Value Chain and Nutritional Analyses of *Warqe* Food Products in Relation to Post-harvest Losses

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Doctoral thesis
Swedish University of Agricultural Sciences
Uppsala 2019

Acta Universitatis agriculturae Sueciae
2019:1

Cover: *Warqe* farming in Haro Wanchi area, Ethiopia.
(Photo: by A. C. Tuffa, 22 June 2014)

ISSN 1652-6880
ISBN (print version) 978-91-7760-278-1
ISBN (electronic version) 978-91-7760-279-8

Print: SLU Service/Repro, Uppsala 2019

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Abstract

Food losses and waste are global problems, but are particularly critical in food-insecure countries. Losses from root and tuber crops are known to be high in developing countries, where much of the population is dependent on these crops. For example, *warqe* (*Ensete ventricosum*) is used as a staple food for millions of Ethiopians, mainly in the form of *kocho* and *bulla* foods. Despite its widespread use, there is no adequate information about the magnitude of food losses in the supply chain for *warqe*, the nutrient content of *warqe* foods and the microbial dynamics of *kocho* fermentation enhancer (*gammaa*). Therefore this thesis examined the nutritional content, value chain and post-harvest losses of *kocho* and *bulla* foods along the supply chain, based on three surveys and two laboratory studies conducted in Ethiopia and Sweden between 2013 and 2018.

Laboratory analyses showed that *warqe* foods are rich in starch (75 g/100g DM in *kocho* and 89 g/100g DM in *bulla*) and a good source of major micronutrients, such as K, Ca, P and Mg. However, both were found to be low in total fat (0.20 g/100g DM in *kocho* and 0.10 g/100g DM in *bulla*), protein (1.67 g/100g DM in *kocho* and 0.45 g/100g DM in *bulla*) and total dietary fibre (3.40 g/100g DM in *kocho* and 0.64 g/100g DM in *bulla*). Field surveys revealed that *warqe* foods reach the final consumer through different suppliers in complex chains involving six principal value chain actors, with farmers and *bulla* processors being the main actors.

Significant amounts of *warqe* foods are wasted throughout the supply chain, with highest losses of *kocho* (24%) occurring at retailer level and of *bulla* (29%) at processor level. Lack of appropriate processing technologies at producer and processor level, use of inferior packaging materials and improper handling in the market are the leading causes of losses. Microbiota analysis showed that *Lactobacillus* species from lactic acid bacteria isolates and Enterobacteriaceae from aerobic mesophilic bacteria isolates are the most abundant and dominant microorganisms in *gammaa* fermentation.

Overall, the results indicate a need for better communication to enable effective information transfer in the supply chain, appropriate packaging and storage to reduce losses and upgrading of the nutritional content of *warqe* foods to provide an adequate staple diet for consumers.

Keywords: bulla, *Ensete ventricosum*, Ethiopia, *kocho*, nutrient profile, post-harvest losses, value chain

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Dedication

To my mother Mulunesh Anchamo Burka and my father Chaka Tuffa Medene for their unconditional love and support.

We cannot solve our problems with the same thinking we used when we created them.

Albert Einstein

Contents

List of publications

This thesis is based on the work contained in the following papers, referred to by Roman numerals in the text:

I Tuffa, A.C*., Landberg, R., Gebresenbet, G. and Andersson, R. (2018). Determination of the nutritional profile of *warqe* foods, *kocho* and *bulla*, in Ethiopia. *Food Research International* (submitted)

II Tuffa, A.C*., Kenea, T. and Gebresenbet, G. (2016). Analysis of the supply chain and logistics practices of *warqe* food products in Ethiopia. *International Journal on Food System Dynamics* 7(3), 213-228.

III Tuffa, A.C*., Amentae, T.K. and Gebresenbet G. (2017). Value chain analysis of *warqe* food products in Ethiopia. *International Journal of Managing Value and Supply Chains* 8(1), 23-42.

IV Tuffa, A.C., Amentae, T.K., Balemi, T. and Gebresenbet, G*. (2017). Assessment of post-harvest losses of *warqe* food products along the supply chain in Central Ethiopia. *African Journal of Agricultural Research* 12(9), 750-763.

V Dibaba, A. H., Tuffa, A.C*., Gebremedhin, E.Z., Nugus, G.G. and Gebresenbet, G. (2018). Microbiota and physicochemical analysis of traditional *kocho* fermentation enhancer (*gammaa*) to reduce losses in the Highlands of Ethiopia. *Microbiology and Biotechnology Letters* 46(3), 210-224.

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The contribution of Ashenafi Chaka Tuffa to the papers included in this thesis was as follows:

I Planned the paper together with the co-authors and supervised the data collection, calculation and analysis of data. Interpreted the data and wrote the manuscript with input from the co-authors.

II Planned the study, performed the data collection, analysis and paper writing together with the co-authors and prepared the data presentation (figures and tables) and calculations.

III Planned the study, performed the data collection, analysis and paper writing together with the co-authors and prepared the data presentation (figures and tables) and calculations.

IV Planned the data collection method, performed the data analysis and paper writing together with the co-authors.

V Planned the data collection method, performed the data analysis and paper writing together with the co-authors.

Abbreviations

AMB	Aerobic mesophilic bacteria
CBB	Chloramphenicol bromophenol blue
cfu/g	Colony-forming units per gram
CSAM	Commodity System Assessment Methodology
DF	Dietary fibre
DM	Dry matter
FAO	Food and Agriculture Organization of the United Nations
GTZ	German Technical Cooperation Agency
IBM	International Business Machines Corporation
ISO	International Organisation for Standardisation
KOH	Potassium Hydroxide
LAB	Lactic acid bacteria
LSD	Least Significant Difference
M4P	Making markets work better for the poor
MRS	de-Man-Rogosa-Sharpe
pH	Hydrogen ion concentration of a solution
STATA	A syllabic abbreviation of the words statistics and data
SE	Standard Error
SLU	Swedish University of Agricultural Sciences
SPSS	Statistical package for the social sciences
TSI	Triple sugar iron test
WHO	World Health Organization

1 Introduction

1.1 Background

Food loss and waste is a global problem, but it is more critical in food-insecure countries. Food waste occurs at different levels in the food supply chain from production through post-harvest handling to consumption (Parfitt *et al.*, 2010). The Food and Agriculture Organization of the United Nations (FAO) estimates that one-third of food produced for human consumption is wasted globally, which is equivalent to about 1.3 billion tons per year, and this loss leads to significant losses of resources used for food production (FAO, 2011). These include land, water, energy and other inputs already used to grow these lost foods (Lundqvist *et al.*, 2008). Food losses are also the cause of unnecessary carbon dioxide (CO_2) emissions, in addition to the economic value of the foods produced. According to FAO (2013), the carbon footprint of this lost food is an estimated 3.3 gigatons of CO_2 every year, without accounting for greenhouse gas emissions from land use change. The total cost is estimated to be about 750 billion US dollars every year when considering post-harvest losses throughout the supply chain (FAO, 2011).

Losses of food from farm to table through storage, transport, processing, retail and the consumer stage are massive. Food losses are also associated with water losses and have a significant impact on water use. Therefore reducing food losses and wastage would reduce the water demand in agriculture (Parfitt *et al.*, 2010; Lundqvist *et al.*, 2008).

The distribution of losses and waste shows significant variation between developed and developing regions. In developed countries, food losses tend to occur at the consumer level, while in developing countries they tend to occur during production and handling and storage (Lipinski *et al.*, 2013). For instance, in Tanzania maize losses that arise in the field are of more economic significance than those which occur during any other single activity from harvesting to marketing (Abass *et al*., 2014). Leading causes of substantial post-harvest losses in the early stage of the supply chain in developing countries include financial and structural limitations in harvesting techniques, storage and transport infrastructure. Inadequate technical and managerial skill in food production and post-harvest in developing regions are often favourable for high food spoilage (FAO, 2013). Bio-deterioration by microorganisms, insects, rodents or birds is another leading cause of post-harvest food losses in low-income countries (Hodges *et al*., 2011). A recent study found that rodents and other pests were the most frequently reported cause of cereal losses in Ethiopia, with the highest loss recorded in maize (52%) and the lowest in teff (32%) based on self-reported farmers' estimates at household level (Hengsdijk & De Boer, 2017).

There are relatively high losses of fresh root and tuber foods at early stages of the food supply chain in developing countries (FAO, 2011). Wastage of starchy roots is among the top 10 food losses at global level, because of high wastage volumes in the growing and post-harvest phases (FAO, 2013). One reason for these high losses is the perishable nature of the crops. This results in them being easily damaged during harvesting and post-harvest activities, especially in warm, humid climates (FAO, 2011). Another reason for spoilage of root and tuber crops is the nature of the plant material, with its high moisture content (60-90%), which leads to physiological deterioration and limits crop utilisation (Uchechukwu-Agua *et al*., 2015). Root and tuber crop losses are also caused by insects, bacteria and moulds during storage, rain, humidity, heat, frost and other adverse environmental conditions, sprouting, and damage by rodents and birds (Willersinn *et al*., 2015; Bourne, 1977). Therefore, the shelf-life of these valuable crops is shortened, leading to wastage, economic losses and a reduction in market quality and associated high post-harvest food losses.

These losses are particularly severe in view of the fact that a high proportion of the population in many countries in sub-Saharan Africa, Asia and Latin America is highly dependent on root and tuber crops as a source of food, nutrition and cash income (Scott *et al*., 2000). For instance, root and tuber crops provide over 50% of calories in the Democratic Republic of Congo and Rwanda (Alexandratos & Bruinsma, 2012). In Ethiopia, root and tuber crops are the third largest national food commodity, after maize and wheat, in terms of quantity produced (CountrySTAT Ethiopia, 2016). The FAO estimates that in 2016, about 282 million tons of root and tuber crops were produced in Africa and 846 million tons were produced world-wide (FAOSTAT, 2018). The main cultivated root and tuber crops in the world are potatoes, cassava, sweet potatoes, yams and aroids. However, some other root and tuber crops are of particular value in specific countries, for instance, *warqe* is a typical staple food in Ethiopia.

1.2 *Warqe* plant and values

Warqe (enset) is an important multipurpose crop in Southern, Central and South-Western Ethiopia. The word '*warqe*' means 'my gold'. The crop plays a vital role in Ethiopian food security because of its capacity for high yield per unit area and its tolerance to drought (Tsegaye & Struik, 2002; Brandt *et al.*, 1997). The *warqe* plant belongs to the family Musaceae, genus *Ensete* (Brandt *et al.*, 1997) and its botanical name is *Ensete ventricosum* (Welw.) Cheesman. *Warqe* is sometimes referred to as 'false banana' because of its resemblance in morphology and growth habit to the banana plant (Pijls *et al.*, 1995). However, unlike banana, the seedy leathery fruits of the *warqe* plant are inedible (Brandt *et al.*, 1997). *Warqe* is a perennial monocarpic plant with broad leaves, a pseudo-stem and a large underground corm (Figure 1A). The plant is domesticated and grown as a food crop only in Ethiopia. However, Mesfin and Gebremedhin (2008) report the existence of about 25 wild species of *Ensete* across Asia and Africa. The plant grows mainly at higher altitudes (1500-3100 m above sea level) (Birmeta *et al.*, 2004; Tsegaye & Struik, 2002).

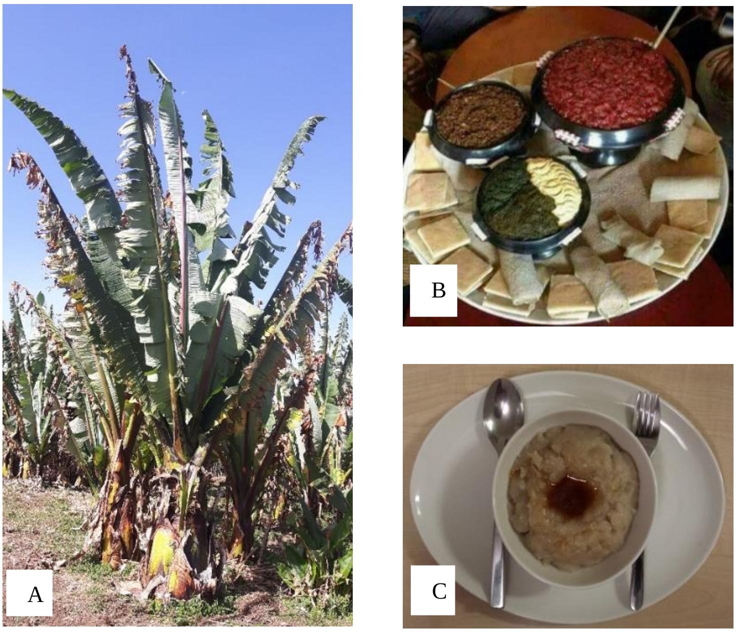

Figure 1. A) *Warqe* plant, B) the traditional Ethiopian food *kitfo* with *kocho* bread and C) *bulla* porridge.

Warqe is one of the most important food crops among root and tuber crops in Ethiopia (Nurfeta *et al.*, 2008). The energy yield of *warqe* (6.1 MJ/m^2/year) is higher than that of all cereals, Irish potato, sweet potato and banana (Pijls *et al.*, 1995). The complex *warqe* farming system is the most sustainable indigenous farming activity in Southern and South-western Ethiopia. It provides food sources for the densely populated highlands in these regions (Tsegaye & Struik, 2002).

The edible part of *warqe* is the pseudo-stem and corm after processing into *kocho* and *bulla* foods. *Kocho* is a dough-like starchy product obtained from the fermented scarped pulp of the pseudo-stem and pulverised corm and stalk of the inflorescence. The bread that is prepared from fermented *warqe* is called *kocho* bread (Figure 1B). In restaurants, *kocho* bread is commonly served with *kitfo* (a traditional Ethiopian food prepared from chopped red meat mixed with spiced butter). *Bulla* is a non-fermented starchy food product obtained by squeezing scarped pulp from the innermost part of the pseudo-stem and pulverised stalk of the inflorescence and corm and allowing it to settle for a day. *Bulla* occurs in the form of either a dry while powder or a white semi-liquid and is eaten as porridge or dumplings (Figure 1C). *Amicho* is another non-fermented form of *warqe* derived from the young *warqe* plant corm. *Amicho* is consumed after boiling, like many other root and tuber crops (Brandt *et al.*, 1997).

Every part of the plant is carefully used, for food or a number of non-food applications. The plant is used for animal feed, particularly during the dry season of the year since the pseudo-stem contains a lot of water (Nurfeta *et al*., 2008). Some *warqe* varieties are used as traditional medicine, *e.g*. the crushed fresh root is used to treat illnesses such as abdominal pain and amoebic dysentery (Bekele & Reddy, 2015). Fibre extracted from *warqe* is used for making bags, ropes, twine, cordage and mats. The fibre and dried petioles of *warqe* are commonly used as construction materials, to build houses and fences (Degu, 2012; Brandt *et al*., 1997).

Warqe also has potential in industrial applications as a raw material for adhesives in the textile and paper industries, while its fibre can be used as a raw material in the manufacture of sacking and string (Bezuneh, 2012; Brandt *et al.*, 1997). It is also reported that *warqe* starch can be used as an alternative starch in pharmaceutical industries (Wondimu *et al.*, 2014). In addition, the plant helps to protect the soil surface from erosion (Degu, 2012; Teamir & Tilahun, 2012; Brandt *et al.*, 1997). As described by Gebresenbet (2012) the plant is sometimes used as an ornamental plant and the leaves are used for wrapping bread during baking. The fresh leaves and dried leaf sheath are used as a packaging material for *kocho*, *bulla*, cheese, butter and *khat* (*Catha* *edulis*). The leaves are also used as a dish in the home and in traditional restaurants. Moreover, the plant is an income source for the family and an indication of wealth and prestige in society. Therefore, as the name indicates, *warqe* is genuinely a golden plant, since all parts are used for multiple purposes and it also has environmental and social value.

1.3 Nutritional profile of *warqe* foods

Nutritional profiling is defined as 'the science of categorising or ranking foods according to their nutritional composition' (WHO, 2011; Azais-Braesco *et al*., 2006). It is useful for food labelling and regulation of health claims and contributes to a balanced diet (Foltran *et al*., 2010; Azais-Braesco *et al*., 2006). *Kocho*, *bulla* and *amicho* are the primary food products of the *warqe* plant. However, despite the importance of *kocho* and *bulla* as staple foods in Ethiopia, their nutritional content and composition are not thoroughly described in the literature.

Mohammed *et al*. (2013) analysed macronutrient components such as crude protein, crude fat, soluble carbohydrates, cellulose, hemicellulose, lignin, starch and sugar in different *warqe* plant parts (leaves, corm and pseudo-stem) and found that *warqe* leaves contain 13% protein, 20% crude fibre and 10% sugar. The pseudo-stem is rich in soluble carbohydrate (80%) and starch (65%), but low in protein (4%) (Mohammed *et al*., 2013). Gebre-Mariam and Schmidt (1996) examined the chemical composition, amylose content and physicochemical properties of *bulla* starch.

Nurfeta *et al*. (2008) analysed different macronutrients and micronutrients in *warqe* plant parts (leaf lamina, leaf midrib, pseudo-stem and corm) and compared the nutritive value of parts used for animal feed. They found that most *warqe* fractions were rich sources of major minerals such as phosphorus (P), potassium (K), calcium (Ca) (except the corm) and magnesium (Mg), while the sodium (Na) content was very low. Most portions of the plant were rich in iron (Fe) and manganese (Mn), but deficient in copper (Cu) (except leaf lamina). The zinc (Zn) content was high in the corm, but low in other fractions (Nurfeta *et al*., 2008).

Atlabachew and Chandravanshi (2008) also determined the content of major, minor and trace elements in commercially available *kocho* and *bulla* samples taken in the Wolkite and Wolliso areas of Ethiopia. Their results showed that *kocho* contains a higher concentration of major mineral nutrients (K, Na, Ca and Mg) than *bulla*. Bosha *et al*. (2016) compared the quality in terms of different nutritive components and perceived food quality of *kocho* made from cultivated varieties and *kocho* made from wild genotypes of *warqe*.

Their results indicated that *kocho* made from cultivated varieties generally has higher protein, fat, sugar and mineral content that *kocho* made from wild genotypes. However, the wild genotypes give the highest content of starch in *kocho*.

The aforementioned studies on the nutrient content and composition of *warqe* foods mainly focused on the mineral, protein, fat and carbohydrate content of processed and unprocessed edible parts and leaves of the *warqe* plant. The results show that *warqe* is generally high in starch and minerals, but low in protein and fat. However, little work has been done to improve *kocho* and *bulla* foods with regard to their nutrient profile, despite large-scale consumption. Moreover, there have been no previous investigations on nutrient losses and the dietary fibre content and composition of *kocho* and *bulla* food products.

1.4 *Warqe* fermentation process

Kocho is one of the most common indigenous fermented foods used in Ethiopia. Fermented foods are produced for consumption world-wide, using various manufacturing techniques, raw materials and microorganisms. In Ethiopia, a variety of fermented and non-fermented foods and beverages are produced and consumed. These fermented foods and drinks are created from a wide range of raw materials, using traditional techniques (Ashenafi, 2006). For generations, *warqe* has been fermented in a traditional earthen pit into carbohydrate-rich *kocho* (Ashenafi, 2006).

Kocho fermentation in an earth pit takes a few weeks in warmer regions or several months or years in colder regions, depending on the ambient temperature of incubation (Gashe, 1987). *Kocho* fermentation is believed to comprise microbial disintegration of the grated corm and pseudo-stem and imparts flavour and textural qualities to the fermented food products (Urga *et al.*, 1997). Microorganisms are active in *kocho* fermentation, which includes processes such as starch hydrolysis, proteolysis and lipolysis, and determine *kocho* product, odour, colour, flavour and spoilage rate (Gizaw *et al.*, 2016). According to Gashe (1987), the microbiology of traditional *kocho* fermentation is similar to that involved in the fermentation of other vegetables. Two groups of lactic acid bacteria (LAB), namely *Leuconostoc* species and *Lactobacillus* species, are reported to be responsible for bringing about the desired changes, including a reduction of the pH and natural flavour development in *kocho* (Gashe, 1987).

Kocho would not ferment by itself, or would take a longer time, without the addition of fermentation enhancer (locally called *gammaa*) to a fermented mass of *kocho* (Urga, 1997). This might be due to low microbial activity because of low temperature at the high altitudes at which *warqe* grows. Thus, addition of an active microbial population to enhance the fermentation mass in the pit is required (Hunduma & Ashenafi, 2011b).

Fermentation enhancer consists of already fermented *kocho*, alone or with various spices and herbs mixed in. Fermenting agents are prepared from the inner portion of the corm, mixed with the decorticated pulp and pulverised corm after some weeks (Ayele & Sahu, 2014). Fermentation enhancer is added to the fermenting mass of *kocho* as a starter culture, *i.e*. a product with high viable microbial counts that, when added to certain foods, accelerates the fermentation leading to a final product with desired changes in the aroma, texture and flavour profile (Holzapfel, 2002, 1997). The quality of the fermentation enhancer culture used is one of the factors determining the final quality and safety of the fermented food (Motarjemi, 2002). However, the existing literature contains no information about the microorganisms involved and the physicochemical changes that occur during the fermentation process for *kocho* using fermentation enhancer.

1.5 Food losses, wastage and post-harvest losses

Losses of food are described in the literature using many different terms. There is no precise definition or demarcation between the terms food losses, food waste and post-harvest losses, and these terms are used in inconsistent ways in the literature and sometimes overlap. It is not easy to find one definition that combines all kinds of food waste. According to Grolleaud (2002), food losses are the losses in quantity which arise from food becoming unfit for human consumption. Food losses and waste are defined in depth by Lipinski *et al.* (2013: 4) as "*the edible parts of plants and animals produced or harvested for human consumption but not ultimately consumed by people. It represents a decrease in the mass, caloric, and nutritional value of edible food intended for human consumption at any stage in the food value chain*."

According to FAO (2013), food losses involve a decrease in the quantity or quality of food initially intended for human consumption. However, food waste is defined as food appropriate for human consumption but not consumed, whether it has spoiled or not. The term 'food wastage' includes both food losses and food waste, and refers to any food lost by deterioration or waste. Food waste can occur at different points of the food supply chain (Parfitt *et al.*, 2010). In sub-Saharan African food value chains, post-harvest losses range from about 21% for cereals up to 66% for fruits and vegetables (FAO, 2011). Studies conducted in Ethiopia by Gebresenbet *et al.* (2016) on seven fruit and vegetable crops (tomato, cabbage, onion, potato, mango, banana and avocado) revealed that the total average post-harvest losses ranged from 14 to 60%. The highest losses (60%) were observed for cabbage and the lowest (14%) for onions.

It is believed that reducing wastage of food by improving post-harvest management is more crucial than production of more food by extensive horizontal expansion of agriculture (Hodges *et al.*, 2011). Those authors also point out that reducing food losses can increase food availability without requiring additional production resources and that it can contribute to rural development and poverty reduction in less developed countries.

1.6 The concept of supply chain and logistics analysis

An adequate supply of products to market is one of the essential metrics when evaluating the performance of supply chain and logistics systems. At this point, it is necessary to define the concepts supply chain and logistics, because it helps to understand the reasoning behind the ideas and apply them to *warqe* food products. According to Khatami *et al.* (2015: 1), a supply chain is defined as "*a network of suppliers, manufacturers, transporters, warehouses, retailers and customers, systematised in such a way that it transforms raw materials into finished products and distributes the final products among customers through retailers*". In this thesis, the supply chain refers to the sequential arrangement of different chain actors involved in the flow of *warqe* food products from producers to end-consumers.

According to the Council of Logistics Management (1998), logistics is defined as "*the part of the supply chain process that plans, implements and controls the efficient and effective forward and reverse flow and storage of goods, services, and related information between the point of origin and the point of consumption for the purpose of conforming to consumer requirements*". Hence, the primary goal of logistics is to have the right product in the right place at the right time and the right cost. The logistics analysis of *warqe* food products in this thesis focused mainly on logistics actors and their relationships in the chain, their responsibilities, warehouse practices, commodity flows, finance and information from producers to consumers and *vice versa*.

Based on the standard terms used in logistics and supply chain management, the appropriate term used for food products is 'food chain logistics'. Food chain logistics covers the production and distribution of fresh or processed vegetables or animal-based products (Soysal *et al.*, 2012). According to Soysal *et al.* (2012) review, logistics has three principal aims in the new concept of sustainable food logistics management: (1) cost reduction and responsiveness, (2) improved food quality and reduction of food waste and (3) improved sustainability and traceability.

1.7 The concept of value chain analysis

Value chain analysis of *warqe* foods is required to identify key players in the chain, and can help understand their interactions and linkages in the chain. The value chain can be defined in various ways. Kaplinsky (2000: 121) and Kaplinsky and Morris (2001: 4) define the value chain as "*the full range of activities which are required to bring a product or service from conception, through the different phase of production which involves a combination of physical transformation and the input of various producer services, delivery to final consumers, and final disposal after use. In value chain system independent actors are performing a sequence of value-adding activities from conception over to phase of production to final consumption*." The value chain can also be defined as a "*sequence of related enterprises conducting activities so as to add value to a product from its primary production, through its processing and marketing to the final of the product to consumers*" (Macfadyen *et al.*, 2012: 4).

According to Trienekens (2011), the primary objective of a value chain is to produce value-added products or services for a market, by transforming resources and by the use of available physical infrastructure in available opportunities and constraints of its institutional environment. Food value chain analysis is a vital and flexible methodology to improve the value of foods to producers and end-consumers (Van Hoang, 2014). Therefore, to increase *warqe* production and supply and to reduce food losses, it is necessary to devise technological and structural solutions based on understanding the value chains and logistics practices along the supply chain of *warqe* foods. It is also crucial to analyse the main challenges in *warqe* food supply chains. Therefore this thesis analysed the value and supply chains for *warqe*-based food products, in order to improve these chains and reduce post-harvest losses.

1.8 Research questions

The role of *warqe* foods in the diet of Ethiopian people is well documented and reported. However, the importance of *kocho* and *bulla* as staple foods in Ethiopia and their nutritional profile (particularly dietary fibre content and composition) have not been systematically analysed with modern techniques. Consequently, there is little information available on the nutritional content of *warqe* foods. Previous studies on the nutrient content and structure of *kocho* and *bulla* have mainly focused on the mineral, protein and carbohydrate content, based on analysis of samples from unprocessed edible parts of the plant and commercially available food products from local markets (Mohammed *et al*., 2013; Atlabachew & Chandravanshi, 2008; Nurfeta *et al*., 2008; Gebre-Mariam & Schmidt, 1996).

Traditional *warqe* fermentation typically takes place in an earth pit and the final product is stored for extended periods in the pit. This conventional practice has been shown to cause spoilage problems and to create an offensive smell (Hunduma, 2012; Brandt *et al*., 1997). Hunduma (2012) pointed out that work on post-fermentation losses of *warqe* primary food products has been insufficient and that no apparent attempts have been made to improve storage facilities for products. Thus this valuable crop has been poorly investigated throughout the whole supply chain, whereas many studies have been conducted on the value chain and supply chain of other major staple food crops and associated food losses. In particular, information on the value chain and on nutrient losses during the post-harvest period and during fermentation of *warqe* foods is limited.

Supply and value chain analyses were performed in this thesis to quantify post-harvest losses of *warqe* food products and to assess the main challenges in the supply chain. Food losses along the supply chain were also studied comprehensively, to obtain basic knowledge. This knowledge can be used to reduce food losses at each level of the supply chain, thereby improving *warqe*-based food quality and adding value. Some previous studies have examined *warqe* storage losses at the producer level. According to Ashenafi and Abebe (1996), about 33% of *warqe* product spoilage occurs during storage.

Moreover, physicochemical changes that occur during the production of traditional *kocho* fermentation enhancer (*gammaa*) and the microbiota involved in the *gammaa* fermentation process have not been investigated so far. Accurate information on the microorganisms involved in the fermentation process for the enhancer culture can be used to define scientifically and to develop a commercial *kocho* fermentation enhancer product. It can also reduce the long fermentation time of *kocho*, increase the quality and quantity of the *kocho* end-product and help to reduce the losses of *kocho* during the fermentation process. Therefore, five core research questions were formulated to guide the studies reported in this thesis on the fermentation process and on reducing food losses by analysing value chains and the nutritional content of products.

These research questions were:

- What is the nutritional composition of the *warqe* foods *kocho* and *bulla* and what subsequent nutrient losses occur during processing and handling of *warqe* foods? Which dietary ingredients are deficient in *warqe* foods?

- What are the key logistics practices in the *warqe* food supply chain? Who are the principal actors involved in the supply chain and logistics process? What are the main constraints in the supply chain for *warqe* food products in Ethiopia and what options are available to improve logistics practices?

- What are the core processing activities in the *warqe* food production system? What kinds of value-adding activities are performed and who carries out the different operations in the *kocho* and *bulla* value chains?

- How much food losses occur at each stage of the supply chain for *warqe* foods and at what levels does significant food wastage occur? What are the main factors responsible for the losses?

- What microorganisms are involved in *kocho* fermentation and spoilage and what kinds of physicochemical changes occur during the fermentation process? What is the optimum time for fermentation of *gammaa* to reduce *kocho* losses?

2 Objectives and structure of the thesis

2.1 Objective of the thesis

The overall aim of this doctoral thesis was to analyse the value chain and nutritional content of *warqe* food products in relation to post-harvest losses along the supply chain.

Specific objectives were to:

- Determine the nutrient content of *kocho* and *bulla*, with particular emphasis on dietary fibre, and estimate losses of nutritional quality during processing and storage (Paper I)

- Analyse the supply chain and logistics practices for *warqe* food products in Ethiopia (Paper II)

- Examine the value chain for *warqe* food products in Ethiopia (Paper III)

- Assess the post-harvest losses of *warqe* food products along the supply chain and identify hotspots for losses in the chain (Paper IV)

- Evaluate the physicochemical properties and microbiota of *kocho* fermentation enhancer culture (*gammaa*), in order to reduce food losses in the highlands of Ethiopia (Paper V).

2.2 Structure and outline of the thesis

The intended outcome of the thesis work was identification of ways to reduce food losses and improve the quality of *warqe*-based foods. The work was structured into five studies, reported in Papers I-V, that fulfilled the main objectives of the thesis, as presented in Figure 2. Paper I quantified the nutritional profile of *warqe* foods, with emphasis on the amount of starch, protein, total fat, total dietary fibre and mineral elements in *kocho* and *bulla* foods. Changes in the content and composition of *warqe* foods resulting from losses during processing and storage were also analysed.

In Paper II, a supply chain analysis was conducted and the logistics practices of *kocho* and *bulla* were examined. Moreover, the transportation system and its constraints were analysed, and logistics infrastructure was evaluated.

In Paper III, value chain analysis was conducted, and the performance of the value chain for *kocho* and *bulla* was assessed. Value addition and value creation activities for the products and the competitiveness of the value chain were also analysed.

In Paper IV, post-harvest losses were quantified and the hotspot of losses of *kocho* and *bulla* along the supply chain were identified. Knowledge of these losses and hotspots enabled suggestions to be made on further research to reduce food losses and to improve the quality of the *warqe* foods.

In Paper V, microorganisms involved in the fermentation process of *kocho* fermentation enhancer and spoilage were identified and physicochemical changes and microbial load during *kocho* fermentation were determined. The aim was to identify potential improvements in the fermentation process and to shorten the fermentation time, which would improve the nutritional quality and reduce losses.

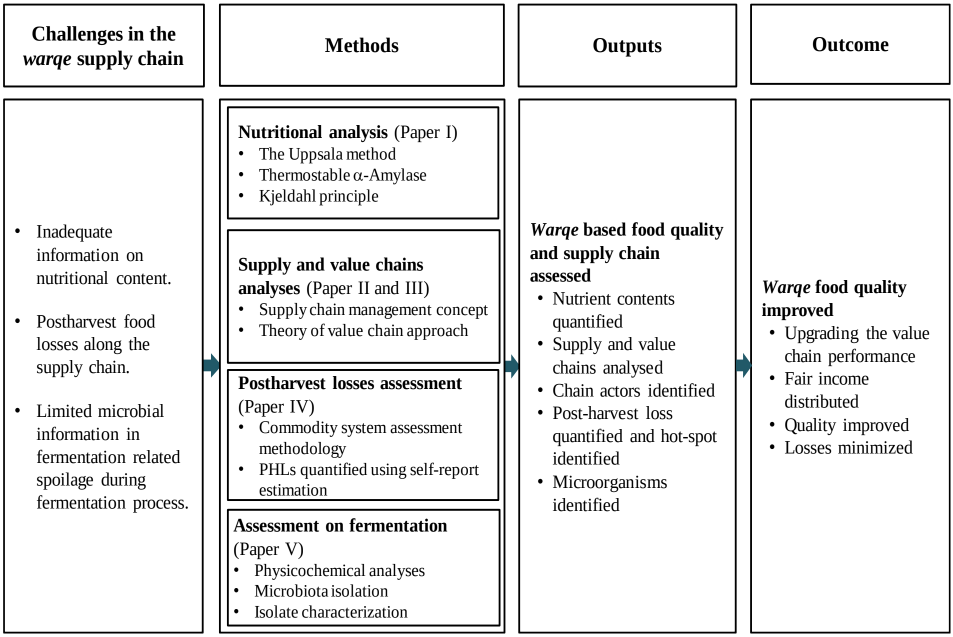

Figure 2. Schematic diagram of the work reported in Papers I-V in this thesis dealing with challenges in *warqe* supply chain, methods used in the studies, outputs and research outcomes.

3 Materials and methods

The studies in this thesis were conducted using the supply chain management concept, theory of value chain approach, commodity system assessment methodology, microbial isolation and characterisation techniques, and food quality analyses methodologies to improve *warqe* foods and reduce losses. The thesis thus combined quantitative and qualitative research methods to answer the research questions. The work comprised surveys, field observations and laboratory studies carried out between 2013 and 2018 in Ethiopia and Sweden. In Paper I, the nutrient content of *kocho* and *bulla* foods was quantified based on laboratory studies. In Papers II, III and IV, the supply chain and value chain of *warqe* food products concerning post-harvest losses and hotspot identification were analysed in one preliminary investigation and two survey studies. In Paper V, the microbiota involved and physicochemical changes during the *kocho* fermentation process and spoilage were investigated based on field observations and laboratory studies.

3.1 Selection of the study areas

The preliminary survey was carried out in the major *warqe*-producing regions throughout Ethiopia and particularly in areas where research and development on *warqe*-related technologies is being conducted (Ambo, Guder, Tikur Enchini, Haro Wanchi, Melkassa, Bako, Wolayita Sodo and Areka) (Figure 3). The aim of this preliminary study was to obtain a general overview of the supply and value chain for *warqe* products. The survey focused on identification of actors in the *warqe* value chain, mapping the *warqe* value chain, identification of constraints to *warqe* production and formulation of possible intervention options. Based on the results of this preliminary survey, together with workshop discussion and literature reviews, the studies reported in Papers II- IV studies were designed and conducted.

Two warqe-growing regions, namely Haro Wanchi in West Shoa Zone and Maruf in Southwest Shoa Zone, Oromia Region, Ethiopia, were purposely selected for the studies in Papers II-IV. Haro Wanchi is located 155 km southwest of Addis Ababa (8°40′N, 37°55′E) and Maruf is located 126 km west of Addis Ababa (8°59′N, 37°46´E). These two areas are known to be major sources of *kocho* and *bulla* supplies to the central market in Addis Ababa, the capital city of Ethiopia. For nutrient analysis, *kocho* and *bulla* samples collected in January 2017 in these two regions were brought to the Department of Molecular Sciences, Swedish University of Agricultural Sciences (SLU), Sweden.

Value chain, supply chain and logistics practices and post-harvest losses assessment studies were conducted on the supply chain for *kocho* and *bulla* starting from Haro Wanchi and Maruf. All markets which are feeders to Addis Merkato market were included in the study. Haro *kocho* market, Haro open market and Haroj and Woliso *kocho* markets were selected by following the *kocho* and *bulla* supply chains in Haro Wanchi. Guder Odo-Bari *kocho* open market and Guder *bulla* market were chosen by observing the supply chain in Maruf. To collect data on *bulla* processing, Addis Ababa and Woliso were selected as the study sites. Consumer-related information was gathered from Haro Wanchi, Guder, Ambo and Addis Ababa.

The study on microbiota and physicochemical changes during production of traditional *kocho* fermentation enhancer was conducted at the Bacteriology Laboratory, Ambo Plant Protection Research Centre, Ethiopian Institute of Agricultural Research. The samples for this investigation were collected in Haro Wanchi and Maruf from February 2016 to March 2017.

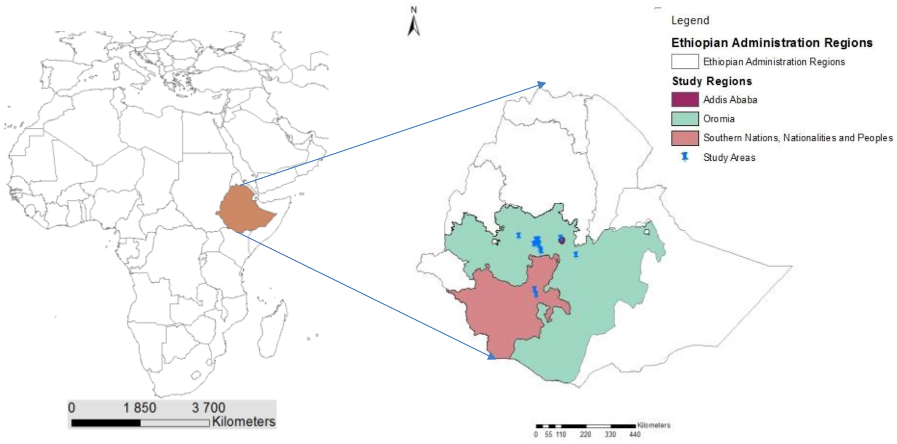

Figure 3. Map of the study areas in Ethiopia.

3.2 Nutrient analysis of *warqe* foods

3.2.1 Sample collection

A total of 16 kg of *kocho* and *bulla* samples were brought from the two *warqe*-growing areas Haro Wanchi and Maruf. At each site, 4 kg of *kocho* and 4 kg of *bulla* samples, each made from two commonly known *warqe* cultivars, *feresiye* and *badadetti*, were collected. Thus there were four types of sample per site, each with two replicates. All samples were placed in airtight plastic bags, flattened to 1 cm thickness and stored at -20 °C immediately after collection. At the laboratory, the samples were freeze-dried in a vacuum freeze drier for 72 hours and milled to a fine powder. The samples were then transferred to plastic bottles and stored at room temperature pending chemical analysis. All analyses were performed in duplicate and reported on a dry matter (DM) basis.

3.2.2 Analytical methods

Dry matter was determined as the weight difference between freeze-dried sample and sample oven-dried at 105 ºC for 16 hours. Ash was defined as the residue after combusting a known amount of dry matter sample at 600 ºC for three hours in a furnace. Duplicate subsamples of around 5 g freeze-dried material were taken for analysis of crude protein and duplicate subsamples of around 2 g freeze-dried material for total fat determination. Crude protein was analysed according to the Kjeldahl principle (Sáez-Plaza *et al.*, 2013), using a 2520 Digester and an 8400 Kjeltec Analyser Unit (FOSS Analytical A/S Hilleröd, Denmark) (ISO, 1969). Total fat content in *kocho* and *bulla* samples was analysed gravimetrically after acid hydrolysis according to European Commission Directive 98/64/EC (1998), using a Foss SoxtecTM 8000 extraction unit and HydrotecTM 8000 hydrolysis unit.

About 10 g of sample was used for mineral analysis. Of this mass of sample, approximately 0.5-1.0 g was digested with concentrated HNO_3 overnight and then diluted with 50 mL water, filtered and analysed by ICP Optima 7300 DV analyser according to modified Swedish Standard method (Eriksson *et al.*, 2016). All samples were analysed in triplicate for the major dietary minerals potassium (K), calcium (Ca), sodium (Na), phosphorus (P) and magnesium (Mg) and the trace elements zinc (Zn), iron (Fe), copper (Cu) and manganese (Mn).

Starch content was determined by enzymatic degradation according to the method of Åman *et al.* (1994) on a 20 mg portion of each type of sample. Two specimens comprising 26 mg of maize were used as a standard laboratory quality control check and four glucose standards (50 mg and 100 mg of each) were used as a check. The absorbance was measured at 510 nm after 20 minutes in a spectrophotometer. The concentration of glucose (mg/mL) in the diluted supernatant was determined from a calibration curve, prepared from a standard solution of pure D-glucose with concentrations in the range 0.002-0.100 mg/mL.

Dietary fibre, defined as the sum of neutral polysaccharide residues, uronic acid residues and Klason lignin, was analysed in samples according to the Uppsala Method developed by Theander *et al.* (1995), but with some modifications to separate soluble and insoluble constituents (Figure 4). Barley and rye bran were used as a standard laboratory quality control check.

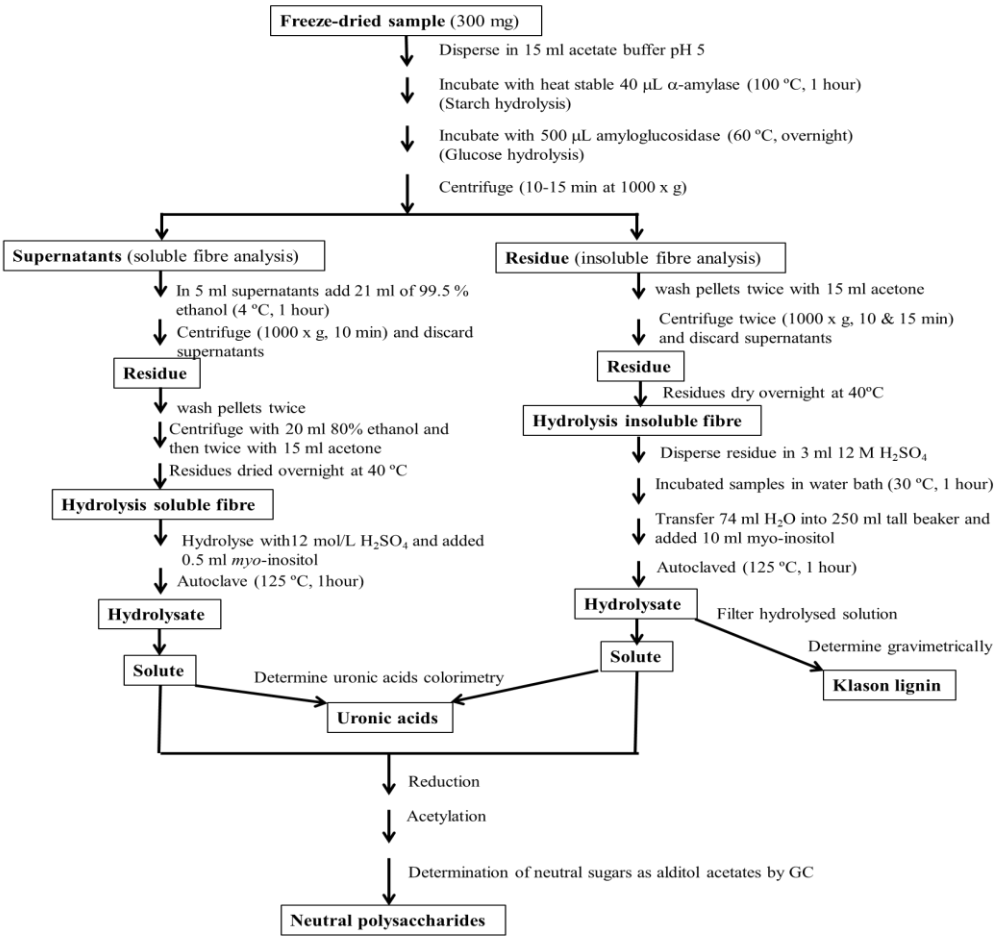

Figure 4. Simplified flowchart of the Uppsala Method used for determination of dietary fibre content (Theander *et al.*, 1995).

3.3 Sampling and sample size in Papers II-IV

Three types of survey questionnaires were developed for the preliminary survey. These questionnaires targeted, respectively, nine groups of *warqe*-producing farmers, four groups of traders (including wholesalers and retailers) and four research and technology development institutions.

Multistage sampling procedures were used to select representative respondents along the supply chain, starting from the two selected *warqe*-growing areas for the main study (Haro Wanchi and Maruf). A total of 522 respondents were randomly selected for the collection of primary data and information. In the first stage, *warqe*-growing households in Haro Wanchi and Maruf were selected. Traders, transport operators, small-scale food processing enterprises and consumers were then selected by following the *warqe* products supplied by the two growing areas. Appropriate sample size was determined using Equation (1), assuming that there is no significant difference in the population of *warqe* grower farmers (Yamane, 1967):

$$n = \frac{N}{1 + N(e^2)} \tag{1}$$

where n is the appropriate sample size, N is the total number of households (680 in Haro Wanchi + 525 in Maruf = 1205), *e* is the maximum variability or margin of error (0.063) and 1 is the probability of the event occurring. Based on this equation, the sample size for *warqe*-growing households was determined to be 209, of which 91 households were from the Maruf area and 118 were from Haro Wanchi.

A total of 56 *kocho* and *bulla* traders were interviewed in the selected markets. About 15 respondents were randomly chosen from *kocho* and *bulla* transport operators. Eight small-scale *bulla* processing enterprises were included in the survey. Interviews were also held with *warqe* food product consumers, at both household and restaurant level, to assess information. A total of 223 *warqe* food consumers at household level were randomly selected and interviewed, while 11 traditional Ethiopian restaurants were chosen randomly within Addis Ababa city.

3.4 Identification and definition of value and supply chain actors

In this thesis, supply chain refers to the sequential arrangement of several chain actors involved in the movement of *warqe* food products from producers to ultimate consumers. Actors were defined in this thesis as stakeholders involved in the value chain and supply chain of *warqe* food products who perform a particular function in the chain. Principal actors engaged in the chains were identified in field observations and key informant interviews. All value-adding activities in the chain were defined, and the roles of different actors were mapped. The mapping started from the production site and continued through local markets to the final destination of the products at the central market. It also included distribution routes from the central market. The method used for actor identification in this work was in line with the methodology developed by Lelea *et al.* (2014) for stakeholder analysis for application in transdisciplinary research projects focusing on actors in food supply chains. Grimble and Wellard (1997: 175) define stakeholders as "*any group of people organised, who share a common interest or stake in a particular issue or system; they can be at any level or position in society.*"

3.5 Value chain analysis

The frameworks of value chain analysis developed by M4P (2008) and GTZ (2007) were used in this thesis work. These frameworks have previously been used as a method in value chain analysis of the pomelo sector in Vietnam by van Hoang (2014). M4P (Making market work better for the poor) has a manual called "*Toolbook*" developed for analysis of value chains with the focus on poverty reduction. This manual has eight practical value chain analysis tools that can be used to analyse different dimensions within value chains. The framework used for interpreting the value chain of *warqe* food products in this thesis focused on planting, processing and marketing of the products and comparing the performance of the chain by analyses of different steps. These steps were: describing and defining *warqe* food products, identifying actors, mapping the main processing steps and mapping the value chain.

3.6 Method for estimation of different post-harvest food losses

Post-harvest food losses in this thesis refer to quantitative and qualitative losses of foods that occur at each level in the supply chain. According to Hodges *et al.* (2011), post-harvest food losses are measurable qualitative and quantitative food losses along the supply chain, starting from time of harvesting and continuing to consumption or other use. A quantitative loss implies the loss of physical substance of food products, which is reflected in weight loss. A qualitative loss implies a change of colour, taste or odour in food products.

However, qualitative losses are more difficult to measure, because of the lack of quality criteria that are easily measurable.

Post-harvest losses were assessed in this thesis by adopting the Commodity System Assessment Methodology (CSAM) developed by LaGra (1990). CSAM is made up of 26 components in four subsections that together account for all the steps associated with the pre-production, production, post-harvest handling and marketing of any given commodity. CSAM helps to quantify the losses and identify the causes of losses at different points in the food supply chain. In this thesis, quantitative field data were collected from different respondents (farmers, transporters, traders, food processors and consumers) on post-harvest losses during various operations and at different levels. The respondents estimated these losses using the self-reporting estimation method. *Warqe* growers were asked in a questionnaire-based interview about the quantity of *kocho* and *bulla* they produced during 2014. Post-harvest losses at farm level were then estimated by asking how much *kocho* and *bulla* products were lost during each operation (harvesting, sorting, processing, fermentation, storage and transport to market).

Trader-level losses were estimated as the quantity of the *warqe* product lost during trading in the same period. In interviews, traders were asked about the amount of *kocho* and *bulla* they bought and sold. The losses at different levels of trading (transportation, handling, etc.) were then estimated relative to the quantity purchased. Losses at consumer level were estimated as the quantity lost at households and restaurants. In all cases, the individual losses were calculated based on the total amount of the *warqe* product and expressed as a percentage. For the calculation of total percentage losses, it should be noted that this cannot be taken as the sum of the percentage losses at each stage. Rather, if the producer losses, wholesaler losses, food processing losses, retailer losses and consumer losses are x_1, x_2, x_3, ...,x_n, then the total losses are $x_1 + (100 - x_1) \times x_2/100 + [100-(100-x_1) \times x_2/100] \times x_3/100 + \ldots$

3.7 Analysis of microbiota and physicochemical changes during *gammaa* fermentation

3.7.1 Sample collection

A cross-sectional study was conducted to analyse the microbiota and physicochemical changes during production of *kocho* fermentation enhancer culture (*gammaa*). A total of 131 *gammaa* samples (80 from Wanchi and 51 from Maruf) were collected, using a purposive sampling technique, from different households in the two study areas. These samples were classified into four groups according to the duration of fermentation practised in various households traditionally. Of the total of 131 samples, 13, 44, 67 and seven households used a fermentation time of 14, 21, 30 and 60 days, respectively. In the selected households, samples of around 50-75 g of *gammaa* were taken from the fermentation pit (*boolla gammaa*) on the first day and the last day of *gammaa* preparation. These samples were collected using a sampling tong and placed into sterilised polyethylene bags. The samples were then packed in an icebox with an icepack and transported to the Bacteriology Laboratory at Ambo Plant Protection Research Centre for microbial analyses within four hours of collection.

3.7.2 Laboratory investigation

The physicochemical analyses involved measuring the temperature, pH and titratable acidity of samples using laboratory techniques according to *Gashe* (1987). For microbiota isolation, a 25 g subsample was taken from each *gammaa* sample, homogenised in 225 mL of distilled water and diluted in 0.1 sterilised peptone water. From serially diluted samples, 0.1 mL aliquots were spread on duplicate pre-dried agar plates containing different grown media for isolation of microbial species.

For aerobic mesophilic bacteria (AMB) counts, samples were spread on plates containing Plate Count (PC) agar, which were incubated in an inverted position at a temperature of 30-32 °C for about 48 hours. The colonies were enumerated and expressed as colony-forming units per gram of sample (cfu/g) according to the method described by Karssa *et al.* (2014).

For coliform counts, the samples were incubated on pre-dried surfaces of violet red bile (VRB) agar at 30-32 °C for 24 hours, after which purplish red colonies surrounded by a reddish zone of precipitated bile were counted as coliforms (Downes & Ido, 2001).

For counts of Enterobacteriaceae, plates containing on pre-dried surfaces of violet red bile glucose agar plates supplemented with 1% glucose were incubated at 30-32 °C for 20 to 24 hours, after which pink to red colonies with or without haloes of bile precipitation were enumerated as members of the Enterobacteriaceae according to the method described by Hunduma and Ashenafi (2011a) and Karssa *et al.*, (2014).

For lactic acid bacteria (LAB) counts, samples were spread on pre-dried surfaces of de-Man-Rogosa-Sharpe (MRS) agar and incubated under anaerobic conditions, using an anaerobic candle jar, at 30-32 °C for 48 hours. All visible colonies were counted as lactic acid bacteria (Karssa *et al.*, 2014; Omemu, 2011).

For yeast and mould counts, the samples were spread on pre-dried surfaces of chloramphenicol bromophenol blue (CBB) agar and incubated at 25-28 °C for 3-5 days. Smooth (non-hairy) colonies without extension at the periphery (margin) were considered yeasts, while hairy colonies with expansion at the edge were considered moulds (Karssa *et al.*, 2014; Hunduma & Ashenafi, 2011a).

Morphological and biochemical characterisation of the isolates was conducted using purified strains of lactic acid bacteria and aerobic mesophilic bacteria. A total of 223 representative colonies of LAB were purified and isolated by repeated streaking of *gammaa* samples from different fermentation days on MRS agar plates. For AMB, a total of 254 representative colonies were isolated and purified by repeated streaking on nutrient agar plates. Biochemical characteristics were determined using the catalase test, oxidase test and starch hydrolysis test, and the ability of the isolates to ferment glucose, sucrose and lactose and their capacity for gas production were determined in triple sugar iron (TSI) slants tests. Colony characteristics of the pure strains, such as colony colour, colony shape and colony size, were assessed on agar plates, in order to determine colony morphology. Microscopic examination of cell morphology and classification as rod and cocci, cell arrangement, motility (unidirectional movement) and presence or absence of endospores was performed on young cultures (Murray *et al*., 1981). The Gram reaction test was carried out using the KOH technique (Gregersen, 1978).

3.8 Data analysis

The collected data were analysed both quantitatively and qualitatively. Descriptive statistics (means, standard deviation and frequencies) were computed using Microsoft Excel and IBM SPSS Statistics software version 24. Multiple comparison tests were done using IBM SPSS Statistics software to identify which fermentation days means of the physicochemical and microbial counts of *gammaa* were significantly different. Data on the amount of starch, crude protein, total fat, minerals and dietary fibre in the different samples were subjected to analysis of variance (ANOVA) to determine the difference between product types and cultivars, using STATA Statistics Data Analysis software version 11.1. Statistical significance was set at $p<0.05$ (95% confidence interval).

4 Results

4.1 *Warqe* production

Warqe production is one of the leading farming activities in the study areas. As shown in Table 1, the size of farms, the area of *warqe* grown per farm and the number of *warqe* plants grown per farm differed between Maruf and Haro Wanchi. Average farm area per household was significantly higher in Maruf (2 ha) than in Haro Wanchi (1 ha). The area of farmland covered by *warqe* was higher in Maruf (3413 m^2 per farm) than in Haro Wanchi (1955 m^2 *per farm*), but this difference was not significant. On the other hand, the number of *warqe* plants per household was significantly higher in Haro Wanchi (688 plants) than in Maruf area (226 plants).

The maturity stage of *warqe* plant differs from place to place, depending on the plant cultivar grown and climate conditions in the area. The survey conducted for this thesis showed that *warqe* plants in Haro Wanchi mature at six years after the last transplanting to the field, while in Maruf this takes five years. Moreover, it was found that *kocho* yield per plant was higher in Maruf (65 kg/plant) than in Haro Wanchi (29 kg/plant). It was also observed that yield of *kocho* was negatively correlated with plant density (number of plants per unit area) (Table 1), *i.e*. when the number of *warqe* plants per unit area was low, the yield of *kocho* per plant was higher. With regard to *bulla* and *amicho* yield per plant, there was no significant difference between the two study areas. However, a highly significant difference was observed in the storage period for all *warqe* foods between the two study areas, with the storage period for *kocho* and *bulla* being much longer in Maruf than in Haro Wanchi (Table 1). In both areas, *kocho* and *bulla* could be stored for a much longer period than *amicho*.

The survey revealed that *warqe* production in both study areas was primarily as an income source (Table 1). However, there was a highly significant difference in revenue generated from *warqe* in the two regions. On average, a household in Haro Wanchi could get up to 3106 Ethiopian Birr per year (1 US dollar ≈ 21 Ethiopian Birr in the study period), whereas a household in Maruf could get about 1336 Ethiopian Birr per year from *warqe* sales. The survey also revealed that Maruf farmers travel a greater distance (9 km) to sell their *warqe* products than Haro Wanchi farmers (4 km).

Table 1. *Farm size, area occupied by* warqe*, maturation time and yield of* warqe*, storage time of different* warqe *food products, the contribution of* warqe *to annual household income and distance to market for farmers in the study areas Maruf and Haro Wanchi (all values mean ± SE)*

Parameter	Area	
	Maruf	Haro Wanchi
Size of farm (hectares)**	1.93 (±0.16)	1.02 (±0.44)
Land occupied by *warqe* plants (m^2)ns	3413.19 (±739.23)	1955.35 (±685.40)
Number of *warqe* plants per farm**	225.86 (±13.32)	687.72(±33.24)
Warqe maturation period (years) **	4.57 (±0.14)	6.08 (±0.11)
Kocho yield (kg/plant) **	64.82 (±3.69)	29.08 (±0.82)
Bulla yield (kg/plant)ns	4.44 (±0.50)	3.67 (±0.18)
Amicho yield (kg/plant)ns	14.14 (±5.20)	17.31 (±1.29)
Kocho storage period (days) **	302.75 (±15.42)	90.75 (±7.53)
Bulla storage period (days) **	262.68 (±18.17)	35.11 (±19.98)
Amicho storage period (days) **	1.00 (±0.00)	1. 89 (±0.08)
Revenue from *warqe* (Birr/year) **	1335.86 (±207.66)	3105.55 (±207.66)
Distance to marketplace (km) **	8.50 (±0.95)	3.86 (±0.09)

**Highly significant difference (*P<0.01*) between *warqe* growing areas (Maruf and Haro Wanchi).
ns Non-significant difference between *warqe*-growing areas.

4.2 Nutritional analysis of *warqe* foods

4.2.1 Macronutrient content in *kocho* and *bulla* foods

The nutrient content of *kocho* and *bulla* is presented in Table 2. The results indicated that the starch content in both *kocho* and *bulla* significantly exceeds the content of protein, fat and dietary fibre. Moreover, the amount of starch was significantly higher (p<0.01) in *bulla* (89 g/100g DM) than in *kocho* (75 g/100g DM), but no difference was found between the two cultivars of *warqe* (*feresiye* and *badadetti*) (p>0.05). *Kocho* was found to contain significantly more crude protein than *bulla*. No difference was found between the *feresiye* and *badadetti* cultivars (p=0.304) in terms of protein content. The amount of total fat in *kocho* and *bulla* was the lowest of all the macronutrients analysed in *warqe* food products, although there was significant variation (p=0.009) in the amount of total fat between *kocho* and *bulla* products, with the content of total fat being higher in *kocho* than in *bulla* (Table 2).

Amount of soluble dietary fibre, insoluble dietary fibre, total dietary fibre and neutral sugar differed significantly ($p<0.001$) between *kocho* and *bulla* products, but there was no difference between the *feresiye* and *badadetti* cultivars in total, soluble or insoluble dietary fibre ($p>0.05$). Overall, total dietary fibre content in *kocho* (3.40 g/100g DM) was five-fold higher than in *bulla* (0.64 g/100g DM). However, most of the dietary fibre in *kocho* was present in insoluble form (Table 2).

Table 2. *Mean ash, starch, crude protein, total fat, soluble, insoluble and total dietary fibre (DF) and neutral sugar content (g/100 g DM) in* kocho *and* bulla *foods made from the two* warqe *cultivars* feresiye *and* badadetti

Product	Cultivars	Ash	Starch	Crude protein	Total fat	Soluble DF	Insoluble DF	Total DF	Neutral Sugar
	Badadetti	1.25	75.63	1.59	0.24	0.34	2.62	2.96	2.64
Kocho	*Feresiye*	1.43	74.49	1.75	0.16	0.42	3.41	3.83	3.44
	Weighted mean	1.34	75.06	1.67	0.20	0.38	3.02	3.40	3.04
	Badadetti	0.45	89.65	0.39	0.10	0.16	0.51	0.67	0.56
Bulla	*Feresiye*	0.70	88.49	0.50	0.09	0.16	0.45	0.62	0.51
	Weighted mean	0.58	89.07	0.45	0.10	0.16	0.48	0.64	0.54

4.2.2 Micronutrient content in *kocho* and *bulla* foods

The content of dietary minerals in *kocho* and *bulla* foods is presented in Table 3. The concentrations in *kocho* followed the order K > Ca > P > Mg > Fe > Na > Zn > Mn > Cu, whereas in *bulla* the order was K > P > Ca > Mg > Fe > Na > Zn > Mn > Cu. Among the elements analysed, potassium was present in the highest concentrations in both *kocho* (4823 mg/kg DM) and *bulla* (2710 mg/kg DM). Copper was present in the lowest concentrations in both *kocho* (3.43 mg/kg DM) and *bulla* (1.27 mg/kg DM).

For P, K and Mg content, there was no significant difference between the two cultivars studied ($p>0.05$). However, there was considerable variation in P, K and Mg content between product types ($p<0.01$), with levels found in *kocho* than in *bulla*. Among the micronutrients, only calcium content was significantly different between the two cultivars tested ($p=0.02$), with *feresiye* giving a higher calcium content in both *kocho* and *bulla* products than *badadetti* (Table 3).

The level of sodium was low in both *kocho* (30 mg/kg DM) and *bulla* (24 mg/kg DM). Moreover, there was no significant variation between products ($p=0.052$) or between cultivars ($p=0.707$) in the content of sodium. The highest concentration of iron detected in *kocho* and *bulla* was 33 mg/kg DM and 25 mg/kg DM, respectively. The iron content differed between product types (p=0.049) and between cultivars (p=0.026), with the cultivar *feresiye* having a higher content. Manganese concentration also differed between product types (p<0.001), but not between cultivars (p=0.177) (Table 3).

Table 3. *Content of dietary micronutrients (mg/kg DM) in* kocho *and* bulla *foods made from the two* warqe *cultivars* feresiye *and* badadetti

Product	Cultivar	Dietary minerals concentration (mg/kg DM)								
		Major minerals					Trace elements			
		P	Ca	Mg	Na	K	Fe	Mn	Cu	Zn
Kocho	*Badadetti*	503.29	879.70	159.58	28.17	4662.70	28.90	5.33	4.60	6.95
	Feresiye	482.70	1088.99	139.76	31.29	4983.49	37.08	6.03	2.27	7.67
	Weighted mean	492.99	984.35	149.67	29.73	4823.10	32.99	5.68	3.43	7.31
Bulla	*Badadetti*	319.80	73.17	40.58	24.06	2110.64	18.76	1.23	1.79	4.07
	Feresiye	340.72	155.21	63.60	23.14	3309.19	30.26	1.83	0.74	4.82
	Weighted mean	330.26	114.19	52.09	23.60	2709.92	24.51	1.53	1.26	4.45

4.3 Identification of actors and mapping of the supply chain

Two main routes of *kocho* and *bulla* supply to central markets were identified (Figure 5). The first route is the Woliso to Addis Merkato route. The Woliso *kocho* market is fed by major *warqe*-growing areas such as Chebo, Darian or Chitu, Haro Wanchi, Merega, Shegege and Tepi. The second supply route is the Guder to Addis Merkato route. The Guder market is supplied by the Tikur Enchi, Ginbi Bila, Maruf and Melke areas. The majority of products from Addis Merkato are sold to Addis Ababa consumers and a small amount to towns outside Addis Ababa, such as Dire Dawa and Adma. A small amount of *bulla* is exported from Woliso and Addis Ababa through purchasing from *bulla* processors. By following these two supply routes of *warqe* foods, value chain actors were identified.

Six principal value chain actors were identified along the *warqe* supply chain in Ethiopia. These were: farmers, collectors, processors, wholesalers, retailers and consumers. In addition to these six actors, two more actors were identified in the supply chain. These were: transporters and open market dealers. Other supporting actors identified in the value and supply chains included market infrastructure owners, local retail shops and agricultural development agents, who supply packaging materials for processors and market information and technical services.

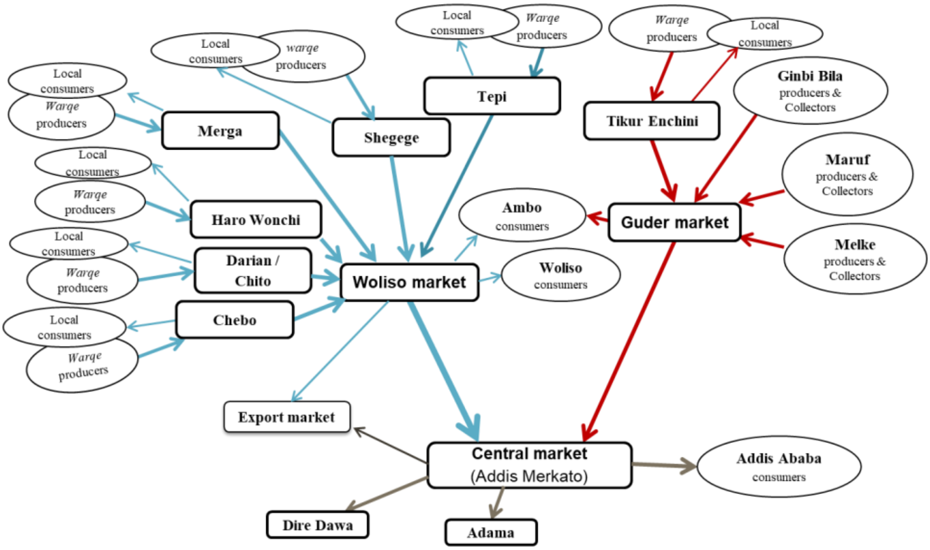

Figure 5. Supply routes of *kocho* and *bulla* to the central market and actors identified in the *warqe* food supply chain in Ethiopia, based on results of a preliminary survey in 2013.

4.4 Supply chain analysis of *warqe* foods

The supply chain of *warqe* food products is illustrated in Figure 6. The relationships between *warqe* supply chain actors proved to be complicated and often overlapping. Producers reported that they sold their products to wholesalers, retailers, collectors and consumers. It was stated that the proportion of product sold to these clients depended on the availability of buyers and proximity to the market. Collectors purchased a considerable amount of *kocho* and fresh *bulla* from producers and wholesalers in the vicinity of farms and at the local market. They sold directly to urban wholesalers. Wholesalers bought *kocho* and fresh *bulla* from producers and then sold to urban wholesalers, retailers and consumers. Urban wholesalers sold their *kocho* and fresh *bulla* to retailers and directly to consumers. Retailers bought from wholesalers and sold a large proportion to consumers and the rest to open market dealers in urban areas. Open market dealers bought from retailers and sold directly to consumers.

It was found that the supply chain for *bulla* is different than that for *kocho*. In the *bulla* supply chain, both fresh and processed *bulla* products are involved. The supply chain of fresh *bulla* is similar to that of *kocho*. For processing, fresh *bulla* is purchased by processors from three different suppliers: producers, wholesalers and retailers. Processed *bulla* is mostly sold to wholesalers, retailers and open market dealers, and some directly to final consumers. A minimal amount of processed *bulla* is sold to exporters. These exporters export the products mainly to Ethiopian traditional restaurants and shops in different countries outside Ethiopia. Thus, final consumers can get *kocho* and fresh and processed *bulla* from various suppliers through different chains.

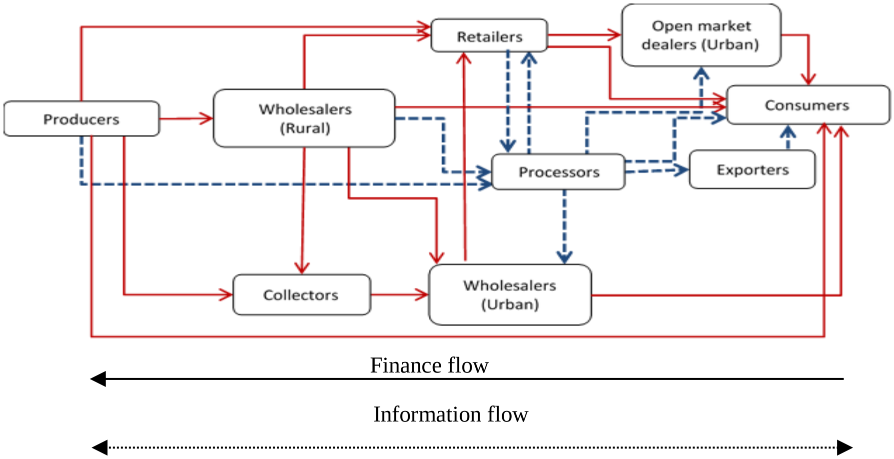

Figure 6. Schematic map of the *kocho* and *bulla* supply chains in Central Ethiopia. Red solid arrows indicate physical flows of *kocho* and fresh *bulla*. Blue dashed arrows indicate physical flows of processed *bulla*.

4.5 Value chain analysis of *warqe* products

4.5.1 Mapping the core production processes of *warqe* products

The main processing steps in *warqe* food production start with mature plant selection and end with final food production. The overall *warqe* processing system is summarised in Figure 7. A slight difference in the procedure used for *warqe* processing was observed between the two study areas. This difference in the method of processing was mainly due to the customs that women followed, which were acquired from their ancestors.

The first step in traditional *warqe* processing starts with identification and selection of a mature plant, followed by preparation of the working area and fermentation pit, removing leaves from the plant and digging out the plant while leaving some parts of the corm in the ground. The plant is then divided or cut into three sections. After that, the primary operations are pulverisation and decortication, and fibre separation (fibre is a by-product), which are done during the decortication process (see Figures A1 and A2 in Appendix). *Bulla* extraction is also performed at this stage. Preparation of fermentation enhancer (*gammaa*) is another operation performed at the same time. Finally, the pulverised and decorticated pulp is placed in the fermentation pit and, at the same time, *gammaa* is mixed thoroughly with ground and decorticated mass and then placed in a concave hollow corm (*boolla gammaa*).

There are two stages of fermentation in *kocho* processing, the primary and secondary fermentation stages. In the first fermentation stage, the mass in the *boolla gammaa* and that in the pit are fermented separately for one month. In the second fermentation stage, the two separately fermented masses are mixed in the pit and then left for a further approximately two months of fermentation. The mass is turned and checked during this time and pit covering leaves are changed occasionally. Sometime the fermenting mass is remixed with fresh decorticated and pulverized pulp and then wrapped in new leaves, if this is considered necessary during the fermentation period.

After two or three months, depending on climate conditions in the area, fully fermented *kocho* is obtained. It undergoes further processing steps to break down tiny fibres by tamping (*tumuu*) to upgrade the quality of the product, and finally a high-quality *kocho* product (*holeta*) is obtained. Some fresh *bulla* is serially further processed by *bulla* processors to produce dried *bulla* product. In this process, the fresh *bulla* is mixed with pure water and stirred to dissolve it thoroughly, after which unwanted material is removed by filtering. The filtrate is left for one day to sediment and the supernatant is removed. The sediment is again mixed with pure water and stirred to dissolve any solids, left for one more day to settle and then decanted. Finally, the combined sediment or crystalline deposit obtained is dried in the sun under continual turning and crushing of aggregated particles to produce dry, very fine powdered *bulla*.

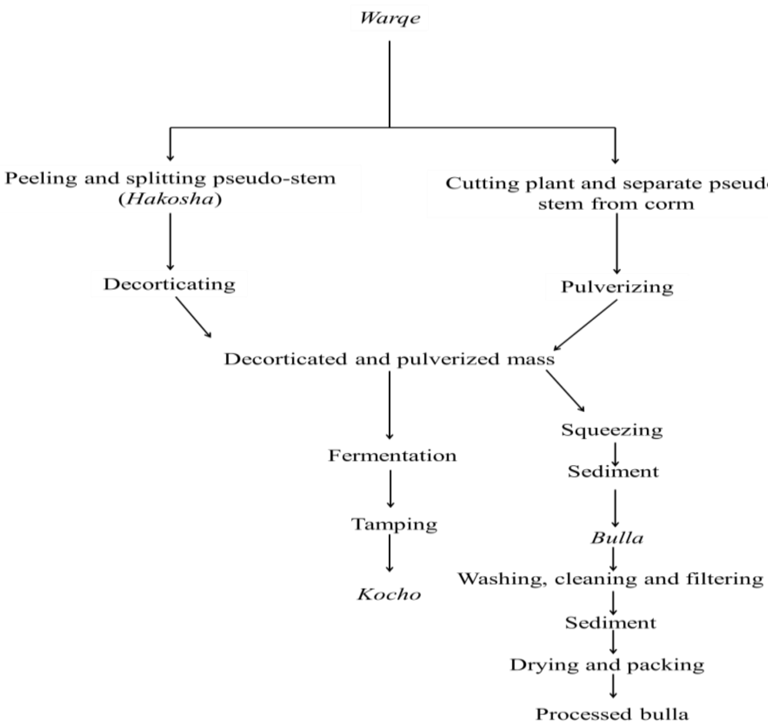

Figure 7. Simple flowchart showing the steps involved in *warqe* processing into *kocho* and *bulla* food products.

4.5.2 Mapping the *kocho* and *bulla* value chains

The value chains for *kocho* and *bulla* products are shown in Figures 8 and 9. It was observed that there is weak coordination in product flow and information exchange between value chain actors within and across different levels of the chains. The chains depend instead on direct links between farmers, processors, collectors, wholesalers, retailers and consumers. The value chain of both *kocho* and *bulla* starts with farming input suppliers.

Warqe-growing farmers and *bulla* processors are the main actors and are responsible for the most value-adding activities in the chain. Actors such as collectors, wholesalers and retailers mainly work in trading activities and value addition. About 82% of *warqe*-producing farmers surveyed use only on-farm inputs such as planting materials and organic fertiliser, and the remaining farmers use farm inputs purchased from the market (10%) or obtained as a gift from relatives (8%). The farmers mainly used labour sources their family labour with traditional or cultural cooperation working trends. This system of working in groups helps to share labour and experiences.

The local market has the critical role of linking *warqe*-producing farmers to the market. Farmers, collectors, wholesalers and rural retailers are value chain actors in the local market. Core value-adding activities in the local market are grading and sorting based on quality parameters, mixing, repacking, transport, storage and selling. Traders usually employ other workers to carry out these value-adding activities and to transport their commodities to central markets.

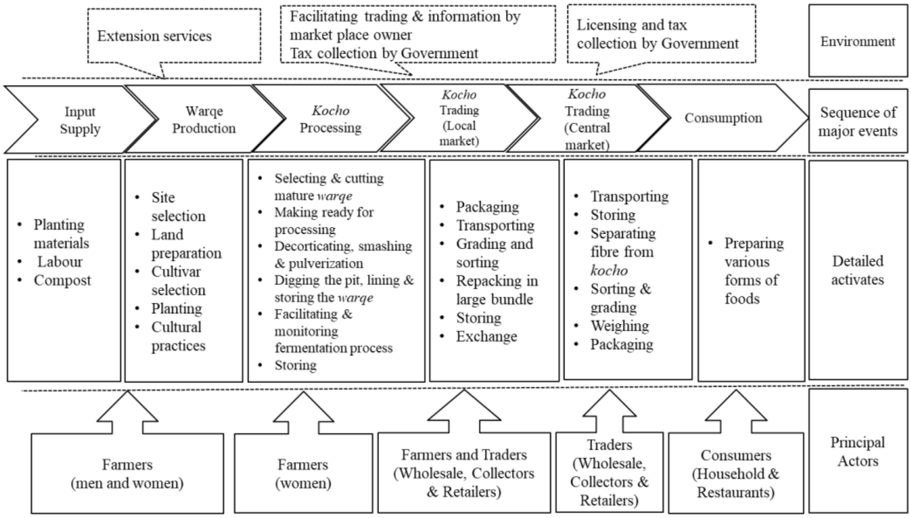

Figure 8. The value chain for *kocho* in Central Ethiopia.

The main value-adding and value-creating activities in *bulla* processing are washing, cleaning by filtering, drying, packaging, storage and selling. Products are dried on plastic sheeting on unlevelled ground, using solar heat on an irregular basis. This was the principal food processing activity observed in the *bulla* value chain. Processors were observed to use simple, locally made and traditional tools and generally specialised in dried *bulla* processing and packaging. The organisational structure of this actor is small-scale, family-based enterprises and family members occupy the key management positions in the enterprise. Most of the workers are hired, but family members do some work. In both cases, all activities are performed by women.

The main actors in the central market were found to be wholesalers, retailers and open market dealers. The central market plays the significant role of linking wholesalers, retailers, open market dealers, processors and consumers to market. Traders generally specialise in *kocho* and *bulla* trading. The main value-adding activities in this value chain are sorting and grading, weighing and packaging, storage and selling of both *kocho* and *bulla*. For *kocho*, separation of fibre from the products is performed to improve the quality of the product. All value-adding activities were reported to be done by women. However, for transporting and arranging the products in shops and stores, male workers are hired. The survey results indicated that all owners in the central market are women. The employees in market activities are usually relatives and without labour contracts.

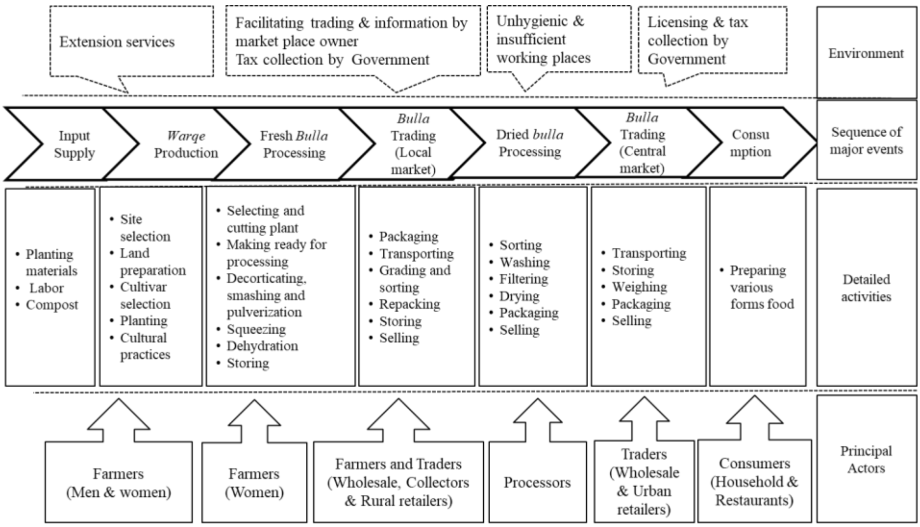

Figure 9. The value chain for *bulla* in Central Ethiopia

4.6 Post-harvest losses of *warqe* foods

Significant losses were observed at each level of the supply chain of *warqe* food products. There was a highly significant (p<0.01) difference in the extent of losses between different stages of the chain for both *kocho* and *bulla* products (Figure 10A, 10B). It was estimated that about 45% of the total marketed product of *kocho* and 46% of *bulla* are lost along the supply chain. In the *kocho* supply chain, the highest loss (24%) was estimated to occur at retailer level. The lowest *kocho* losses were estimated to occur at producer and consumer levels (6% of *kocho* product in both cases).

Similarly, in the *bulla* supply chain, the highest waste (29%) was reported to occur at processor level (Figure 10B). The lowest loss in *bulla* was observed at producer level (about 1% of the total *bulla* produced). In general, the losses of *bulla* and *kocho* displayed similar trends along the chains, with lower losses at upstream and downstream stages and the highest losses observed at midstream stages of the supply chain.

It was observed that the highest losses of *kocho* occur at the retailer level and the highest losses of *bulla* occur at the processor level, so these two levels are hotspots of *warqe* food losses. Lack of appropriate processing technology at producer and processor level, use of inadequate storage facilities, packaging materials and transport methods, improper handling in the market and air exposure during market display, insect pests at producer level and rodent problems at farm and market level are the leading causes of *kocho* and *bulla* losses.

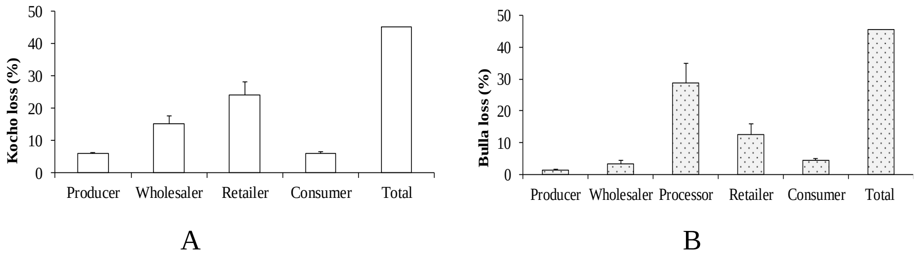

Figure 10. Losses (%, mean ± S.E) of *kocho* (A) and *bulla* (B) at different stages of the *warqe* supply chain in Central Ethiopia.

4.7 Physicochemical changes and microbiota composition during *gammaa* fermentation

4.7.1 Physicochemical analysis

The results of laboratory analyses of pH, titratable acidity and temperature of *gammaa* during the fermentation period are presented in Figure 11. On the first day, the pH of *gammaa* samples was 6 ± 0.43. *Gammaa* samples fermented for different periods of time had significantly different mean pH (p<0.001), with the pH decreasing with increasing fermentation time. As the pH of *gammaa* dropped, the titratable acidity increased with increasing fermentation time (Figure 11B). On the first day, the mean titratable acidity of *gammaa* samples was 0.23 ± 0.10 %, but *gammaa* samples fermented for different periods of time (14, 21, 30 and 60 days) had significantly higher mean titratable acidity

(p<0.001). This declining pH and increasing titratable acidity over time indicated dominant involvement of acid-producing microorganisms in the *gammaa* fermentation process.

Initially, the temperature in *gammaa* samples ranged from 11 to 17 ºC, with mean 14 ± 1.20 ºC. Thereafter, *gammaa* samples fermented for different periods of time had significantly different mean temperature (p<0.001). Multiple comparisons using LSD tests indicated that the mean temperature of *gammaa* fermented for 14 days (15 ±1.01) was significantly lower than the mean temperature of *gammaa* fermented for 21 days (16 ±1.07; p<0.001) or 30 days (17 ±1.41; p<0.001). The overall trend was for the temperature to increase up to day 30 and then decrease by day 60 of fermentation (Figure 11C). This indicates that the *gammaa* fermentation process takes place within the low temperature range (13-20 ºC).

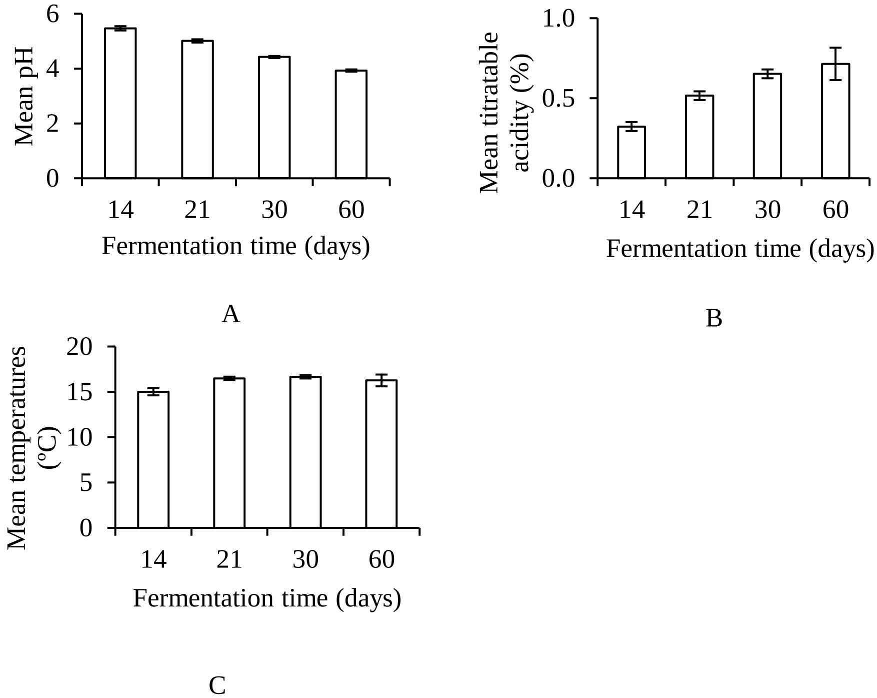

Figure 11. Physicochemical changes in *kocho* fermentation enhancer (*gammaa*) at different fermentation days. A) pH, B) titratable acidity (%) and C) temperature (°C).

4.7.2 Microbiota analysis

In this thesis, only specific microorganisms which are potentially involved in the fermentation process were analysed. These included lactic acid bacteria

(LAB), aerobic mesophilic bacteria (AMB), total coliforms, Enterobacteriaceae, yeasts and moulds. At the beginning of fermentation, the LAB count in the samples of *gammaa* varied from 3.90 to 7.00 log_{10} cfu/g (mean 5.12 ± 0.72 log_{10} cfu/g). As Figure 12A shows, the LAB count in *gammaa* samples then increased until day 30 and declined by day 60 of fermentation. This indicates ability of the LAB to grow at low pH and to create acidic conditions up to 30 days, and then their multiplication rate decreased with increasing time of fermentation.

At the beginning of fermentation, the AMB count in *gammaa* samples varied from 8.20 to 10.40 log_{10} cfu/g (mean 9.05 ± 0.42 log_{10} cfu/g). However, as fermentation time increased, the AMB count showed a sharply decreasing trend (Figure 12B). This indicates that AMB dominated at the initial stage of fermentation time in *gammaa* samples, but as fermentation time increased AMB decreased rapidly.

At the beginning of fermentation, coliform count in the *gammaa* samples varied from 6.50 to 9.50 log_{10} cfu/g (mean 8.16 ± 0.45 log_{10} cfu/g). As shown in Figure 12C, coliforms in *gammaa* samples decreased significantly until day 30. However, *gammaa* fermented for different periods of time had significantly different mean coliform counts (p<0.001), with the counts decreasing as the fermentation time increased.

At the beginning of fermentation, Enterobacteriaceae counts in the *gammaa* samples varied from 6.20 to 8.00 log_{10} cfu/g (mean 7.15 ± 0.39 log_{10} cfu/g). However, g*ammaa* samples fermented for different periods of time had significantly different mean Enterobacteriaceae counts (p<0.001). As shown in Figure 12D, the counts decreased as fermentation time increased. This was possibly due to dropping the pH in the tightly packed *gammaa* as fermentation time increased.

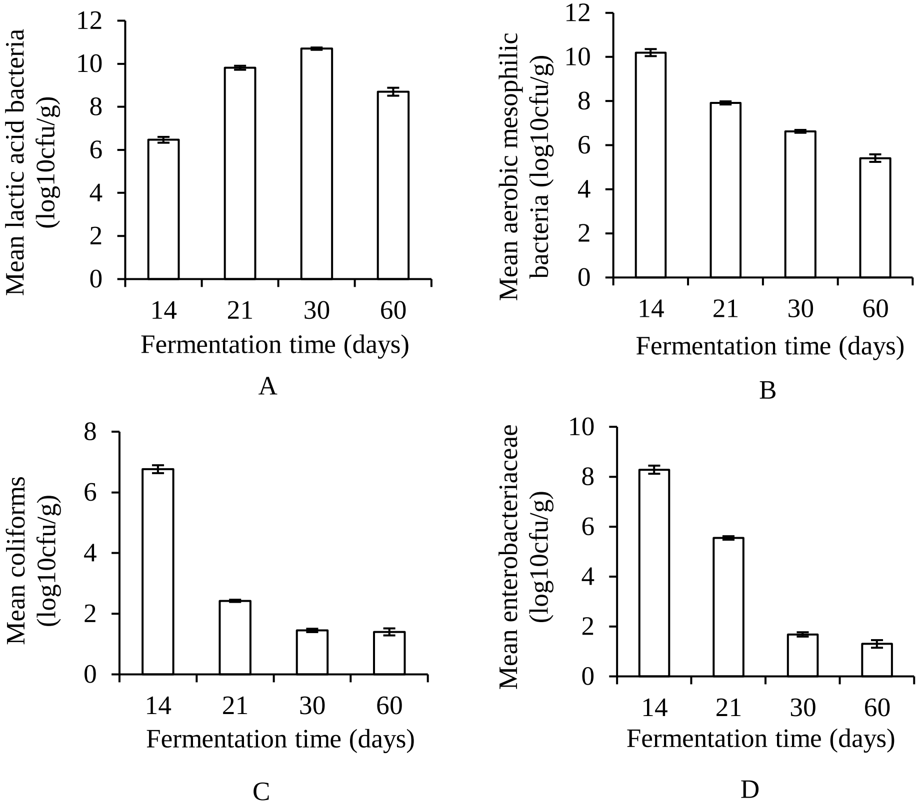

Figure 12. Microbiota counts (log_{10} cfu/g) at different fermentation days of *kocho* fermentation enhancer (*gammaa*). A) Lactic acid bacteria, B) aerobic mesophilic bacteria, C) total coliforms and (D) Enterobacteriaceae.

At the beginning of fermentation, yeast and mould count in the samples varied from 3.00 to 5.10 log_{10} cfu/g (mean 3.82 ± 0.52 log_{10} cfu/g). As shown in Figure 13, yeasts and moulds were detected throughout the fermentation period. However, the count increased from day 14 to day 21 of fermentation and then showed a decreasing trend with increasing fermentation times. This reduction in yeast and mould count might be due to the anaerobic conditions of *gammaa* fermentation, followed by a decrease in pH and increase in titratable acidity.

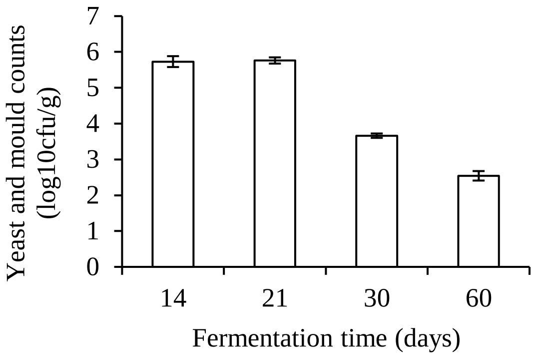

Figure 13. Yeast and mould count ($\log_{10}$ cfu/g) in *kocho* fermentation enhancer (*gammaa*) at different fermentation days.

4.7.3 Morphological and biochemical characterisation of isolates

Lactic acid bacteria isolation frequency and percentage in different *gammaa* fermentation days are presented in Table 4. Of 223 representative colonies of LAB, about 173 (78%) were Gram-positive, catalase-negative, oxidase-negative, cocci or rod-shaped and non-motile. *Lactobacillus* species was found to be the most dominant LAB isolate at 14, 21 and 30 days of fermentation. However, at day 60 of fermentation, only *Leuconostoc* species was found and the occurrence was low (1.16% of the total LAB isolate). Gram-positive and non-motile cocci belonging to *Leuconostoc* species and *Streptococcus* species constituted 28% and 13% of the LAB isolates, respectively, and dominated the initial stages of *gammaa* fermentation. The other 3.47% of isolates were Gram-positive and non-motile rods and grouped as *Lactobacillus* species.

Table 4. Frequency and percentage of lactic acid bacteria (LAB) isolated at different *gammaa* fermentation days

LAB isolates	Number and proportion of isolates on fermentation day										Total	%
	First day		14		21		30		60			
	No.	%	No.	%	No.	%	No.	%	No.	%		
Leuconostoc spp.	48	27.74	5	2.89	-	-	6	3.47	2	1.16	61	35.26
Streptococcus spp.	22	12.72	4	2.31	-	-	1	0.58	-	-	27	15.61
Lactobacillus spp.	6	3.47	25	14.45	2	1.16	31	17.92	-	-	64	36.99
Pediococcus spp.	-	-	14	8.09	-	-	7	4.05	-	-	21	12.14
Total	76	43.93	48	27.75	2	1.16	45	26.01	2	1.16	173	100

From a total of 254 representative colonies of aerobic mesophilic bacteria isolates, about 206 isolates (81%) were Gram-negative rods and Gram-positive cocci bacteria. The frequency of AMB isolates and their relative percentages on different *gammaa* fermentation days are shown in Table 5. From the total isolates identified, on the first day of fermentation 109 were Gram-negative rods (Enterobacteriaceae, *Aeromonas* species and *Pseudomonas* species) and on the same fermentation day only about six isolates were Gram-positive cocci (*Staphylococcus* species and *Micrococcus* species). The majority of isolates on the first day of fermentation were identified as Gram-negative rods and oxidase-negative (Enterobacteriaceae) and all fermented glucose on TSI agar slants. Only 20 isolates of Enterobacteriaceae members produced gas from glucose on TSI agar slants.

Table 5. Frequency and percentage of aerobic mesophilic bacteria (AMB) isolated at different fermentation days

AMB Isolates	Number and proportion of isolates on fermentation day										Total	%
	First day		14		21		30		60			
	No.	%	No.	%	No.	%	No.	%	No.	%		
Enterobacteriaceae	69	33.50	45	21.84	7	3.40	2	0.97	-	-	123	59.71
Aeromonas spp.	26	12.62	4	1.94	1	0.49	4	1.94	1	0.49	36	17.48
Pseudomonas spp.	14	6.80	3	1.46	2	0.97	1	0.49	-	-	20	9.71
Staphylococcus spp.	5	2.43	-	-	1	0.49	6	2.91	1	0.49	13	6.31
Micrococcus spp.	1	0.49	1	0.49	1	0.49	1	0.49	1	0.49	5	2.43
Streptococcus spp.	-	-	3	1.46	1	0.49	-	-	-	-	4	1.94
Enterococcus spp.	-	-	2	0.97	2	0.97	1	0.49	-	-	5	2.43
Total	115	55.83	58	28.16	15	7.28	15	7.28	3	1.47	206	100

5 Discussion

This thesis examined the nutritional content of *kocho* and *bulla* foods and analysed the supply chain and value chain of these *warqe* food products. Post-harvest losses of *warqe* foods were assessed and hotspots for these losses were identified. Physicochemical changes and microbial dynamics during production of *kocho* fermentation enhancer (*gammaa*) were investigated in relation to losses. Many previous studies have been conducted on food losses, involving nutritional and microbiota analyses of different food crops, but none of these has provided sufficient information about food losses, physicochemical changes and the microbiota of *gammaa* and the nutrient content of *warqe* foods. Related research has focused on other root and tuber crops, particularly on potato and cassava crops. Therefore, this discussion chapter concentrates on *warqe* production and its nutritional significance, the value and supply chains of *warqe* foods and associated losses, and modification of the fermentation process in order to improve the nutritional quality and reduce the losses of *kocho* foods.

5.1 *Warqe* production and nutritional significance

5.1.1 *Warqe* production

Warqe belongs to root and tuber crops, which are the second most important source of carbohydrates after cereals in tropical regions of the world (Chandrasekara & Kumar, 2016; Lebot, 2009). The results obtained in this thesis indicate that *warqe* is grown in the study areas for multipurpose uses, in addition to food for human consumption. The farmers surveyed reported that *warqe* is essential for their livelihood, *e.g.* it is food, feed to animals and a traditional medicine, its leaves are used as packaging and as plates, and fibre components are used as construction materials to build houses and fences. Hundreds of millions of people in many other developing countries also use root and tuber crops as the main staple foods in their diet (Lebot, 2009; Scott *et al*., 2000). These crops provide a substantial source of food, animal feed, processed products for human consumption and industrial use as raw material for paper, textile and alcoholic drinks (Lebot, 2009; Scott *et al*., 2000). Thus like *warqe*, other root and tuber crops are used for food and non-food applications.

Warqe production differs from production of cereal and other root and tuber crops in that it requires complicated processing steps to obtain the final products, *kocho* and *bulla* foods, from pseudo-stem and corm. A fully matured *warqe* plant needs on average five to seven years growing time after transplanting to the permanent planting site. Production of fermented food (*kocho*) requires a further two to three months of fermentation in a pit.

The exact number of people in Ethiopia that depend on *warqe* food is not known. However, based on an agricultural sample survey report for 2014 by the Central Statistical Agency of Ethiopia (ECSA, 2014) and population projections from 2012 (ECSA, 2013), it can be estimated that about 35% of Ethiopians living in the main *warqe* production areas use *warqe* as their staple food. Likewise, *warqe* foods are commonly used in cities such as Addis Ababa, Awassa, Dilla, Adama, Jimma, Sodo, Hosaena, Wolkite, Woliso, Bonga, Arba Minch, and other highly populated cities in Ethiopia. With these included, it is clear that much more than 35% of the Ethiopian population consumes *warqe* as a food.

Warqe is grown predominantly by small-scale farmers with limited resources in densely populated peri-urban areas. The survey reported in this thesis revealed that the majority (82%) of farmers use farm inputs obtained from their own on-farm sources. A small number of farmers buy plant materials from local markets when they experience a shortage of seedlings during the planting season, or in some cases they obtain seedlings and organic fertilisers from relatives or neighbours. This indicates a lack of external input supply in the *warqe* production system. It supports previous findings by Brandt *et al*. (1997) that the *warqe* farming system allows long-term high productivity with minimal external inputs. Olango *et al*. (2014) also reported that *warqe* cultivation is an organic farming system using farmyard manures only, with no external chemical fertilisers, herbicides or insecticides. This implies that *warqe*-growing farmers do not have the option of using improved technologies such as planting materials and fertilisers and therefore must still rely on their own sources of farm inputs.

The survey reported in this thesis indicated that *warqe* occupies about 20% of farmers' land and contributes up to 75% of family income. Similarly, Olango *et al*. (2014) found that *warqe* is a dominant perennial plant and one of the most important food security crops in southern Ethiopia, particularly in the area of Wolaita. Thus *warqe* is one of the major crops in Central Ethiopia and is also used as a staple food and source of income for families.

5.1.2 Nutritional significance of *warqe* foods

Warqe foods are the main staple foods in the highlands of Southern, South-western and Central Ethiopian. *Kocho* and *bulla* are particularly the main diet for women and children (Olango *et al*., 2014; Tsegaye & Struik, 2002). This thesis work confirmed that *warqe* foods are a significant food source in the study areas. Laboratory analyses revealed that *kocho* and *bulla* are rich in starch. Gebre-Mariam and Schmidt (1996) also identified starch as the main component of *bulla*, accounting for more than 90% on a dry weight basis. Pijls *et al*. (1995) reported that *bulla* is a more energy-rich food (850 kJ/100 g) than *kocho* (650 kJ/100 g). Foods made from *warqe* are rich in carbohydrates, predominantly in the form of starch (Atlabachew & Chandravanshi, 2008) and this means they have a high energy content (Pijls *et al*., 1995). The high starch content of *warqe* foods may make them suitable substrates for the production of maltodextrin and glucose syrup using starch liquefaction technology. Moreover, starch extract from *bulla* may be used as an alternative starch source in pharmaceutical industries.

Laboratory analyses also revealed that *kocho* contains significantly more crude protein and total fat than *bulla*. This is in line with findings by Forsido *et al*. (2013) that *kocho* has a higher crude protein content (2.57 g/100g) and crude fat content (1.39 g/100g) than *bulla* (1.07 g/100g of crude protein and 0.75g/100g of crude fat). However, *kocho* has a lower protein content than another Ethiopian staple food crop *teff* (12.84 g/100g) (Hager *et al*., 2012). In this thesis, it was found that the protein content in *warqe* foods is low, and therefore excessive consumption of *warqe* foods alone for a prolonged period could lead to protein malnutrition. Similarly, Pijls *et al*. (1995) found that foods prepared from *warqe* in the Gurage area of Ethiopia contain low amounts of proteins (0.4-2.2 g/100g) and concluded that young children will have difficulty in obtaining sufficient protein from a diet comprising only *warqe* foods. Nutritionally, roots and tubers are generally excellent sources of dietary energy in the form of carbohydrates. However, the protein content of roots and tubers is low. For example, the protein content in cassava is 1-3% on a DM basis (Montagnac *et al*., 2009a). Based on their low protein and fat content, *warqe* foods might not satisfy the fat and protein requirements of people who consume *kocho* and *bulla* as their staple foods.

It has been reported that roots and tubers generally contain a significant amount of dietary fibre (Chandrasekara & Kumar, 2016). However, in this thesis it was found that the total dietary fibre content in *kocho* (3.40 g/100g DM) and *bulla* (0.64 g/100g DM) was generally very low compared with that in *e.g*. wheat flour (12 g/100g DM) (Lunn & Buttriss, 2007), carrot (26 g/100g DM) and oats (9.87 g/100g DM) (Englyst & Hudson, 1996). The lower total dietary fibre content in *kocho* and *bulla* foods may be related to their high starch content. As indicated by Dhingra *et al*. (2012), a fibre-rich diet is low in energy density. High-fibre foods are usually lower in fat and higher in antioxidant vitamins and minerals (Lunn & Buttriss, 2007). However, laboratory analysis of *kocho* and *bulla* samples in this thesis revealed both low dietary fibre and low fat content (Table 2).

One of the most significant findings in this thesis is that *kocho* and *bulla* foods contain an adequate amount of dietary minerals that are essential for the human body (Table 3). Other root and tuber crops are also good sources of micronutrients, *e.g*. potato tubers and cassava roots have high contents of calcium, iron, potassium, magnesium, copper, zinc and manganese, comparable to those in many legumes (Montagnac *et al*., 2009a). In the analyses in this thesis, *kocho* was found to contain significantly highly levels than *bulla* of all micronutrients analysed. Similarly, Atlabachew and Chandravanshi (2008) reported that *kocho* contains higher amounts of the majority of micronutrients than *bulla* food products. This difference in nutrient content may be due to the different processing methods used to produce the two foods. *Bulla* is produced by squeezing and decantation of pulverised and decorticated mass of corm and pseudo-stem of the *warqe* plant. Some minerals may be lost during the decanting process, since only water-soluble metals will pass into the *bulla*.

The results in this thesis also confirmed that the essential nutrients potassium, calcium, phosphorus and magnesium were the dominant minerals in both *kocho* and *bulla*. This confirms findings by Forsido *et al.* (2013) that *warqe*-based food products have a higher potassium, calcium and manganese content than wheat or maize. Abebe *et al*. (2007) found that fermented *kocho* is much richer in calcium than *teff* or maize, while Pijls *et al*. (1995) found that *bulla* contained only half as much calcium as *kocho*. Other studies have also found that the concentration of calcium is high in *kocho* (Bosha *et al*., 2016; Yeshitila *et al*., 2011; Atlabachew & Chandravanshi, 2008). According to EHNRI (1998), calcium and phosphorus are the dominant micronutrients in *warqe* foods and *kocho* contains higher amounts of these than *bulla*. Thus overall, *warqe* foods are good sources of energy in the form of carbohydrate and a good source of micronutrients which are essential for human health, but are deficient in protein and fat content in the same way as other root and tuber crops. However, unlike most other root and tuber crops, *warqe* foods are low in dietary fibre. Therefore, there is a need for research on upgrading the nutritional content of *kocho* and *bulla* foods to create fibre-, vitamin-, protein- and fat-rich foods that provide adequate nutrients for the people who consume them as their staple diet.

5.2 The value and supply chains of *warqe* foods and associated losses

5.2.1 Supply and value chains of *warqe*

In this thesis, it was found that significant amounts of *kocho* and *bulla* produced in Maruf and Haro Wanchi are supplied to the central market (Addis Merkato market) via different routes. The two major supply routes identified were: Haro Wanchi to Addis Ababa and Guder to Addis Ababa. Similarly, Degu (2012) reported that high-quality *bulla* supplied to Addis Ababa originates from rural areas of Amaro in Southern Ethiopia through the Hawassa and Shashemene market chains. The survey in this thesis indicated that farmers in Maruf and Haro Wanchi areas produce *kocho* and *bulla* by targeting the market to generate income, besides as a food source for the family. This could be because both these areas are near to the central market, so buyers can easily come to buy and collect the produce regularly, and also because the high quality of the *warqe* products produced in these areas means that they are in demand in the market.

This thesis mapped the value chain of *warqe* food products and found that six principal value chain actors are involved in the chain. *Warqe*-growing farmers and *bulla* processors are the principal actors and create the most value in the *kocho* and *bulla* value chains. Actors such as collectors, wholesalers and retailers mainly work in trading activities and value addition. However, it was observed that product information flows between value chain actors within and across different stages of the chain are weak.

It was found that the supply chain of *warqe* foods is longer and more complicated (see Figure 6) than that of other food supply chains. For instance, the Dutch potato supply chain has both vertical and horizontal links between chain actors through co-operative inter-firm arrangements that achieve access to high-quality raw materials, increase production capacity and reach large customers (Rademakers & McKnight, 1998). The complexity in the *warqe* supply chains explains the existence of many actors between producers and consumers. *Kocho* and *bulla* reach their final consumers through different suppliers in these complex chains.

In this thesis, it was found that *kocho* and *bulla* reach consumers in various ways. Rural consumers get the products directly from producers and wholesalers in local marketplaces, while urban consumers in cities access them through retailers, processors and open market dealers. The supply chain of processed *bulla* is different from the supply chain of fresh *bulla*. Degu (2012) identified similar pathways in the supply chain for fresh *bulla* in Southern Ethiopia. There are multiple possible causes for the complexity of the *warqe* food product supply chains, *e.g*. producers and wholesalers in rural areas do not have information about central markets; the transportation and market facilities are inadequate; there is an absence of links between producers and retailers, processors and consumers; and there is a lack of cooperation among producers. These multiple problems are compounded by the nature of the products, with characteristics such as bulkiness and perishability, which makes the supply chain complex and sometimes even overlapping. Besides, there is a lack of support from government to *warqe* markets and the central market suppliers are dominated by a few people, which makes it difficult for new players to enter the central markets.

5.2.2 *Warqe* food losses along the supply chain

This thesis showed that about 45% of *kocho* and 46% of *bulla* are lost from the total marketed production of *warqe* foods along the supply chain. This confirms the trend in developing countries for about 45% of the total production of roots and tubers to be lost or wasted (FAO, 2015). Spoilage of root and tuber crops is a significant challenge limiting commercial production of these crops (Chandrasekara & Kumar, 2016). The investigations in this thesis also showed that a substantial amount of *warqe* foods is wasted throughout the supply chain, from initial *warqe* growing down to final consumer level (see Figure 10).

Overall, the highest losses of *kocho* were found to occur at retailer level and the highest losses of *bulla* at processor level, while the lowest losses were recorded at producer and consumer levels for both food types. According to FAO (2013), food losses in low-income countries mainly occur at early and middle levels of food supply chain and less food is wasted at the consumer level. As found in this thesis, FAO (2011) concluded that the highest losses of root and tuber foods in sub-Saharan Africa occur in post-harvest handling and storage and in processing and packaging, and the lowest losses occur in consumption. This indicates that *warqe* food losses display the same trends of losses as other root and tuber crops in sub-Saharan Africa.

High losses of *kocho* (24.0%) and *bulla* (12.6%) were observed to occur at retailer level, particularly in market storage. These high losses reflect the fact that *warqe* food products are traded under poor sanitary conditions in the market. Traders sell the products by displaying them in the open air, there is no proper storage place for the products, and traders use the same site for selling and storage. This system is not suitable for efficient sales and warehousing. The markets are also very crowded and do not have a good ventilation system. In addition, it was observed that *kocho* and *bulla* are handled roughly during loading and unloading and even stacking in the storage place. Other reasons for losses of *warqe* foods relate to the long and complicated supply chain. This could cause a delay in the products reaching the final consumer, leading to substantial losses and waste of *warqe* food.

The packaging material used for *kocho* at local markets, which consists of a wrapping formed of *warqe* leaves, is not replaced until it reaches the final consumer. The leaves become dry and deteriorate when they reach the central market because of rough handling during transport and due to the delicate nature of leaves. Moreover, to check the quality of the products, traders employ the practice of piercing the packaging leaves to take out samples in the marketing chain. This open hole risks exposing the product to air and even to flies, which can lay their eggs and larvae can develop during storage. All these stresses contribute to the deterioration of *kocho* at the retailer stage and may be the main reason for the high *kocho* and *bulla* losses at retailer level.

This thesis revealed that losses during *bulla* processing are the most significant source of waste in the *bulla* supply chain, with about 29% *bulla* lost at processing level. These losses occur during the main processing operation. In general, one of the causes of high food losses in developing countries is a lack of processing facilities (FAO, 2011). Using improper and traditional methods of processing may be the leading cause of *bulla* wastage.

Bulla processors often use inappropriate tools for processing, like large barrels and sieves, which may increase the loss. Moreover, the practice of drying *bulla* in the open air on plastic sheeting on the ground may expose it to dust contamination and wind drift. As a result, this inadequate way of drying *bulla* can cause substantial losses. Discarding of fresh *bulla* due to quality problems was observed in the survey. Lack of quality products for processing, poor packaging of the fresh and processed *bulla*, inadequate transportation and handling are additional causes for this high loss. For cassava, discard during processing due to small and woody tubers is reported to be the leading cause of cassava processing losses (Oguntade, 2013). This indicates that one of the leading reasons for wastage at processor stage for root and tuber crops, including *warqe*, is a lack of quality and suitable raw materials for processing.

5.3 Fermentation to improve nutritional quality and to reduce losses

Fermentation is the main method used to improve the flavour and taste and extend the shelf-life of root and tuber crops like cassava (Falade & Akingbala, 2010). Fermentation is also used as a primary method to reduce the cyanide level in cassava and to detoxify the root of cassava (Montagnac *et al*., 2009b; Kostinek *et al*., 2005). In the case of *warqe*, fermentation is used to convert decorticated and pulverised pulp into the starchy food *kocho*. The results presented in this thesis indicate that the fermentation process improves the nutritional quality of *kocho* compared with the unfermented *warqe* product *bulla* for all nutrients studied except starch (Tables 2 and 3). Similarly, Kabeir *et al*. (2004) reported that fermentation increases both the energy density and the protein content in rice. Fermentation also enhances the bioavailability of micronutrients in plant-based diets and reduces anti-nutritional factors (Hotz & Gibson, 2007; Fagbemi *et al*., 2005). Food losses can be reduced by using the appropriate time for fermentation, *i.e*. preventing losses that occur due to over fermentation. In the case of *kocho*, spoilage could be reduced by using *gammaa* taken at 30 days of fermentation, rather than 60 days.

Physicochemical analysis indicated that, as the fermentation of *gammaa* progresses from the first day to day 60, the pH drops and the titratable acidity increases. Previous investigations of *kocho* fermentation have found similar results (Karssa *et al*., 2014; Yirmaga, 2013). Gashe (1987) identified *Leuconostoc* species and *Lactobacillus* species as the most influential bacteria in lowering the pH of *kocho*. As all lactic acid bacteria are homofermentative, more acid is produced per mole of fermentable sugar and the rate of pH decline is faster when these species dominate (Hunduma & Ashenafi, 2011a). This indicates that in *gammaa* fermentation, acid-producing bacterial species are mainly responsible for the fermentation process.

The temperature of the *gammaa* samples increased as fermentation time increased up to day 30, and then it decreased to day 60 of fermentation. Overall, it was observed that the temperature range of *gammaa* fermentation was between 13 and 20 ºC. Gashe (1987) found that *kocho* fermentation also takes place within a low fermentation temperature range (14-18 ºC).

The microbiota analysis results showed that aerobic mesophilic bacteria counts were high at the initial stage of *gammaa* fermentation and then exhibited a considerable decrease by day 60 of fermentation. This result is in agreement with previous findings in *kocho* fermentation studies (Karssa *et al*., 2014; Hunduma & Ashenafi, 2011a). This indicates that the initial stage of *gammaa* fermentation is dominated by AMB and that as fermentation progresses, the AMB decline rapidly. At the same time, the number of lactic acid bacteria increases as fermentation progresses, so they are the dominant microbiota by day 30 of fermentation.

According to Karssa *et al.* (2014), the decrease in pH and increase in titratable acidity during the *kocho* fermentation process can be attributed to the activities of acid-producing microorganisms, mainly lactic acid bacteria. Yirmaga (2013) also observed that when the fermentation time of *kocho* increases, the counts of LAB also increase, due to the ability of the LAB to grow at low pH. Similarly, Lu *et al.* (2008) reported that there is general agreement on the dominance and beneficial effects of the LAB on the fermentation process of starchy food products. This may be explained by their tolerance to acidic environments. Furthermore, during *gammaa* fermentation the anaerobic conditions created in the tightly packed pit may favour the growth of LAB.

The elimination of coliforms and Enterobacteriaceae observed by day 30 of *gammaa* fermentation is in agreement with findings by Hunduma and Ashenafi (2011a), who detected no coliforms following the proliferation of LAB and the corresponding fall in pH. Lactic acid bacteria are also known to produce antimicrobial substances during fermentation of different foods (Jay *et al.*, 2005; Tadesse *et al.*, 2005). Thus the creation of anaerobic conditions and the lowering of pH by the lactic acid bacteria may be able to eliminate both coliforms and Enterobacteriaceae in the late *gammaa* fermentation period. In this thesis, the unfavourable conditions created due to a reduction in pH over fermentation time might have eliminated Enterobacteriaceae members from the fermenting *gammaa* mass, supporting findings by Karssa *et al.* (2014). A pH of 3.5-4.0 is reported to inhibit Enterobacteriaceae and other Gram-negative bacteria (Steinkraus *et al.*, 1996). The elimination of Enterobacteriaceae may indicate the safety of *kocho* in terms of enteric pathogen load. Fermentation has been demonstrated to be efficient in the removal of Gram-negative bacteria (Chelule *et al.*, 2010; Sobowale *et al.*, 2007).

Similarly, yeast and mould counts slightly increased until 21 days and then showed a marked decrease. It has been suggested that the low number of yeasts in fermenting *kocho* could be due to unavailability of sufficient oxygen in the tightly packed and sealed fermenting mass (Yirmaga, 2013). Some reports indicate that the fermentative activity of yeast increases along with that of lactic acid bacteria during similar fermentation processes (Urga *et al.*, 1997; Amoa-Awua *et al.*, 1997; Amoa-Awua *et al.*, 1996; Oyewole, 1992). However, Gashe (1987) isolated four yeast genera (*Trichosporon*, *Torulopsis*, *Rhodotorulla* and *Candida*) from fermenting *kocho* mass and found that they reached the highest counts between 22 and 43 days of fermentation and then significantly decreased. Gashe (1987) also concluded that the proliferation of yeasts requires an abundant and continuous supply of oxygen. This all indicates that the reduction in yeasts and moulds in the later stages of *gammaa* fermentation is possibly due to the development of high acidity levels and anaerobic conditions as fermentation time increases. It also indicates that yeasts are involved in *gammaa* fermentation in the first three weeks, in starting the fermentation process, and then their role decreases because of creation of an acidic environment. Likewise, Karssa *et al.* (2014) and Andeta *et al.* (2018) reported the co-occurrence of yeast and lactic acid bacteria in *kocho* fermentation. Lactic acid bacteria and yeasts are also the two major groups of microorganisms involved in the cassava fermentation process (Montagnac *et al.*, 2009b).

Biochemical and morphological characterisation of the *gammaa* fermentation isolates in this thesis confirmed that about 78% of 223 representative colonies of lactic acid bacteria were Gram-positive, catalase-negative, oxidase-negative, cocci or rod-shaped and non-motile. These are the unique characteristics of lactic acid bacteria, as described by Holzapfel *et al.* (2001). Zewdie (1996) also reported that lactic acid bacteria are natural microbiota involved in the *warqe* fermentation process. In a study of *kocho* fermentation, Gashe (1987) concluded that two groups of lactic acid bacteria, namely *Leuconostoc* species and *Lactobacillus* species, are responsible for bringing about the desired changes, including the reduction in the pH and natural flavour development, in *kocho*. That author also reported that *Leuconostoc mesenteroide*s initiate the fermentation and dominate the lactic acid flora in the early stages of fermentation.

In another study, hetero-fermentative cocci were found to be dominant during the initial stage of fermentation and to play an essential role in starting *kocho* fermentation (Haile, 2015). Gashe (1987) concluded that *Lactobacillus* species succeed *Leuconostoc* species as the most abundant and actively growing microorganism in *kocho*. Through the activities of these *Lactobacilli* species, the pH of *kocho* is reduced. The strong acid producer *Pediococcus cerevisiae*, which is usually active in the upper range of mesophilic temperatures, is also present in fermenting *kocho*. In addition, Girma and Gashe (1985) identified *Lactobacillus* species, *Pediococcus* species, *Leuconostoc* species and *Streptococcus* species from *kocho* and *bulla* purchased from different markets in Addis Ababa and suspected these microorganisms to be involved in the fermentation process.

It was observed in this thesis that Enterobacteriaceae was the most dominant of the aerobic mesophilic bacteria isolates on the first day and on days 14 and 21 of *gammaa* fermentation, but thereafter showed a decreasing trend (Table 5). This may indicate that the low pH as fermentation time increases creates unfavourable conditions for the Enterobacteriaceae. Similarly, Karssa *et al*. (2014) reported that a reduction in pH over fermentation time eliminated Enterobacteriaceae members from fermenting *kocho* mass by creating unfavourable conditions for these bacteria.

In combination, these findings indicate that *gammaa* fermentation takes place in the low-temperature range in an acidic environment and that manipulation of lactic acid bacteria and fermentation duration can play a decisive role in future work to improve the nutrient content and reduce spoilage of *kocho*.

6 Conclusions

This thesis assessed the nutritional value of *warqe* foods and mapped supply and value chains in order to identify hotspots for post-harvest losses. In particular, analyses were conducted on the fermentation process, which was evaluated for ways to reduce nutrient losses. This was done mainly by identifying the main microorganisms responsible for fermentation and spoilage, the critical time for optimum fermentation and the losses due to over fermentation.

The main conclusions from the work presented in the thesis are as follows:

- The chemical composition of *kocho* and *bulla* foods comprises high concentrations of starch and micronutrients, but low concentrations of crude protein, total fat and dietary fibre. The highest amount of starch was found in *bulla* (89%), could make this product a potential substrate for production of maltodextrin and glucose syrup. On the other hand, the high post-harvest losses of *bulla* (about 46% loss of marketed product along the supply chain) would cause substantial losses in production of maltodextrin and glucose syrup.

- The supply chain for *warqe* foods is long and complicated, which results in a delay in the products reaching the final consumer on time and in substantial losses and waste of *warqe* foods. *Kocho* and *bulla* reach their end consumers through multiple channels. Limited information flow, inadequate transportation system, using perishable packaging and lack of cooperation between actors are leading constraints in the supply chain. There is a need to develop integrated, efficient and effective logistics for the *warqe* supply and marketing chain, with specific consideration of food quality and logistics costs, which could streamline the food supply chain and thereby reduce food losses. It is also necessary to achieve cooperation and coordination between value and supply chain actors in order to create an effective information sharing system using modern communications technology such as mobile application software.

- Mapping of the value chain of *warqe* food products identified key chain actors. *Warqe*-growing farmers and *bulla* processors are the principal actors and create the most value in the chain. Product and information flows between value chain actors within and across different levels of the chain are weak. The critical roles of farmers and *bulla* processors could be supported by providing credit, developing and supplying improved *warqe* varieties, extension services, market facilities and market information.

- Significant amounts of *warqe* foods are wasted throughout the supply chain. The overall losses of marketed *kocho* and *bulla* in the supply chain were 45% and 46%, respectively. The highest loss of *kocho* (24%) was observed at the retailer level and the most significant loss of *bulla* (29%) at the processor level. Lack of appropriate processing technology at producer and processor levels, use of inferior packaging materials and improper handling in the market are the leading causes of *kocho* and *bulla* losses. Therefore, it is crucial to improve processing technology, storage, packaging, handling and market conditions, in order to reduce post-harvest losses of *warqe* foods.

- Long fermentation periods can cause spoilage of *kocho* in the fermentation pit, and *kocho* spoilage could be reduced by using *gammaa* starter culture at 30 days of fermentation. Lactic acid bacteria are the dominant microbiota by day 30 of *gammaa* fermentation. However, coliform and Enterobacteriaceae counts are higher at the start of fermentation, but decline significantly as fermentation progresses. Yeast and mould counts increase slightly until 21 days and then decrease markedly. *Lactobacillus* species from lactic acid bacteria isolates and Enterobacteriaceae from aerobic mesophilic bacteria isolates are the most abundant and dominant microorganisms in *gammaa* fermentation. Further investigations are needed at species and strain level to identify all the microorganisms involved in *gammaa* fermentation.

7 Future research and development

- Research is required to upgrade the nutritional content of *kocho* and *bulla* foods by supplementing them with fibre, vitamin, fat and protein-rich foods, so that they provide an adequate diet.

- A comprehensive investigation is required on *kocho* fermentation and on improvements in process techniques to reduce losses and improve *kocho* food quality.

- Better food packaging and storage methods and new technologies need to be developed to minimise losses and enhance the quality of *warqe* foods.

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Acknowledgements

Many people were involved in helping me, next to God, in both my educational and personal life during the time I carried out this doctoral study. I am very grateful for all their help, and I wish to thank most sincerely all those involved. However, for reasons of space, only a few of them are mentioned by name in these acknowledgements.

To start with, I wish to express my sincerest thanks to my supervisor Prof. Girma Gebresenbet. I particularly appreciate his great ability in giving me guidance in all the work which I did. I thank him for his unwavering and unconditional love, inspiration and encouragement. I also offer many thanks to my assistant supervisors for support and input during these years. Prof. Rikard Landberg, you have helped me to get a much broader understanding of nutrition and health and teaching me how writing scientific papers. Thank you, Rikard. Special thanks to Dr. Tesfaye Balemi for his support during the planning, and as I executed the study.

I gratefully acknowledge the German Federal Ministry of Education and Research for funding the RELOAD project. My special thanks go to Prof. Oliver Hensel, Prof. Brigitte Kaufmann and Mr. Michael Hesse for their great idea and job in the RELOAD project.

I want to thank all my colleagues at the Department of Energy and Technology at SLU, who were supportive and provided me with help whenever I needed it. I am highly indebted to Dr. David Ljungberg for his inputs as an opponent during the pre-dissertation seminar and Mr. Seven Smårs for his IT support. Special thanks to Dr. Tadesse Kenea, Dr. Techane Bosona, Dr. Samuel Aradom, and Dr. Anas Almustafa for their excellent collaboration and encouragement. I wish to express my sincere thanks to Prof Roger Andersson from Department of Molecular Sciences in SLU, and Tariku Hunduma from Ambo Plant Protection Research Centre for the providing of their laboratory facilities during the laboratory works.

I express my gratitude to my dear wife, Azeb Bekele, and my daughter, Mahlet Ashenafi, for your patience, encouragement, and support! Thank you, my mother, Mulunesh Anechamo, my brothers Teshom Chaka, Shebeshe Chaka, Dereje Chaka, Solomon Bekele, Alemayehu Bekele, Tadeyos Bekele and Adane Bekele, and my sisters Yeshi Chaka, Shewaye Chaka, Kasech Denbel and Lemelem Chaka for your endless love and support throughout the time I was carrying out my studies. And my father Chaka Tuffa thanks for always being there in my heart, it is all because of you.

Last but not least, I am grateful to my friends Wosene Gebreselassie, Jemal Abedo, Dereje Belay, Dr. Daniel Belay, Dr. Ermias Habte, Dr. Fufa Sorri, Tadele Gutu, Nejda Abedulhadi, Besher Hamed, Tesfaye Fekede, Solomon Zekaris, Adane Hailu, Fiseha Kejela, and Motumma Teressa for their encouragement and support during both data collection and in writing the papers and thesis.

Appendix 1. Photo gallery of traditional *warqe* processing method

Figure A1. A) Peeling and splitting the pseudo-stem (*hakosha*) and B) *bulla* squeezing.

Figure A2. A) Decorticating, B) pseudo-stem pulverising, C) corm pulverising and D) underground corm pulverising.