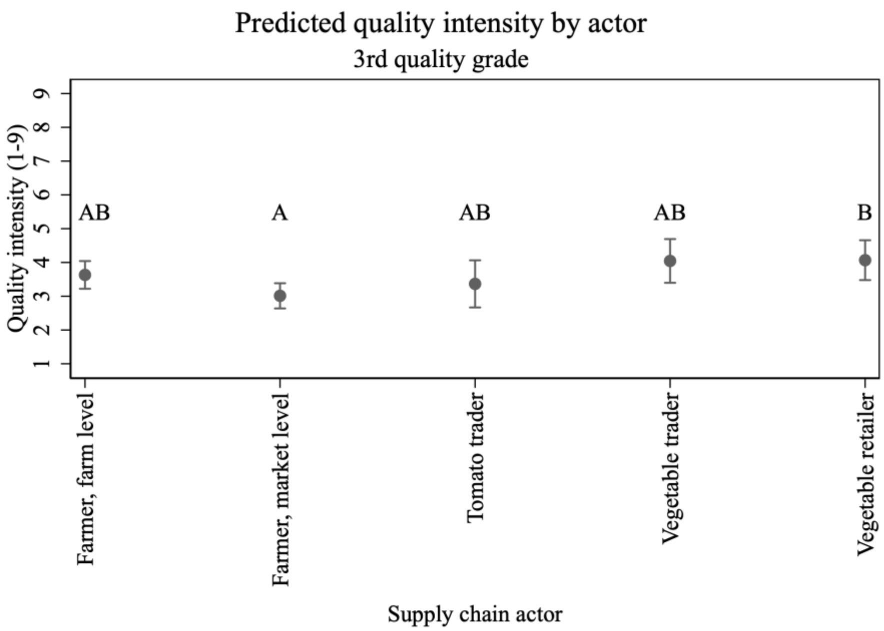
Error bars denoted 95% CI. Bars sharing a letter are not significantly different at $p < 0.05$: analyzed by pairwise comparison with Bonferroni correction. (a) 1st quality; (b) 2nd quality (c) 3rd quality; (d) 4th quality; (e) Damaged



(a)

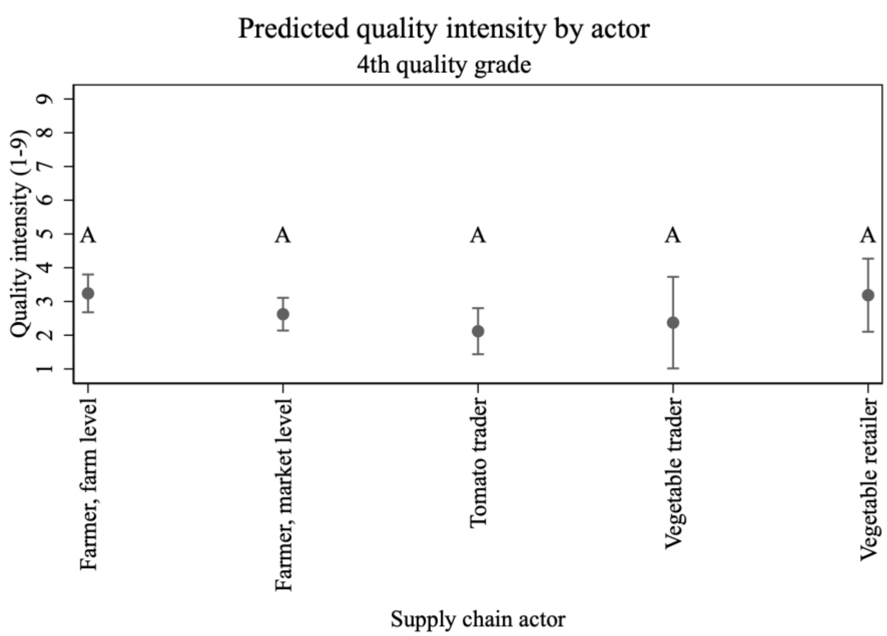


(b)



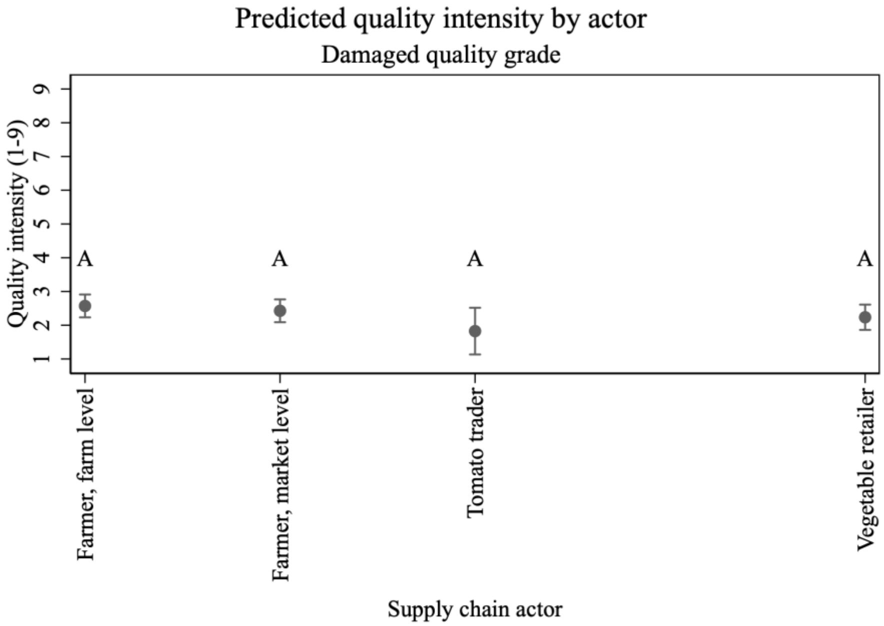
Predicted quality intensity by actor
3rd quality grade
Quality intensity (1-9)
1
2
3
4
5
6
7
8
9
AB
A
AB
AB
B
Farmer, farm level
Farmer, market level
Tomato trader
Vegetable trader
Vegetable retailer
Supply chain actor

(c)



Predicted quality intensity by actor
4th quality grade
Quality intensity (1-9)
1
2
3
4
5
6
7
8
9
A
A
A
A
A
Farmer, farm level
Farmer, market level
Tomato trader
Vegetable trader
Vegetable retailer
Supply chain actor

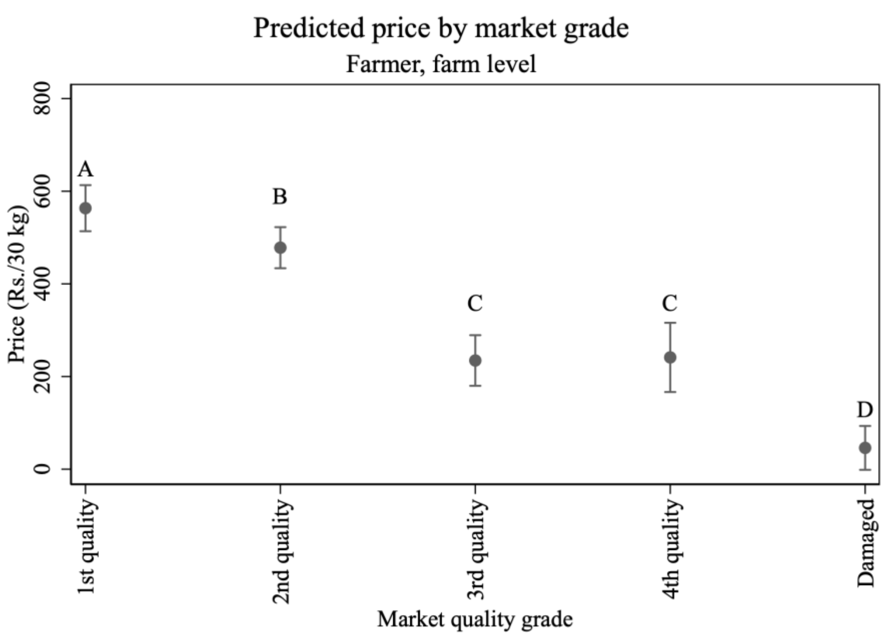
(d)



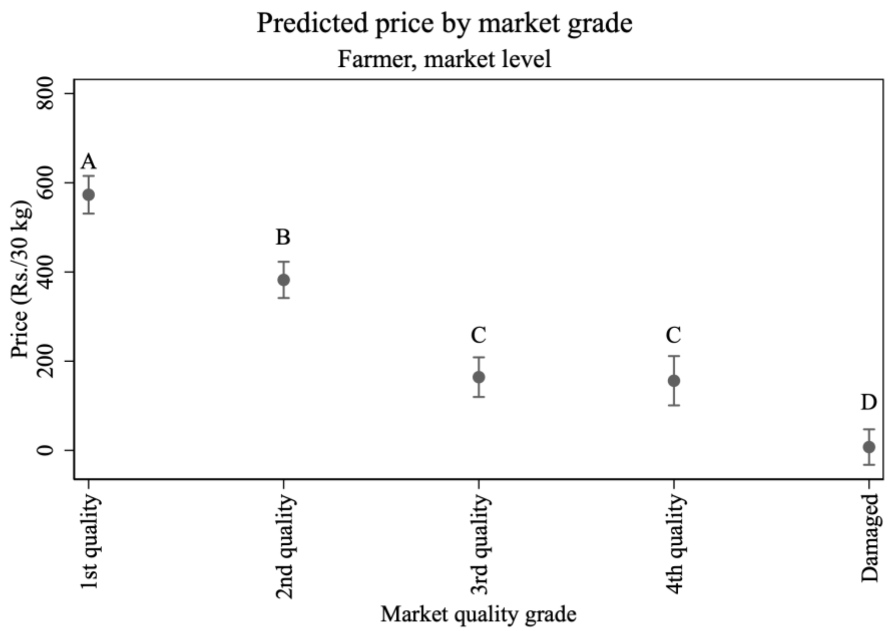
(e)

Figure 7. Marginal mean price by market grade reported across supply chain stages.

Error bars denoted 95% CI. Bars sharing a letter are not significantly different at p < 0.05: analyzed by pairwise comparison with Bonferroni correction. (a) Farmer at farm; (b) Farmer at tomato market (c) Tomato trader at tomato market; (d) Vegetable trader at vegetable market; (e) Vegetable retailer at vegetable retail

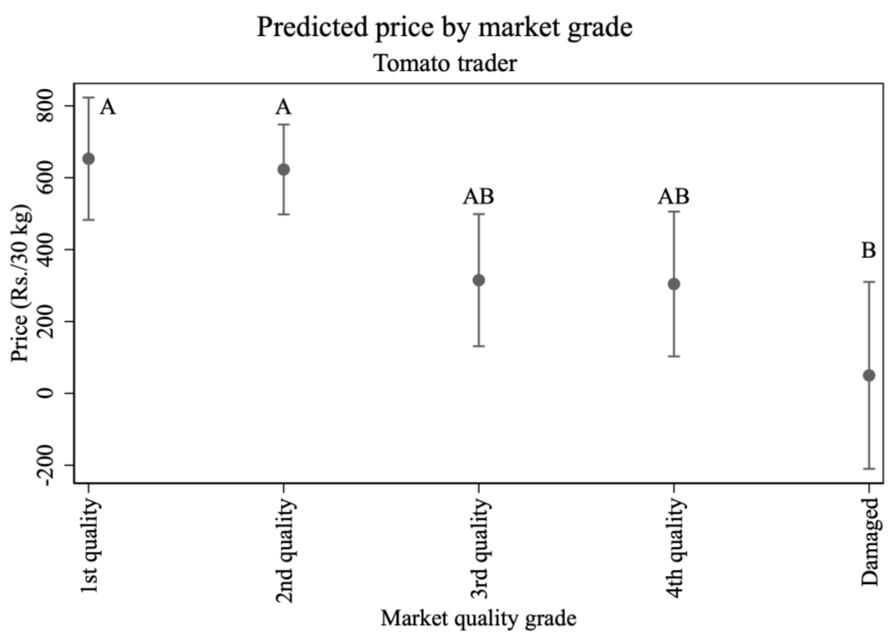


(a)



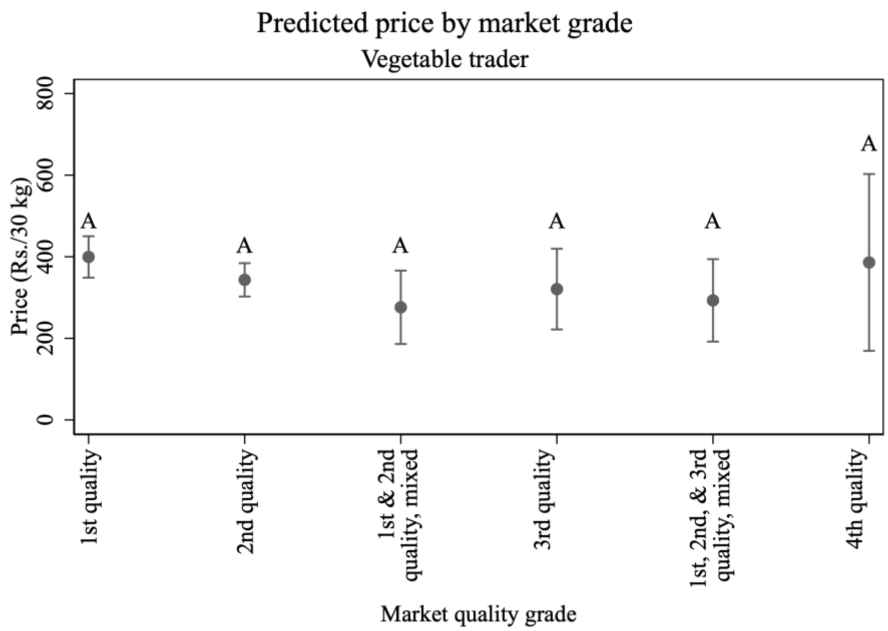
Predicted price by market grade
Farmer, market level
Price (Rs./30 kg)
800
600
400
200
0
A
B
C
C
D
1st quality
2nd quality
3rd quality
4th quality
Damaged
Market quality grade

(b)

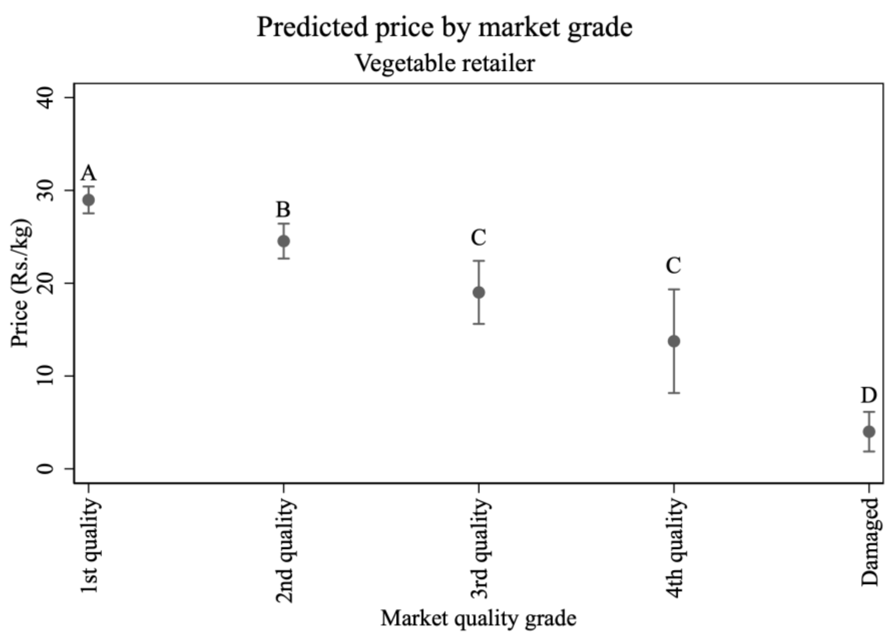


Predicted price by market grade
Tomato trader
Price (Rs./30 kg)
800
600
400
200
0
-200
A
A
AB
AB
B
1st quality
2nd quality
3rd quality
4th quality
Damaged
Market quality grade

(c)


Predicted price by market grade
Vegetable trader
Price (Rs./30 kg)
0
200
400
600
800
A
A
A
A
A
A
1st quality
2nd quality
1st & 2nd quality, mixed
3rd quality
1st, 2nd, & 3rd quality, mixed
4th quality
Market quality grade

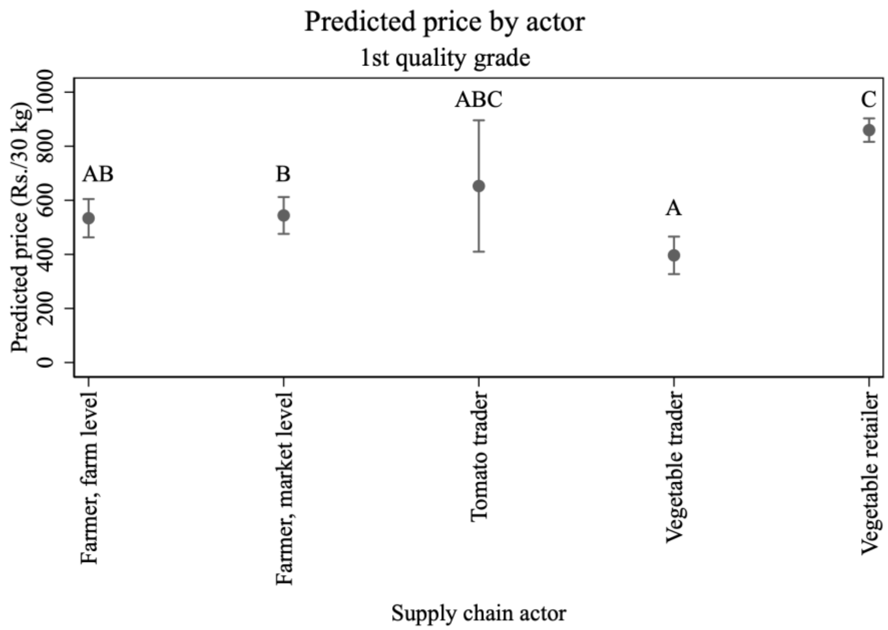
(d)


Predicted price by market grade
Vegetable retailer
Price (Rs./kg)
0
10
20
30
40
A
B
C
C
D
1st quality
2nd quality
3rd quality
4th quality
Damaged
Market quality grade

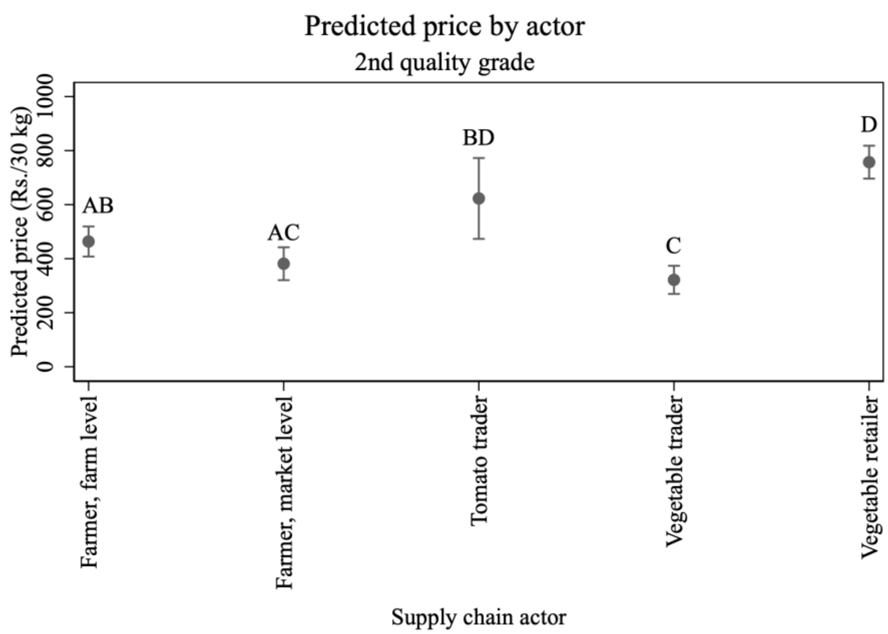
(e)

Figure 8. Marginal mean price by supply chain stage for individual market grades.

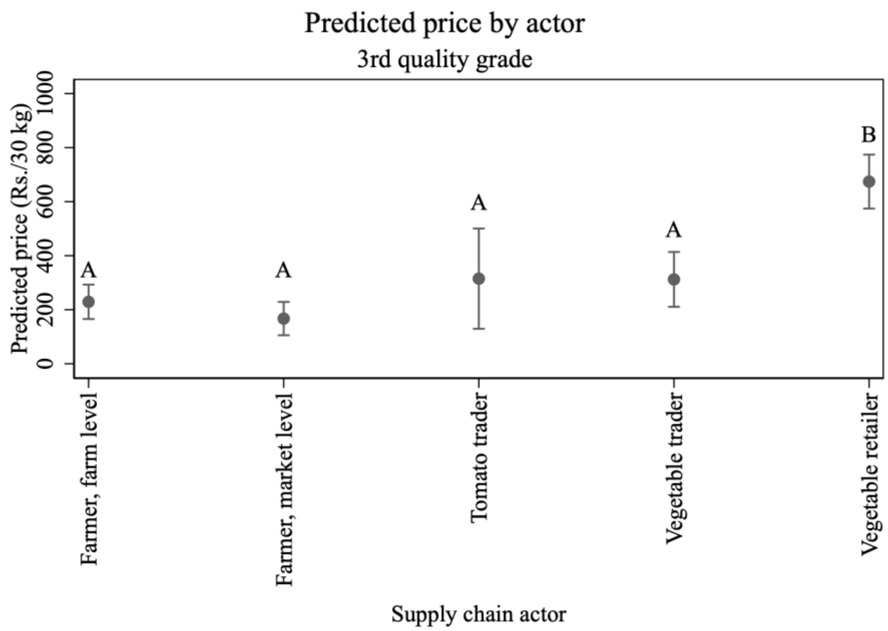
Error bars denoted 95% CI. Bars sharing a letter are not significantly different at $p < 0.05$: analyzed by pairwise comparison with Bonferroni correction. (a) 1st quality; (b) 2nd quality (c) 3rd quality; (d) 4th quality; (e) Damaged



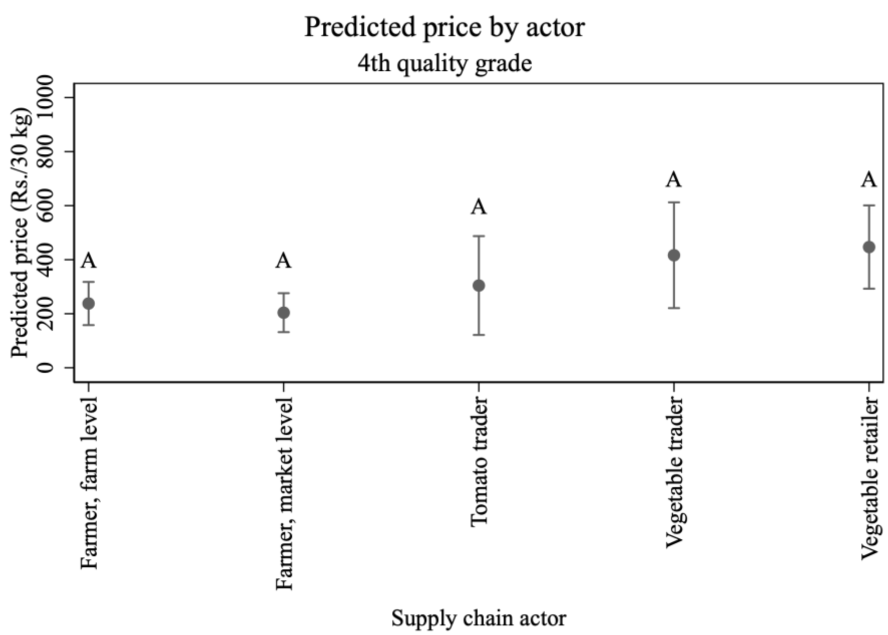
(a)



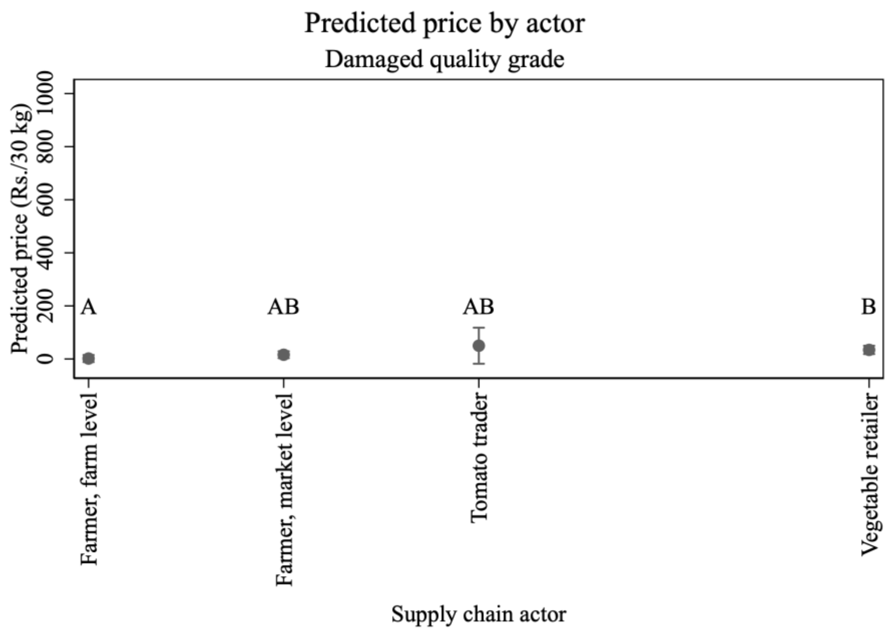
(b)


Predicted price by actor
3rd quality grade
Predicted price (Rs./30 kg)
0
200
400
600
800
1000
A
A
A
A
B
Farmer, farm level
Farmer, market level
Tomato trader
Vegetable trader
Vegetable retailer
Supply chain actor

(c)


Predicted price by actor
4th quality grade
Predicted price (Rs./30 kg)
0
200
400
600
800
1000
A
A
A
A
A
Farmer, farm level
Farmer, market level
Tomato trader
Vegetable trader
Vegetable retailer
Supply chain actor

(d)



(e)

Ascorbic acid and associations with search attributes

Among 534 tomatoes sampled, 309 tomato samples had complete data and were included in our analysis. The summary statistics for the tomatoes included for analysis are presented in **Table 13**. The majority of tomatoes, 81%, were PHS 448 breed, and 61% of harvests occurred during the peak tomato harvest season (Apr-Jul). With regard to quality attributes, farmers reported the quality intensity and ripeness stages among tomato in each quality group. Most tomato groups had a maximum ripeness stage of red or super red. Within a group of tomatoes taken for sampling, the ripeness stages were on average within one stage of each other, meaning that the minimum ripeness stage was one stage below the group's maximum ripeness stage. Results from the linear mixed model exploring associations of search attributes and ascorbic acid are presented in **Table 14.** We found that a one-unit increase in quality intensity was associated with a 1.8% lower ascorbic acid concentration (SE = 0.006, $p < 0.01$). Tomatoes sampled from a quality group with a maximum pink/light red ripeness stage were associated with a 12.5% lower ascorbic acid concentration than tomatoes from a quality group with maximum red ripeness stage (SE =0.053, $p < 0.05$). Tomatoes sampled from a quality group with a maximum super red ripeness stage were associated with a 10.3% higher ascorbic acid concentration than tomatoes from a quality group with a maximum red ripeness stage (SE=0.043, $p < 0.05$).

Table 13. Sample tomato summary statistics

	n (%) or mean (SD)	Ascorbic acid concentration (mg/100g), mean (SD)
Full sample	309 (100%)	31.70 (14.66)
Location/day where sample was taken		
Farm level, harvest day	159 (51%)	29.58 (13.28)
Market level, day after harvest	150 (49%)	33.95 (15.72)
Tomato breed		
Saaho	60 (19%)	18.35 (4.12)
PHS 448	249 (81%)	34.92 (14.47)
Harvest season		
Off-peak harvest season (Sep-Mar)	120 (39%)	18.14 (4.68)
Peak harvest season (Apr-Jul)	189 (61%)	40.31 (12.09)
Quality intensity (1-9)	5.51 (2.92)	-
Maximum ripeness level		
Pink/light red	30 (10%)	19.05 (5.42)
Red	144 (47%)	28.17 (14.56)
Super red	135 (44%)	38.27 (12.98)

Table 14. Mixed-effects linear model of factors associated with tomato ascorbic acid concentration (natural log-transformed)

	β-coefficient (SE)
Location/day where sample was taken	
Farm level, harvest day	Referent
	-
Market level, day after harvest	0.116***
	(0.0291)
Tomato breed	
Saaho	Referent
	-
PHS 448	-0.104
	(0.262)
Harvest season	

Off-peak harvest season (Sep-Mar)	Referent
	-
Peak harvest season (Apr-Jul)	0.858***
	(0.186)
Quality intensity (1-9)	-0.0185**
	(0.00605)
Maximum ripeness level	
Pink/light red	-0.133*
	(0.0529)
Red	Referent
	-
Super red	0.0986*
	(0.0430)
Constant	2.597***
	(0.218)
Random effects	
Farmer variance	-1.556***
	(0.288)
Residual variance	-1.540***
	(0.0407)
Observations	309
Number of groups	7

Abbreviations: SE, standard error
* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

Discussion and conclusions

In this study we sought to explore food quality assessment from the perspective of supply chain actors along a tomato supply chain in South India, and associations between search attributes and a credence attribute. We find that supply chain actors consider several quality attributes when assessing tomato quality, nearly all being search attributes and observable without having to destroy the product. Farmers, in particular, are the first supply chain actors to assess tomato quality during grading and sorting at the farm and market levels. During pile sort group discussions, farmers revealed many different quality attributes they use to describe tomato groups belonging to different market grades. Importantly, farmers did not use all quality attribute categories to describe tomatoes from each market grade. For example, big size was frequently used to describe 1st quality grade tomatoes. In contrast, size was not often used to describe damaged tomatoes; instead, evidence of pest, disease or physical damage is the most common attribute used to describe this quality grade. Surveys with farmers also revealed that, in addition to size and damage, color is also an important tomato quality attribute. Importantly, many of these quality attributes are established pre-harvest.

Farmers appear to use color as an indicator of ripeness to decide whether or not tomatoes are ready for harvest. Once tomatoes have been harvested, size and damage are important quality attributes during grading and sorting. Johnson et al. (2018) report several quality attributes including bruised or cracked skin, evidence of disease or decay, and sun-blisters, that indicate the vegetable product in inedible (Johnson et al., 2018). Sorting out tomatoes with damage is important because the extent of damage impacts tomato firmness and risk of decay (A. A. Kader, 1986). Proper sorting processes to discard decaying produce are important to reduce potential for contamination and ensure the food is safe and edible (A. A. Kader, 2010). At the tomato wholesale stage, tomato firmness becomes an important quality attribute to tomato traders. Food quality loss from biological deterioration can be caused by compositional changes including texture/firmness changes (A. A. Kader, 2005). Thus, firmness is an important attribute for traders to transport tomatoes long distances by truck within and outside of Andhra Pradesh. Vegetable traders and retailers in Hyderabad also report similar important tomato quality attributes: color, firmness and size. These supply chain actors are closer to the consumer and the quality attributes may reflect consumer preferences rather than supply chain function.

We find that, within each supply chain stage, 1st, 2nd and 3rd market quality grades appear to have distinct quality intensities. Damaged tomatoes also have a distinct quality intensity, but not when farmers are evaluating tomatoes at the wholesale market level. Across supply chain stages, we do not find significant differences in quality intensity for each market grade. These results indicate that, market grades do distinguish different quality tomatoes and, perhaps more importantly, that supply chain actors do not perceive the quality intensity for each market grade differently than other actors. When we consider market grades and price, we find that expected prices are significantly different between 1st, 2nd and 3rd market quality grade and damaged tomatoes among farmers and vegetable retailers. However, tomato and vegetable traders report a wider variability in pricing, and we do not find significant differences across the top three market quality grades. These results indicate that using price reports across the supply chain by different actors may not be an appropriate indicator of food quality.

Finally, we explored the associations between search attributes, quality intensity and ripeness, with a credence attribute, ascorbic acid. We find that increasing quality intensity is associated with a significant decrease in ascorbic acid concentration. We also find that tomato ripeness is significantly associated with ascorbic acid concentration; compared to red ripe tomatoes, pink/light red tomatoes are associated with lower ascorbic acid whereas super red ripe tomatoes are associated with higher ascorbic acid. While we find that tomatoes sampled one day post-harvest were significantly associated with a higher ascorbic acid concentration than tomatoes sampled on day of harvest, tomatoes in our study were not harvested at green or breaker stages but were already at least pink/light red with the majority of tomatoes red-ripe. Previous research has found that tomatoes accumulate ascorbic acid during on-vine and post-harvest ripening. Giovanelli et al. (1999) found that as tomatoes ripen on the vine, ascorbic acid first accumulates and then begins to decrease; whereas when tomatoes ripen post-harvest, ascorbic acid first decreases and then increases in the later ripening stages (Giovanelli et al., 1999). Ascorbic acid increases were found to be greater when tomatoes were fully ripened on the vine versus when they were harvested at a green or breaker stage and then ripened post-harvest (Betancourt, Stevens, & Kader, 1977; Adel A. Kader, Stevens, Albright-Holton, Morris, & Algazi, 1977).

Importantly, we consider ascorbic acid as an indicator nutrient to understand overall vitamin degradation of water soluble vitamins that are affected by post-harvest storage conditions, timing and environment (Rickman, Barrett, et al., 2007; Rickman, Bruhn, et al., 2007). This approach to estimating food quality loss by measuring changes in nutrient concentration is different from previous studies that estimate FL&W in terms of nutrients removed from the food chain. In the later approach, the nutritional value of FL&W is calculated from the FL&W mass estimate. Recently, numerous studies have estimated nutritional value loss across food chain stages and global contexts, using nutrient databases and FL&W estimates (Cooper et al., 2018; Garcia-Herrero et al., 2019; Khalid et al., 2019; Scherhaufer et al., 2015; Sharma et al., 2019; Spiker, Hiza, Siddiqi, & Neff, 2017). Nutritional value loss estimates may be useful for bringing awareness to FL&W, understanding gaps in dietary intake, and engaging with public and private sectors (Scherhaufer et al., 2015; Spiker et al., 2017). However, the nutritional value of FL&W does not account for nutrient losses in food that remains in the supply chain and can still be consumed.

Food quality loss refers to a decrease in food quality attributes along the supply chain without the entire food product being diverted away from human consumptions. Food quality loss reduction is important to ensure the product does not fall below a certain quality threshold (that would lead to the entire food being diverted), as well as to ensure that credence attributes such as nutrient content and food safety are met. As supermarkets become more widespread in India, several approaches have emerged to link smallholder farmers to these modern markets (T. Reardon, Timmer, & Minten, 2012). The required quality standards set by supermarket chains in India tend to be more stringent than quality standards of traditional supply chains (Trebbin, 2014). Nuthalapati et al. (2020) find that farmers sell their highest-quality produce to supermarkets, and sell their lower-quality produce in traditional markets (Nuthalapati et al., 2020). An increase in food quality standards may lead to an increase in FL&W if there are fewer and insufficient markets to absorb the lower-quality products. Importantly, lower-quality produce sold in markets should still meet quality standards to supply safe and nutritious foods. Therefore, food supply chains should balance food quality standards geared towards consumer preferences that do not impact edibility and those that are important for performance along the supply chain (i.e., transportation and storage), nutrition and safety. This is particularly important for perishable fruits and vegetables.

Study limitations

This study had several limitations. With regard to quality and price, we used the price supply chain actors expect to receive for their product. As tomatoes move along the supply chain, value is added, and prices change. Further, bargaining power between different supply chain actors might bias the reported price. Future work should account for bargaining power as it relates to tomato quality assessment and marketability. Secondly, we were not able to validate use of the reflectometer and ascorbic acid testing strips with HPLC methods using tomatoes sourced from India. Analysis methods using HPLC are the most preferred methods for measuring ascorbic acid concentrations in foods because they are typically the most accurate and precise (Nováková, Solich, & Solichová, 2008). In the Indian Food Composition Tables, HPLC methods were used to measure ascorbic acid in food samples taken at the retail stage; ripe, oblong (*hybrid*) tomatoes contained 25.27 ±3.52 mg ascorbic acid per 100 g sample and ripe, round (*local*) tomatoes contained 27.47 ±1.77 mg ascorbic acid per 100 g sample (Longvah et al., 2017). While the RQFlex reflectometer has been used to measure ascorbic acid in fruit and vegetable samples previously (Ashebir et al., 2009; Drogoudi et al., 2008; Neocleous & Vasilakakis, 2008; Yilmaz et al., 2009), we would have more confidence in our protocol if we had validated this method against an HPLC method with tomatoes sourced in India from the farm to retail stages. Finally, due to the COVID-19 pandemic, our original data collection plan to sample tomatoes from Chittoor district farmers to Madanapalle wholesale market to Bowenpally market in Hyderabad was not possible. We were therefore unable to investigate changes in ascorbic acid as tomatoes from the same harvest are transported to a distant wholesale market.

Future directions

The findings from our study are useful for understanding supply chain actor perceptions along tomato supply chains in South India. Supply chain actors consider similar search quality attributes, but perhaps for different reasons important to their respective position along the supply chain. Importantly, several quality attributes including size, ripeness and pest/disease damage occur at the pre-harvest/harvest stage. Future work is needed to elucidate individual search quality attributes and distinguishing more clearly between thresholds important for marketability versus edibility. Finally, future work is needed to understand the changes in nutrient content as perishable products move along the supply chain from farm to retail in a real-world setting. Ultimately, better measurement methods that can be used at the supply chain level can help to estimate food quality loss and identify opportunities for both food quality loss and food loss reduction.

CHAPTER 5

ALIGNING FOOD LOSS AND WASTE DEFINITIONAL FRAMEWORKS TO SMALLHOLDER FARMER OBJECTIVES

Introduction

Over the past decade, since the widely cited one-third global food loss and waste estimate was reported (FAO, 2011), efforts to define, measure and reduce food loss and waste (FL&W) have proliferated. Under Sustainable Development Goal (SDG) 12, the United Nations has set SDG target 12.3 to reduce by half food waste at the retail and consumer levels and to reduce food loss along production and supply chains by 2030. Under this global target, many different stakeholders exist including global, country-level and regional institutions, as well as supply chain actors along different types of food supply chains. Each set of stakeholders maintains their own priorities and objectives for FL&W reduction, based on their perspectives. At the same time, there is no harmonized definition of FL&W (HLPE, 2014). We can imagine that the interpretation of FL&W, how it is defined and therefore measured, is dependent on the perspective and motivation of each stakeholder. A necessary first step is to articulate stakeholder objectives for FL&W reduction and examine where similarities and differences occur across stakeholders.

Fruits and vegetables are important sources of micronutrients but are also among the most perishable food groups. Across all global regions, the agricultural production stage is an important supply chain stage where loss of fruits and vegetables occurs, though the underlying causes may differ by region (FAO, 2011). Farmers are clearly an important stakeholder for FL&W reduction, yet there is a knowledge gap with regard to their perspectives and experiences related to FL&W. To our knowledge, there are only two peer-reviewed qualitative studies that explore FL&W from fruit and vegetable farmer perspectives, taking place in Scotland and California, United States (U.S.) (Beausang, Hall, & Toma, 2017; Gillman, Campbell, & Spang, 2019). To the best of our knowledge, there have been no published qualitative studies exploring the perspective of farmers from a low- or middle-income country on food loss at the producer stage.

The objective of this study was to critically compare institutional FL&W definitional frameworks with a definitional framework conceptualized from discussions with smallholder vegetable farmers in South India. We first examined major and influential food loss and waste definitional frameworks, comparing each of the key definitional elements. We then used a case study of farmers in South India to explore farmers' perceived causes of food loss and motivations for food loss reduction. Finally, we assessed the compatibility of several institutional definitional frameworks that inform policy with that of smallholder vegetable farmers to identify opportunities to better align influential frameworks with the livelihood objectives of a key stakeholder group.

Institutional food loss and waste definitional frameworks

When the SDG target 12.3 was included in the Global Indicator Framework, the target indicator was classified as a Tier III indicator, meaning the measurement methodology needed to be developed and validated (Fabi & English, 2019). Since then, two indicators have been developed by the Food Agriculture Organization and United Nations Environment Programme, respectively: the Food Loss Index (FLI) and the Food Waste Index (FWI) (Fabi & English, 2019; UNEP, 2021). We used the analysis framework developed by Chaboud and Daviron (Chaboud & Daviron, 2017) to assess the similarities and differences of the SDG 12.3 indicators (FLI and FWI) definitional frameworks with the FAO 2014 definitional framework (FAO, 2014) and the Food Loss & Waste Protocol Accounting and Reporting Standard *(*FLW Standard) developed by the FLW Protocol Committee (Craig Hanson et al., 2016). Because the FWI is applied to only the later stages of the food supply chain, we treat the FWI as an extension of the FLI and note only differences between the FLI and FWI. **Table 15** summarizes the key definitional elements across each institutional FL&W framework.

We first considered the definitional perspective, which we argue is the most important element in the definitional framework as it influences the FL&W reduction objectives and all other framework elements. As such, the first step of the FLW Standard is for an entity to define goals for quantifying FL&W. Goals typically relate, broadly, to food security and nutrition, economic and/or environmental perspectives.

In contrast, the FAO 2014 makes clear that the definitional framework takes on a food security perspective. As indicators for SDG target 12.3, the FLI and FWI perspectives align with those identified for SDG target 12.3, including economic, environmental and food security. This target falls within SDG 12: to ensure sustainable consumption and production patterns, which is inherently grounded in environmental and economic perspectives related to resource use, degradation and pollution.

The definitions are similar with regard to timing; FL&W are only considered once foods are ready for harvest or slaughter (hereafter referred to as harvest). While there is similarity in scope with regard to the food supply chain, there are differences with regard to intended use. The FAO 2014 and FLW Standard describe the food supply chain as plant and animal products intended for human consumption (Craig Hanson et al., 2016; FAO, 2014). Both the FAO 2014 framework and FLW Standard provide guidance on estimating the loss when the intended use is unknown supply chain stages. In contrast, the FLI considers plant and animal products that are human-edible, without mention of the intended use (Fabi & English, 2019). In addition to scope, we compared the supply chain stages where FL&W is examined under each definition. Food loss and waste is measured at the pre-harvest to consumption stages under FAO 2014. Users of the FLW Standard have the option to measure FL&W along the supply chain from pre-harvest to consumption stages. Under this scope, food that is harvest-ready but unintentionally spoils in the pre-harvest phase is counted as FL&W. The FLI, at the international level, considers food loss at the on-farm, post-harvest up to, but not including retail. At the national level, harvest losses may be counted. The FLI makes it clear that losses at the pre-harvest stage are excluded from the SDG 12.3 indicator, noting that policies to improve supply chain efficiencies cannot address unpredictable extreme events and natural disasters (Fabi & English, 2019). Instead, these pre-harvest losses are captured in SDG indicator 1.5.2, direct agricultural losses attributed to disasters. Pre-harvest losses that are not due to extreme events or natural disasters remain, in effect, uncounted. The FWI picks up from the FLI, and includes the retail, food service and household consumption stages, as well as food product manufacturing when commodities are combined to produce a processed food product (UNEP, 2021). The terminologies of each definition reflect the supply chain stages included in the scope. The FAO 2014 uses the term "food loss and waste", distinguishing food waste by the conscious removal of food or food spoilage due to negligence. The FLW Standard defers to the user-defined FL&W reduction goals and supply chain stages with regard to distinguishing food loss and food waste. The FLI and FWI align with supply chain stage breakdown set in SDG target 12.3, using the terms food loss and food waste, respectively.

The criterion used in each definition are further broken down into utilization and edibility. Utilization refers to uses or destinations that are counted as FL&W. According to the FAO 2104 definition, FL&W includes any non-food use, including food diverted to animal feed or another productive, non-food use. As with the supply chain stages, FL&W utilization under the FLW Standard are defined based on the user's stated objective. The FLI and FWI take a different approach, and only count non-food, non-productive uses as food loss or food waste. Therefore, uses such as animal feed and industrial, economically productive uses fall outside of loss and waste destinations. Similar divergence exists with regard to edibility. The FAO 2014 framework only considers the edible food part, whereas the FLI and FWI consider the food as a whole (edible and non-edible). The FLW Standard, again, defers to the user's objective to define FL&W in terms of edible and/or non-edible portions.

Finally, the definitional frameworks distinguish between the type of FL&W, quantitative and qualitative. Quantitative FL&W refers to a decrease in the mass of food and is included in all definitional frameworks. Unique to the FAO 2014 framework, qualitative FL&W is included and refers to a decrease in quality attributes (e.g., sensory attributes, nutritional value, food safety) among products that have not been removed from the supply chain.

Applications of the FLW Standard: United States and the European Union

Food loss and waste definitional frameworks used in the U.S. and the European Union (E.U.) are aligned with the FLW Standard. **Table 16** summarizes the ReFED and FUSIONS definitional frameworks according to key definitional elements. Historically, FL&W in the U.S. has been reported by the U.S. Department of Agriculture Economic Research Service, and was limited to data at the retail and consumer levels due to limitations of the Loss Adjusted Food Availability data series used (Buzby, Farah-Wells, & Hyman, 2014). In 2019, the U.S. government entered a formal agreement with ReFED, Inc. (ReFED), a U.S. non-governmental organization, to collaborate and coordinate on FL&W reduction efforts, including the advancement of data collection and measurement activities related to FL&W (EPA, FDA, & USDA, 2019). The ReFED measurement methodology applies a definitional framework to five supply chain stages: farm, manufacturing, retail, foodservice, and residential (Powell & Curtis, 2020). Only harvest-ready, U.S.-grown fruits and vegetables are considered at the farm stage. Along the remaining stages, all food products that enter the food supply are included in the definitional framework. Diverging from the FLW Standard, the ReFED definitional framework counts food donation as a loss destination across all supply chain stages. The FUSIONS definitional framework covers all food products, starting when they are ready for harvest or slaughter (EU FUSIONS, 2014). Food loss and waste is captured at the primary production/post-harvest to food preparation and consumption stages. When harvest-ready crops are left unharvested in the field for resource efficiency, they are not counted as FL&W. The FUSIONS framework considers only non-food, non-productive uses as loss destinations.

Table 15. Food loss and waste definition similarities and differences

	Definitions		FAO (2014)	FLW Standard (2016)	Food Loss Index (2019)	Food Waste Index (2021)
(1)	Perspective		Food security	Economic, environmental, food security	Economic, environmental, food security	Economic, environmental, food security
(2)	Timing		Ready for harvest/slaughter	Ready for harvest/slaughter	Ready for harvest/slaughter	*Unspecified*
(3)	Scope	Intention	Food supply chain: intended for human consumption	Food supply chain: intended for human consumption	Food supply chain: human-edible	Food supply chain: human-edible
		Stage	Pre-harvest/pre-slaughter to consumption	Pre-harvest/pre-slaughter to consumption (User-defined based on quantification goals)	On-farm post-harvest up to, and excluding, the retail (Harvest/slaughter included at the national level)	Retail, food service, manufacturing complex food products, households
(4)	Terminology		Food loss and waste	Food loss and waste	Food loss	Food waste
			Food waste is part of food loss, and refers to removal of food by choice or food spoilage from negligence	User-defined based on quantification goals	Human-edible commodities that exit the food supply chain at the specified stages.	Human-edible commodities that exit the food supply chain at the specified stages.
(5)	Criterion	Utilization	Non-food use	User-defined based on quantification goals	Non-food, non-productive	Non-food, non-productive
		Edibility	Edible	Edible and/or non-edible	Edible and non-edible	Edible and non-edible
(6)	Type		Quantitative, Qualitative	Quantitative	Quantitative	Quantitative

Source: Adapted from (Chaboud & Daviron, 2017); Definitions from (Craig Hanson et al., 2016; Fabi & English, 2019; FAO, 2014; UNEP, 2021)

Table 16. Key FL&W definitional elements of ReFED and EU FUSIONS frameworks

Definitions			Re-FED (2020)	FUSIONS (2014)
(1)	Perspective		*Unspecified*	Economic, environmental, food security
(2)	Timing		Ready for harvest/entry into supply chain stage (see stage)	Ready for harvest/slaughter
(3)	Scope	Intention	Food supply chain: intended for human consumption	Food supply chain: intended for human consumption
		Stage	**Farm** (includes field, packhouse, and distribution to buyers): U.S. domestically grown fruits and vegetables **Manufacturing** (facilities and delivery to buyers): U.S. consumer food products **Retail** (stores and retailer-owned distribution centers): U.S. grocery retail food **Foodservice** (onsite dining and catering events): U.S. foodservice food **Residential**: all food categories	Primary production ready for/post-harvest to food preparation and consumption * Harvest-ready crops left in the field for resource efficiency reasons are not counted as food waste when they were not originally intended to be eaten/consumed.
(4)	Terminology		Food waste; Food loss and waste; Surplus Terms used interchangeably	Food waste
(5)	Criterion	Utilization	Food donation Non-food, non-productive uses	Non-food, non-productive uses
		Edibility	Edible and non-edible	Edible and non-edible
(6)	Type		Quantitative	Quantitative

Source: Adapted from (Chaboud & Daviron, 2017); Definitions from (EU FUSIONS, 2014; Powell & Curtis, 2020)

Food loss and waste definitional framework from the producer perspective: a case study of smallholder vegetable farmers in South India

In this section, we present a case study to assess the FL&W definitional framework from the perspective of perishable vegetable producers. The study was conducted along the tomato supply chain in Chittoor District, Andhra Pradesh. After briefly presenting the study context and background information, we provide further details about data collection and analysis procedures. We present our findings using the same framework used to compare institutional definitional frameworks in the previous section. In addition, we examine the underlying causes of food loss as perceived by farmers.

Background information

India is the second largest producer of tomatoes, behind China (FAOSTAT, 2020). Tomatoes are produced and consumed globally. In low- and middle-income countries, tomatoes are the fourth most economically-valuable food crop produced (Schreinemachers et al., 2018). In India, Andhra Pradesh is one of the states that produces the most tomatoes (GOI, 2019b). Chittoor district, located in the southernmost part of the state and sharing boarders with Karnataka and Tamil Nadu, is a major tomato producing district in Andhra Pradesh (Government of Andhra Pradesh, 2018c). The majority of people in Chittoor district are involved in agriculture, either as cultivators or laborers (GOI, 2011a).

We carried out a quantitative survey on food loss with tomato farm households and tomato traders in Chittoor district and the Madanapalle tomato market, respectively, from February 2019 – December 2019. The Madanapalle tomato market is the largest tomato trading hub in Andhra Pradesh, and is a major tomato wholesale market in India (Modekurti, 2016). Recruitment and data collection methods for these surveys are described in detail in the previous chapters. The primary researcher (J. Boiteau) resided in Madanapalle, Chittoor district from November 2018 – October 2019 and oversaw all research activities.

In this current study we broadened our scope to include any perishable vegetable production. While tomatoes are the most widely cultivated vegetable in Chittoor district, farmers, to a lesser extent, produce other vegetables including beans, potatoes, okra, chilies, guards, and eggplant (Government of Andhra Pradesh, 2019). When farmers produce larger quantities of vegetables, they may choose to send their production to large wholesale markets. For example, in Chennai, Tamil Nadu, the Koyambedu Wholesale Market Complex is a major marketing hub for fresh vegetables, fruits and flowers in India (Stephen et al., 2015). This market is located about 250 km east of Madanapalle. Alternatively, for smaller productions, farmers may sell their produce at weekly or daily vegetable markets throughout Chittoor district.

Sampling procedure and recruitment

Participant recruitment took place within villages where we were conducting a quantitative survey. Village selection is detailed in the previous chapter. Focus group participants were recruited by reaching out to study participants and using snowball sampling to recruit additional participants from the same village. The date and time of each focus group discussion was set based on participant availability to ensure participants had enough time for the discussion. At the time of the focus group discussion, the project coordinator provided each farmer with additional details about the study and the objective of the focus group discussion and obtained informed consent. None of the farmers withdrew from the discussions, and all consented to being audio-recorded. Refreshments, snacks and cold drinks were provided to participants.

Interview procedure and participants

Focus group discussions were carried out by a trained project coordinator using a semi-structured discussion guide with 13 questions organized in an hourglass design (Hennink & Leavy, 2014). After reviewing the informed consent and discussion procedures, we opened the discussion with "ice breaker" questions. We encouraged each participant to answer simple questions about vegetable production, including how long they have been a producer and the types of vegetables they grow, to make them feel comfortable contributing to the discussion (Hennink & Leavy, 2014). To continue building rapport with participants, we transitioned to discuss the main reasons for growing perishable vegetables and the production and post-harvest activities they are involved in. Our aim for these introductory questions was to transition participants into the mindset of perishable vegetable supply chains, focusing on activities that farmers are involved in. Key questions outlined several scenarios where food loss may occur, such as leaving market-ready vegetables in the field, not bringing harvested vegetables to the market, and not selling vegetables that they had brought to the market. We then asked participants specifically about food loss (quantity) and food quality loss, describing each term based on their experiences and if/how it affects their decision-making. We closed the discussion with questions on strategies to reduce losses and future considerations for growing vegetables. We carried out 10 focus group discussions from May through December 2019. A total of 62 farmers, 55 male and 7 female, participated across the discussions.

Agriculture was a primary source of income for all farmers, and all farmers grew tomatoes in addition to other perishable vegetables. Discussion lengths ranged from 30 to 50 minutes. All discussions were conducted in Telugu. Audio recordings were translated and transcribed into English.

Thematic Analysis

Focus group discussion transcripts were organized and coded using Atlas.ti (v8) software. I used a thematic analytical approach to explore the underlying causes and pathways of food loss and food quality loss of perishable vegetables as well as farmers' perceived factors, circumstances and priorities that influence their decision-making with regard to the movement of vegetable produce from the farm-fields to the market (Braun & Clarke, 2006). I first read through the transcripts to become familiar with the data, making notes of potential ideas and observed patterns. After coding the dataset for content relevant to the research aim, I generated initial themes to conceptualize the relationships between codes and different levels of themes. After sorting codes into relevant themes, I generated sub-themes through an iterative, constant comparison process to create like and unlike groupings (Corbin & Strauss, 1990). This process consisted of generating new themes and demoting initial themes to sub-themes; and generating new sub-themes within an existing theme. Most themes were conceptualized during the coding process, with the exception of "produce value when removed from the food supply chain", which was generated *a priori*. Details on the coding framework including themes and sub-themes are detailed in **Table 17**.

Table 17. Coding framework

Theme	Sub-theme	Code
Risk/uncertainty (not under farmer's control, "nothing we can do")	Production challenge due to ecological environment	Weather events (too much sun/rain; hail; wind)
		Climate too hot/too much sun
		Lack of water available
		Soil quality
Modifiable (as perceived by farmer) causes of loss	Production issues that cause low quality or reduced yield	Bad seed variety / poor sapling quality
		Improper chemical application
		Animal pests
		Plant pests and disease
Modifiable (as perceived by farmer) causes of loss	Unmarketable quality attribute	Small size
		Sun blisters, moles, discoloration
		Soft

		Overripe
		Insect bites/worms
		Cannot be stored/transported
Modifiable (as perceived by farmer) causes of loss	Harvest and postharvest practices that cause food quality loss and food loss	Poor harvest practices (e.g., missing ripe products; bumping ripe products onto the ground)
		Poor packing practices (e.g., over-filling crates)
Modifiable (as perceived by farmer) causes of loss	Production strategies to reduce production-level quality loss / yield loss	Application of chemicals/biochemicals
		Type of vegetable selection based on season and climate conditions
		Seed variety that suits growing location and desirable attributes
		Staking
Modifiable (as perceived by farmer) causes of loss	Harvest and on-farm, post-harvest strategies to reduce food quality loss and/or food loss	Storage (vegetables other than tomato)
		Drying (such as chilies)
		Grading and sorting (remove spoiled product so others do not get damaged)
	Government programs/policies	Government not responsive to farmer issues
		Collective action
		Insurance/protection
		Input subsidies
Risk/uncertainty (not under farmer's control, "nothing we can do")	Variable market rate	Seasonal market rate
		Supply impacting market rate
		Market rate changing: monthly/weekly/daily
		Market rate changing: same-day
		Receiving market price information
		Market rates good, but no produce to sell
		Profitable but not every year
		Market rate too low to earn profit
		Market rate too low to sell produce of any quality
		Produce unsold at market
Decision-making based on marginal cost-benefit	Costs that reduce farmer profit	Input costs
		Production labor costs
		Harvest and post-harvest labor costs
		Transportation costs
Decision-making based on marginal cost-benefit	Cutting losses: financial loss reduction strategies	Stop applying water and chemical inputs
		Harvesting product once rates increase
		Leave market-ready produce on plant
		If harvested, bring produce to the market
		Leave harvested produce on-farm

		Leave unsold produce at the market
		Experience profit loss 1-2 times at market
		Bring produce to market even when rates are low
		Send produce to alternative market
		Use for home consumption
		Exit vegetable production as income source
Value of produce removed from food supply chain	Removed from supply chain: pre-harvest	Produce left on plant, spoils and falls off
		Plant will not survive if tomatoes are left on the vine
		Produce left on plant, animals allowed into field and eat from the plant
	Removed from supply chain: post-harvest	Produce harvested, left unused on-farm
		Produce harvested, given as animal feed
		Produce not sold, thrown out/to dump
		Produce not sold, collected for animal feed
		Produce sold for animal feed

Causal loop diagram/causal mapping

We used a collective causal loop diagram to explore farmers' perceptions of food loss within the supply chain system and to capture their models of production, postharvest and marketing complexities (McGill et al., 2021; Nicholson et al., 2020). The causal loops diagram illustrates variables and their causal linkages. The linkages are described using arrows with positive or negative polarities indicating the direction of the causal relationship. A positive polarity indicates that the two linked variables change in the same direction. Whereas a link with a negative polarity indicates that the variables change in the opposite direction. Feedback loops follow the cause-effect pathway as the output from a variable is looped back to the same variable, forming a circle. Feedback loops are either reinforcing, the effect is the same polarity as the output; or balancing, the effect is the opposite polarity as the output. The causal loop diagram of farmer-perceived causes of food quality loss and food loss was modeled in Vensim PLE version 8.2 (Ventana Inc.) modeling software using themes and sub-themes were generated from the thematic analysis.

Results: Causal loop diagram

To describe the FL&W definitional framework from the farmer perspective, we first sought to understand farmers' collective mental model of the causes of food loss and motivations for FL&W reduction. **Figure 9** shows the dynamics of farmers' profit/income, food quality loss, food diverted away from human consumption and market prices. The causal loop diagram contains two main components – farmer profit and food diverted away from human consumption. The pathways of identified feedback loops are described in **Table 18**. While the focus group discussions asked questions about any vegetable produced, farmers most often referred to tomatoes. Vegetables may be removed from the food supply chain at several stages including pre-harvest, on-farm post-harvest, and at the market. Causes of this removal include food quality loss at the same or earlier supply chain stage, as well as unprofitable market rates. Ultimately, vegetable farmers incur profit losses when their products are diverted away from the food supply chain or when market rates are not sufficient to cover production and post-harvest investments.

Figure 9. Causal loop diagram of food loss from farmers' perspectives

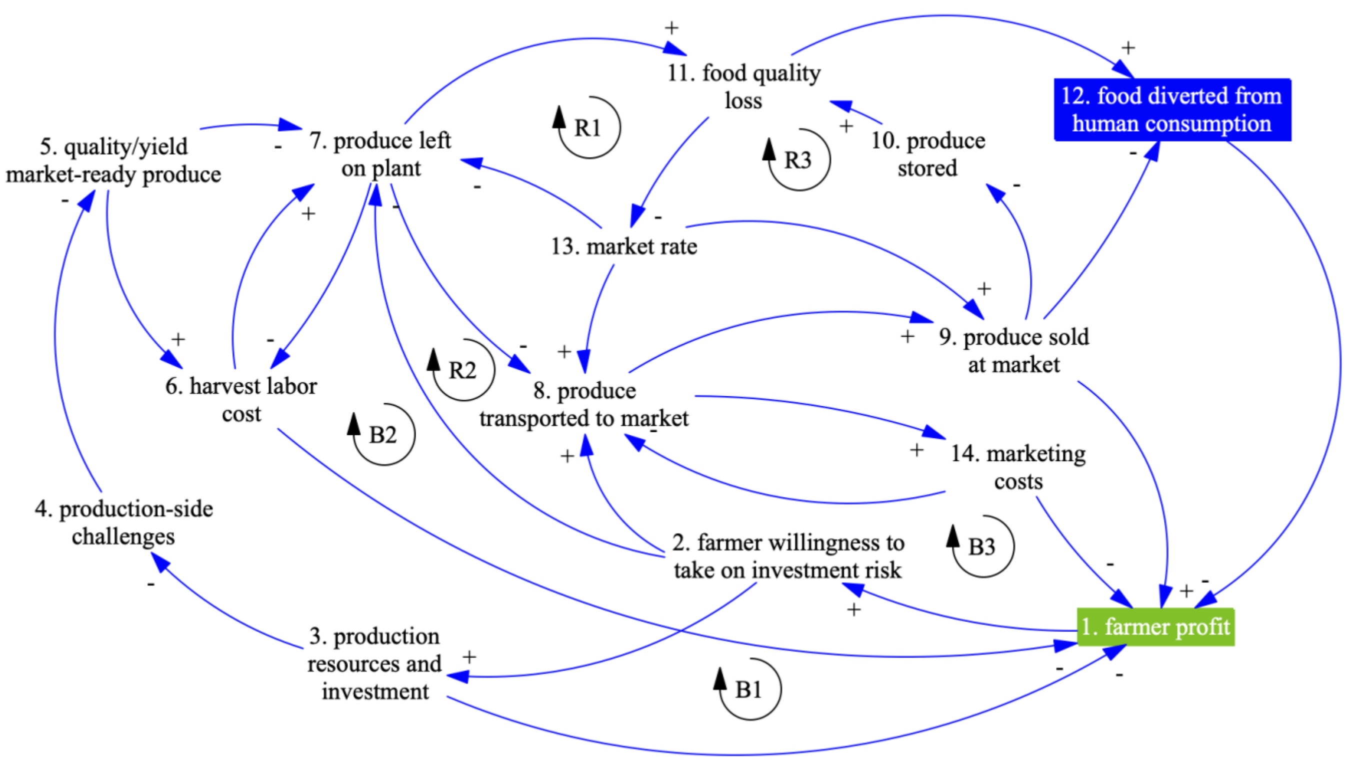


Table 18. Feedback loop pathways identified in the causal loop diagram

	Feedback loop	Paths
B1	Production investment	1 → 2 → 3 → 1
B2	Harvest investment	1 → 2 → 7 → 6 → 1
B3	Marketing investment	1 → 2 → 8 → 14 → 1
R1	Produce stays on plant	13 → 7 → 11 → 13
R2	Produce never harvested	7 → 11 → 12 → 1 → 2 → 7
R3	Food quality loss with storage	10 → 11 → 13 → 9 → 10

Farmer profit and income loss

From the farmer perspective, the main outcome of interest in any discussion of "loss" was the farmer's profit from producing and selling vegetables as a main source of income. Farmers described several direct linkages to profit losses. When farmers do not sell their vegetables that are market-ready and edible, the vegetables are diverted away from human consumption and the farmers lose any investment they have put into the production. We will further discuss the pathways leading to food removed from the food supply chain in the following section. Farmers also encounter losses even when vegetables remain in the food supply chain. This often occurs when market rates are too low for the farmer to cover their investments.

While market rates are outside of the farmer's control, farmers identified points along the supply chain where they make decisions to reduce their financial losses. Farmer profits and willingness to take on investment risks are linked with investments at the production, harvest and marketing stages, identified in balancing Feedback loops B1, B2 and B3 respectively. The production stage requires the most investment. Farmers also encounter expenses once produce is ready for harvest, including harvest labor and marketing costs (transportation, crate rentals and market labor). Depending on the market rate and the product quality, farmers may decide not to harvest and/or market their produce as a strategy to reduce their financial loss. Decisions to harvest and market produce is further complicated by the shifts in seasonal labor and marketing costs, which tend to rise during peak harvest season.

Because farmer livelihoods depend on vegetable production, profits and losses impact their ability and willingness to take on investment risks. Farmers described situations where they can no longer take on the risk of investing resources into production to address production-side challenges. Farmers may then shift to working as laborers for an alternative income source. Farmers often portray agricultural labor work as a temporary, seasonal income source, with the potential to return to primary vegetable production. In contrast, farmers who have profited from vegetable production may take on additional risk by further investing in production resources, harvesting product, and marketing.

Farmers discussed situations when they sold produce at profitable market rates, and reinvested their earnings back into agriculture, at times taking out additional loans, only for the market rates to drop to an unprofitable level. Farmers expressed frustration with the way farmers are expected to take on financial risks to produce vegetables without confidence that they will be able to consistently earn a profit. One group of farmers explained how government officials would react when farmers are forced to throw away their vegetable products because of low market rates:

> *P4: The Collector (IAS Officer) will not put this incident [throwing away tomatoes] in the newspapers. If we sell our tomatoes for 1000 rupees then he will put in the paper saying tomatoes are very costly, how will a common man buy and eat them.*
>
> *P1: They say how can a common man buy and eat. They don't bother about farmers.*
>
> *P4: One DAP packet 1700 rupees madam, we should invest more money but when it comes to our turn, we will get less money.*
>
> *P2: Everyone has fixed rates except a farmer. Be it milk or tomatoes, they don't have a fixed rate, others all have fixed rate.*
>
> *[Thavalam/Thavalam]*

Here, one farmer mentions "fixed rates", which is a reference to a policy to procure food grains, rice and wheat, from farmers at guaranteed Minimum Support Prices and distribution to poor consumers at subsidized rates through the Public Distribution System (Pingali et al., 2017). Perishable vegetables fall outside of this policy and no minimum price in guaranteed.

From production to marketing, farmers are constantly making decisions based on their perceived marginal cost-benefit. Farmers identify production, harvest, and post-harvest practices that are modifiable. However, many of the production and market-side challenges farmers face are not under farmers' control; these challenges are most commonly related to water unavailability, plant pests and diseases, and low market rates. Especially when discussing product quality, farmers referred to production issues that reduce quality before vegetables are harvest ready. Specifically for tomatoes, these affected quality attributes included size, sun blisters and pest or disease damage.

<u>Food diverted away from human consumption</u>

In this study, food diverted away from human consumption was the main research outcome of interest. Farmers distinguished destinations for vegetables diverted away from human consumption, into two categories: animal feed and trash/discarded matter. Farmers did not report using diverted food as compost, either during the focus group discussions or the main survey. Importantly, farmers expressed that animal feed was not useful and that they do not invest in vegetable production to produce animal feed. Farmers distinguished the option to use rice (paddy), millet, and maize as both human food and animal feed, but the same is not true for tomatoes:

> *Participant 2: We planted tomatoes now right, if the land is plain we will be planting paddy, we will get grains from that, if we don't get more grains at least we will get grass from that and we will utilize that for cattle feed, whereas tomato is not like that we may get or we may not get money out of that.*
>
> *[Pothapolu, Peddachennaiahgaripalle]*
>
> *Participant 7: Karralu [millet], maize, there is demand for that to feed cattle. Even if I am sitting somewhere a person came to me and asked to come and give me some maize. Because now there is demand and I am sitting peacefully. There is no grass now to feed cattle so they*

called me for giving maize, if it was tomatoes none of them would have called me and asked me for my yield.

[CTM/Kotharuakulapalle]

At the time vegetables are market-ready, farmers must decide to invest in harvesting and marketing. The lack of post-harvest storage limits farmers' options at times when produce is market-ready, but market rates are unprofitable. Faced with these situations, farmers may opt to keep vegetables on the plant to stay fresh, with the hopes that market rates will increase. Feedback loop R1 demonstrates the reinforcing pathway linking market rate and on-field food quality loss. As market-ready produce sits on the plant, the quality begins to deteriorate. If market rates rise to profitable levels, farmers go through the fields, picking off spoiled produce and harvesting marketable produce.

In the case of tomatoes, most farmers report that the fruit quality usually deteriorates faster than market prices increase to a profitable rate. Farmers agreed that they do not invest in plucking tomatoes that will not be transported to the market. Feedback loop R2 follows this reinforcing pathway from leaving produce on the vine to subsequent quality deterioration and on-field food loss that, in turn, reducing farmers' profits and willingness to take the risk of harvesting later on. Tomatoes are left on the vine until they fall off and are turned into the soil. It is common for farmers to allow their cattle into the fields to eat tomatoes as well.

Opportunities to process vegetables and make more shelf-stable products are limited. Chilies are the one vegetable farmers identified that can be dried, stored and later sold. For other vegetables, pickling and, in the case of tomatoes, juicing, are other processing options. With regard to tomatoes, juice factories may purchase low quality, low priced tomatoes at the wholesale market.

At times, farmers learn that market rates are low after they have already harvested tomatoes. Farmers may view the marginal cost of packing and transporting small enough that, if they have harvested tomatoes, they will bring tomatoes to the market. Not all farmers shared this perspective; some farmers described discarding or giving tomatoes to cattle at the field level to avoid further financial loss.

Once produce has been transported to the market, rates might be so low that farmers cannot sell their produce at all. Farmers might opt to store their produce overnight at the market. The Feedback loop R3 demonstrates the reinforcing pathway of storage and food quality. Due to lack of formal storage and adequate storage conditions, the food quality is likely to deteriorate when stored, further reducing the potential rate and probability of being sold. Tomatoes are highly perishable, and farmers describe spoilage as a major issue that prevents them from being able to store unsold tomatoes at the market. Other vegetables, such as beans, gourd and okra, can be stored up to a few days after harvest. When farmers sell these products at local daily markets, they can leave their produce at the market to continue selling the next day.

Food quality loss and food remaining unsold at the market are the two causes directly linked with food removed from the food supply chain. In the case of tomatoes, farmers bring tomatoes to wholesale auctions. The Madanapalle tomato wholesale market in Chittoor district is the major tomato hub in Andhra Pradesh. Farmers that make the harvest and post-harvest investment to bring their tomatoes to the wholesale market are not guaranteed a sale at the open auction. Acceptable quality thresholds change depending on the supply and demand. When market rates are very high, farmers can sell a wider quality range. In comparison, when market rates are low, only higher quality tomatoes can be sold at all. Tomato prices fluctuate quickly because of the highly perishable nature of tomatoes, seasonality and storage and processing limitations (Reddy, 2019).

Storage is not an option for tomatoes, as previous mentioned, as well as other products, such as eggplant, that are brought to distant wholesale markets (e.g., Chennai). Therefore, when buyers reject tomatoes put up for auction, farmers feel that they have no option but to cut their losses and discard the tomatoes at the market. Transporting tomatoes from the market, either back to the farm or to an alternative market, would be an expense to the farmer that they would likely not recover. Farmers either leave their produce at the market, unsold or, farmers are responsible for disposing the food, usually throwing it in a refuse area at the market or on the roadside. At the Madanapalle wholesale market, a side channel exists for diverting tomatoes to animal feed where people can come and collect bags filled with tomatoes that were not sold in the auction. Based on our survey findings in Chapter 3, farmers rarely receive money for tomatoes given for animal feed. The municipality discards any remaining food from the market, bringing it to a landfill area. Produce left unsold at the market and, ultimately, removed from the food supply chain negatively impacts farmers' profits. Farmers may experience financial losses at the market one or two times before they decide they are no longer willing to take on risk, and they stop further investment.

Results: Definitional framework

Similar to the analysis of institutional definitions, we first considered the farmer perspective and motivation that influences any FL&W reduction objective and framework elements. We summarized the framework definitional elements in **Table 19**. Farmers in this study shared an economic perspective, specifically with regard to their profit and livelihood as vegetable producers. Across the discussions, farmers expressed a sense of risk with regard to investing in vegetable production as a livelihood, particularly for tomatoes. Farmers most often refer to market rates when mentioning the uncertainties that farmers face:

> *Participant 2: Our crop will be like a lottery for us, sometimes if we are lucky we will get good benefit or else we don't have any assurance that we may receive good price, farmer doesn't have faith on the rates.*
>
> *[Rachavetivaripalle/D. Machireddigari Palle]*

Based on this economic livelihood perspective, farmers can only sell their products that are market-ready. Therefore, the timing element of the definitional framework is ready for harvest. In the coding framework, we distinguished production-side issues that cause low quality produce or reduced yields from causes of loss once vegetables are market-ready. Farmers grow perishable vegetables for the human consumption, without exception. Faced with unprofitable market rates, farmers neglect vegetables, leading to deteriorating and ultimately removal from the food supply chain as early as pre-harvest. Farmers' intention for growing vegetables is also closely linked with how farmers define food loss based on utilization. Because vegetables are produced for food supply chains, farmers consider any diversion to non-food uses as loss. Farmers consider the foods as a whole, never distinguishing between edible or inedible portions. Finally, in many cases, food quality loss occurs before vegetables are removed from the food supply chain. Therefore, qualitative and quantitative types of loss are key factors.

Table 19. Smallholder farmer FL&W definitional framework

	Definitions		Farmer
(1)	Perspective		Economic
(2)	Timing		Ready for harvest
(3)	Scope	Intention	Food supply chain - intended for human consumption
		Stage	Pre-harvest to market
(4)	Terminology		*Unspecified*
(5)	Criterion	Utilization	Non-food use
		Edibility	Edible/non-edible
(6)	Type		Quantitative, Qualitative

Discussion and conclusions

In this study we compared the FL&W definitional frameworks at the institutional level and the level of smallholder vegetable farmer in South India. Due to its flexibility, we find that the FLW Standard aligns closest to the farmer's framework, timing, scope and criterion. The FAO 2014 definitional framework was the only institutional framework that also incorporated qualitative type loss, which was also a factor in the farmer framework. The FLI and FWI were the least compatible with the farmer's framework. This discrepancy is important because the SDG target 12.3 uses the FLI and FWI to monitor progress. From the farmer's perspective, the major factors not captured in the FLI or FWI are the scope, criterion and type of FL&W.

Food loss and waste is associated with food availability, affordability and desirability (HLPE, 2014). At the most basic level, food availability affects dietary choices (Herforth & Ahmed, 2015)**.** Globally, fruit and vegetable availability is insufficient to meet dietary intake recommendations, particularly in sub-Saharan Africa and South Asia (Bahadur KC et al., 2018; Mason-D'Croz et al., 2019; Siegel et al., 2014). Smallholder vegetable farmers produce vegetable exclusively for human consumption. The majority of vegetables in India are sold fresh, with less than 3% of fruits and vegetables sent for processing (Netscribes Pvt Ltd, 2019). With regard to exporting vegetables (either in fresh or processed form), India exported 1.4% of vegetables produced in 2017-2018 (GOI, 2019a). Perishable vegetable supply chains are different in intention and structure than cereal grain supply chains. Cereal grains are used for food and feed. Currently, about one third of all grains are used as animal feed (Willett et al., 2019). When cereal grains intended for food (or with an unclear intention) are diverted, an established feed supply chain can absorb the diverted food. Farmers in our study reported animal feed as a use for diverted tomatoes. However, farmers do not sell their produce in the feed channels; their only option is to let their own animals eat vegetables or give it away for free. This stands in contrast to fruit and vegetable farmers in Scotland and California who reported selling diverted produce for animal feed, and that this was the least expensive option (Beausang et al., 2017; Gillman et al., 2019).

Losses of food at the pre-harvest stage are another important gap in the FLI framework. As a means to avoid further financial loss due to low market rates, farmers in Chittoor district choose to leave vegetables on the plant even when they are ready for harvest. When pre-harvest losses lie outside the scope of FL&W estimation, no methods are developed to estimate this loss and the issue, therefore, cannot be monitored. Fruits and vegetables may be harvested several times over the course of the season from the same plot of land. Therefore, farmers must make harvest decisions several times over each plot in a season, and hope that market rates do not drop too low once their produce is ready. The ReFED group has attempted to quantify pre-harvest losses and has determined that the quality of evidence, in the U.S. context, is very low to low, due to the reliance on farm case studies that are not easy to update frequently and have a narrow scope of geography and coverage (Powell & Curtis, 2020).

Farmers reveal that they have limited market options. Tomato varieties intended for fresh markets have different important attributes than tomato varieties intended for processing; e.g. taste, appearance, handling characteristics versus viscosity and soluble solids, respectively (Shuch & Bird, 1994). The World Vegetable Center has developed several "dual purpose" tomato varieties for use in both fresh and processing supply chains, however these are not yet available commercially as local testing is still underway (World Vegetable Center, 2020). Juice factories in Chittoor district do purchase tomatoes from farmers at the wholesale market, however they opt for the lowest quality tomatoes at the lowest prices.

Smallholder farmers have higher transaction costs because of low economies of scale and low bargaining power (Pingali et al., 2019). Farmer producer organizations (FPOs) may reduce these costs and address some of the disadvantages of smallholder farmers. Cooperative and contract farming helps to shift the risk of price fluctuations from farmers to retailers (Reddy, 2019). In Chapter 3 we found that FPO participation was not associated with food loss at any farmer stage. However, we did not account for the quality or level of household participation in the FPO. In the future, farmers might also benefit from the National Agriculture Market (eNAM), India's online trading platform, where traders can bid on wholesale auctions without physically being at the auction site. During our study we did not observe the eNAM platform being used for auctions, rather auctions were conducted in-person. However, as wholesale markets transition to the eNAM platform, farmers will have access to accurate prices to make informed decisions.

Finally, among the institutional frameworks, the FAO 2014 was the only framework to capture qualitative loss. Farmers in our study considered sensory quality attributes such as size, level of ripeness, and evidence of pest or disease damage. At several points from field to market, vegetable quality can deteriorate to the point of not meeting market quality thresholds. The eNAM platform has set commodity quality parameters for most fresh fruits and vegetables traded in wholesale markets. For example, quality criteria for tomato grade designation include defects, sunburn, discoloration (green, green top, blotchy), and mechanical injury, as well as size (diameter) (Government of India, 2021).

Farmers in Scotland and California also encountered challenges meeting quality attribute thresholds, which led to food diverted from the food supply chain (Beausang et al., 2017; Gillman et al., 2019). Issues with produce quality may be derived from production level issues. Farmers in Chittoor district described tomatoes losing quality when they were left on the vine or after storage at the market, rendering them unmarketable. Particularly for fruit and vegetable food groups that are perishable and where quality standards can be broad and quality loss often leads to quantity losses, measuring the extent of qualitative loss and understanding the underlying causes and repercussions is important for FL&W reduction from a food security, economic and environmental perspective.

Study limitations

This current study had several limitations. Firstly, due to the nature of the study design, we were limited to speaking with vegetable farmers in an area where tomatoes are the dominant vegetable. This led to discussions focusing mostly on issues concerning tomato production and marketing. It would be valuable to explore regions with different perishable vegetable supply chains, both within and beyond India, to elucidate similarities and differences in smallholder farmer definitional frameworks. Another limitation to this work was the inability to return to our study site, due to COVID-19, and review the causal loop diagram and definitional framework with participant farmers. Reviewing our findings with farmers would have allowed us to verify the pathways and relationships of food loss outcomes as well as provide an opportunity to make revisions and have participants' final approval. Finally, we did not construct definitional frameworks for the other supply chain actors in our study: tomato traders, vegetable traders, and vegetable retailers. Organizing focus group discussions among traders proved to be difficult due to their willingness to give their time. In the case of vegetable retailers, retailers were geographically spread out over Hyderabad, making it infeasible to bring a group together.

Future directions

Our findings from this study demonstrate that the current framework used to monitor the SDG target 12.3 does not align with the objectives and needs of smallholder vegetable farmers in South India. Food loss and waste definitional frameworks should consider supply chain actor perspectives and motivations. In the case of smallholder vegetable farmers, pre-harvest losses of market-ready vegetables are a likely critical stage for food loss. Failure to measure FL&W at this stage may severely underestimate on-farm losses and hinder efforts to meet stated objectives (e.g., economic, food security, environmental) through FL&W reduction efforts. Additionally, the criterion used for defining utilization should align better with the perspective taken. For fruit and vegetable food groups, from the food security and the farmer's economic perspective, non-food, productive uses (including animal feed) should be counted as FL&W. Definitional frameworks and FL&W measurement should capture and distinguish qualitative losses, as qualitative losses consistently precede quantitative losses. Food loss and waste measurement is only useful when the definitional framework aligns with the stated objectives. The objectives for FL&W reduction are dependent on the perspectives taken, which may vary by food group and context. Future work on FL&W should consider how similar or unique the objectives are between contexts and food groups to establish comparable and useful metrics.

APPENDIX

Table A.1. Definition of variables and measurement for farmer models

Variable	Type	Definition and measurement
Outcome variables		
Pre-harvest damage	Dummy	= 1 if pre-harvest damage is >0%
Extent of pre-harvest damage	Continuous	Share of harvest with pre-harvest damage among harvests with pre-harvest damage >0%
Post-harvest, farm-level food loss	Dummy	= 1 if post-harvest, on-farm food loss is >0%
Extent of post-harvest, farm-level food loss	Continuous	Share of harvest with post-harvest, on-farm food loss among harvests with post-harvest, on-farm food loss >0%
Pre-auction, market-level food loss	Dummy	= 1 if pre-auction, market-level food loss is >0%
Extent of pre-auction, market-level food loss	Continuous	Share of harvest with pre-auction, market-level food loss among harvests with pre-auction, market-level food loss >0%
Covariate variables		
Local NGO	Dummy	= 1 if *panchayat* falls under local NGO program area
Caste	Dummy	= 1 if household is SC, ST or BC
Independent variables		
Education	Dummy	= 1 if household member respondent highest education is at least secondary (grade 8)
Income source	Dummy	= 1 if household primary income from agriculture
Experience	Continuous	Number of years' experience in tomato production

Variable	Type	Definition and measurement
FPO	Dummy	= 1 if household is a member of a Farmer Producer Organization (FPO)
Land owned, acres	Continuous	Number of acres of land household owns
Land leased, acres	Continuous	Number of acres of land household leases
Sapling density	Continuous	Number of saplings (100) per acre
Grow area	Continuous	Number of acres planted
PHS 448 breed	Dummy	= 1 if planted PHS 448 breed
Saaho breed	Dummy	= 1 if planted Saaho breed
US 440 breed	Dummy	= 1 if planted US 440 breed
Other breed used	Dummy	= 1 if planted breed other than PHS 448, Saaho, or US 440
Drip irrigation	Dummy	= 1 if used drip irrigation
Canal irrigation	Dummy	= 1 if used canal irrigation
Staking	Dummy	= 1 if used staking and twine
Plastic sheeting	Dummy	= 1 if used plastic sheeting
Chemical fertilizer applied	Dummy	= 1 if used chemical fertilizer
Farmyard manure applied	Dummy	= 1 if used farmyard manure
Fungicide applied	Dummy	= 1 if used fungicide
Harvest number	Continuous	Number of harvest for the production area
Peak harvest season	Dummy	=1 if harvest during peak season (April-July)
Max. market price expected, at farm-level	Continuous	Maximum price per 30 kg farmer expects to receive at auction (100 rs.), reported at farm-level on day of harvest
Harvest based on ripeness level	Dummy	=1 if major reason for harvesting was the ripeness level
Maximum ripeness level	Categorical	= 0 if maximum ripeness level is pink/light red

Variable	Type	Definition and measurement
		= 1 if maximum ripeness level is red
		= 2 if maximum ripeness level is super red
Harvest quality intensity	Continuous	Quality intensity of harvest tomatoes from low to high quality (scale 1-9)
Harvest labor: hired, female	Dummy	= 1 if hired, female participated in harvesting
Harvest labor: hired, male	Dummy	= 1 if hired, male participated in harvesting
Harvest labor: family, female	Dummy	= 1 if family, female participated in harvesting
Harvest labor: family, male	Dummy	= 1 if family, male participated in harvesting
Harvest labor: family, female child	Dummy	= 1 if family, female child participated in harvesting
Harvest labor: family, male child	Dummy	= 1 if family, male child participated in harvesting
Harvest container: basket	Dummy	= 1 if harvesting container is a basket
Harvest container: plastic crate	Dummy	= 1 if harvesting container is a plastic crate
Harvest container: plastic bucket	Dummy	= 1 if harvesting container is a plastic bucket
Harvest container: aluminum bucket	Dummy	= 1 if harvesting container is an aluminum bucket
Harvest total	Continuous	Total amount of harvested tomatoes (30 kg)
Field shade	Dummy	= 1 if harvested tomatoes are kept in a shaded area at the field
Field container	Categorical	= 0 if no container used to hold harvested tomatoes at the field

Variable	Type	Definition and measurement
		= 1 if crate ≤ 20 kg container used to hold harvested tomatoes at the field
		= 2 if crate ≥ 25 kg container used to hold harvested tomatoes at the field
Release field head	Dummy	= 1 if release field heat from tomatoes after harvest
Farm-level grading	Dummy	= 1 if grading done at the farm-level
Grading done before transport to market	Dummy	= 1 if grading done before transport to market
Aggregate	Dummy	= 1 if farmer aggregated with other farmers to transport tomatoes to market
Packing labor: hired, female	Dummy	= 1 if hired, female participated in packing
Packing labor: hired, male	Dummy	= 1 if hired, male participated in packing
Packing labor: family, female	Dummy	= 1 if family, female participated in packing
Packing labor: family, male	Dummy	= 1 if family, male participated in packing
Madanapalle market	Dummy	= 1 if farmer plans to sell tomatoes at Madanapalle tomato wholesale market
Production limitation: climate	Dummy	= 1 if climate is a problem to producing quality tomatoes
Production limitation: insects/disease	Dummy	= 1 if insect/disease is a problem to producing/marketing quality tomatoes
Production limitation: Price fluctuations	Dummy	= 1 if price fluctuations is a problem to producing/marketing quality tomatoes
Production limitation: Poor transport	Dummy	= 1 if poor transport is a problem to producing/marketing quality tomatoes

Variable	Type	Definition and measurement
Production limitation: Cost of inputs	Dummy	= 1 if cost of inputs is a problem to producing/marketing quality tomatoes
Loss reduction strategy: Apply pesticides	Dummy	= 1 if applying pesticides is a loss reduction strategy
Loss reduction strategy: Careful harvest handling	Dummy	= 1 if careful handling during harvest is a loss reduction strategy
Market transport, hired	Dummy	= 1 if use hired transporter to bring tomatoes to market
Transport day	Dummy	= 1 if tomatoes transported to market day after harvest
Transport during daylight	Dummy	= 1 if tomatoes transported during daylight hours
Unloading labor: hired, female	Dummy	= 1 if hired, female participated in unloading tomatoes at market
Max. number of crates stacked	Continuous	Maximum number of crates (filled with tomatoes) stacked together
Market grading covered	Dummy	= 1 if market grading is done in a covered area
Market grading labor: hired, female	Dummy	= 1 if hired, female participated in market grading
Market grading labor: hired, male	Dummy	= 1 if hired, male participated in market grading
Market grading labor: family, female	Dummy	= 1 if family, female participated in market grading
Market grading labor: family, male	Dummy	= 1 if family, male participated in market grading
Max. market price expected, at market-level	Continuous	Maximum price per 30 kg farmer expects to receive at auction (100 rs.), reported at market-level

Variable	Type	Definition and measurement
Marketing limitation: Climate	Dummy	= 1 if climate is a problem for marketing quality tomatoes
Marketing limitation: Price fluctuations	Dummy	= 1 if price fluctuations are a problem for marketing quality tomatoes
Marketing limitation: Poor transport	Dummy	= 1 if poor transport is a problem for marketing quality tomatoes
Marketing limitation: Transport costs	Dummy	= 1 if transport costs are a problem for marketing quality tomatoes
Production information: other farmers	Dummy	= 1 if other farmers are a source for production information
Production information: agricultural officers	Dummy	= 1 if agricultural officers are a source for production information
Production information: input suppliers	Dummy	= 1 if input suppliers are a source for production information
Production information: family	Dummy	= 1 if family are a source for production information
Post-harvest information: other farmers	Dummy	= 1 if other farmers are a source of post-harvest information
Post-harvest information: tomato traders/mandi owners	Dummy	= 1 if tomato traders/mandi owners are a source of post-harvest information
Post-harvest information: family	Dummy	= 1 if family are a source of post-harvest information
Grading information: tomato traders/mandi owners	Dummy	= 1 if tomato traders/mandi owners are a source of grading information
Grading information: farmer, themselves	Dummy	= 1 if the farmer's own experience is a source of grading information

Variable	Type	Definition and measurement
Grading information: family	Dummy	= 1 if family are a source of grading information
Grading information: laborers/market laborers	Dummy	= 1 if laborers/market laborers are a source of grading information
Price information: other farmers	Dummy	= 1 if other farmers are a source of price information
Price information: tomato traders/mandi owners	Dummy	= 1 if tomato traders/mandi owners are a source of price information
Price information: phone/online messaging groups	Dummy	= 1 if phone/online messaging groups are a source of price information
Price information: transporters	Dummy	= 1 if transporters are a source of price information
Agent choice: provides credit	Dummy	= 1 if farmer chooses commission agent because agent provides credit
Agent choice: on-time payment	Dummy	= 1 if farmer chooses commission agent because agent gives payments on-time
Agent choice: trustful	Dummy	= 1 if farmer chooses commission agent because agent is trustful, overall
Agent choice: fixes rate	Dummy	= 1 if farmer chooses commission agent because agent fixes the auction rate
Agent choice: provides crates	Dummy	= 1 if farmer chooses commission agent because agent provides plastic crates

Table A.2. Definition of variables and measurement for retailer models

Variable	Type	Definition and measurement
Covariate variables		
Gender	Dummy	= 1 if retailer is female
Caste	Dummy	= 1 if retailer is SC, ST or BC
Independent variables		
Retail type	Categorical	= 1 if retailer sells from a brick and mortar shop/local retail shop
		= 2 if retailer sells from a pushcart or roadside shop
		= 3 if retailer sells from a daily market
		= 4 if retailer sells from a weekly market
Education	Dummy	= 1 if retailer highest education is at least secondary (grade 8)
Experience	Continuous	Number of years' experience in tomato business
Display ground	Dummy	= 1 if retailer displays tomatoes on the ground for selling
Display cover	Categorical	= 0 if retailer displays tomatoes uncovered in an open air outlet
		= 1 if retailer displays tomatoes covered in an open air outlet
		= 2 if retailer displays tomatoes in an indoor outlet
Purchase selection	Categorical	= 0 if customers choose/handpick tomatoes to purchase
		= 1 if retailer chooses/handpicks tomatoes for the customer
		= 2 if tomatoes are pre-packed for sale
Buyer	Categorical	= 0 if most common buyers are household consumers
		= 1 if most common buyers are hotels/restaurants

Variable	Type	Definition and measurement
		= 2 if most common buyers are other vegetable vendors
Procurement source	Categorical	= 0 if retailer purchased tomatoes from Bowenpally
		= 1 if retailer purchased tomatoes from Gudimalkapur
		= 2 if retailer purchased tomatoes from Madannapeta
		= 3 if retailer purchased tomatoes from other source
Distance	Continuous	Distance (km) from purchase source to retail location
Purchase time	Dummy	= 1 if retailer purchased tomatoes after sunrise
Purchased grade: 1st quality	Dummy	= 1 if retailer purchased 1st quality grade tomatoes
Purchased grade: 2nd quality	Dummy	= 1 if retailer purchased 2nd quality grade tomatoes
Purchased grade: 3rd quality	Dummy	= 1 if retailer purchased 3rd quality grade tomatoes
Maximum ripeness level	Categorical	= 0 if maximum ripeness level is breaker to light red
		= 1 if maximum ripeness level is red
		= 2 if maximum ripeness level is super red
Ripeness level range	Continuous	Range of ripeness levels
Quality intensity	Continuous	Maximum quality intensity of tomatoes from low to high quality (scale 1-9)
Maximum price	Continuous	Maximum price (10 rs) per kg of tomatoes

REFERENCES

Abbott, J. A. (1999). Quality measurement of fruits and vegetables. *Postharvest Biology and Technology*, *15*(3), 207–225. https://doi.org/10.1016/S0925-5214(98)00086-6

AOAC. (1990). *Official methods of analysis of the Association of Official Analytical Chemists* (15th ed.). Arlington, VA: Association of Official Analytical Chemists.

Ariyawardana, A., Ganegodage, K., & Mortlock, M. Y. (2017). Consumers' trust in vegetable supply chain members and their behavioural responses: A study based in Queensland, Australia. *Food Control*, *73*, 193–201. https://doi.org/10.1016/j.foodcont.2016.08.006

Ashebir, D., Jezik, K., Weingartemann, H., & Gretzmacher, R. (2009). Change in color and other fruit quality characteristics of tomato cultivars after hot-air drying at low final-moisture content. *International Journal of Food Sciences and Nutrition*, *60*(S7), 308–315. https://doi.org/10.1080/09637480903114128

Bahadur KC, K., Dias, G. M., Veeramani, A., Swanton, C. J., Fraser, D., Steinke, D., … Fraser, E. D. G. (2018). When too much isn't enough: Does current food production meet global nutritional needs? *PLoS ONE*, *13*(10), 1–16. https://doi.org/10.1371/journal.pone.0205683

Beausang, C., Hall, C., & Toma, L. (2017). Food waste and losses in primary production: Qualitative insights from horticulture. *Resources, Conservation and Recycling*, *126*(July), 177–185. https://doi.org/10.1016/j.resconrec.2017.07.042

Bellemare, M. F., Çakir, M., Peterson, H. H., Novak, L., & Rudi, J. (2017). On the Measurement of Food Waste. *American Journal of Agricultural Economics*, 1–20. https://doi.org/10.1093/ajae/aax034

Belotti, F., Deb, P., Manning, W. G., & Norton, E. C. (2015). twopm: Two-part models. *Stata Journal*, *15*(1), 3–20. https://doi.org/10.1177/1536867x1501500102

Benson, T. D. (2004). *Africa's food and nutrition security situation: where are we an dhow did we get here?* (Vol. 37). International Food Policy Research Institute.

Betancourt, L. a., Stevens, M. A., & Kader, A. a. (1977). Accumulation and loss of sugars and reduced ascorbic acid in attached and detached tomato fruit. *Journal of the American Society for Horticultural Science*, *102*(6), 721–723.

Birthal, P. S., Roy, D., & Negi, D. S. (2015). Assessing the impact of crop diversification on farm poverty in India. *World Development*, *72*, 70–92. https://doi.org/10.1016/j.worlddev.2015.02.015

Bouzari, A., Holstege, D., & Barrett, D. M. (2015). Vitamin retention in eight fruits and vegetables: A comparison of refrigerated and frozen storage. *Journal of Agricultural and Food Chemistry*, *63*(3), 957–962. https://doi.org/10.1021/jf5058793

Braun, V., & Clarke, V. (2006). Using thematic analysis in psychology. *Qualitative Research in Psychology*, *3*(2), 77–101. https://doi.org/10.1191/1478088706qp063oa

Buragohain, P., Saikia, D. K., Sotelo-Cardona, P., & Srinivasan, R. (2021). Development and validation of an integrated pest management strategy against the invasive South American tomato leaf miner, Tuta absoluta in South India. *Crop Protection*, *139*(August 2020), 105348. https://doi.org/10.1016/j.cropro.2020.105348

Buzby, J. C., Farah-Wells, H., & Hyman, J. (2014). The Estimated Amount, Value, and Calories of Postharvest Food Losses at the Retail and Consumer Levels in the United States. *SSRN Electronic Journal*, (February). https://doi.org/10.2139/ssrn.2501659

Chaboud, G. (2017). Assessing food losses and waste with a methodological framework : Insights from a case study. *Resources, Conservation & Recycling*, *125*, 188–197. https://doi.org/10.1016/j.resconrec.2017.06.008

Chaboud, G., & Daviron, B. (2017). Food losses and waste : Navigating the inconsistencies. *Global Food Security*, *12*(November 2016), 1–7. https://doi.org/10.1016/j.gfs.2016.11.004

Chaboud, G., & Moustier, P. (2020). The role of diverse distribution channels in reducing food loss and waste: The case of the Cali tomato supply chain in Colombia. *Food Policy*, (March), 101881. https://doi.org/10.1016/j.foodpol.2020.101881

Cooper, K. A., Quested, T. E., Lanctuit, H., Zimmermann, D., Espinoza-Orias, N., & Roulin, A. (2018). Nutrition in the Bin: A Nutritional and Environmental Assessment of Food Wasted in the UK. *Frontiers in Nutrition*, *5*(March). https://doi.org/10.3389/fnut.2018.00019

Corbin, J., & Strauss, A. (1990). Grounded Theory Research: Procesures, Canons and Evaluative Criteria. *Zeitschrift Fuer Soziologie*, *19*(6), 418–427.

Crabtree, B., & Miller, W. (1999). A template approach to text analysis: Developing and using codebooks. In B. Crabtree & W. Miller (Eds.), *Doing qualitative research* (pp. 163–177). Newbury Park, CA: Sage.

Craig Hanson, Lipinski, B., Robertson, K., Dias, D., Gavilan, I., Gréverath, P., … Quested, T. (2016). *Food Loss and Waste Accounting and Reporting Standard (FLW Standard)*.

Darby, M. R., & Karni, E. (1973). Free Competition and the Optimal Amount of Fraud. *The Journal of Law and Economics*, *16*(1), 67–88. https://doi.org/10.1086/466756

Delgado, L., Schuster, M., & Torero, M. (2017). *Reality of Food Losses: A New Measurement Methodology*.

Delgado, L., Schuster, M., & Torero, M. (2020). Quantity and quality food losses across the value Chain: A Comparative analysis. *Food Policy*, (August 2019), 101958. https://doi.org/10.1016/j.foodpol.2020.101958

Desneux, N., Wajnberg, E., Wyckhuys, K. A. G., Burgio, G., Arpaia, S., Narváez-Vasquez, C. A., … Urbaneja, A. (2010). Biological invasion of European tomato crops by Tuta absoluta: Ecology, geographic expansion and prospects for biological control. *Journal of Pest Science*, *83*(3), 197–215. https://doi.org/10.1007/s10340-010-0321-6

Diamond, P. A., & Hausman, J. A. (1994). Contingent valuation: Is some number better than no number? *Journal of Economic Perspectives*, *8*(4), 45–64. https://doi.org/10.1257/jep.8.4.45

Drogoudi, P. D., Michailidis, Z., & Pantelidis, G. (2008). Peel and flesh antioxidant content and harvest quality characteristics of seven apple cultivars. *Scientia Horticulturae*, *115*(2), 149–153. https://doi.org/10.1016/j.scienta.2007.08.010

Dunning, R., Johnson, L., & Boys, K. (2019). Putting Dollars to Waste: Estimating the Value of On-Farm Food Loss. *Choices*, *34*(1), 1–9.

EPA, FDA, & USDA. (2019). Formal Agreement among EPA/FDA/USDA relative to a Federal-

Nongovernmental Organization Formal Agreement with ReRED, Inc. in Order to Better Evaluate and Improve Upon Strategies to Reduce Food Loss and Waste. Retrieved from https://www.usda.gov/sites/default/files/documents/usda-epa-fda-formal-agreement-food-loss-waste.pdf

EU FUSIONS. (2014). FUSIONS definitional framework for food waste. Brussels. Retrieved from http://www.eu-fusions.org/phocadownload/Publications/FUSIONS Definitional Framework for Food Waste 2014.pdf

Fabi, C., Cachia, F., Conforti, P., English, A., & Rosero Moncayo, J. (2021). Improving data on food losses and waste: From theory to practice. *Food Policy*, *98*. https://doi.org/10.1016/j.foodpol.2020.101934

Fabi, C., & English, A. (2019). *Methodological Proposal for Monitoring SDG Target 12.3. Sub-Indicator 12.3.1.a The Food Loss Index Design, Data Collection Methods and Challenges*.

Fafchamps, M., Hill, R. V., & Minten, B. (2008). Quality control in nonstaple food markets: Evidence from India. *Agricultural Economics*, *38*(3), 251–266. https://doi.org/10.1111/j.1574-0862.2008.00297.x

FAO. (2011). *Global food losses and food waste - Extent, causes and prevention*. Rome.

FAO. (2014). *Definitional Framework of Food Loss*. Rome.

FAO. (2018). *Gender and food loss in sustainable food value chains - A guiding note*.

FAO. (2019). *The State of Food and Agriculture 2019. Moving forward on food loss and waste reduction*. Rome.

FAOSTAT. (2018). *FAO STAT statistical database*. Rome.

FAOSTAT. (2020). FAOSTAT Database. Rome, Italy: FAO. Retrieved from http://www.fao.org/faostat

Garcia-Herrero, I., Margallo, M., Laso, J., Batlle-Bayer, L., Bala, A., Fullana-i-Palmer, P., … Aldaco, R. (2019). Nutritional data management of food losses and waste under a life cycle approach: Case study of the Spanish agri-food system. *Journal of Food Composition and Analysis*, *82*(October 2018), 103223. https://doi.org/10.1016/j.jfca.2019.05.006

Garson, G. (2013). Fundamentals of hierarchical linear and multilevel modeling. In *Hierarchical linear modeling: Guide and applications* (pp. 3–25). Retrieved from http://books.google.com/books?hl=en&lr=&id=u6mRkR4TKFcC&oi=fnd&pg=PR1&dq=Fundamentals+of+hierarchical+linear+and+multilevel+modeling+garson&ots=nzuK7eiSgd&sig=84MlDJRYkB8S1YZ2ZqQBDjuKavM#v=onepage&q=Fundamentals of hierarchical linear and multilevel model

Gillespie, S., & Haddad, L. J. (2003). *The double burden of malnutrition in Asia: causes, consequences, and solutions*. New Delhi: Sage Publications. Retrieved from https://us.sagepub.com/en-us/nam/the-double-burden-of-malnutrition-in-asia/book226117

Gillman, A., Campbell, D. C., & Spang, E. S. (2019). Does on-farm food loss prevent waste? Insights from California produce growers. *Resources, Conservation and Recycling*, *150*, 104408. https://doi.org/10.1016/j.resconrec.2019.104408

Giovanelli, G., Lavelli, V., Peri, C., & Nobili, S. (1999). Variation in antioxidant components of tomato during vine and post-harvest ripening. *Journal of the Science of Food and Agriculture*, *79*(12), 1583–1588. https://doi.org/10.1002/(SICI)1097-0010(199909)79:12<1583::AID-JSFA405>3.0.CO;2-J

Global Strategy to improve Agricultural and Rural Statistics (GSARS). (2017). *Field Test Report on the Estimation of Crop Yields and Post-Harvest Losses in Ghana*. Rome. Retrieved from http://gsars.org/wp-content/uploads/2017/11/TR-14.11.2017-Field-test-Report-on-the-Estimation-of-Crop-Yields.pdf

GOI. (2011a). *Census of India, 2011. Andhra Pradesh, Chittoor district, Part B*. Retrieved from http://www.censusindia.gov.in/2011census/dchb/2823_PART_B_DCHB_CHITTOOR.pdf

GOI. (2011b). *Provisional Population Totals, Census of India 2011: Urban aggolomerations/cities having population 1 lakh and above*. Retrieved from https://censusindia.gov.in/2011-prov-results/paper2/data_files/India2/Table_3_PR_UA_Citiees_1Lakh_and_Above.pdf

GOI. (2019a). *Agricultural Statistics at a Glance 2019*. Retrieved from http://agricoop.nic.in/agristatistics.htm

GOI. (2019b). Selected State-wise Area , Production and Productivity of Tomato in India (2017-2018). Ministry of Agriculture and Farmers Welfare, Government of India.

Gómez, M. I., & Ricketts, K. D. (2013). Food value chain transformations in developing countries: Selected hypotheses on nutritional implications. *Food Policy*, *42*, 139–150. https://doi.org/10.1016/j.foodpol.2013.06.010

Government of Andhra Pradesh. (2018a). *Census of land holdings 2015-16 Andhra Pradesh*. Retrieved from https://core.ap.gov.in/CMDASHBOARD/Download/Publications/Census of Land Holdings 2015-16.pdf

Government of Andhra Pradesh. (2018b). Horticulture Farmers Survey Report 2017-2018. Retrieved from https://horticulturedept.ap.gov.in

Government of Andhra Pradesh. (2018c). *Season and crop report 2016-17 Andhra Pradesh*. Gollapudi.

Government of Andhra Pradesh. (2019). Area & Production (2014-15 to 2020-21 IIAE). Retrieved from https://horticulture.ap.nic.in/Section wise/MIDH/guidelines.htm

Government of India. (2021). National Agriculture Market commodity quality. Retrieved March 31, 2021, from https://enam.gov.in/web/commodity/commodity-quality

Gulati, A., Ganesh-Kumar, A., Shreedhar, G., & Nandakumar, T. (2012). Agriculture and malnutrition in India. *Food and Nutrition Bulletin*, *33*(1), 74–86. https://doi.org/10.1177/156482651203300108

Guo, S. S., Wu, W., Chumlea, W. C., & Roche, A. F. (2002). Predicting overweight and obesity in adulthood from body mass index values in childhood and adolescence. *Am J Clin Nutr*, *76*(3), 653–658. Retrieved from http://ajcn.nutrition.org/content/76/3/653.full.pdf

Gupta, S., Vemireddy, V., Singh, D. K., & Pingali, P. (2021). Ground truthing the cost of achieving the EAT lancet recommended diets : Evidence from rural India. *Global Food Security*, *28*(July 2020), 100498. https://doi.org/10.1016/j.gfs.2021.100498

Heinonen, J. K., & Lahti, R. J. (1981). A new and convenient colorimetric determination of inorganic orthophosphate and its application to the assay of inorganic pyrophosphatase. *Analytical Biochemistry*, *113*(2), 313–317. https://doi.org/10.1016/0003-2697(81)90082-8

Hennink, M. M., & Leavy, P. (2014). *Focus Group Discussions*. Oxford University Press.

Herforth, A., & Ahmed, S. (2015). The food environment, its effects on dietary consumption, and potential for measurement within agriculture-nutrition interventions. *Food Security*, *7*(3), 505–520. https://doi.org/10.1007/s12571-015-0455-8

Hirvonen, K., Bai, Y., Headey, D., & Masters, W. A. (2020). Affordability of the EAT–Lancet reference diet: a global analysis. *The Lancet Global Health*, *8*(1), e59–e66. https://doi.org/10.1016/S2214-109X(19)30447-4

HLPE. (2014). *Food losses and waste in the context of sustainable food systems. A report by the High Level Panel of Experts on Food Security and Nutrition of the Committee on World Food Security*. Rome. https://doi.org/65842315

Hodges, R. J., Buzby, J. C., & Bennett, B. (2011). Postharvest losses and waste in developed and less developed countries: Opportunities to improve resource use. *Journal of Agricultural Science*, *149*(S1), 37–45. https://doi.org/10.1017/S0021859610000936

HSPH. (2011). Healthy eating plate. Retrieved from https://www.hsph.harvard.edu/nutritionsource/healthy-eating-plate/

Huckle, W. G., & Lalor, E. (1955). Inorganic pigments. *Industrial & Engineering Chemistry*, *47*(8), 1501–1506. https://doi.org/10.1007/978-3-540-38522-6-8

IHME. (2019). GBD Compare, 2009-2019. Retrieved April 17, 2021, from http://www.healthdata.org/gbd-compare

Intergovernmental Panel on Climate Change. (2019). *Climate Change and Land: an IPCC Special Report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems*. Geneva. Retrieved from https://www.ipcc.ch/site/assets/uploads/2018/07/sr2_background_report_final.pdf

Johnson, L. K., Dunning, R. D., Bloom, J. D., Gunter, C. C., Boyette, M. D., & Creamer, N. G. (2018). Estimating on-farm food loss at the field level: A methodology and applied case study on a North Carolina farm. *Resources, Conservation and Recycling*, *137*(January), 243–250. https://doi.org/10.1016/j.resconrec.2018.05.017

Kader, A. A. (1986). Effects of postharvest handling procedures on tomato quality. *Acta Horticulturae*.

Kader, A. A. (2005). Increasing food availability by reducing postharvest losses of fresh produce. In *In Proceedings of the 5th International Postharvest Symposium, Acta Hort. 682* (pp. 2169–2176). https://doi.org/10.17660/ActaHortic.2005.682.296

Kader, A. A. (2010). Handling of horticultural perishables in developing vs. developed countries. *Acta Horticulturae*, *877*, 121–126. https://doi.org/10.17660/ActaHortic.2010.877.8

Kader, Adel A. (1992). Postharvest biology and technology: An overview. *Postharvest Technology of Horticultural Crops*. Oakland, CA.

Kader, Adel A., & Rolle, R. S. (2004). *The role of post-harvest management in assuring the quality and safety of horticultural produce*. *FAO Agricultural Services Bulletin*. Rome. Retrieved from http://www.fao.org/3/a-y5431e.pdf/

Kader, Adel A., Stevens, M. A., Albright-Holton, M., Morris, L. L., & Algazi, M. (1977). Effect of fruit ripeness when picked on flavor and composition in fresh market tomatoes. *Journal of American Society of*

Horticulture Science, *102*, 724–731. Retrieved from https://ucanr.edu/sites/Postharvest_Technology_Center_/files/230849.pdf

Kambara, C. (2015). FDI in retail: plight of women vegetable vendors. *Indian Journal of Labour Economics*, *58*(4), 677–693. https://doi.org/10.1007/s41027-016-0041-4

Kapoor, S., & Kumar, N. (2015). Fruit and Vegetable Consumers' Behavior: Implications for Organized Retailers in Emerging Markets. *Journal of International Food and Agribusiness Marketing*, *27*(3), 203–227. https://doi.org/10.1080/08974438.2014.940118

Khalid, S., Naseer, A., Shahid, M., Shah, G. M., Ullah, M. I., Waqar, A., … Rehman, F. (2019). Assessment of nutritional loss with food waste and factors governing this waste at household level in Pakistan. *Journal of Cleaner Production*, *206*, 1015–1024. https://doi.org/10.1016/j.jclepro.2018.09.138

Kitinoja, L., & Kader, A. (2002). Small-Scale Postharvest Practices A Manual for Horticultural Crops - Postharvest Technology Center. Retrieved from http://ucce.ucdavis.edu/files/datastore/234-1450.pdf

Kleinjans, K. J. (2013). The man of the house-How the use of household head characteristics may lead to omitted variable bias. *Economics Letters*, *119*(2), 133–135. https://doi.org/10.1016/j.econlet.2013.01.031

Krishna, V. V., Aravalath, L. M., & Vikraman, S. (2019). Does caste determine farmer access to quality information? *PLoS ONE*, *14*(1), 1–22. https://doi.org/10.1371/journal.pone.0210721

Kumar, S. M. (2013). Does Access to Formal Agricultural Credit Depend on Caste? *World Development*, *43*, 315–328. https://doi.org/10.1016/j.worlddev.2012.11.001

Kusuma, D. K., & Basavraja, H. (2014). Stability Analysis of Mango Export Markets of India – Markov Chain Approach. *Karnataka Journal of Agricultural Science*, *27*(1), 36–39. https://doi.org/10.5958/0976-4666.2015.00038.8

Kyriacou, M. C., & Rouphael, Y. (2018). Towards a new definition of quality for fresh fruits and vegetables. *Scientia Horticulturae*, *234*(August 2017), 463–469. https://doi.org/10.1016/j.scienta.2017.09.046

Lawless, H. T., & Heymann, H. (2010). *Sensory Evaluation of Food* (Second Edi). Springer. Retrieved from http://www.springer.com/series/5999

Lee, S. K., & Kader, A. A. (2000). Preharvest and postharvest factors influencing vitamin C content of horticultural crops. *Postharvest Biology and Technology*, *20*(3), 207–220. https://doi.org/10.1016/S0925-5214(00)00133-2

Leonard, S. A., & Rasmussen, K. M. (2011). Larger Infant Size at Birth Reduces the Negative Association between Maternal Prepregnancy Body Mass Index and Breastfeeding Duration. *Journal of Nutrition*, *141*(4), 645–653. https://doi.org/10.3945/jn.110.129874

Longvah, T., Ananthan, R., Bhaskarachary, K., & Venkaiah, K. (2017). *Indian Food Composition Tables 2017*. (T. Longvah, Ed.). Hyderabad: National Institute of Nutrition.

Lowry, O. H., & Lopez, J. A. (1946). The determination of inorganic phosphate in the presence of labile phosphate esters. *Journal of Biological Chemistry*, (162), 421–428.

Macheka, L., Spelt, E. J. H., Bakker, E. J., van der Vorst, J. G. A. J., & Luning, P. A. (2018). Identification of determinants of postharvest losses in Zimbabwean tomato supply chains as basis for dedicated interventions. *Food Control*, *87*, 135–144. https://doi.org/10.1016/j.foodcont.2017.12.017

Magalhães, V. S. M., Ferreira, L. M. D. F., & Silva, C. (2021). Using a methodological approach to model causes of food loss and waste in fruit and vegetable supply chains. *Journal of Cleaner Production*, *283*. https://doi.org/10.1016/j.jclepro.2020.124574

Mason-D'Croz, D., Bogard, J. R., Sulser, T. B., Cenacchi, N., Dunston, S., Herrero, M., & Wiebe, K. (2019). Gaps between fruit and vegetable production, demand, and recommended consumption at global and national levels: an integrated modelling study. *The Lancet Planetary Health*, *3*(7), e318–e329. https://doi.org/10.1016/S2542-5196(19)30095-6

McGill, E., Er, V., Penney, T., Egan, M., White, M., Meier, P., … Petticrew, M. (2021). Evaluation of public health interventions from a complex systems perspective: A research methods review. *Social Science and Medicine*, *272*, 113697. https://doi.org/10.1016/j.socscimed.2021.113697

McKenzie, T. J., Singh-Peterson, L., & Underhill, S. J. R. (2017). Quantifying Postharvest Loss and the Implication of Market-Based Decisions: A Case Study of Two Commercial Domestic Tomato Supply Chains in Queensland, Australia. *Horticulturae*, *3*(3), 44. https://doi.org/10.3390/horticulturae3030044

Miller, B. D. D., & Welch, R. M. (2013). Food system strategies for preventing micronutrient malnutrition. *Food Policy*, *42*, 115–128. https://doi.org/10.1016/j.foodpol.2013.06.008

Millipore Sigma. (2021a). Application Notes: Reflectometry - Ascorbic Acid in Apple Purees. Reflectometric determination after reaction with molybdophosphoric acid to phosphomolybdenum blue. Retrieved from https://www.sigmaaldrich.com/technical-documents/articles/analytical-applications/reflectometry/ascorbic-acid-in-apple-purees.html

Millipore Sigma. (2021b). Application Notes: Reflectometry – Ascorbic Acid in Tomato Juice. Reflectometric determination after reaction with molybdophosphoric acid to phosphomolybdenum blue. Retrieved from https://www.sigmaaldrich.com/technical-documents/articles/analytical-applications/reflectometry/ascorbic-acid-in-tomato-juic

Minten, B., Reardon, T., Gupta, S. Das, Hu, D., & Murshid, K. A. S. (2016). Wastage in Food Value Chains in Developing Countries: Evidence from the Potato Sector in Asia. *Food Security in a Food Abundant World*, 225–238. https://doi.org/10.1108/S1574-871520150000016010

Minten, B., Reardon, T., Singh, K. M., & Sutradhar, R. (2014). The new and changing roles of cold storages in the potato supply chain in Bihar. *Economic and Political Weekly*, *49*(52), 98–108.

Modekurti, D. P. V. (2016). Automation of modified marketing procedural system to maximize transparency: A case study of vegetables in Madanapalle market. *Journal of Agribusiness in Developing and Emerging Economies*, *6*(1), 72–88. https://doi.org/10.1108/JADEE-08-2014-0027

Mohammed, M., & Craig, K. (2018). *Food loss analysis : causes and solutions Case study on the tomato value chain in the Republic of Guyana*.

Munshi, K. (2019). Caste and the Indian economy. *Journal of Economic Literature*, *57*(4), 781–784. https://doi.org/10.1257/jel.20171307

Nelson, P. (1970). Information and Consumer Behavior. *Journal of Political Economy*, *78*(2), 311–329.

https://doi.org/10.1086/259630

Nelson, P. (1974). Advertising as Information. *Journal of Political Economy*, *82*(4), 729–754. https://doi.org/10.1086/260231

Neocleous, D., & Vasilakakis, M. (2008). Fruit quality of red raspberry as affected by salinity. *European Journal of Horticultural Science*, *73*(3), 131–137.

Netscribes Pvt Ltd. (2019). *Fruit and Vegetable Processing Industry in India 2020*. Retrieved from https://www.researchandmarkets.com/reports/5017305/fruit-and-vegetable-processing-industry-in-india

Nicholson, C. F., Kopainsky, B., Stephens, E. C., Parsons, D., Jones, A. D., Garrett, J., & Phillips, E. L. (2020). Conceptual frameworks linking agriculture and food security. *Nature Food*, *1*(September), 541–551. https://doi.org/10.1038/s43016-020-00142-3

Nielsen, S. S. (Ed.). (2017). *Food Analysis* (5th ed.). Cham, Switzerland: Springer International Publishing. https://doi.org/10.1007/978-1-4419-1478-1

Nommsen-Rivers, L. A., Chantry, C. J., Peerson, J. M., Cohen, R. J., & Dewey, K. G. (2010). Delayed onset of lactogenesis among first-time mothers is related to maternal obesity and factors associated with ineffective breastfeeding. *American Journal of Clinical Nutrition*, *92*(3), 574–584. https://doi.org/10.3945/ajcn.2010.29192

Nováková, L., Solich, P., & Solichová, D. (2008). HPLC methods for simultaneous determination of ascorbic and dehydroascorbic acids. *Trends in Analytical Chemistry*, *27*(10), 942–958. https://doi.org/10.1016/j.trac.2008.08.006

Nuthalapati, C. S. R., Sutradhar, R., Reardon, T., & Qaim, M. (2020). Supermarket procurement and farmgate prices in India. *World Development*, *134*, 105034. https://doi.org/10.1016/j.worlddev.2020.105034

Pingali, P. (2006). Westernization of Asian diets and the transformation of food systems: Implications for research and policy. *Food Policy*, *32*, 281–298. https://doi.org/10.1016/j.foodpol.2006.08.001

Pingali, P., Aiyar, A., Abraham, M., & Rahman, A. (2019). *Food Systems for a Rising India*. Ithaca, NY: palgrave macmillan. https://doi.org/10.1007/978-3-030-14409-8

Pingali, P., Mittra, B., & Rahman, A. (2017). The bumpy road from food to nutrition security – Slow evolution of India's food policy. *Global Food Security*, *15*(December 2016), 77–84. https://doi.org/10.1016/j.gfs.2017.05.002

Pinstrup-Andersen; P.; Watson II; D.D. (2011). *Food Policy for Developing Countries: The Role of Government in Global, National, and Local Food Systems*. Ithaca, New York: Cornell University Press. https://doi.org/10.1093/erae/jbs023

Powell, C., & Curtis, P. (2020). *Insights engine food waste monitor 2020 methodology*.

Raghunathan, K., Headey, D., & Herforth, A. (2021). Affordability of nutritious diets in rural India. *Food Policy*, *99*(October 2020), 101982. https://doi.org/10.1016/j.foodpol.2020.101982

Rao, C. A. R., Raju, B. M. K., Rao, A. V. M. S., Rao, K. V., Samuel, J., Ramachandran, K., … Shankar, K. R. (2017). Assessing vulnerability and adaptation of agriculture to Climate change in Andhra Pradesh. *Indian*

Journal of Agricultural Economics, *72*(3), 375–384.

Reardon, T., Timmer, C. P., & Minten, B. (2012). Supermarket revolution in Asia and emerging development strategies to include small farmers. *Proceedings of the National Academy of Sciences*, *109*(31), 12332–12337. https://doi.org/10.1073/pnas.1003160108

Reardon, Thomas, Echeverria, R., Berdegué, J., Minten, B., Liverpool-Tasie, S., Tschirley, D., & Zilberman, D. (2018). Rapid transformation of food systems in developing regions: Highlighting the role of agricultural research & innovations. *Agricultural Systems*, (September 2017), 0–1. https://doi.org/10.1016/j.agsy.2018.01.022

Reardon, Thomas, & Minten, B. (2011). The quiet revolution in India's food supply chains. *IFPRI Discussion Papers*, (September). Retrieved from http://www.environmentportal.in/files/file/India's Food Supply Chains.pdf

Reddy, A. A. (2019). Price Forecasting of Tomatoes. *International Journal of Vegetable Science*, *25*(2), 176–184. https://doi.org/10.1080/19315260.2018.1495674

Rickman, J. C., Barrett, D. M., & Bruhn, C. M. (2007). Nutritional comparison of fresh, frozen and canned fruits and vegetables. Part 1. Vitamins C and B and phenolic compounds. *Journal of the Science of Food and Agriculture*. https://doi.org/10.1002/jsfa

Rickman, J. C., Bruhn, C. M., & Barrett, D. M. (2007). Nutritional comparison of fresh, frozen, and canned fruits and vegetables II. Vitamin A and carotenoids, vitamin E, minerals and fiber. *Journal of the Science of Food and Agriculture*. https://doi.org/10.1002/jsfa

Rizzolo, A., Brambilla, A., Valsecchi, S., & Eccher-Zerbini, P. (2002). Evaluation of sampling and extraction procedures for the analysis of ascorbic acid from pear fruit tissue. *Food Chemistry*, *77*(2), 257–262. https://doi.org/10.1016/S0308-8146(02)00107-3

Rolle, R. S. (Ed.). (2006). *Reports of the APO seminar on Reduction of Postharvest Losses of Fruit and Vegetables held in India, 5–11 October 2004 and Marketing and Food Safety: Challenges in Postharvest Management of Agricultural/Horticultural Products in Islamic Republic of Iran,* . Rome.

Ruel-Bergeron, J. C., Stevens, G. A., Sugimoto, J. D., Roos, F. F., Ezzati, M., Black, R. E., & Kraemer, K. (2015). Global update and trends of hidden hunger, 1995-2011: The hidden hunger Index. *PLoS ONE*, *10*(12). https://doi.org/10.1371/journal.pone.0143497

Ryan, D. (2007). Obesity in women: A life cycle of medical risk. *International Journal of Obesity*, *31*(S2), S3–S7. https://doi.org/10.1038/sj.ijo.0803729

Scherhaufer, S., Lebersorger, S., Pertl, A., Obersteiner, G., Schneider, F., Falasconi, L., … Easteal, S. (2015). *Criteria for and baseline assessment of environmental and socio-economic impacts of food waste*.

Schreinemachers, P., Simmons, E. B., & Wopereis, M. C. S. (2018). Tapping the economic and nutritional power of vegetables. *Global Food Security*, *16*(June 2017), 36–45. https://doi.org/10.1016/j.gfs.2017.09.005

Schummers, L., Hutcheon, J. A., Bodnar, L. M., Lieberman, E., & Himes, K. P. (2015). Risk of adverse pregnancy outcomes by prepregnancy body mass index : A population-based study to inform prepregnancy weight loss counseling. *Obstetrics and Gynecology*, *125*(1), 133–143. https://doi.org/10.1097/AOG.0000000000000591

Sharma, S., Marshall, A., Chow, J., Ranjit, N., Bounds, G., Hearne, K., … Markham, C. (2019). Impact of a Pilot School-Based Nutrition Intervention on Fruit and Vegetable Waste at School Lunches. *Journal of Nutrition Education and Behavior*, *51*(10), 1202-1210.e1. https://doi.org/10.1016/j.jneb.2019.08.002

Shashank, P. R., Chandrashekar, K., Meshram, N. M., & Sreedevi, K. (2015). Occurrence of tuta absoluta (Lepidoptera: Gelechiidae) An invasive pest from India. *Indian Journal of Entomology*, *77*(4), 323. https://doi.org/10.5958/0974-8172.2015.00070.x

Sheoran A, R. M. (2015). Scope of Supply Chain Management in Fruits and Vegetables in India. *Journal of Food Processing & Technology*, *06*(03). https://doi.org/10.4172/2157-7110.1000427

Shuch, W., & Bird, C. (1994). Improving tomato fruit quality using bioscience. *Acta Horticulturae*, *376*, 75–80. https://doi.org/10.17660/ActaHortic

Siegel, K. R., Ali, M. K., Srinivasiah, A., Nugent, R. A., & Narayan, K. M. V. (2014). Do we produce enough fruits and vegetables to meet global health need? *PLoS ONE*, *9*(8), 1–7.

Spiker, M. L., Hiza, H. A. B., Siddiqi, S. M., & Neff, R. A. (2017). Wasted Food, Wasted Nutrients: Nutrient Loss from Wasted Food in the United States and Comparison to Gaps in Dietary Intake. *Journal of the Academy of Nutrition and Dietetics*. https://doi.org/10.1016/j.jand.2017.03.015

Stephen, A., Suresh, R., Balaji, M., Sarathkumar, S., Parthiban, S., & Vinothraj, S. (2015). Diversity of vegetalbes from the markets of Chennai, Tamil Nadu, India. *Journal of Academia and Industrial Research*, *3*(11), 546–561. Retrieved from http://jairjp.com/APRIL 2015/05 STEPHEN 02.pdf

Subramanian, R. (2016). *India Processing Tomato Segment Current Status, Trends and Opportunities for Engagement*.

Suslow, T. V., & Cantwell, M. (1997). Tomato: Recommendations for Maintaining Postharvest Quality. Retrieved from http://postharvest.ucdavis.edu/Commodity_Resources/Fact_Sheets/Datastores/Vegetables_English/?uid=36&ds=799

Tang, S., & Lee, H. K. (2016). Syringe needle-based sampling coupled with liquid-phase extraction for determination of the three-dimensional distribution of l-ascorbic acid in apples. *Food Chemistry*, *199*, 535–540. https://doi.org/10.1016/j.foodchem.2015.12.044

Thow, A. M., Verma, G., Soni, D., Soni, D., Beri, D. K., Kumar, P., … Khandelwal, S. (2018). How can health, agriculture and economic policy actors work together to enhance the external food environment for fruit and vegetables? A qualitative policy analysis in India. *Food Policy*, *77*, 143–151. https://doi.org/10.1016/j.foodpol.2018.04.012

Tontisirin, K., Nantel, G., & Bhattacharjee, L. (2002). Food-based strategies to meet the challenges of micronutrient malnutrition in the developing world. *Proceedings of the Nutrition Society*, *61*(02), 243–250. https://doi.org/10.1079/PNS2002155

Trebbin, A. (2014). Linking small farmers to modern retail through producer organizations - Experiences with producer companies in India. *Food Policy*, *45*, 35–44. https://doi.org/10.1016/j.foodpol.2013.12.007

UNEP. (2021). Food Waste Index Report 2021. Nairobi.

United Fresh Fruit and Vegtable Association, & USDA Agricultural Marketing Service Fruit and Vegetable Division. (1975). Color classification requirements in United States Standards for grades of fresh tomatoes. Retrieved from http://www.cn.nysed.gov/common/cn/files/tomatocolorchart.pdf

Uribe, R., Infante, R., Kusch, C., Contador, L., Pacheco, I., & Mesa, K. (2020). Do Consumers Evaluate New and Existing Fruit Varieties in the Same Way? Modeling the Role of Search and Experience Intrinsic Attributes. *Journal of Food Products Marketing*, *26*(8), 521–534. https://doi.org/10.1080/10454446.2020.1821419

USDA. (2020). *Dietary Guidelines for Americans 2020-2025*.

Vandeplas, A., & Minten, B. (2015). Food quality in domestic markets of developing economies: A comparative study of two countries. *Agricultural Economics (United Kingdom)*, *46*(5), 617–628. https://doi.org/10.1111/agec.12158

Vanitha, S. M., Kumari, G., & Singh, R. (2014). Export Competitiveness of Fresh Vegetables in India. *International Journal of Vegetable Science*, *20*(3), 227–234. https://doi.org/10.1080/19315260.2013.789812

Webb, P., & Block, S. (2012). Support for agriculture during economic transformation: Impacts on poverty and undernutrition. *Proceedings of the National Academy of Sciences*, *109*(31), 12309–12314. https://doi.org/10.1073/pnas.0913334108

Weller, S., & Romney, A. (2011). Pile Sort I: Single Sorts. In *Systematic Data Collection* (pp. 21–26). Newbury Park: SAGE Publications, Inc.

WHO. (2020). Healthy diet fact sheet. Retrieved from https://www.who.int/news-room/fact-sheets/detail/healthy-diet

Willett, W., Rockström, J., Loken, B., Springmann, M., Lang, T., Vermeulen, S., … Murray, C. J. L. (2019). Food in the Anthropocene: the EAT–Lancet Commission on healthy diets from sustainable food systems. *The Lancet*. https://doi.org/10.1016/S0140-6736(18)31788-4

World Vegetable Center. (2020). Processing/dual purpose tomato. Retrieved from https://avrdc.org/seed/improved-lines/processingdual-purpose-tomato/

Xue, L., Liu, G., Parfitt, J., Liu, X., Van Herpen, E., Stenmarck, Å., … Cheng, S. (2017). Missing Food, Missing Data? A Critical Review of Global Food Losses and Food Waste Data. *Environmental Science & Technology*, *51*(12), 6618–6633. https://doi.org/10.1021/acs.est.7b00401

Yilmaz, K. U., Ercisli, S., Zengin, Y., Sengul, M., & Kafkas, E. Y. (2009). Preliminary characterisation of cornelian cherry (Cornus mas L.) genotypes for their physico-chemical properties. *Food Chemistry*, *114*(2), 408–412. https://doi.org/10.1016/j.foodchem.2008.09.055