INNOVATIVE MILLET FOODS TO IMPROVE NUTRITION AND EXPAND MARKETS IN WEST AFRICA

by

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To the millions of people dying of hunger and malnutrition every day in Africa and the rest of the world caused by food insecurity, climatic change and regional conflicts

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Figure H.1. Consumer's overall liking/acceptability (taste, color, odor, texture) of decorticated millet extruded foods (thin and thick porridge) versus traditionally made thin and thick porridges in niamey. 226

ABSTRACT

Sorghum and millet crops are the staple foods for most people in the Sahelian region of West Africa. Preparation of millet and sorghum foods are labor-intensive and time-consuming. This thesis work was conducted with the goal of developing competitive and innovative processes to make better quality and higher quantity of extruded *couscous*, and instant, or fast cooking, millet food products to improve markets for smallholders' famers, improve nutrition, and to meet the changing demands of local consumers in West Africa. Processing conditions, of a low-cost single screw mini-extruder were assessed and optimized. The process has the advantage of shortening production steps, and time, of making number of products with appealing appearance, good taste, and texture, and designed for the preferences of local consumers. The products can be reconstituted by adding hot or tap water. Results of the first study on a newly developed extruded *couscous* indicated that consumers in general preferred it, that it was fast cooking *couscous,* and credited it to be smoother in texture than the traditionally-prepared *couscous*. It had 10x the daily yield as *couscous* typically prepared for commercial sale by women in a processing unit. The smoother texture was attributed to the presence of starch fragments of somewhat lower molecular size, than in the control *couscous*, as illustrated by size-exclusion chromatography analysis of the hot-water dispersed starch. In the second study, the extruder was used to make instant porridge flour, and locally available roasting process was optimized to make a fast cooking porridge flour, and each flour was formulated using natural and locally obtained plant fortificants to nutritionally enhance cereal-legume-fortified flours. Results of consumers sensory tests and textural characterization by RVA and dynamic oscillatory rheometry of fortified porridge samples revealed that the innovated formulas had better viscosity, taste, and flavor, and were more preferred by children and their mothers than food aid vitamin-mineral premix fortified flours distributed at rural government health centers. Bioaccessibility of provitamin A carotenoid and lycopene derivatives, including lutein, α- and β-carotenes, using an *in vitro* digestion system coupled with a HPLC-C30SHORT column, shown that the formulated fortified flour samples had high bioaccessibility values of provitamin A carotenoids, lutein, and α- and β-carotenes. In the third study, rheological results indicated that instant *tuwo* (thick) and *fura* (thin) porridges had better viscosity and textural attributes (creamy, elastic, gelling) compared to traditional corresponding porridges. In the fourth study, a home use testing (HUT) of instant *tuwo* and *fura* porridges in Niamey, Niger indicated

that overall consumers' acceptability was good. In a market test conducted in Niamey over 20 weeks, in collaboration with local cereal processors and distributors, showed repeat purchases with good frequency of sale of instant *tuwo* and *fura* porridges that have generated about 1/3 in total sales of 35 products related millet and cereal based foods in the period. In conclusion, the low-cost single screw extruder has the potential to catalyze and increase demand and diversification of uses of millet grains, to develop market-driven nutritious and healthy grain-based foods, to benefit smallholders' farmers, and favor growth of small- and medium-scale entrepreneur processors in West Africa.

CHAPTER 1. OVERVIEW

1.1 Introduction

Traditional preparations of cereal foods in West Africa are laborious, time intensive, and often entail fastidious processes. Final product yields often indicate low efficiency of the processes, and preparations are usually limited only to household use, and consumption. Large and sustained supply of value-added grain-based foods in local markets is a challenge in West Africa (Hollinger and Staatz, 2015). In the past years, with support from the National Agricultural Research Centers in the Sahelian region of West Africa (INRAN, Niger; ITA, Senegal; IRSAT, Burkina Faso; IER, Mali) and international institutions (i.e. Purdue University), and support from donors such as the United States Agency for International Development (USAID), the McKnight Foundation, and others (e.g. FAO, IFAD), a few successful grain processor entrepreneurs have emerged. Most are women and include both urban processors and rural women processor associations in Niger, Senegal, Burkina Faso, and Mali (Hollinger and Staatz, 2015). Still, the lack of innovative cereal food products may partly explain the minimum penetration of locally processed products into urban markets in West Africa.

Growing urban populations in Africa have increased pressure on time for food preparation and increases in the middle socioeconomic class are predicted to continue impacting demand of cereal-based foods. In contrast, little work has been done to innovate and produce value added grain-based foods through processing. It appears that significant market opportunities exist for millet and sorghum products in urban and rural areas in West Africa.

Low and cost-effective extrusion processing of millet and sorghum has brought forth the possibility of processing instant porridge flours and other products such as *couscous* that have comparative overall consumer demand as they are traditionally consumed and liked in West Africa (Zhang et al., 2014; Moussa et al., 2011). Extrusion and other food processing technologies have the potential with product development work to make a range of competitive popular cereal-based products. Nutritional enhancement of products can be achieved through addition of natural or synthetic micronutrients. For the pro-vitamin A carotenoids, research has shown improved stability and bioaccessibility of carotenoids, and processing methods including roasting and fermentation of grain, were shown to improve the value of pro vitamin A compounds in local foods that could be used to address vitamin A deficiency in at risk population in West Africa (Aragón et al., 2018).

We believe that a nutrition-based approach that is market-driven would eventually help ensure that deficient populations have access to nutritionally-enhanced and acceptable foods in West Africa (De Groote et al., 2017). Consumer acceptance is necessary for processors and other technology end-users to adopting new technologies, and market and home-use-studies can be used to understand adoption and market penetration (De Groote et al., 2014).

In this thesis study, a low-cost single screw extruder process, designed and developed at Purdue University, was used to (a) increase and diversify processed food products along the millet value chain in West Africa, (b) develop an efficient and sustainable market-driven food processing model that can be expanded/scaled up to increase production, sales, and consumption of nutritionally-enhanced millet foods, (c) meet changing demands of local consumers, (d) improve nutrition of local communities, by promoting processed nutrient-fortified millet foods made from these studies, (e) promote and increase the market for millet and sorghum grains to benefit smallholder farmers and to strengthen their links with markets, and (f) build through the Hub-and-Spoke Food Innovation Center model a more stable and locally sustainable food processing industry with impact on nutrition, making successful entrepreneurs, and empowering women and youth in West Africa.

1.2 Overall Goal and Specific Objectives

This work was conducted with the goal of developing competitive and innovative food products to make better quality and high-yielding instant or fast-cooking millet food products, preferred by local consumers as good, or as equally good as traditionally handmade millet products.

Specific study objectives were to:

(1) Design a new process of making high quality and high-yielding extruded *couscous*.

(2) Using the extruder, and a locally available roaster, design competitive and innovative process of making nutritionally-enhanced cereal-legume-fortified instant flours.

(3**)** Explore the potential of the low-cost single screw extruder to make high quality instant *tuwo* (thick) and *fura* (thin) porridges.

(4) Evaluate acceptance of extruded instant *tuwo* (thick) and *fura* (thin) porridges by local consumers through modified Home-Use-Testing (HUT) and test the market for instant *tuwo* and *fura* porridges over a 20-week period.

1.3 Literature Review

Sorghum and millet crops are the staple foods for most people in Sahelian region of West Africa. Their adaptation to different agro-ecological zones and suitability for a myriad of foods positions them as major cereal grains for the region's food security. Millet and sorghum have grain production estimated to be 9.13 and 12.67 million metric tons, respectively (FAOSTAT, 2019). They are the major source of carbohydrates and often protein and provide more than 50% of the total calories in the diet (FAO, 2017; FAO 2019).

Millet and sorghum grains are commonly processed to flours for preparation of products that are popular in many African countries. Products include porridges, agglomerated couscous and similar products, beverages, composite foods, fried-like pancakes, bread, biscuits, and other related snacks and cookies **(**Aboubacar et al., 1999; Aboubacar et al., 2006; Taylor et al., 2006, Moussa et al., 2011). Quality of millet and sorghum foods can vary significantly due to methods of preparation and the wide range of genetic variation inherent in millet and sorghum crops, resulting in food products of different taste, colors, flavors, and textures. Product taste, texture (viscosity and particle size), and color are considered the most important quality attributes that affect consumer acceptability of millet and sorghum foods (Moussa et al., 2011; Aboubacar et al., 2006; Murty et al.,1995; Scheuring et al.,1982).

Our research group has shown in previous work the processing and value of instant sorghum flours

(Moussa et al., 2011), and flour parameters required for good *couscous* processing (Aboubacar et al., 2006). However, there are still challenges in the West African Sahelian region on how to drive consumer markets for processed millet foods in a meaningful and sustaining way to benefit smallholder farmers. There are constraints and limiting factors that hinder market penetration and expansion which include inexistence of efficient processing technologies along the crop value chain. Processing methods currently being used are manually-intensive and laborious processes and have a low efficiency. At the same time, growing West African urban populations of the middle socioeconomic class with pressure on time for food preparation and with increasing disposable incomes are stimulating demand for high quality processed products. Thus, there are anticipated opportunities to expand market access for locally processed foods. Despite the increase in consumption of imported grains and processed foods made from wheat, maize, rice, and related cereals, millet and sorghum grains continue to remain as popular foods consumed in both rural and urban areas in West Africa (Hollinger et al., 2015, Reardon et al., 2012; Reardon et al., 2009).

Undernourishment is a prevalent concern in West African populations, where the percentage of malnourished children under age of 5 is still high (FAO, 2019; FAO, 2017; DeGroote et al., 2017, Muthayya et al., 2013; Ferruzzi et al., 2012). Even though there has been more interest and increased support for food fortification and micronutrient supplementation, iron, zinc, and vitamin A deficiencies continue to be prevalent in poor countries, including those in West Africa (El Sheikha, 2015). Foods mainly made of sorghum or millet grain are generally characterized by low levels of lysine, iron, zinc, and vitamin A, and when consumed at high levels at the expense of other complementary foods can lead to nutritional deficiencies. Fortification programs distribute fortified flour blends that are provided by local and international food aid programs made of non-local soy and maize grains, which are not always well accepted by children.

It was reported that these micronutrient deficiencies are main modulators of increased risk for perinatal complications, morbidity from infectious disease and mortality, impaired mental and physical development, and reduced productivity in poor countries (Muthayya et al., 2013). Iron (Fe) and zinc (Zn) deficiencies are among the most serious nutritional problems in West Africa, mostly related to high consumption of local cereal-based diets (Merwe et al., 2019). Compounding the problem is that locally grown cereals, including millet and sorghum, contain antinutritional factors including phytate content, which chelates iron and zinc making them less bioaccessible, phenolic compounds, dietary fiber, and calcium (Raes et al., 2014). Vitamin A deficiency increases mortality in children under 5 years of age in West Africa (Lipkie et al., 2013, Black et al., 2008). Vitamin A refers to the fat-soluble all-trans-retinol. It is considered one of the vital micronutrients relating to physiological processes in the human including immune response, vision, differentiation and proliferation of cells, intercellular communication, and cell reproduction. Vitamin A and plant-based pro-vitamin A are fat-soluble compounds (Debelo et al., 2017). In the human diet, vitamin A is derived from animal products providing preformed retinol or retinyl esters, and from fruits, vegetables, cereals, legumes, and roots and tubers as sources of pro-vitamin A carotenoids. Carotenoids are found in high amount in yellow and orange vegetables such as carrot, sweet potato, and pumpkin; in yellow and orange non-citrus fruits (e.g. mango, apricot, and papaya); and dark-green leafy vegetables (e.g. kale, spinach, and collards) (Debelo et al., 2017).

Carotenoids are the main class of lipophilic hydrocarbons and are considered as secondary plant metabolites responsible of forming a myriad of pigments, including the red, yellow, and orange pigments in plants, and in other living materials. The activity of pro-vitamin A was found to be limited to compounds possessing > or =1 of the β-ionone ring along with the polyene chain, including β -carotene, α -carotene, and β -cryptoxanthin. Theoretically, the metabolism of β -carotene yields 2 molecules of retinol because β -carotene possesses 2 β-ionone rings, where as α -carotene and β -cryptoxanthin have half the pro-vitamin A activity of β -carotene by virtue of their structure containing only one β -ionone ring (Debelo et al., 2017; Lipkie et al., 2013; Ford et al., 2017; WHO, 2009; WHO, 2004).

One possibility to improve nutritional status of rural populations in West Africa is through local processing of crops that are fortified with indigenous nutrient-rich plants. Cost-effective and socially innovative food processing and nutrition technologies exist, however rural women and youth who can adopt new food processing technologies have limited access to them. This is mainly due to lack of a system approach capable of facilitating and maximizing relevant changes expected in nutrition improvement in rural areas to realize the potential of the market side of value-chains. Studies have revealed that the fortification of local foods by incorporating local ingredients, as well as vitamin and mineral premixes, can be a potential route for alleviation of micronutrient deficiencies in developing countries (Gunaratna et al., 2017; WHO/FAO/UNICEF, 2017; Ferruzzi et al., 2012). Development of nutritionally-enhanced products using local nutrient-rich plant sources has been done using relatively low-cost extrusion (Bouvier et al., 2014; Zhang et al., 2014; Moussa et al., 2011). Nutritionally-enhanced and preferred fortified local foods with key micronutrients (pro-vitamin A, iron, zinc) hold promise of alleviating child malnutrition in West Africa (DeGroote et al., 2017).

1.3.1 Description of Food Processing Innovation Centers

Our research explores the concept of technology-based food processing innovation centers, developed in a participatory manner with entrepreneurs, women processors, farmer groups, and government for processing local crops in urban and rural areas in West Africa. The dynamic of establishing the concept was developed over the last two decades by INRAN, Niamey, Niger in collaboration with Purdue University, through United States Agency for International Development projects (INTSORMIL and SMIL) and with other donors including the McKnight Foundation. The model consists of the Hub-and-Spoke Food Innovation System, with the Hub Food Innovator implemented at the National Agriculture Research Systems (NARS) or universities, located in cities including INRAN in Niamey, Niger and IRSAT in Ouagadougou, Burkina Faso, IER in Bamako, Mali, and ITA in Dakar, Senegal. On the other hand, "Spokes", are mainly located in rural locations and are connected to Hub Food Innovators. Size of Spokes vary from small to medium-scale mechanized entrepreneurial processing essential to make final products (as defined by the value chain and market demand).

In Niger, the central Hub at INRAN, Niamey supports and backstops more than 15 women processor groups/entrepreneurs in Niamey, and four Spokes operated by women processor associations in rural locations in Niger and one in Burkina Faso. Similar models are now being developed and implemented in Mali and Senegal. Major objectives include: dissemination of food and nutrition technologies, research and development function, and continuous technical support, which empower rural and urban women and youth, improves nutrition through the market, increases incomes, and catalyzes sustainable private and social entrepreneurship.

We perceived that such a model could facilitate and maximize adoption of innovative food and nutrition technologies to local entrepreneurs and women processing groups in West Africa Other outcomes have included building and strengthening capacity of urban and rural women processors groups to solve technical problems related to food processes and product refinement, market development, and knowledge generation and sharing. As a result, food innovation centers serve as platforms where women processor groups and emerging entrepreneurs converge to receive training on new or improved food processing technologies. They develop and formulate new foods, are allowed to use food innovator facilities, and to test food making ability of improved millet and sorghum and related grain varieties. We view the Hub-and-Spoke Food Innovation Centers as way to improve nutrition of local communities through consumers of nutritionally-enhanced grain-based foods and development markets for fortified products. Technical support is given to mechanize and improve local food processing enterprises and improve ways of operations.

1.3.2 Starch structure and digestion

Starch is the most important carbohydrate component in plants, and it is commonly consumed in the human diet. It is composed of two polymers of glucose – amylose and amylopectin. Amylose is a primarily linear chain of 1,4-linked α -D-glucopyranosyl units and conformationally forms single or double helices. Amylose is smaller than amylopectin, which is highly branched comprising 1,4-linked linear chains of varying sizes with 1,6-linked branches (Liu et al., 2017; BeMiller et al., 2007). When starch is totally debranched, the highly branched amylopectin is converted to linear short chains. Linear chains from amylose, including normal and high amylose one, have a broad molecular weight distribution. On the other hand, linear short chains released from waxy starch have relatively narrow molecular weight distribution. (Liu et al., 2017; Liu et al., 2015 ; Cai et al., 2010 ; Shi et al., 2006). (Figures 1.1 and 1.2).

After heating starch in water, starch granules swell due to melting of the crystallite structures and amylose starts to leach out of the swollen granule. Starch gelatinization is referred to as melting and disruption of double helices of the starch polymer chains. (Liu et al., 2017; BeMiller et al., 2007). This is an irreversible process related to crystalline melting and coincides with a loss of birefringence. Increased translucency in appearance, and viscosity are observed during the gelatinization process (Lee et al., 1991).

Amylose and amylopectin molecules may reassociate into ordered structures upon cooling, a process which is termed as retrogradation and may ultimately affect starch digestibility by human (Liu et al., 2017, Atwell et al., 1988). The slower retrogradation of the amylopectin molecule is associated with slowly digestible starch (Zhang et al., 2006). Amylose-to-amylopectin ratio depends on starch source, though amylose generally comprises about 20% of total starch, and the rest is amylopectin. The relationship between amylose-to-amylopectin ratio and digestibility has been studied in terms of development of resistant and slowly digestible starches (Srichuwon et al., 2005; Zhang et al., 2006). Starch polymers with higher proportion of internal and external long chains retrograde faster and may eventually possess a slow digestion property, as well as very highly branched chains of amylopectin molecules (Zhang et al., 2008).

Starch is nutritionally classified into three groups that are known as rapidly digestible starch (RDS), slowly digestible starch (SDS), and resistant starch (RS) (Englyst et al., 1992; Liu et al., 2017) by human. RDS represents the fraction that is rapidly digested and absorbed in the upper small intestine and causes high glycemic index (GI). SDS is slowly but completely digested in the small intestine and is associated with long term glycemic control. In contrast, RS cannot be digested in the small intestine, but is fermented by the gut bacteria and converted to short chain fatty acids (Figure 1.3) (Zhang et al., 2009; Englyst et al., 1992). SDS and RS were found to be beneficial for human health (Liu et al., 2017).

1.3.3 Millet and sorghum starch digestibility, and physiological and metabolic effects on human health

Cooked millet and sorghum foods have relatively slow starch digestion rate in human, which is a good property for managing blood glucose level and supplying sustained energy to the body (Aryee et al., 2006; Zhang et al., 1998; Lichtenwalner, 1978). Starches with slow digesting property may be beneficial in preventing and controlling obesity and diabetes and other non-communicable diseases. After consumption, slowly digestible starch was found to release glucose more slowly for extended absorption, and latter digestion into the ileal part of the small intestine (Liu et al., 2006; Aprianita et al., 2009). Extended release and absorption of glucose can be a sustainable means of supplying energy to the body. It was shown that slowly digestible starches decrease initial rise in blood glucose and delay gastric emptying rate of diets through the ileal brake mechanism (Lee et al., 2013) (Figure 1.4).

Glucose release and absorption in the small intestine and associated health risks and problems are positively correlated to rate of starch digestion. Postprandial blood glucose excursion is termed glycemic response (Gropper et al., 2005) and its rapid and sharp initial peak are associated with diabetes, obesity and other related cardiovascular disease (Ludwig et al., 2002). Slowly digestible starch not only contributes to reduce and control glycemic response in people associated with diabetes, but also can help maintain better level of overall glucose homeostasis (Björck et al., 1994). Reduced risks of type 2 diabetes and obesity and other cardiovascular diseases may be associated with diets containing a high proportion of foods with low glycemic response (Roman et al., 2017, Zhang et al., 2009).

1.3.4 Relationship between food forms, and characteristics, and gastric emptying rate

An important food property that is associated to gastric emptying rate is the form in which food is ingested. Food is mostly ingested by human in solid or liquid form. Studies have shown that when food is ingested in liquid form, a sudden increase and sharp decrease were observed in blood glucose level. While, when ingested in solid form, a reverse phenomenon was noted in blood glucose levels (Ranawana et al., 2011).

1.3.5 Viscosity

Viscosity is defined as a material’s resistance to flow and is associated with gastric motility and satiety (Bourne, 2002). Highly viscous foods are thick and resistant to flow, thus, their passage through the stomach may be longer in duration than for less viscous foods. Sorghum and millet porridges are generally prepared and consumed in several forms that vary from solid (medium to very thick) to liquid (thin, with or without granules) (Cissé et al., 2018; Moussa et al., 2011). A recent study by Cissé et al. (2018) (Table 1.1) revealed that traditionally-prepared highly viscous millet and sorghum thick porridges have slow gastric emptying for moderated nutrient delivery, and this may be due to low starch degradation and less glucose release in the small intestine (Cissé et al., 2018; Hasek et al., 2018; Pletsch, 2017). Highly viscous African porridges may have the potential to combat diseases associated with the nutrition transition. Moreover, when Malian villagers moved to the city, they made less viscous millet and sorghum thick porridges that were less satiating (Diarra et al., 2018, unpublished). Thick porridges with slower starch digestion (Cissé et al., 2018; Pletsch et al., 2017) and good gelling properties (Moussa et al., 2011) should promote longer exposure to small intestinal ileal-located enteroendocrine L-cell receptors, which will increase feelings of satiety via the gut-brain axis and ileal brake mechanisms. Moreover, urban dwellers who consume thinner thick porridges may not respond as well to thick porridges in terms of slow gastric emptying and low glycemic response due to less L-cell response. In millet foods, elucidation of starch molecular dispersions and the relationship of starch with the food matrix could provide information on processing methods that retain these properties.

1.3.6 Particle size

Decortication, milling, grinding, and sieving are essential steps that are generally followed as grains are processed to produce flours of desirable particle sizes suitable for making cereal foods including *couscous* and porridges (Pletsch et al., 2017; Moussa et al., 2011; Aboubacar et al., 2006). Previous work revealed that particle size was inversely associated to starch digestibility and starch digestion rate in human (Edwards et al., 2015; Guo et al., 2017). Cereal foods made from flours of different particle sizes exhibited varying glycemic responses in humans (Pletsch et al., 2017; Mandalari et al., 2016; Edwards et al., 2015). It was asserted that, there may be a relationship between larger particle size of cereal-based foods, including millet and sorghum, and lower glycemic response in humans (Pletsch et al., 2017; Cissé et al., 2018).

1.3.7 Recent studies

Recent studies have shown that the high viscosity property attributed to millet and sorghum thick porridges could contribute to slow gastric emptying (Cissé et al., 2018). Results in Table 1.1 show gastric half-emptying and lag phase times (main study (n = 14), and a validation study (n = 6) from different food sources in Bamako, Mali.

1.3.8 Bioaccessiblity of provitamin A carotenoids, and relationship with digestibility

Bioaccessibility is termed as the proportion of carotenoids released from the food matrix during digestion and broken down into mixed micelles that are available for subsequent absorption by the intestine. Bioaccessibility is considered as the first step in total bioavailability and is seen as an indicator of absorption *in vivo* (Reboul et al., 2006). Carotenoid bioavailability is influenced by quite a number of parameters, and conditions, including food matrix, type and extent of processing and method of processing, and also the presence of lipid (Figures 1.5 and 1.6) (Lipkie et al., 2013, Maiani et al., 2009).

1.4 Final remarks

In West Africa, there currently exists interest and opportunity for expanding consumer markets for sorghum and millet foods. We believe that only through a mechanistic approach of supporting and backstopping grain processing entrepreneurship, and innovative grain processing technologies, can catalyze and effectively drive market expansion for locally grown crop-based foods, particularly those made from millet and sorghum. In addition, we are confident that a market-led nutrition model would contribute to improve nutritional status of at-risk populations, notably of vulnerable women and children. Such an approach would also dynamize and maximize ways of exploring and promoting increase of millet foods to attenuate obesity and diabetes in West African urban areas.

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Table 1.1. Gastric half-emptying and lag phase times [main study (n = 14); validation study (n = 6)] from different food sources (Taken from Cissé et al., 2018)**.**

Meal Type	Main Study Mean $T_{1/2}$ (h)	Validation Study Mean $T_{1/2}$ (h)	Main Study Mean T(Lag) (h)	Validation Study Mean T(Lag) (h)
Rice	3.1a ± 0.8	2.6a ± 0.3	1.7a ± 0.4	1.3a ± 0.2
Boiled potatoes	3.3a ± 0.4	2.9a ± 0.3	1.5a ± 0.2	1.5a ± 0.1
Pasta	3.4a ± 0.3	28.a ± 0.2	1.8a ± 0.2	1.2a ± 0.05
Sorghum thick porridge	6.1b ± 0.4	5.4b ± 0.4	3.4b ± 0.2	2.5b ± 0.04
Millet thick porridge	6.6b ± 0.6	4.5b ± 0.1	3.6b ± 0.3	2.1b ± 0.1
Millet couscous	7.5b ± 0.5	5.3b ± 0.1	4.5b ± 0.3	2.5b ± 0.1
Thin porridge with granules	4.2a ± 0.3	3.0a ± 0.2	2.4a ± 0.2	1.4a ± 0.1
Thin porridge without granules	4.4a ± 0.1	3.2a ± 0.3	2.2a ± 0.1	1.4a ± 0.1

Values ± SEM, standard error of the mean. For ab, and c, Means not sharing the same letter are significantly different ($p<0.05$, statistical analysis was done separately for solid and liquid test meals). $T_{1/2}$ = gastric half-emptying time; T(Lag) = lag phase.

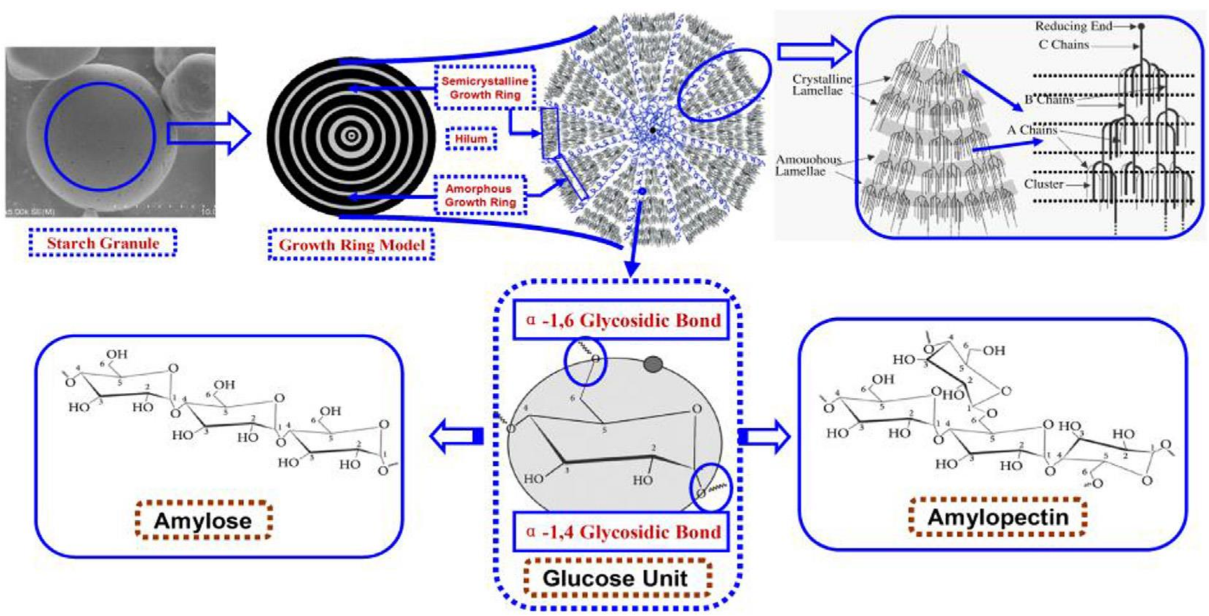

Figure 1.1. Schematic diagram of starch structure (Taken from Liu et al., 2017)**.**

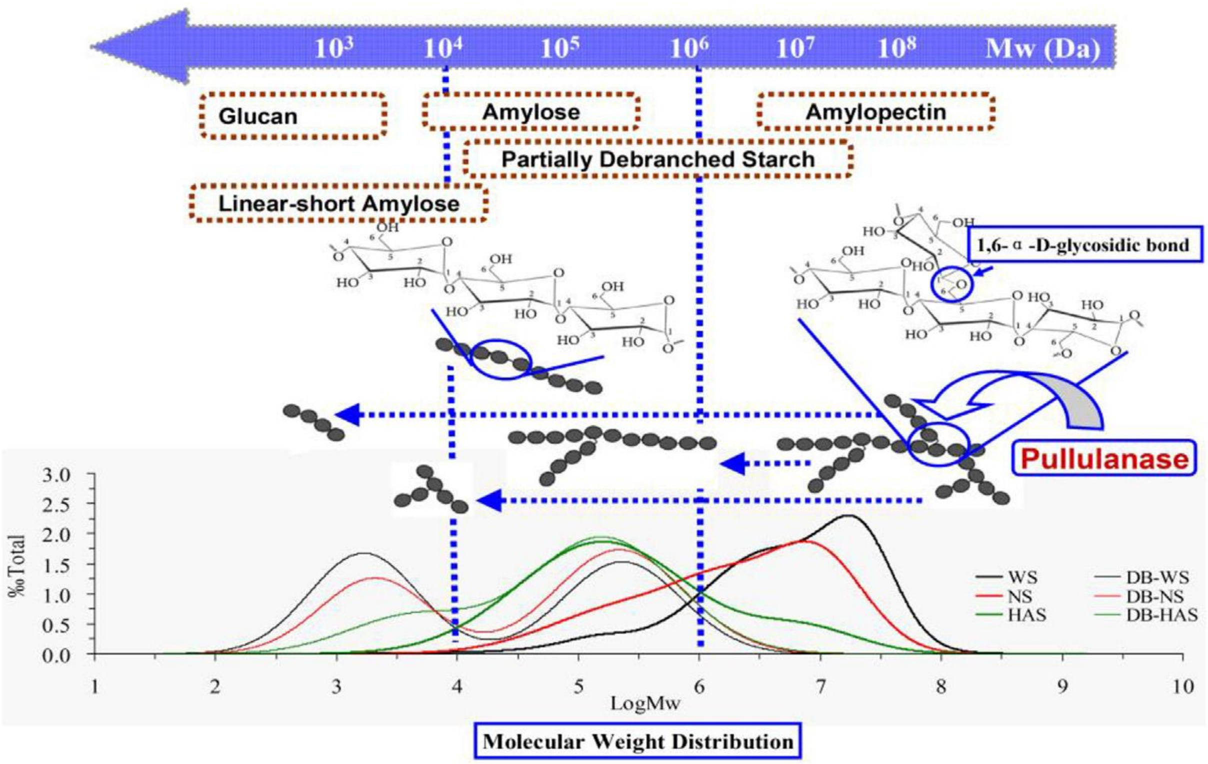

Figure 1.2. Schematic diagram of pullulanase hydrolysis and debranched starch composition. WS, waxy maize starch; NS, normal maize starch; HAS, high amylose maize starch; DB, debranched (Taken from Liu et al., 2017).

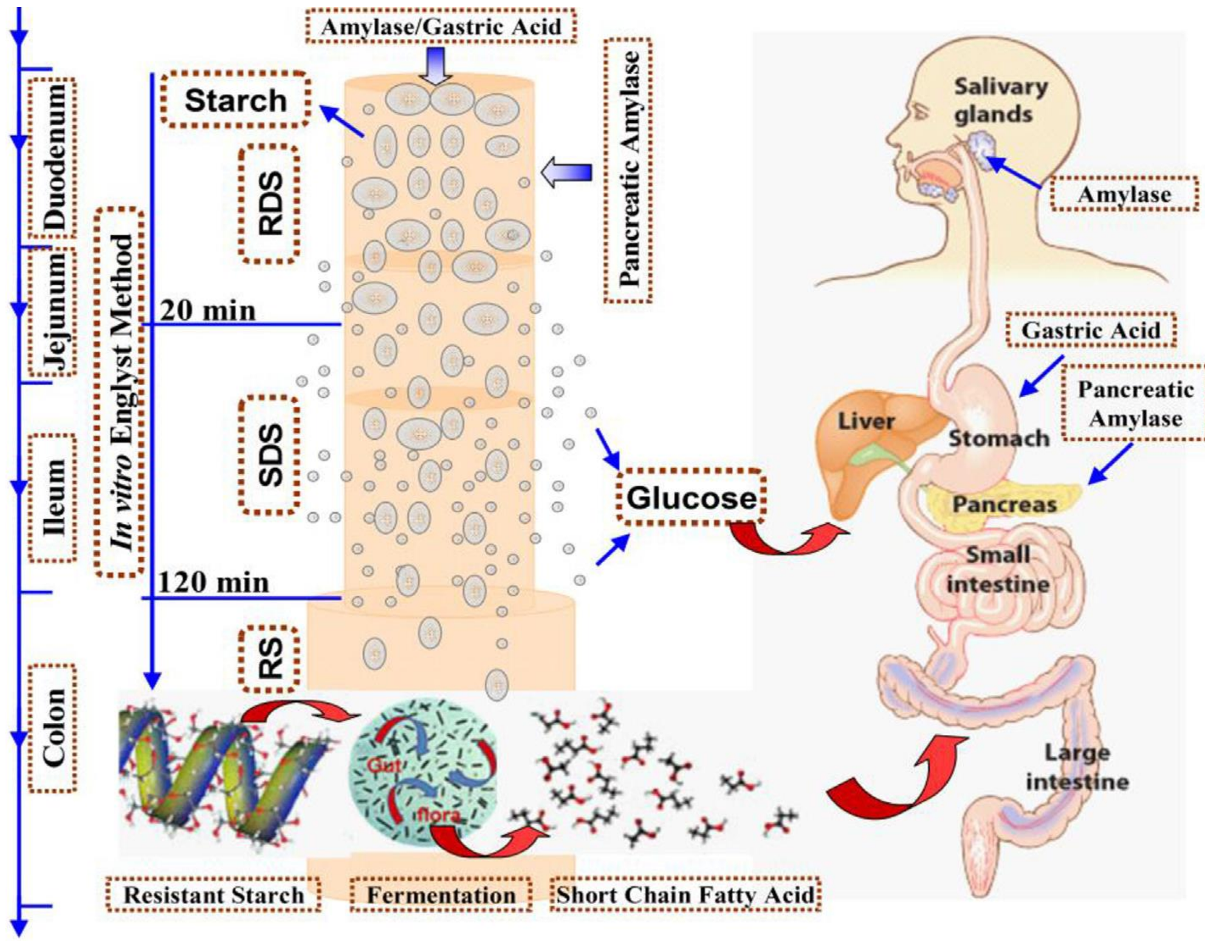

Figure 1.3. Schematic diagram of starch digestion in the human gastrointestinal tract. Approximate digestion times according to Englyst method are indicated. RDS, rapidly digestible starch; SDS, slowly digestible starch; RS, resistant starch (Taken from Liu et al., 2017).

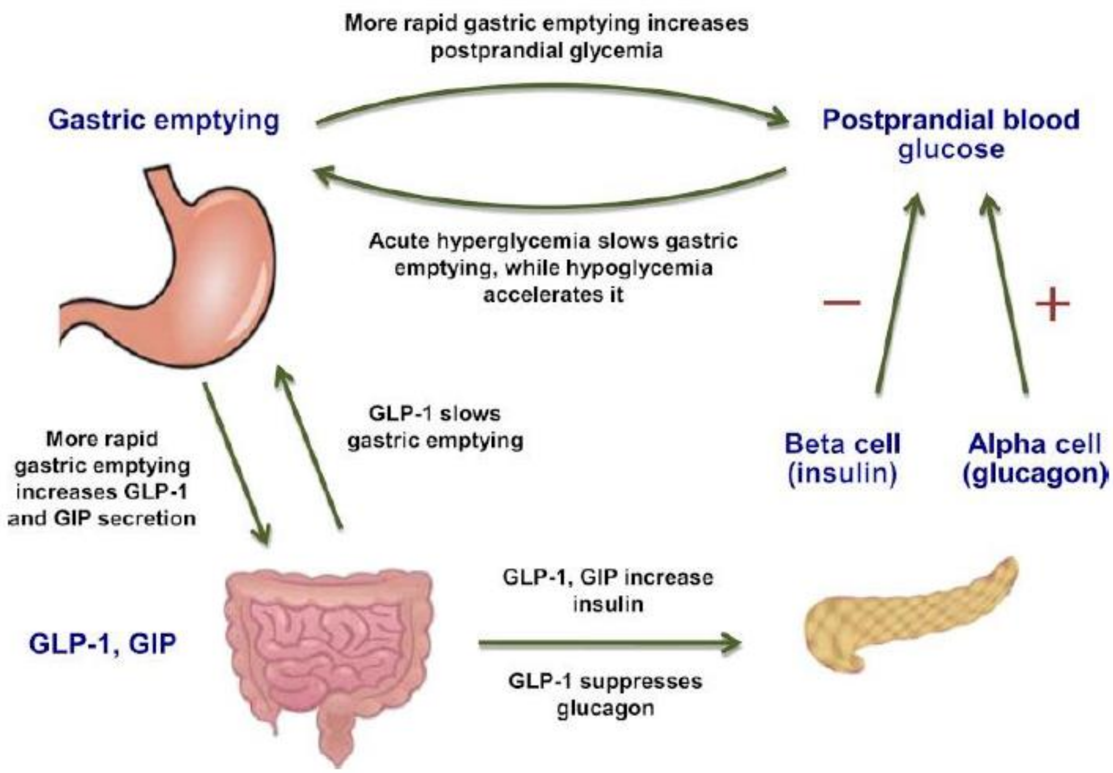

Figure 1.4. Relationships among gastric emptying, postprandial glycemic response, and incretin hormones (Taken from Marathe et al., 2013)**.**

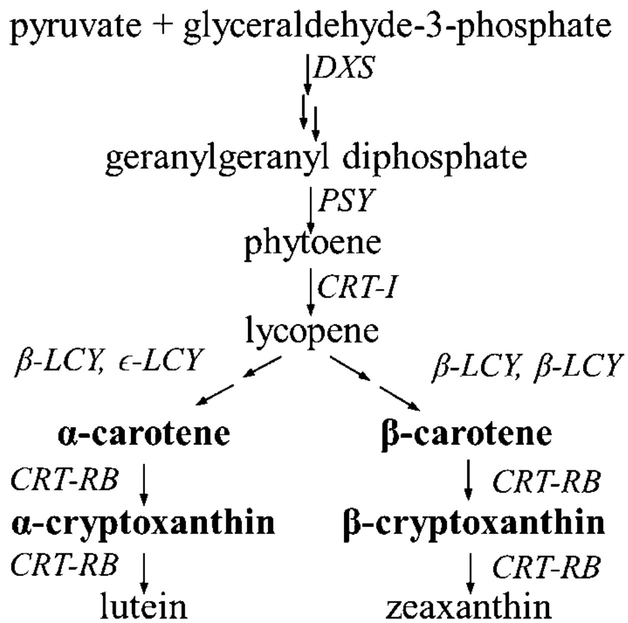

Figure 1. 5. **Overview of carotenoid biosynthesis** (From: Lipkie et al., 2013)**.**

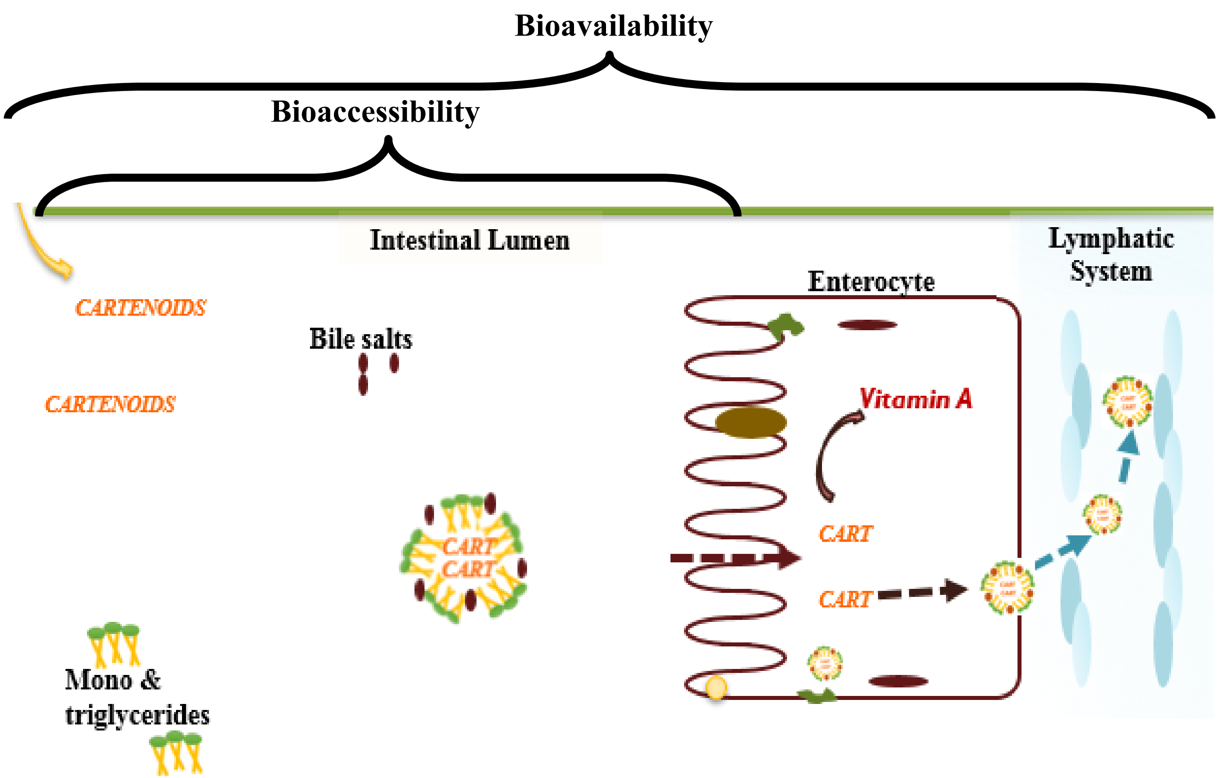

Figure 1.6. Bioaccessibility and bioavailability of provitamin A carotenoids (From: Debelo et al., 2017, Lipkie et al., 2013)**.**

CHAPTER 2. AN INNOVATIVE WAY OF MAKING MILLET *COUSCOUS* USING A SINGLE SCREW MINI-EXTRUDER FOR THE WEST AFRICAN MARKET

2.1 Abstract

Traditional West African preparation of millet (or sorghum) *couscous* is tedious and time-consuming, involving decortication, milling of the grain to flour, agglomeration, steaming, drying, and sieving steps. This study was conducted with the goal of developing a competitive and innovative process to make high-yielding extruded millet *couscous*.

Extruded millet *couscous* has the advantage of shortening process time. The products were designed for the preferences of local consumers and reconstituted by adding hot or tap water. The process had 10x the daily yield as *couscous* typically prepared for commercial sale by women in a processing unit. There were more starch fragments of somewhat lower molecular size in the extruded *couscous*, than in the control *couscous*, as illustrated by size-exclusion chromatography analysis of the hot-water dispersed starch.

A low-cost single screw mini-extruder (SSME) developed by engineers at Purdue University, which is located at the INRAN Niger Food Innovation Center was used for this study. Prior to extrusion, millet grains were decorticated to achieve 75-80% extraction, and separation of mainly starchy endosperm from bran. Decorticated grains were then washed and milled to flour of desired particle size ranging between 600-700 µm. Samples were equilibrated to a feed moisture content of 35% for 30 min at ambient temperature. Processing conditions of the low-cost single screw mini-extruder were assessed and optimized. Samples were processed using the SSME set at an adjustable frequency of 50 Hz. The temperature ranged from 125-140^0 C during use, and the screw speed was 870-875 rpm. Extrudate samples of 15-16% moisture were produced and further dried to 6-8% moisture using a gas drier set at 50^0 C. Dried extrudates were ground to flour of 500 µm particle-size. These conditions yielded a good quality extruded *couscous*, that falls within the range of desirable *couscous* particle size varying from medium (2 mm) to fine (1 mm).

Consumer sensory studies held in Niamey, Niger, showed that newly developed extruded millet *couscous* was as equally accepted as the traditionally-prepared *couscous*, though this was

dependent on selection of the proper millet variety. Thus, the SSME is an innovative way to obtain high yielding extruded millet *couscous*. Consumers in general preferred it and indicated that it was a fast cooking *couscous,* and that it had an appealing appearance, good taste and texture similar to the traditionally-prepared *couscous*. Size-exclusion chromatography analysis of the hot-water dispersed starch indicated the presence of a fraction of lower molecular size fragments. These results showed that yield of extruded millet *couscous*, in terms of amount produced per day, increased ten-fold over hand-prepared traditional *couscous* (i.e., amount made by 5 women hand agglomerating, steaming, drying and sieving *couscous*), making it a good option for commercial *couscous* processing.

2.2 Introduction

Sorghum and millet are the major staple foods for the majority of people in the Sahelian region of West Africa (with >80% smallholder's farmers in Niger). The adaptation of sorghum and millet to different agro-ecological zones, particularly semi-arid regions, and their suitability for a large range of foods makes them have a leading role in the region's food security. Annual grain production in 2017 for millet and sorghum averaged 9.13 and 12.67 million metric tons, respectively (FAO, 2017).

Previous work on sorghum and millet grain have contributed to development of processing technologies, including an agglomeration process for rolling *couscous* and related products (Aboubacar et al., 2006; Aboubacar and Hamaker, 1999), and continuous cooking for making instant flours in West Africa (Moussa et al., 2011). Results showed that consumers prefer processed local grains provided they have comparative overall acceptability as foods commonly consumed. There exist significant market opportunities for millet and sorghum products in urban and rural areas in West Africa.

Millets and sorghum grains have been found to have considerable potential to be used in processed foods. Millet foods including *couscous*, porridges and beverages are popular products in many African countries. Despite this, preparations of millet foods are manually-intensive and laborious processes that have low efficiency. Production is generally limited to household use and limited amounts of ready-to-use or instant foods are available in marketplace.

Couscous is described as a popular pasta-like agglomerated and steamed product made from cereal flours. Production steps for the traditional method include milling grain into flour, mixing flour with water, and agglomerating the flour-water mixture into *couscous* granules by hand rolling, steaming and drying. Readily available *couscous* commonly found in urban market includes North African type *couscous* made from wheat flour (Yüksel et al., 2017; Aboubacar et al., 2006; Galiba et al., 1988). In contrast, a minor amount of similar commercial *couscous* made from sorghum and millet, often less consistent and of low quality, is now found in urban markets in West Africa. This is mostly due to the tedious and time-consuming step of flour agglomeration into granules, which constitutes the most critical step in *couscous* processing of sorghum and millet. This step was partially mechanized in West Africa with the fabrication of three types of mechanical flour agglomerators. However, this processing still includes several laborious and time-consuming steps. In previous years, quite a number of attempts were made to produce wheat-based pasta type *couscous* using extrusion technologies. Results showed the potential of making an extruded wheat-based *couscous* of uniform size and with an appealing yellow color and a high degree of starch gelatinization (Celik et al 2004; Debbouz and Donnelly, 1996).

On the other hand, little or no work has been done on the use of millet and sorghum grain in extrusion processes to make agglomerated *couscous* and related products. Extrusion cooking is currently considered among the most popular, cost-effective, and efficient technologies used in grain processing. Extruded products include snacks, breakfast cereals like instant porridges and expanded products, and infant and baby foods (Zhang et al, 2014; Moussa et al., 2011). Extrusion processing has a potential to produce a wide range of products with a varied degree of cooking, from less to fully cooked products (Gonzalez et al, 2013). Extrusion technology allows for high production of grain-based foods and with capability to incorporate fortificants, whether natural nutrient-rich plant materials or synthetic vitamin and mineral premixes. Extrusion technology improves grain processing capacity and scale up, and makes uniform desirable nutritious products that are safe and of high quality to capture consumer markets (Bouvier and Campanella, 2014).
The objective of this study was to develop a new extruded millet *couscous* process, to test and evaluate processing and physico-chemical parameters, and to test consumer acceptability compared to millet *couscous* made using the traditional hand-rolling method.

2.3 Materials and methods

2.3.1. Materials

Six (6) millet varieties naturally high in iron and zinc, comprised of *Icritabi*, *GB*, *Sosat*, *Jirani*, *94206*, *221* and one (1) local control (*mil local*), were used in this study. They were selected by ICRISAT and INRAN scientists and grown on farm in Falwel, Dosso, Niger by the Moribeen farmers group during the summer of 2016.

2.3.2. Methods

2.3.2.1 Extrusion of millet samples

Preliminary experiments were conducted to determine instrumental settings necessary to produce good quality product with the single screw mini-extruder (Insta-Pro, Technochem International, Inc., Boone, IA, USA). Process variables included rotating speed, temperature, and moisture content of feed flour. Prior to the extrusion process, millet grain samples were decorticated to achieve between 75-80% extraction level (grain endosperm separation from bran). Decorticated millet grains were then washed and ground to grits of desired particle size ranging between 600-700 µm using a hammer mill. Samples were then equilibrated to feed moisture, which varied between 20-40%, for 30 min at ambient temperature. The single screw extruder was appropriately set up to run at a temperature that varied between 115-140^0 C, and at a frequency of 50 Hz. Speed was adjusted between 700-900 rpm. Equipment was then run to produce the various millet extrudate samples. A conventional *couscous* sample (control) was prepared using a method previously described (Aboubacar et al., 2006; Aboubacar and Hamaker, 1999).

2.3.2.2. Color of *couscous* sample

Couscous color was determined using a Hunter Lab Colorimeter (Model D25, Hunter Associates Lab, Inc., Virginia, USA). After calibration of the colorimeter with standard black and white tiles, *couscous* samples were placed in a 5.5 cm cell with an optically transparent glass bottom and CIE Lab scale, readings were taken. The parameters determined were L*, a* and b* (L* value as the lightness, a* value the red-greenness, and b* value the blue-yellowness).

2.3.2.3 *Couscous* moisture content

Moisture content of 1g of conventional and instant millet *couscous* was measured in 3 min, and at a temperature of 130^0 C using an HE53 Moisture Analyzer (Mettler Toledo, Greifensee, Switzerland).

2.3.2.4 *Couscous* particle size distribution

Flour particle-size distribution was determined by air-sifting 20 g of flour for 3 min on an air jet sieve (Alpine, Natick, MA) using U.S. standard sieves (250 μm opening) and U.S. no. 120 (125 μm) sieves. Flour was separated into fine (<125 μm), intermediate (125–250 μm), and coarse (>250 μm) fractions.

2.3.2.5 Texture analysis of *couscous* samples

Texture measurements of final *couscous* products were performed using a texture profile analyzer (TPA) (TA-XT2 Texture Analyzer, Texture Technologies Corp., Scarsdale, NY). Freshly cooked *couscous* (15-20 g) was weighed in a small plastic petri dish filled to the top. Test speed to set was to 1.0 mm/s and distance parameter was set to 6 mm until *couscous* was compressed to 6 mm from the point of contact with the probe. Test time was set to 5 seconds between strokes. Hardness values were obtained from TPA. Measurement was taken four times for each *couscous* sample.

2.3.2.6 High-performance size-exclusion chromatography

Chromatography size distribution profiles of debranched starch of *couscous* samples was performed in duplicate using a high-performance size exclusion chromatography (HPSEC) system (Agilent 1260 series, Agilent Technologies, Waldbronn, Germany) equipped with a refractive index detector (RID) (RID-10A, Shimadzu, Kyoto, Japan).

Eight (8) mg of each processed millet *couscous* sample (ground finely using a hammer mill with screen opening of 500 μm) were dissolved in 1.5 mL pure DMSO containing 0.5% (w/w) lithium bromide (DMSO/0.05% LiBr) at 80 °C for 24 h in a Thermomixer (Eppendorf, Hamburg, Germany). Samples were then precipitated twice with absolute ethanol (10 mL) and re-dissolved in 0.9 mL warm deionized water for 15 min in a boiling water bath. Thereafter, samples were cooled to room temperature and mixed with the following, in sequence, to facilitate the debranching reaction: 5 μL sodium azide solution (40 mg/mL), 0.1 mL acetate buffer (0.1 M, pH 3.5), and 2.5 μL isoamylase (E-ISAMY, Megazyme, Wicklow, Ireland). The reaction was carried out for 3 h at 37 °C. In order to terminate the reaction, the enzyme was inactivated by neutralizing the resulting debranched starch dispersion to pH 7 with 0.1 M NaOH solution followed by heating at 80 °C in a Thermomixer for 1 h. Debranched starch samples were then freeze-dried, dispersed in 1 mL DMSO/0.05% LiBr, transferred into SEC vials, and injected into GRAM 100 and 1000 columns (PSS GmbH, Mainz, Germany) connected in series. The columns provided separation in the range of 100 to ~10^6 Da. Injection volume, flow rate, and temperature of samples injected were 100 μL, 0.3 mL/min, and 80 °C, respectively. The size distribution of debranched starches was plotted as SEC weight distribution, w(logV_h) [V_h = hydrodynamic volume, determined from hydrodynamic radius], derived from refractive index detector (RID) signals against R_h (hydrodynamic radius). The Mark-Houwink equation was used to calculate the degree of polymerization (DP) of linear branches from V_h (Vilaplana and Gilbert, 2010).

2.3.2.7 Sensory testing

Sensory testing was conducted in Niamey, Niger with assistance from the INRAN staff and according procedures described by Moussa et al. (2011). A hedonic preference test with a nine-point numeric scale (9=like extremely, 1=dislike extremely) was used to evaluate the extruded *couscous* samples compared to conventional prepared *couscous* control samples. Thirty-five panelists were provided with a copy of the sensory questionnaire and water. They were instructed to go over the questionnaire and rinse their mouths before testing each sample. Data collected included socio-economic/ gender, and organoleptic acceptability (color, taste, texture, flavor/odor).

Couscous samples were prepared using 6 varieties from extruded millet flours samples. A comprehensive questionnaire was used to collect information related to socio-economic factors (income, willingness to buy extruded *couscous*, food preferences, gender, age and education level) and organoleptic preferences (taste, color, texture, flavor, and overall liking).

2.3.2.8 Statistical analyses

Mean values for physicochemical and sensory testing, as well as process performance, were determined and compared to local controls using ANOVA by Genstat and GMP 12 (statistical software packages) at the 5% significance level.

2.4. Results and discussion

This is the first demonstration that a small low-cost single screw extruder can be used to process high-quality millet (and sorghum) *couscous* in West Africa, that is also competitive in consumer preference tests to high quality traditionally-prepared millet *couscous*. Because this extruder is fairly simple in its operation, and is robust and dependable, there is a growing interest from entrepreneurs in the Niamey area to purchase it. A ten-fold increase (> 300 kg/day for extrusion process versus 30kg/day for conventional manual process) in production of consistently high-quality millet *couscous* over the conventional manual processing method is projected to yield commercial revenues that would make the extruder a reasonable investment for an entrepreneur processor or financial institution.

Figures 2.1 and 2.2 show flow charts of steps involved in processing millet grain to *couscous* using traditional and extrusion methods. Figure 2.1 illustrates the most tedious and time-consuming steps used to make traditional *couscous*, which are performed manually and take up to two days before producing a final *couscous*, which is often of inconsistent quality and limited in quantity. Using single screw extrusion, most of the tedious steps of making millet, were shortened. The process that was hereby designed produces a high-quality millet *couscous* that is equal to the traditional product and preferred by local consumers. Sensory tests showed the extruded product to have better texture – less hard and with more stable and smoother granules than the traditional, handmade, millet *couscous*. The innovative millet *couscous* is reconstituted just by adding hot or tap water. It had 10x the daily yield as *couscous* typically prepared for commercial sale by women in a processing unit (> 300 kg/day for extrusion process versus 30 kg/day for conventional manual process). In addition, other advantages of the *couscous* extrusion process include a large product range, no effluents produced during the process (smoke, waste).

The conditions of single screw extrusion including temperature, frequency, speed, and feed moisture were determined for processing of different millet varieties to instant flours for making *couscous*. Results (Table 2.1) show that maximum extruded product recoveries (97%) were obtained for millet varieties Mil de Siaka and Icritabi at about the same temperature (130 and 128 ºC) and speed (874 and 875 rpm). An adequate feed moisture content of 35% was found for acceptable degree of cook and with no interruption of extrusion operations. A similar value was previously reported (Moussa et al., 2011) as optimum for extrusion of sorghum and millet grain-based materials. Moisture content of millet extrudates soon after extrusion varied between 14-15%. Final moisture of millet extrudates after additional drying with a gas dryer, set at 55℃, ranged between 6-8% in less than 8 h of drying.

Optimization of the extruded millet *couscous* product was done to improve final product quality (texture, taste, color) and the efficiency of the equipment. This resulted in an important shortening of the grain tempering time from 24 h to 30 min with additional energy savings due to not having to refrigerate the grain samples.

2.4.1. Yield of *couscous*

The mini-single screw extruder produced 10x more product (~300 vs. ~30 kg/day) than millet (or sorghum) *couscous* made from the conventional and traditional manual method (Figure 2.3). While the traditional preparation by women takes 1-2 days in the village (or sometimes even longer) as indicated by flow sheet in Figure 2.1, steps, including, hands decortication, milling, mixing, agglomeration, steaming, sieving, and drying are tedious, time consuming, and final product is generally of low quality. The new process for making instant millet *couscous* reduces most processing steps, as shown in the flow chart (Figure 2.2), and allows for much higher daily production in a small processing enterprise than conventionally-made *couscous*.

2.4.2 Moisture content of *couscous* samples

Moisture content results for extruded *couscous* samples made from different millet varieties ranged from 6.3-7.7% (Table 2.2**)**. These values are within acceptable ranges similar to dried commercial cereal foods, even though they were higher than the control conventionally-prepared millet *couscous* which had low moisture content due to over sun drying for several days. Note that the moisture content of the extruded samples at 14-15%, required drying to <10% using a gas dryer for less than 8 h.

2.4.3 Particle size distribution

In Niger, consumers, whether urban or rural, prefer *couscous* with small to medium granule particle size, ranging between 1-2 mm. Thus, making extruded milled products with higher amounts of small to medium granule particle size fraction is of higher value to a processor. In contrast**,** overs remaining on the large size screen sieve (>2 mm), and passing through small size (<1 mm,), were not considered as desirable *couscous* by consumers (Aboubacar et al., 2006; Aboubacar and Hamaker, 1999) although it could still be consumed with milk as beverage. Particle size distribution of millet *couscous* samples made from different varieties is shown in Table 2.2. Varieties that yielded the highest amount of the largest particle size (>2 mm), and smallest (<1 mm) were less desirable. Extruded *couscous* of millet varieties showed variable particle size distributions with higher yield size particle (1.68 mm) in a range of (67.4-33.5%) and fell within range of desired particle sizes of millet *couscous*. Conventionally-prepared control millet *couscous* had the lowest fraction (13.4%) of the 1.68 mm and highest fraction of the smaller 1 mm fraction (64.6%) that combined had a high amount of the desired small particle size. Some extruded samples had appreciable *couscous* particles in the small particle size range of 1 mm [Icritabi (43.2%), 221 (32.2%), and 94206 (32.3%)], desired by consumers and showed a dependence on variety type. Lowest yield of undesirable *couscous* of particle size <1 mm was found with Jirani (13.3%) and GB (10.6%), while highest values of *couscous* of particle size <1 mm include, 221 (28.3%), 94206 (28.3%), Icritabi (23.0%), and the conventional control (22.0%). Undesirable *couscous* of particle size >2 mm was mostly absent in the majority of *couscous* samples. Previous work on sorghum *couscous* (Aboubacar et al., 2006; Aboubacar and Hamaker, 1999) revealed that acceptable *couscous* particle size range between (1-2 mm) showed that *couscous* quality is mainly associated with parameters as flour particle size distribution and damaged starch content.

2.4.4 Color of *couscous* samples

In general, extruded *couscous* samples made from different millet varieties had higher L^*(36.5-

43.5) values than conventionally-prepared *couscous* (27.7) (Table 2.3**)**. On the other hand, extruded *couscous* a^*(1.1-1.9) values were lower than those of their corresponding conventional *couscous* (3.7). There were significant differences in b^* values among most extruded *couscous* samples compared to the conventional one. Values for b^* ranged for extruded samples from 17.0-11.5, compared to 14.9 for the conventional one. Thus, extruded *couscous* samples appeared whiter than the corresponding conventional ones and this is a desirable attribute both for the consumer and processor. Variation of *couscous* color is consistent with results reported from previous works (Aboubacar et al., 2006; Singh et al., 2007). They reported that changes in L*, a* and b* values may be attributed to the difference in color and type of respective grain endosperms, and the extent of bran removal or extraction level, though, other causes may also include processing parameters.

2.4.5 Texture measurements

The most desirable *couscous* is soft and not sticky. Values obtained indicate that extruded *couscous* sample were soft, palatable, and tender compared to the traditionally prepared one. These qualities are very important to the consumer. Hardness profile is defined (Ays et al., 2017) as the maximum height of the peak of the first compression cycle (first bite). Texture profile curves (Figure 2.4) representing *couscous* textural characteristic indicate that extruded *couscous* samples have lowest peaks of hardness (green curve) versus conventional *couscous*, characterized with the highest peak (red curve). Such a change in textural characteristics in *couscous* samples may be partly due to differences in the processing methods used. Feed moisture and screw speed in combination with temperature were found to have a significant ($P < 0.05$) effect on the hardness. (Bouvier and Campanella, 2014; Yang et al, 2008; Smith et al., 1992).

2.4.6 SEC patterns of conventional and extruded *couscous*

Size-exclusion chromatography patterns of debranched starch isolated from extruded and conventional *couscous* are shown in Figure 2.5. Peak area [w(logVh), indicating SEC distribution versus degree of polymerization] for extruded *couscous* was reduced compared to conventional *couscous*. This indicates process-induced amylopectin fragmentation caused by extrusion process. Similar studies on other grain types, including rice, showed that during extrusion cooking, starch (mainly amylopectin) undergoes degradation (Zhang et al., 2014; González et al., 2013). It was also asserted that such a starch fragmentation may be responsible for smoother and stable texture observed for the instant sorghum foods (Moussa et al., 2011) and for tender and smoother mouthfeel texture observed when instant *couscous* made from this study were consumed.

2.4.7 Sensory evaluation

Consumer acceptability of extruded millet *couscous* in Niamey showed it to compete well against local traditionally-prepared millet *couscous*, though this was dependent on the type of millet variety used in making the *couscous*. Results (Figure 2.6) indicate that millet *couscous* consumption frequency differed between male and female consumers in urban Niamey. Most males consumed millet *couscous* 3 times/week, while females consumed *couscous* 2 times/week. Sensory studies held in Niamey showed that the newly developed extruded millet *couscous* was accepted equal to the traditionally-prepared *couscous.* Extruded *couscous* made from variety 221 received a hedonic score of 7.5/9, almost similar to that obtained by the traditional control *couscous* (7.7/9). Extruded *couscous* made from SOSAT received a hedonic score of 6.5/9, which was slightly lower but still acceptable. Millet varieties with better ability of making foods will likely give better extruded *couscous*, and that quality and acceptance of the extruded *couscous* was dependent on selection of the proper millet variety. Figure 2.8 shows the “Weight Estimate of Consumers Preference of *Couscous* Characteristics”, including taste, texture, color, and odor. Most subjects based their choices for preferences on the four sensory characteristics with fairly similar weight, and importance.

2.5 Conclusions

Using a single-screw low cost extruder technology, production of highly acceptable millet *couscous* achieved a production rate of 10x higher yield than that made by the traditional manual process . In addition, extruded *couscous* had higher number of small and medium-sized *couscous* particles desired by consumers. This study revealed the potential for developing and diversifying extruded millet *couscous* using the extrusion technology. Availability of this technology would also enhance diversification and uses of local grains and would create a bigger market for smallholder’s farmers to sell their surplus grain, and at the same time, increasing women and other entrepreneur’s income in West Africa. The use of extrusion in processing millet and sorghum grain would give the urban populations access to higher quality and desirable processed foods with similar convenience to other alternatives and at more affordable prices, and capable of meet the changing demands of local consumers in West Africa

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Table 2. 1 Table 2.1 Varietal differences in millet grain processing capacity and conditions of the single screw extruder**.**

Millet Varieties	Initial Grain (kg/h)	T (ºC)	Speed (RPM)	Extrusion Output (kg/h)	Product Recovery (%)
ICRI TABI	36	130	874	34.8	97
9SOSAT	36	138	875	33.6	93
89305	36	131	875	31.8	88
99001	36	130	875	31.2	87
PPBSerkin H	36	128	872	31.2	87
MIL DE SIAKA	36	128	875	34.8	97

Note : Differences in product recovery was partly caused by differences in varieties and grain quality

Table 2.2. Particle size distribution of millet *couscous* samples made from different varieties and compared to a conventionally-prepared *couscous* product (% of particle size fraction that are above the mesh size) and moisture content (%).

Couscous Samples	*>2.0mm*	*1.68mm*	*1mm*	*<1mm*	*Moisture (%)*
Control (conventional)	-	13.4^{c}	64.6^{a}	22.0^{b}	2.8^{d}
Extruded (94206)	-	39.5^{b}	32.3^{b}	28.3^{a}	6.8^{bc}
Extruded (Sosat)	-	61.6^{a}	19.1^{c}	19.3^{c}	7.3^{ab}
Extruded (GB)	0.53	67.4^{a}	21.5^{c}	10.6^{e}	7.7^{a}
Extruded (Jirani)	0.05	67.0^{a}	19.6^{c}	13.3^{d}	6.8^{bc}
Extruded (Icritabi)	0.34	33.5^{b}	43.1^{b}	23.0^{c}	7.1^{ab}
Extruded (221)	-	39.6^{b}	32.1^{b}	28.3^{a}	6.3^{c}

Corresponding mesh size:>2.0 mm 1.68 mm, 1 mm, < 1 mm. Values are means of triplicate determinations. Different superscripts within columns indicate significant differences ($P<0.05$, Duncan's Multiple Range test).

Table 2.3. Color of millet *couscous* made from different varieties and compared to a conventionally-prepared *couscous* product.

Couscous Samples	*L**	*a**	*b**
Control (conventional)	27.7^{d}	3.7^{a}	14.9^{b}
Extruded (94206)	36.7^{c}	2.0^{b}	14.1^{bc}
Extruded (Sosat)	39.6^{b}	1.8^{b}	14.3^{bc}
Extruded (GB)	42.3^{ab}	1.6^{b}	13.5^{c}
Extruded (Jirani)	41.7^{ab}	1.1^{c}	11.5^{d}
Extruded (Icri tabi)	41.3^{ab}	2.1^{b}	14.3^{bc}
Extruded (221)	43.5^{a}	1.9^{b}	17.0^{a}

L*= black (0) to white (100), a*=green (-) to red (+), b*= blue (-) to yellow (+). Values are means of triplicate determinations. Different superscripts within columns indicate significant differences (P<0.05, Duncan's Multiple Range test).

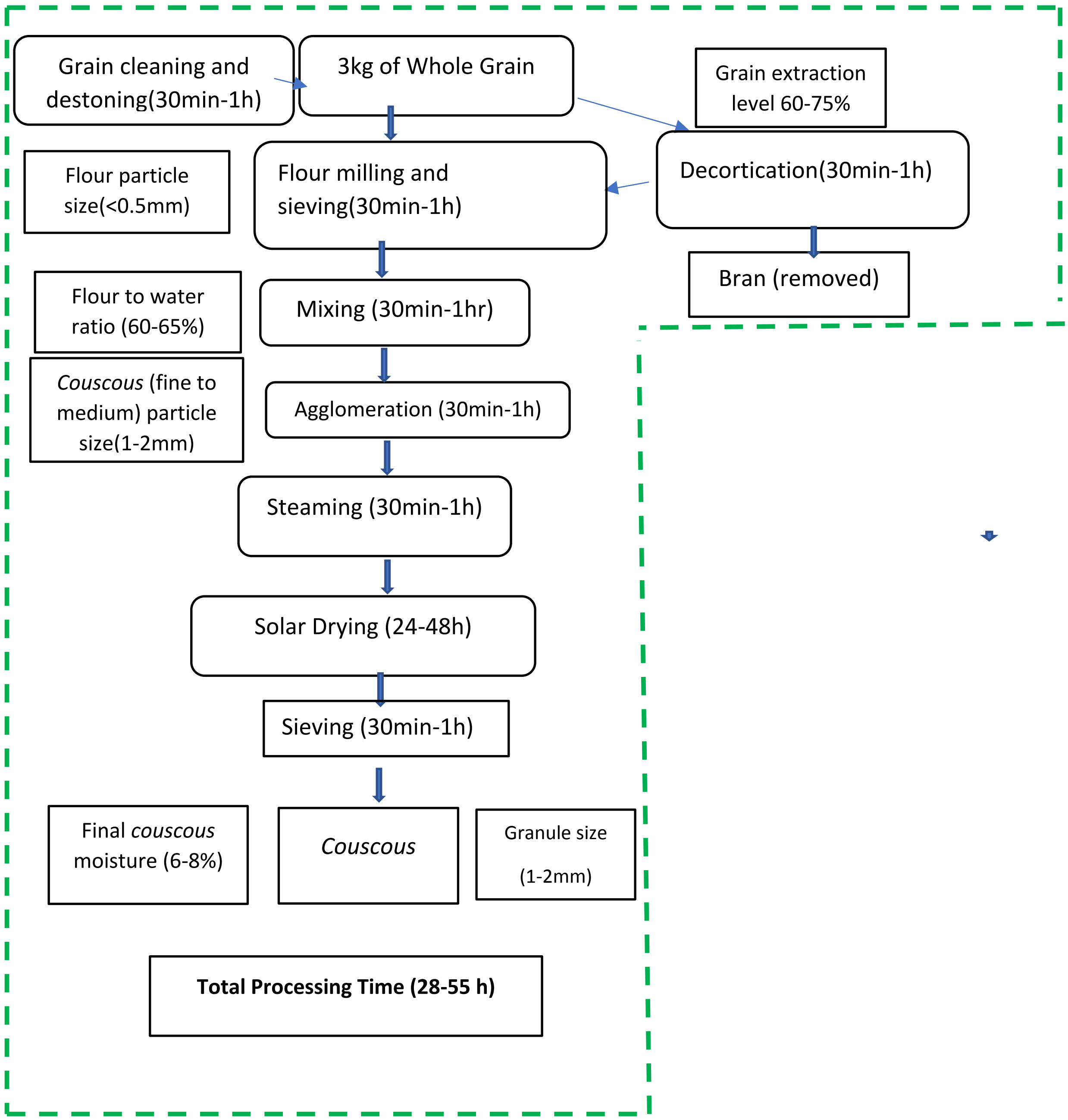

Figure 2.1. Flow chart of traditional grain processing for making millet *couscous*.

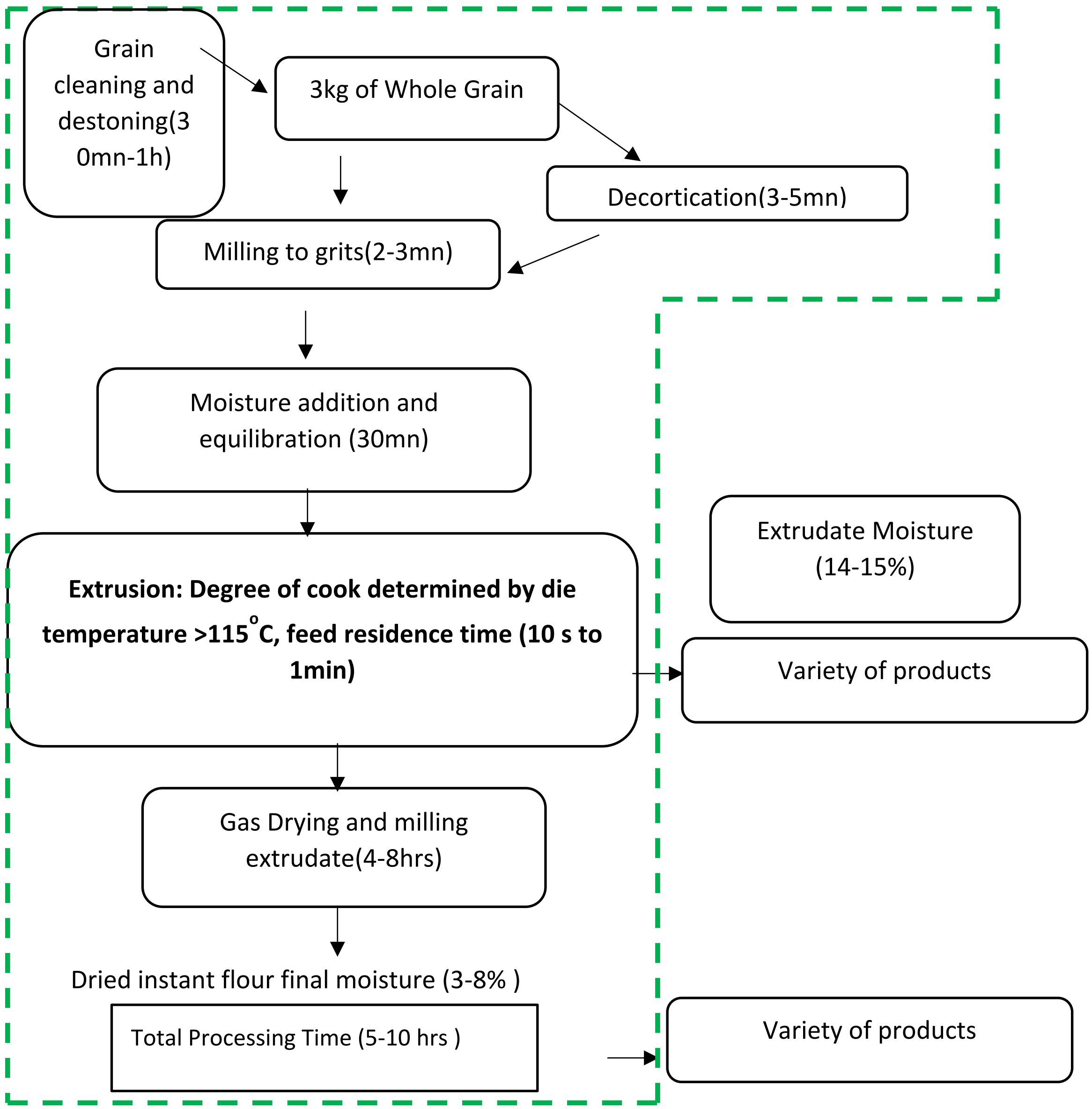

Figure 2.2. Flow Chart of processing millet grain to instant *couscous*, and variety of other food products using a single screw extrusion method.

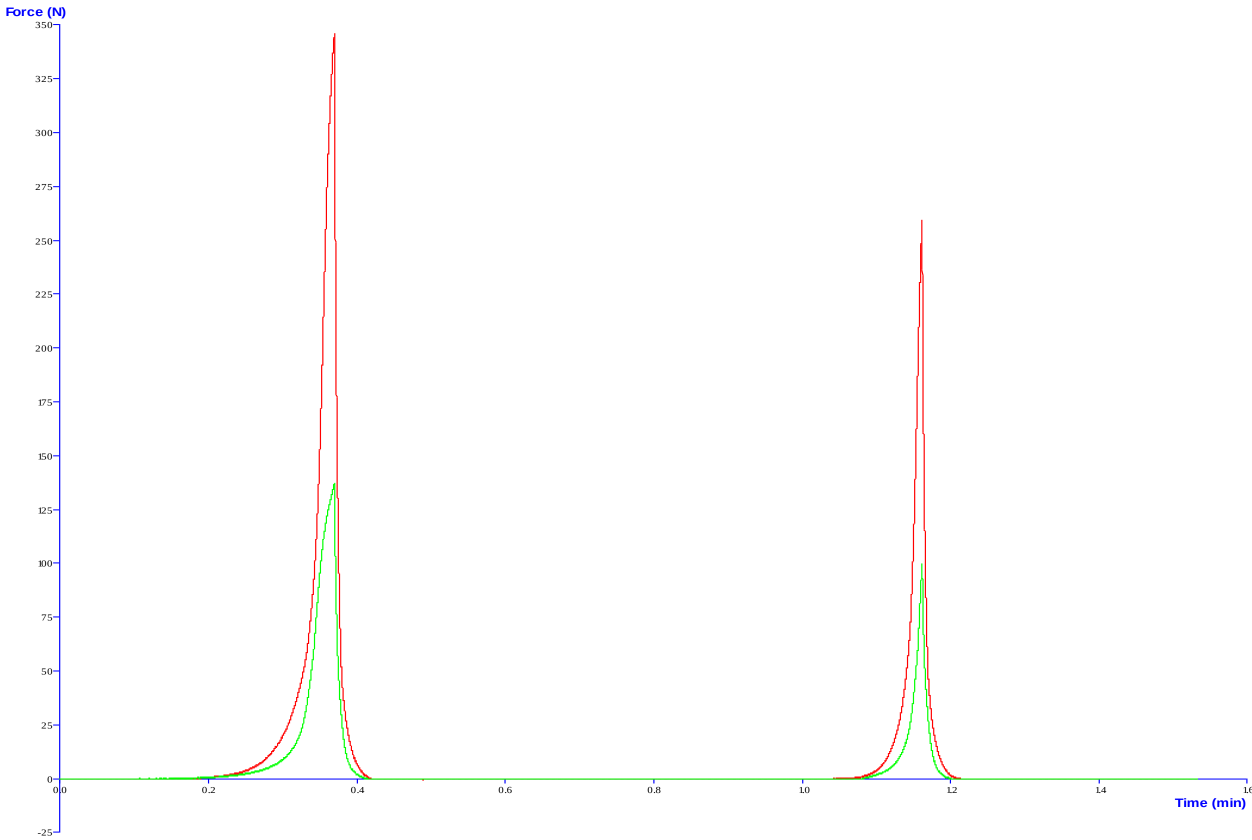

Figure 2.3. Texture profile analysis plot showing the hardness of extruded millet (variety 221) *couscous* (green line) versus conventional local millet *couscous* (red line). Values are means of triplicate determinations. Note: Texture analyzer conditions: 50 kg load cell, 75% strain, test speed 0.5mm/s; 50g trigger force.

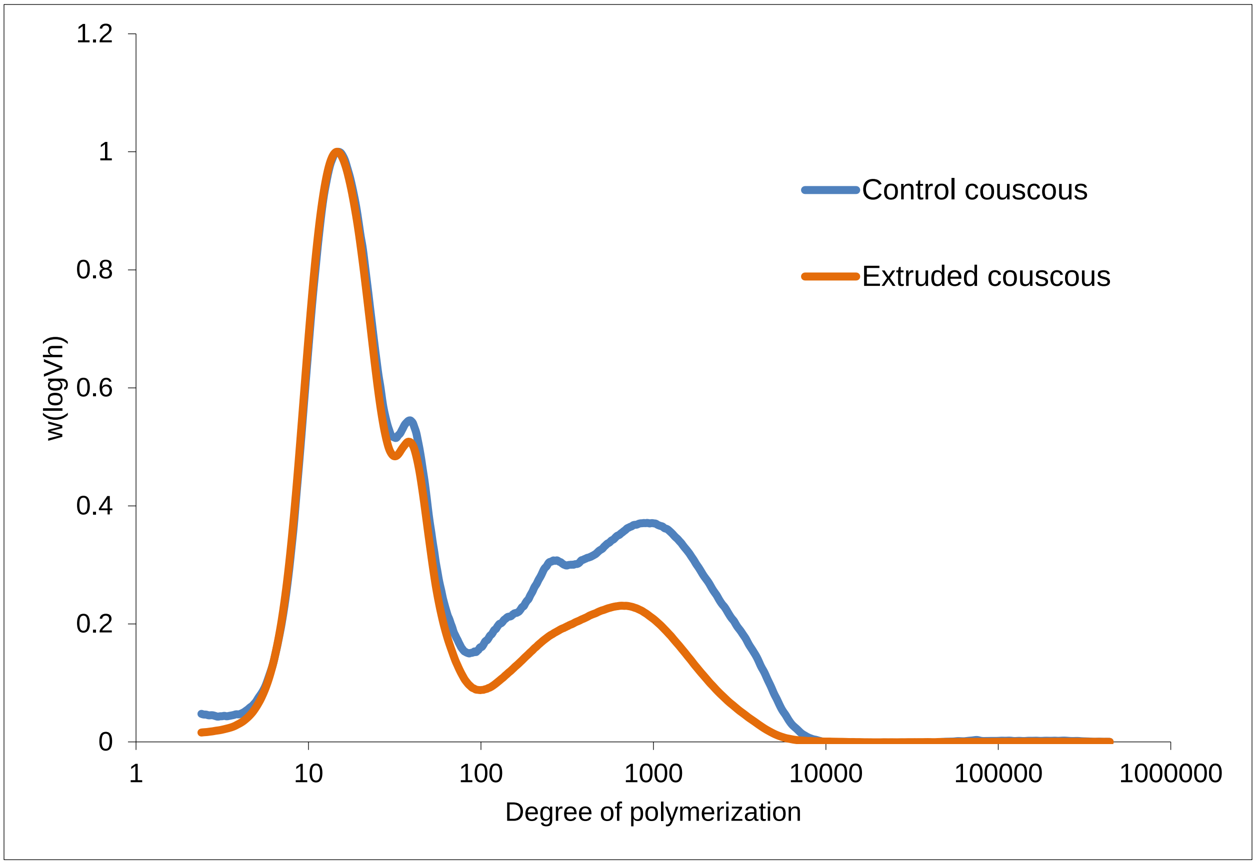

Figure 2.4. Size-exclusion chromatogram (size distribution [w(logVh)] versus degree of polymerization) patterns of debranched starch from *couscous* samples. Extruded *couscous* (millet variety 221) shown in orange, and conventional local millet *couscous* shown in blue.

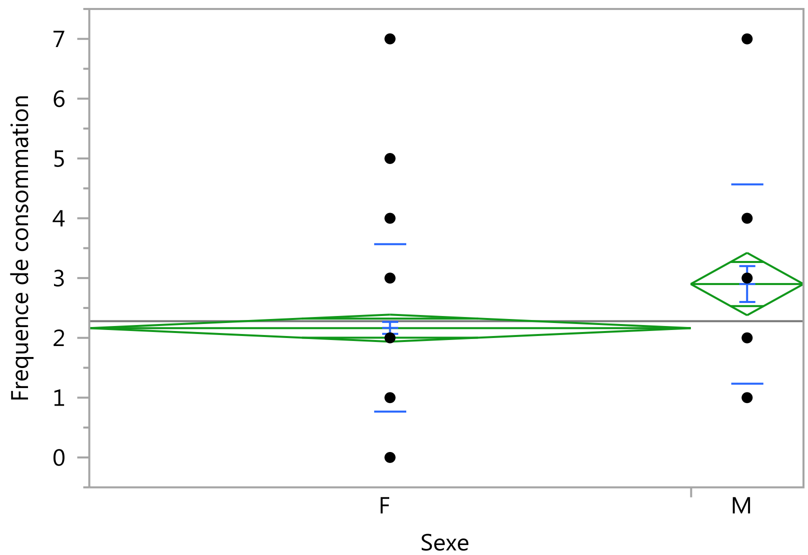

Figure 2.5. *Couscous* consumption frequency between males and females consumers in Niamey (male= 3 times/week and female=2 times/week). Values are means of panelist scores analyzed at P<0.05.

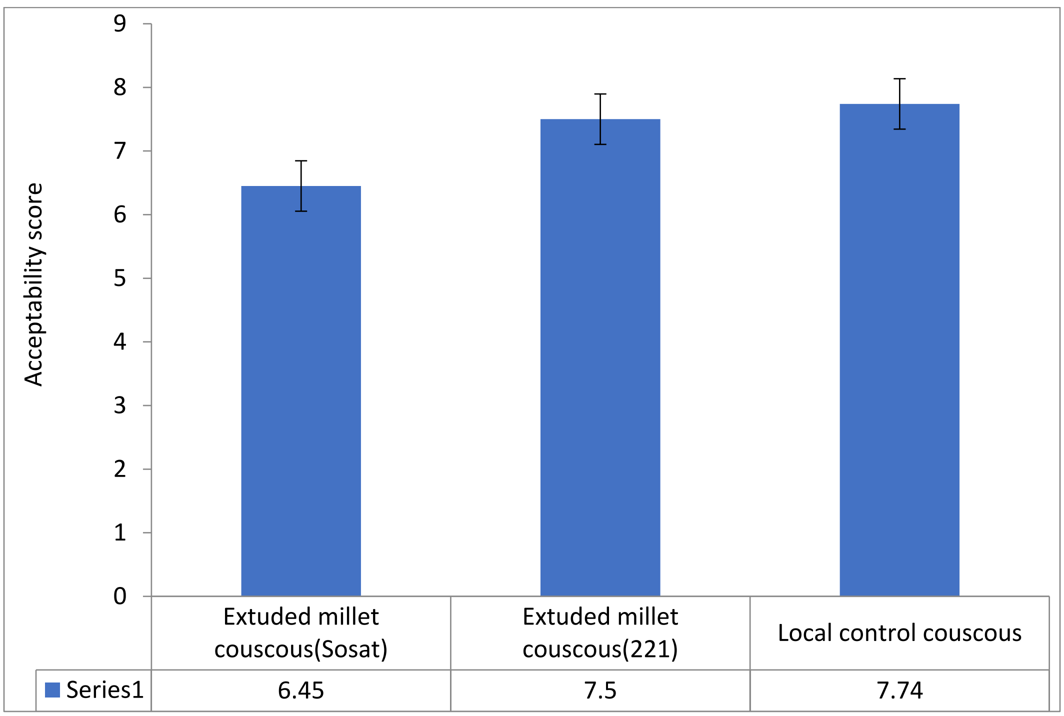

Figure 2.6. **Consumer acceptability/perception of extruded millet *couscous* versus local control *couscous* in Niamey urban City**. Values are means of panelist scores analyzed at P<0.05.

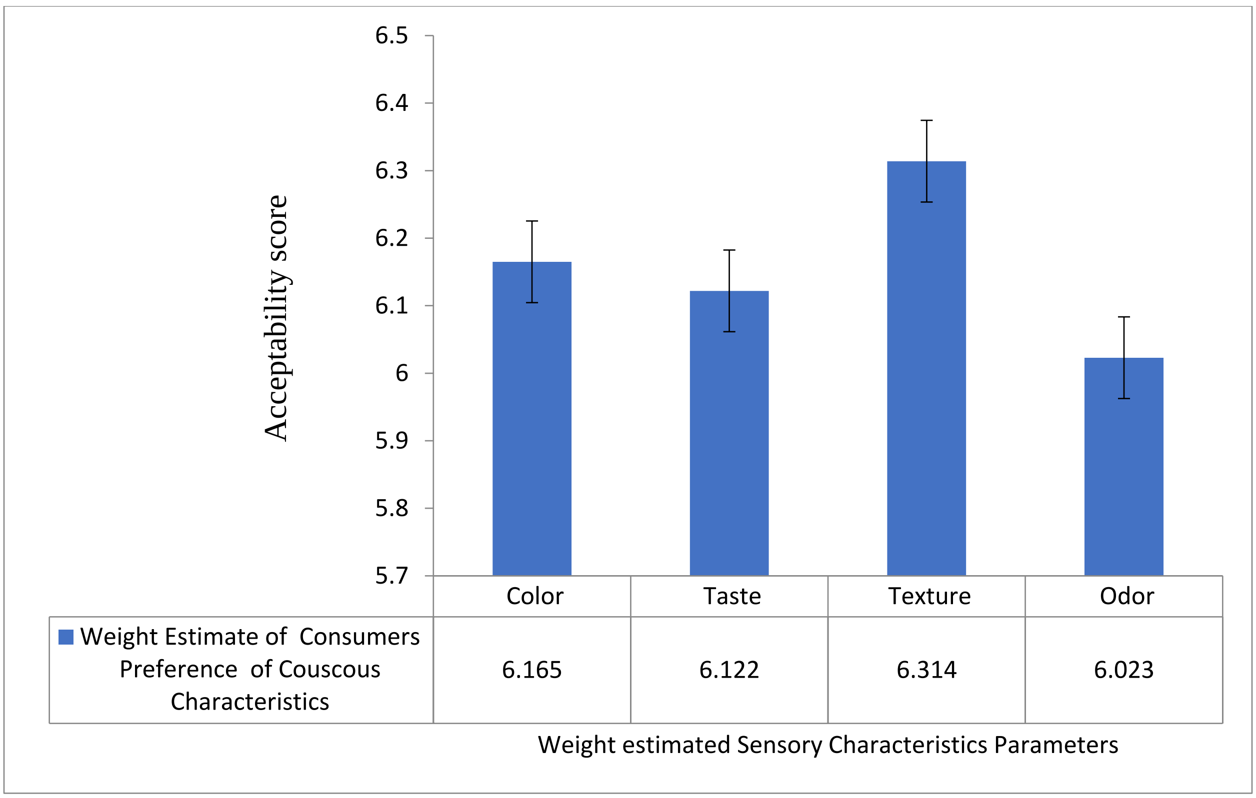

Figure 2.7. Weight estimate of consumers preference of *couscous* characteristics. Values are means of panelist scores analyzed at P<0.05.

CHAPTER 3. FORTIFYING MILLET GRAIN WITH LEGUMES AND NATURAL FORTIFICANTS USING INNOVATIVE TECHNOLOGIES TO IMPROVE NUTRITION IN NIGER AND WEST AFRICA

3.1 Abstract

The prevalence of undernourishment in the population of West Africa, and more specifically the percentage of malnourished children under age of 5, continues to be a major concern in the region. Most fortified flour blends that are provided by local and international food aid programs are made of non-local soy and maize grains, they are often not well accepted by children, and are most of the time not very accessible to local populations. The objective of this study was to develop and optimize cost-effective and innovative fortified flour formulas using: (1) roasting for fast-cooking cereal-legume-based instant and/or (2) extrusion technologies to produce high quality and nutritionally enhanced cereal-legume-based instant flours for making thin porridges, and consisting of improved grains varieties and native nutrient-dense plant materials/species (baobab, moringa, carrot, and pumpkin). Standard laboratory methods were used to analyze fortified formula samples. These involved textural characterization (RVA and dynamic/oscillation rheology) and nutritional analysis for iron (Fe) and zinc (Zn) contents by ICP-OES. Bioaccessibility of provitamin A carotenoid and lycopene derivatives (lutein, α-, and β-carotenes) were also assessed using an *in vitro* digestion system coupled with a HPLC-C30SHORT method for analysis. A hedonic preference test was used to evaluate the fortified porridge samples. Rheological results show significant differences ($p<0.05$) among samples, as indicated by innovated flour formulas forming desirable viscoelastic polysaccharide solid-like gels, exhibiting shear thinning behavior, possessing greater and more stable storage (G´) and loss (G´´) moduli, and having lower phase angle (higher elasticity) values when compared to controls (fortified blends provided by food aid programs). In general, controls were found to form more watery liquid-like porridges. Iron analysis revealed higher Fe contents for most novel flour formulas that were within an acceptable range. Despite the low values of Zn obtained in the innovated samples when compared to controls, a slight increase in Zn was observed in samples prepared using a co-extrusion method. Results suggest there were variable but high levels (>20% relative bioaccessibility) of provitamin A carotenoids, lutein, α-, and β-carotenes, in most innovated fortified porridges when compared to commercial control samples. Preference testing scores were

generally good for the innovated porridge formulas for taste, texture, and color, and were better than control samples ($P<0.05$) Thus, overall acceptability of the fortified products was good and better than the food aid products, in some cases with markedly lower variability among subject's response. This was related to their good taste, creamy character, stable texture, and good color (high L^* and a^* values, and low b^* values) compared to control samples. Furthermore, local children preferred to eat these innovated fortified formula products more than food aid blended fortified products. Continued production, distribution, and consumption of these innovated products could help reduce the prevalence of child malnutrition in West Africa.

3.2 Introduction

The prevalence of undernourishment in the total population in West Africa is an average of 12.3%, ranging from 6.3% in Mali, 11.3% in Senegal, 16.5% in Niger, and up to 20.0% in Burkina Faso (FAO et al., 2019). Also, child malnutrition, stunting (moderate or severe) and the percentage of malnutrition in children under age of 5 continues to be a major problem in the region, with incidences of 17.1% in Senegal, 27.3 % in Burkina Faso, 30.4% in Mali, and 42.2 % in Niger (FAO, 2019). Beside food shortage causing undernourishment, often related to drought and erratic rainfall, other related factors are migration, conflicts, limited access to land and water, and low income.

One possibility to improve nutritional status of rural populations in these countries is through local processing of crops that are fortified with indigenous nutrient-rich plants. Cost effective and socially innovative food processing and nutrition technologies exist; however, rural women and youth who adopt new technologies have limited access to them. This is mainly due to lack of a systems approach capable of facilitating and maximizing relevant changes expected in nutrition improvement, and in rural areas to realize the potential of the market side of value-chains.

Studies have revealed that the fortification of local foods by incorporating local ingredients, as well as vitamin and mineral premixes, can be a potential route for alleviation of micronutrient deficiencies in developing countries (Gunaratna et al., 2016; FAO, 2017; FAO, 2019; Ferruzzi et al., 2012). Most fortified flour blended formulas that are provided by food aid programs to community health centers in West Africa are made of non-local soy and maize grains, and other ingredients. The problem with blended flours provided by food aid programs is that they are often not accepted by children. Also, the majority of the at-risk populations in West Africa cannot access food aid blended flours and are essentially not impacted by imported fortified infant formulas manufactured by large multinational companies (e.g. Nestle, Danone), due to their high cost.

Food technology and nutrition laboratories in local National Agricultural Systems (NARS) in West Africa, including INRAN, Niger; and ITA, Senegal, in collaboration with food science and nutrition departments at Purdue and North Carolina State Universities, are working to develop and innovate fortified local foods in West Africa by bringing skills in translational nutrition along with new technologies. The aim is to improve existing cereal-based fortified formulas. Key insights are needed to design quality fortified formulas fitting preferences of at-risk populations, and to reduce the prevalence of stunting and malnutrition of vulnerable children under 5 years old in West Africa (De Groote et al., 2017; Ferruzzi et al., 2012*)*. Innovation of locally-made fortified food formulas, with natural micronutrient-rich sources for iron, zinc, and pro-vitamin A, can be viewed among the top nutritional strategies that can be used to reduce malnutrition and stunting in West Africa.

To address this challenge, we are now emphasizing the concept of market-led nutritional fortification of staple foods through establishment of Food Innovation Centers in rural West Africa. This effort is supported through the McKnight Foundation CCRP West Africa project titled “Diversifying Uses of Legumes and Cereals by Grain Processing to Improve Nutrition and Expand Markets” by INRAN/Niger and IRSAT/Burkina Faso, and the USAID “Feed the Future Sorghum and Millet Innovation Lab (SMIL)”. These efforts have led to the formation of successful rural women processor associations through the establishment of five Food Innovation Centers in rural Niger and Burkina Faso. This is part of a larger “Hub-and-Spoke” Food Innovation System developed through this joint project to support rural and urban women and youth food processors. The system involves disseminating technologies from the Hub and engaging with processors in Spokes, and it allows research-based solutions in processing and nutrient-fortification to be effectively extended to the field. The system uses targeted consumer insights of traditional and popular products to map new product formulations, and facilitates processing technology innovations, sharing of knowledge and experience, and market access for locally innovated nutrient-fortified food formulas.

Through this model, we also foster increased use of improved grain varieties and local nutrient dense plant ingredients, with better food making ability, by using innovative and cost-effective technologies from inexpensive roasting to relatively low-cost single screw extrusion (Bouvier and Campanella, 2014; Zhang et al., 2014; Moussa et al., 2011) to make nutritionally-enhanced and preferred fortified local foods with key micronutrients (pro-vitamin A, iron, zinc) that are needed to alleviate child malnutrition in West Africa (DeGroote et al., 2017).

Our premise is that judicious and optimized selection of cereal and legume grain varieties, with improved food making ability, and developed by plant breeding and other related programs in West Africa, can be used as base materials for the development of market-led fortified cereal-based foods. Then, coupled to locally-sourced natural nutrient-rich plants species (e.g. moringa, baobab, nere, carrot, pumpkin), and responding to target consumers preferences, these foods can serve as corrective sources of key shortfall macro- and micronutrients. Such a fortification approach, linked to the use of appropriate processing technologies and support of local entrepreneur processors, can be an innovative way of contributing to significantly improve levels of minerals (Fe and Zn) and pro-vitamin A in West African local foods.

We predict that a nutrition-based effort, including study on the impact of food processing on micronutrient stability and bioavailability, holds the promise of improving the health status of rural communities. This approach would also help demonstrate and create a sustainable market-driven model, which may ultimately help ensure that the poorer populations in West Africa have access to nutritionally-enhanced innovative and acceptable foods (De Groote et al., 2017), and with somewhat similar convenience to expensive alternatives at an affordable cost even for rural consumers.

The objective of this study was to develop and optimize: (1) roasting technology for fast-cooking cereal-legume-based instant flours, and (2) extrusion technology for making high quality and nutritionally enhanced cereal-legume-based instant flours. An important aspect in these developed processes was that they consider attributes of new grain varieties (millet, cowpea, and peanut), and locally available nutrient-rich plant materials/species (baobab, moringa, carrot, and pumpkin). The innovative fortified products were found to be more accepted by at-risk populations, particularly vulnerable children in rural areas in Niger, than existing flour formulas provided by food aid programs, and which are often not locally accessible. The innovated fortified products are now being promoted and commercialized in local village markets and community health centers by women processor groups operating food innovation centers in rural Niger.

3.3 Materials and methods

3.3.1 Materials

Twelve (12) millet varieties, including new lines high in iron and zinc, were used for this study, (89305, 99001, 221, 94206, GB 8735, SOSAT, CHAKTI, Tabi, PPB Tera, PPB Falwel, PPB Sherkin Haoussa, and Mil de Siaka). Also, one (1) cowpea (TN378) and one (1) peanut (5544) variety were selected from several others grain legumes utilized in the previous 2 years' work. Grain samples were provided by ICRISAT and INRAN scientists and grown on farms in Falwel, Tera, and Sherkin Haoussa in Niger by Moribeen and Fuma Gaskiya farmer groups during the summers of 2017 and 2018, respectively. The natural fortificants sources were moringa leaves and baobab fruits for minerals, and carrot roots and pumpkin flesh for pro-vitamin A. All fortificants were provided by women processor group members of the above-mentioned farmer groups at the locations indicated.

3.3.2 Methods

3.3.2.1 Roasting of grain samples

Roasting process variables included rotation speed, time, and temperature. Prior to the roasting process, whole millet, cowpea, and peanut grain samples were appropriately cleaned to remove extraneous materials. Roasting temperature and time ranges used for sample preparation, were selected, after preliminary optimization by rapid sensory acceptability tests conducted for this study.

3.3.2.2 Extrusion, and co-extrusion of millet, and natural fortificants

Preliminary experiments were conducted to determine the equipment settings necessary to produce high quality products with the single screw mini-extruder (Insta-Pro, Technochem International, Inc. Boone, IA, USA). Process variables included rotation speed, temperature, and moisture content of feed flour. Prior to extrusion, millet whole grain samples were cleaned to remove extraneous materials and milled to grits of a particle size ranging between 600-700 µm. Samples were then equilibrated to 35% feed moisture content for 30 min at ambient temperature.

Natural fortificant samples (moringa, baobab fruit, carrot, pumpkin) were thoroughly cleaned to remove extraneous materials. Samples were washed when necessary, partially milled, and equilibrated to feed moisture as performed for millet grits. Then, natural fortificants were blended together with equilibrated millet grits prior to co-extrusion.

The single screw extruder was set up to a temperature that varied between 115-140° C and a frequency of 50 Hz. The screw speed was set between 700-900 rpm. Equipment was then run to produce the various extrudates and co-extruded millet-fortificant blended samples.

3.3.2.3 Formulation, codification, and description of fortified products

Naturally fortified formulations were made using improved millet and legume varieties and micronutrient-rich plants (moringa, baobab fruit, carrot, pumpkin) described in section (3.3.1). Sample codes were assigned by a group of letters corresponding to: processing method: E=Extruded, R=Roasted; grain type: C=Cowpea, Mi=Millet, P=Peanut; pro-vitamin A fortificant: Ca=Carrot, Pu=Pumpkin; and iron and zinc fortificant: M=Moringa, B=Baobab. Fortified product formulations were designed, optimized, and prepared based on treatment methods, grains type, variety, and plant sources micronutrient ingredients, and required proportion (%) to be used as described in the following sections .

3.3.2.4 Codification and description of roasted samples

The base formulation for the roasting method used on dry weight basis was 60% millet, 20% cowpea, 15% peanut, 4% sugar, and 1% salt, and the other three formulations reduced millet content to 50%, and varied the remaining 10% in composition with moringa, baobab fruit, carrot, or pumpkin depending on location and formula.

RMiCP = 60% whole grain (millet 89305) + 20% (cowpea TN378) + 15% (peanut 5544) + 4% sugar + 1% salt
RMiCP +MB = 50% whole grain (millet 99001) + 20% (cowpea TN378) + 15% (peanut 5544) + 5% moringa + 5% baobab + 4% sugar + 1% salt
RMiCP+CaB = 50% whole grain (millet PPB Tera) + 20% (cowpea TN378) + 15% (peanut 5544) + 5% carrot + 5% baobab + 4% sugar + 1% salt
RMiCP +MPu = 50% whole grain (millet local variety) + 20% (cowpea TN378) + 15% (peanut 5544) + 5% moringa + 5% pumpkin + 4% sugar + 1% salt

3.3.2.5 Codification and description of extruded and co-extruded samples

The base formulation for extrusion method was 95% millet, 4% sugar, and 1% salt, and the other three formulations for co-extrusion reduced millet to 85%, 4% sugar, 1% salt, and varied the remaining 10% in composition with moringa, baobab fruit, carrot, or pumpkin depending on location and formula.

EMi = 95% whole grain (millet 89305) + 4% sugar + 1% salt
EMiMB= 85% whole grain (millet 99001) + 5% moringa + 5% baobab, + 4% sugar + 1% salt
EMiCaB = 85% whole grain (millet PPBTERA) + 5% carrot + 5% baobab, + 4% sugar + 1% salt
EMiMPu = 85% whole grain (millet Mil Local) + 5% moringa + 5% pumpkin + 4% sugar + 1% salt

3.3.2.6 Codification and description of roasted-extruded blend samples

The base formulation for the roasting-extrusion mixed methods used 60% millet, 20 % cowpea, 15% peanut, 4% sugar, and 1% salt, and the other three formulations reduced millet to 50%, and varied the remaining 10% in composition with moringa, baobab fruit, carrot, or pumpkin depending on location and formula.

EMi + RCP = 60% whole grain (millet 89305) + 20% cowpea (TN378) + 15% peanut (5544) + 4% sugar + 1% salt
EMiMB + RCP= 50% whole grain (millet 99001) + 20% cowpea (TN378) + 15% peanut (5544) + 5% moringa + 5% baobab + 4% sugar + 1% salt
EMiCaB + RCP = 50% whole grain (millet PPBTERA) + 20% cowpea (TN378) + 15% peanut (5544)] + 5% carrot /5% + 5% baobab + 4% sugar + 1% salt
EMiPuM + RCP= 50% whole grain (millet Mil Local) + 20% cowpea (TN378) + 15% peanut (5544) + 5% pumpkin + 5% moringa + 4% sugar + 1% salt

3.3.2.7 Codification and description of control formulas (Misola and Food Aid)

Two food aid products distributed by rural health centers were used in the study as controls: 1) a locally-made fortified formula (Misola) made with millet, cowpea, and vitamin-mineral premix, and 2) an imported maize-soybean-premix blend provided by the World Food Program (WFP). Depending on locations and trials, the following formula codification system was used for control samples:

Misola 1 = Cont.1 Misola/Niger West. Major ingredients included whole grains (millet, cowpea/or soy + peanut] + premix (vitamin + mineral)
Misola 2= Cont.2 Misola/NigerEast. Major ingredients included whole grains (millet, cowpea/or soy + peanut] + premix (vitamin + mineral)
Food Aid. Major ingredients included (degermed maize + soy) + premix (vitamin + mineral)

3.3.2.8 Preparation of fortified flour samples made from roasting method

Roasted whole grains (millet, cowpea, peanut) were first cooled, cleaned, and appropriately mixed with dried, cleaned, and partially milled natural fortificants (one or more of baobab, carrots, moringa, and pumpkin), and then blended together along with sugar, and salt in relative proportion (%) as recommended and described in Section 3.3.2.3.1. The resulting mixtures were then milled to a fine flour of particle size ranging between 500-200 µm. Samples were stored in polyethene bags, sealed, and kept in a refrigerated room at 6℃ prior to testing.

3.3.2.9 Preparation of fortified flour samples made using extrusion/co-extrusion method

Extrudates and samples were first cooled, cut into pieces, and appropriately dried (<10% moisture content) in a gas drier (locally fabricated, Niamey, Niger). Dried samples were partially milled and then blended together, along with sugar and salt in relative proportions (%) as recommended and described in Section 3.3.2.3.2. The resulting mixtures were milled to a fine flour of particle size ranging between 500-200 µm and stored as previously described.

3.3.2.10 Preparation of fortified flour blends made using roasting and extrusion mixed methods

Roasted whole grains (cowpea, peanut) and co-extrudate (whole millet grain plus natural fortificants) samples were separately prepared as described in Sections 3.3.2.1 and 3.3.2.2. Samples were then mixed and blended together, along with sugar and salt in relative proportions (%) as recommended and described in Section 3.3.2.3.3, and milled to a fine flour of particle size, ranging between 500-200 µm, and stored as previously described.

3.3.2.11 Pasting properties of fortified porridges samples using RVA

The pasting properties of the fortified flour formulas (3 g in 25 ml water) were determined using a Rapid Visco Analyzer (RVA, Newport Scientific Pty. Ltd., Narabeen, Australia). Standard method 1 (short temperature profile) was used. The mixtures were first stirred at 960 rpm for 10 s and then at 160 rpm for the rest of the testing period. The temperature profile included a hold at 50^{o}C for 2 min, heating to 95^{o}C in 6 min, hold at 95^{o}C for 4 min, cooling to 50^{o}C for 6 min, and a hold at 50^{o}C for 4 min. From the pasting curve the following values were obtained: pasting temperature and peak viscosity (P) (the maximum hot paste viscosity), holding strength (H) (trough at minimum paste viscosity), final viscosity (C), and viscosities of setback from trough (C-H), and of breakdown (P-H) as described by Moussa et al. (2011).

3.3.2.12 Dynamic oscillation and steady shear measurements of fortified porridges

Dynamic oscillation measurements on porridges were performed using a rheometer (TA Instruments, Inc., NJ, USA) with a parallel plate geometry. After warming the instrument to 30℃, a strain sweep was carried out to determine the viscoelastic linear region of strain for dynamic measurement of porridge samples. Frequency sweep measurements were made at a strain of 1%, which was within the linear viscoelastic region. Dynamic oscillatory measurements were taken on the thin porridge samples loaded on the plate at a constant strain of 1% (0.01), in a frequency range of 0.4 to 10 Hz, and at a temperature of 30ºC.

Apparent viscosity characteristics of the thin porridge samples were determined from the flow curve obtained. After warming the instrument, a small portion (about 0.5 g) of porridge sample was loaded onto the parallel plates and viscosity was determined up to shear rates of 310/s at 30ºC, according to procedures described by Moussa et al. (2011).

3.3.2.13 Color of porridge samples

Porridge color was determined using a Hunter Lab Colorimeter (Model D25, Hunter Associates Lab, Inc., Virginia, USA), as described by others (Rodríguez et al., 2011; Aboubacar et al., 2006). After calibration of the colorimeter with standard black and white tiles, porridge samples were placed in a 5.5 cm cell with an optically transparent glass bottom. Color parameters determined were lightness (L*) , redness-greeness (a*), and blueness-yellowness (b*). The greater were the L*, a*, and b* values, the lighter, redder, and more yellow were the samples, respectively.

3.3.2.14 Determination of iron (Fe) and zinc (Zn) content

Flours (0.5 g) were weighed in crucibles and burned to ash in a muffle furnace at 300ºC for 20 h and at 600ºC for 3 d. Ash samples were then dissolved with 1 ml of concentrated nitric acid overnight and diluted with purified water. Prior to analysis, dissolved ash samples were diluted with 2% nitric acid, and iron and zinc content were measured using inductively coupled plasma-optical emission spectrometry (ICP-OES) (Optima 4300DV, Perkin Elmer, Shelton, CT, USA) set appropriately and as recommended by the Standard Methods of Analysis (AOAC, 2000).

3.3.2.15 Provitamin A carotenoid bioaccessibility and delivery of carotenoids

Porridge samples were analyzed using a three-stage in vitro digestion (Figure 3.1) (Debelo et al., 2018; Lipke et al., 2013) to assess pro-vitamin A carotenoid bioaccessibility at the Ferruzzi Laboratory, Institute of Plants for Health and Nutrition, North Carolina State University as follows.

3.3.2.16 Preparation of porridge samples used for bioaccessibility determination

Test porridges were prepared using fortified flour blends from each sample and made with hot water in the ratio of 1:4 flour to water, as described by Lipkie et al. (2013). Samples (20 g) were mixed with 40 mL of hot distilled water with a spatula for 1 min. Then, another 40 mL hot water was added to the mixture and the resulting mixture was stirred for 5 min. The final mixture was covered with foil and kept for 10 min at ambient temperature, and then stored at -80°C until analysis or simulated digestion.

3.3.2.17 Carotenoids, total provitamin A carotenoid, lutein, α- and β-carotenes bioaccessibility

Porridges (2 g) from the fortified millet flour samples and their dry blends were subjected to a three-stage in vitro digestion (Figure 3.1) as described by Lipke et al. (2013). Canola oil (2.5%, w/w) was added to the reconstituted porridge prior to digestion in order to enhance micellarization of carotenoids. Micellarization efficiency (bioaccessibility) is an established predictor of bioavailability (Reboul et al., 2006). Digestive enzymes, including lipase, pancreatin, as well as bile extract, were included at 0.40, 0.80, and 1.80 g/L, respectively, in the small intestinal phase to ensure complete digestion of the porridge samples. Following digestion, samples were centrifuged (10,000 g, 4ºC) for 1 h and filtered (PTFE filters, 0.22 µm pore size) to isolate the aqueous micellar fractions from digesta. Aliquots of undigested fortified millet products, final digesta, and aqueous micellar fractions were collected in 15 ml tubes, flushed with nitrogen, and stored at -80ºC until further analysis.

3.3.2.18 Extraction and analysis of carotenoid from porridges

Carotenoid extraction from raw porridge formulations was conducted as described by Lipkie et al. (2013) with modifications. Briefly, porridge (2 g) was spiked with 80 µl internal standard (β-apo-8′-carotenal in ethanol). Carotenoids were extracted twice with 5 ml of cold acetone and once with 2 ml of methyl tert-butyl ether. After centrifugation at 3000 rpm for 10 min, the combined extract was dried under a stream of nitrogen, and resolubilized in 1:1 methanol:ethyl acetate. As for the digestive fractions, intestinal digesta and aqueous micellar fractions were extracted three times with 1:3 acetone:petroleum ether with 0.1% w/v butylated hydroxytoluene (BHT), dried under nitrogen, and resolubilized in 1:1 methanol:ethyl acetate. Carotenoid content of raw and digested material was determined using Waters HPLC (Alliance e2695) equipped with diode array detector as previously described (Lipke et al. 2013).

3.3.2.19 Sensory testing of fortified porridge samples

Sensory preference testing was conducted to evaluate, optimize, and innovate the fortified flour formulas. Preference testing was conducted on the thin porridge samples, prepared from naturally fortified formulations by the roasting method and using improved millet and legume varieties as well as micronutrient-rich plant materials (moringa, baobab fruit, carrot, pumpkin). Experimental samples were compared to food aid conventionally fortified blends [Misola - millet/cowpea/premix, World Food Programme (WFP) - maize/soy/premix]. The tests were conducted on four (4) porridge samples in 3 rural locations (total of 8 villages) and compared to two (2) porridge samples made from the food aid fortified blends (Misola, WFP). Panelists consisted of 320 mothers in the 8 locations and preference testing was done, according to procedures described by Moussa et al. (2011).

A hedonic preference test with a nine-point numeric scale (9=like extremely, 1=dislike extremely) was used to evaluate the fortified porridge samples in comparison to local control samples prepared or food aid blends. Panelists were provided with a copy of the questionnaire and water. They were instructed to go over the questionnaire and rinse their mouths before testing each sample. Data on sensory characteristics, socio-economic/ gender and organoleptic preference/ acceptability (color, taste, texture, flavor/odor) were collected.

3.3.2.20 Statistical analyses

Mean values for physicochemical and sensory testing measurements, as well as process performance data were determined and compared to local controls using ANOVA by statistical software packages GMP (14 edition, SAS, 2019) and SPSS (26.1 edition, 2019) using a significance level of 5%.

3.4 Results and discussion

3.4.1. Grain roasting parameters

Table 3.1 shows preliminary sensory acceptability scores of fortified formulas to know which millet varieties give better preference in combination with peanut and cowpea varieties previously selected by local consumers.

Figures 3.2 (a) and (b) summarize the variability in the range of critical processing parameters [roasting temperature (℃) per food type (millet, cowpea, peanut)]. Results in Figure 3.2 (a) indicate that roasting temperature of cowpea, millet, and peanut were variety dependent. Roasting temperature for cowpea fluctuated between 155-220 °C, for millet between 125-170 °C, and peanut values ranged from 138-142 °C among varieties. Roasting time in Figure 3.2 (b) shows that for cowpea fluctuated between 20-35 min, for millet between 20-23 min, and for peanut within 17-29 min. Results show significant variability in processing temperature (℃) and time (min) per grain type and among varieties. Values for roasting temperature and time obtained in this study were close to those used in previous studies for roasting of millet and related grains (Obadina et al., 2016). Grain roasting is performed to improve final product functional and sensory properties, to achieve a degree of grain starch gelatinization, and to inactivate pathogenic microbial growth. The roasting end point for each grain type was determined using a qualitative smell test by women processor groups in respective testing sites.

3.4.2 RVA profiles of fortified millet thin porridges

RVA analysis was used to assess pasting properties of fortified flours by measuring viscosity of flour suspensions through heating and cooling cycles. This rheological measurement commonly appears as a graphical shoulder peak. Table 3.2 and Figure 3.4 show RVA results for flour formulas (RMiCP, RMiCP+MB, RMiCP+CaB, and RMiCP+MPu) made using the roasting method compared to control samples. RVA profiles show that flour formulas made using roasting were characterized by a continuous increase in viscosity during the cooling cycle when compared to control samples ($P<0.05$). Roasted samples also had higher, peak, trough, final viscosity, and setback values than control samples (Table 3.1). This behavior may indicate that starch molecules in roasted samples had lower retrogradation and syneresis compared to control samples. Control samples by Misola appeared to be overcooked compared to their corresponding roasted samples.

Table 3.3 and Figure 3.5 show RVA profiles for co-extruded blended samples (EMi , EMiMB, EMiCaB, and EMiMPu). Figure 3.6 shows profiles for extruded-roasted blended samples (EMi +RCP, EMiMB+RCP, EMiCaB+RCP, and EMiPuM +RCP). Results indicate that all extruded, co-extruded, extruded-roasted blended, and control samples were characterized as having lower, peak, trough, final viscosity, and setback values compared to samples made by the roasting method (RMiCP, RMiCP +MB,RMiCP+CaB and RMiCP +MPu) as shown in Tables 3.2-3.3 and Figures 3.4 and 3.6. These results may indicate that starch molecules in roasted samples had less retrogradation and syneresis upon cooling. On the other hand, control samples appeared to be overcooked, which may have been responsible for the low quality of porridges obtained from them. Profiles obtained from co-extruded flour formulas are in agreement with those found for sorghum and rice cooked flours, showing a decrease in final, peak, trough, and setback viscosities compared to roasted samples, which may be caused by swelling of starch granules (Srichuwong et al., 2017; Sun et al., 2014; Moussa et al., 2011). Control samples, Misola1 and Misola2, were characterized by very low values of pasting properties, and low peak, trough, breakdown, final, and setback viscosities compared to co-extruded samples (Table 3.2). This may indicate that the control samples were overcooked and more retrograded compared to the co-extruded samples (Srichuwong et al., 2017; Srichuwong et al., 2005; Zhang et al., 2006; Zhang et al., 2014; Atwell et al., 1988), and which may explain differences in viscosities of porridges obtained for control samples when compared to innovated samples.

3.4.3 Dynamic oscillatory analysis of fortified thin porridges

Dynamic oscillatory tests were conducted to estimate the degree of paste strength. Figures 3.7 and 3.8 show profiles of shear rate (1/S) versus frequency (Hz) for fortified thin porridge formulas. Flow behavior of fortified porridge samples was measured via a steady measurement by controlling the stress (force/area) and shear rate (velocity/distance) (Bourne, 2002; Steffe and Green, 1997). Shear thinning behavior showed significant differences in apparent viscosity termed as resistance to flow among fortified porridge samples made by both roasting and extrusion methods. At lower shear rate, a large difference ($P<0.05$) was observed among samples. Figure

3.7 indicates that fortified samples (RMiCP, RMiCP+MPu) made using the roasting method had higher viscosity than control samples (Misola, Misola2).

Meanwhile, except for control sample (Food Aid), Figures 3.8 and 3.9 reveal that samples (EMi, EMiMPu), and (EMi+RCP, EMiPuM+RCP), made by co-extrusion, and followed by extrusion-roasting blended methods had 2 times lower apparent viscosities compared to corresponding porridge samples made by the roasting method. All samples made by roasting, co-extrusion, and extrusion-roasting blended methods were characterized by higher apparent viscosity (non-Newtonian flow behavior) compared to control samples made by Misola. The variation in viscosity observed among samples is believed to be caused not only by differences in processing methods, but also in the different plant materials incorporated in the respective porridge formulations. Values obtained agreed with those previously found (Moussa et al., 2011) and may be associated to differences in acceptance among samples as well.

Figures 3.10, 3.11, and 3.12 show profiles of phase angle (°) versus frequency (Hz) of fortified thin porridge samples. Results in Figure 3.10 reveal that four (RMiCP, RMiCP+MPu) fortified porridge formulas made by the roasting method, are characterized by lower phase angle values compared to control samples (Misola1, Misola2) which had high phase angle. As a result, porridge formulas (RMiCP, RMiCP +MPu) were found to have higher viscosities, and to exhibit a greater viscoelastic solid property and elasticity similar to traditional porridges, than the corresponding Misola controls (Misola1, Misola2) typified by non-viscoelastic and more watery liquid-like porridges.

Figures 3.11 and 3.12 show that formulated samples, made both by co-extrusion (EMi, EMiMPu) and by extrusion-roasting blended (EMi+RCP, EMi PuM+RCP) methods, had higher phase angles, indicating lower elasticity for these porridges compared to control sample (Food Aid). This shows a drastic reduction in elasticity for porridges made by extrusion. Values were significantly different ($P<0.05$) and in agreement with other porridges made using extrusion processing (Moussa et al., 2011; Singh et al., 2007; Pan, et al., 2002; Zhang et al., 2014).

Figures 3.13 and 3.24 show profiles of storage (G´) and loss (G´´) moduli versus frequency (Hz) of fortified porridges samples made by both roasting and co-extrusion blended methods. G’ and G’’ represent, respectively, the elastic nature and viscous dissipation energy of a given material in the linear viscoelasticity range, and the values obtained agreed with values found previously (Moussa et al., 2011; Zhang et al., 2008; Copetti et al., 1997; Atwell et al.,1988). Results indicate that fortified porridges produced by roasting (RMiCP, RMiCP+MB, RMiCP+CaB, and RMiCP+MPu) and co-extrusion (EMi, EMiMB, EMiCaB, and EMiMPu) methods, as well as Food Aid sample, had higher storage (G´) and loss (G´´) moduli, which were 10 times greater in G’ and G’’ values than those obtained for control samples (Misola1, Misola2).

As a result, innovated fortified porridges were characterized by the formation of a visual creamy and viscoelastic polysaccharide solid-like gels, and with G´ greater than G´´ and that was mostly independent of the applied frequency. It was also observed that G’ and G’’ profiles among the porridges were quite similar, despite the large differences found compared to control samples by Misola, and confirmed rheological results found above.

3.4.4 Color of fortified thin porridges

Color values of fortified thin porridge samples showed significance differences ($P<0.05$) for *L**, *a**, and *b** values among samples (Tables 3.4, 3.5, and 3.6). In general, fortified formulated samples made by both roasting and extrusion methods were found to have higher L* values when compared to their corresponding control samples (Misola1 and Misola2), except for control sample (Food Aid), which had somewhat equivalent values with some of the formulated samples. Thus, porridge sample formulas (RMiCP, RMiCP+CaB, EMi, EMiCaB, EMi+RCP, and EMiCaB+RCP), and (Food Aid) control appeared whiter in *L** values than the rest. In contrast, *a** values for formulas RMiCP+CaB, EMiCaB, and EMiCaB +RCP produced by both roasting and co-extrusion were higher than the control samples (Misola1 and Misola2). This noticeable variation in *a** value among samples can be attributed not only to differences in processing methods, but also to variation in color of the various plant materials incorporated in the porridge formulations, including grain type and variety (millet, cowpea, peanut) and natural fortifying ingredients (carrot, moringa leaves, baobab fruit, pumpkin pulp). As a result, porridge formula samples (RMiCP+MB ,RMiCP+MPu , EMiMB, EMiMPu, EMiMB+RCP, and EMiPuM +RCP), in which moringa and baobab were incorporated, appeared greener in color and were found to have the lowest *a** value, 0.21, 0.42, 1.06, .920, and .9550, respectively. Control sample (Food Aid) was also found to have a lower *b** value of 18.7. A similar color behavioral change was observed for *b** values among samples with incorporation of carrot, baobab, pumpkin, and moringa. Porridge formulas RMiCP+CaB, RMiCP+MB ,RMiCP+MPu , and RMiCP, and EMiCaB, EMiMB, EMiMPu, EMi; EMiCaB+RCP , EMiMB+RCP, EMiPuM+RCP, and EMiCaB+RCP were found to have higher *b** values than control samples. Most color values fell within ranges found generally accepted for porridges (Moussa et al., 2011; Aboubacar et al., 2006). Innovated porridge formulas generally had good color scores in the sensory test, which may be credited to consumers' preferences for high *L** and *a** value, and lower *b** values.

3.4.5 Iron (Fe) and zinc (Zn) contents of samples

Iron (Fe) and zinc (Zn) contents were found to be significantly different among samples.
Except for the control, Misola2 (Table 3.7), (Fe) content of flour formulas prepared using both roasting and co-extrusion methods were higher than the control samples. Higher iron (Fe) contents were also observed for formulas with incorporation of fortifying ingredients (baobab, moringa, carrot, pumpkin) and agreed with literature values found for similar products (Renee, Ferruzzi, Taylor, et al. 2019, Zaman et al. 2017, Stadlmayr et al. 2013). Interestingly, iron (Fe) content for most co-extruded innovated samples were higher than their corresponding samples prepared using the roasting method. This aligns with previous work reporting that thermal treatment, including a roasting process, could contribute to higher iron content through transfer from cooking pots (Obadina et al., 2016; Bhati, et al., 2016; Gabrielibanos et al., 2013).

In contrast, Table 3.8 revealed lower zinc (Zn) content for fortified samples made by both roasting and co-extrusion methods, compared to their corresponding control samples. Relatively low values in zinc (Zn) were found in previous work, on local grain (Krishnan and Meera, 2018). Despite that the fortified samples had the lowest zinc (Zn) contents, a slight increase in values of Zn was observed in most flour samples prepared using both co-extrusions and roasting-extrusion blend methods compared to samples made using the roasting method. Increase in mineral content and bioaccessibility have been found to be associated with processing methods (Krishnan and Meera, 2017). As a result, the extrusion process used in making the flour formulations may have increased of iron (Fe) and zinc (Zn) contents.

3.4.6 Carotenoid bioaccessibility

Relative bioaccessibility of carotenoids was determined based on the ratio of carotenoid content in the aqueous micellar fraction to that of the digesta fraction of porridge samples. As shown in Figure 3.25, significant difference in the relative bioaccessibility of total provitamin A carotenoids were observed among the different porridge formulations. Total provitamin A carotenoid content was calculated as the sum of all-trans-β-carotene + 1/2(α-cryptoxanthin+ α-carotene + cis-β-carotene). Results indicate that innovated fortified porridges, including EMiMB (25%), RMiCP+MPu (25%), EMiPuM+RCP(23%), EMiCaB +RCP (17%), followed by RMiCP+CaB (15%), EMi MB +RCP(13%), EMiCaB (12%), EMiMPu (11%) were found to have the highest values of total provitamin A carotenoid bioaccessibility. The corresponding control samples, Food Aid (6%), and Misola1 (0%) were credited with lowest values. These findings indicate that 10% incorporation of natural fortificants, including moringa, baobab fruit, carrot, or pumpkin in the total composition of innovated flours, per prorate of formula and location do appear to positively impact bioaccessibility of total provitamin A carotenoids. Previous studies ascertained that the type of treatment methods can contribute to improve nutrient bioaccessibility and bioavailability of cereal foods (Singh et al., 2007; Wang et al. 2014).

Analysis of individual carotenoid bioaccessibility also revealed significant ($P<0.05$) differences among porridge samples. Highest α-carotene bioaccessibility value was obtained for innovated fortified porridge formula, RMiCP+MPu (43%), followed by EMiMB (27%), EMiPuM+RCP (21%,), EMiCaB+RCP (17%), RMiCP+CaB (15%), EMiMB+RCP(14%), and EMiMPu (8%). Lowest values were observed in EMiCaB (0%), and control samples, Food Aid (0%), and Misola1 (0%). Meanwhile, highest values of β-carotene bioaccessibility were found in fortified porridges samples, EMiPuM+RCP(24%), EMiMB (23%), and EMiCaB (22%). Acceptable values, with no significance differences, were found among samples that ranged from RMiCP+MPu (17%), EMiCaB+RCP (17%), RMiCP+CaB(15%), EMiMPu(13%), and EMiMB+RCP(13%). Control samples, Food Aid (2%) and Misola1 (0%), were found to have the lowest values of β-carotene bioaccessibility overall. Innovated fortified formulas resulting in higher values of β-carotene bioaccessibility might have been facilitated by the incorporation of natural fortificants including, moringa, baobab fruit, carrot, or pumpkin, which are considered potential modulators of provitamin A carotenoid bioaccessibility (Debelo et al., 2017). Figure 3.29 indicates significant differences ($P<0.5$) in relative bioaccessibility of lutein among porridges in samples. The highest value was found in sample, EMiCaB (34%), which was then followed by porridges, EMiMB (29%), EMiCaB+RCP (27%), EMiPuM+RCP(27%), RMiCP+MPu (26%), EMiMB+RCP (22%), Misola1 (21%), and RMiCP+CaB (21%). Lowest values in lutein were found in, Food Aid control sample (14%), and EMiMPu (13%). It was found that thermal processing, including extrusion, in which process conditions are set at high feed moisture (e.g. ~27%) and barrel temperatures (~127°C) yielded better bioaccessibility of β carotene in cereal foods (Nallely, 2014). Our findings revealed that the co-extrusion and roasting conditions used did improve bioaccessibility of most samples.

In summary, total provitamin A carotenoid bioaccessibility appeared to be higher in most innovated fortified porridges when compared to their corresponding commercial control samples. Furthermore, 10% incorporation of natural fortificants, including, moringa, baobab fruit, carrot, or pumpkin, in the total composition of innovated flours per of percentage formula, and location do appear to positively impact carotenoid bioaccessibility of innovated fortified porridge samples. Results also indicate that the processing methods used, including extrusion, and roasting did not significant impact carotenoid bioaccessibility as compared to those formulations that were not processed. Results for absolute bioaccessibility are included in Appendix A.

3.4.7 Sensory evaluation

Previous studies showed that, among several grain cultivars (Table 3.1), porridges made using three improved millet (89305, PPBTERA, 99001), cowpea (TN378), and peanut (55437) varieties, were best accepted by the local mothers and children in three different locations (Falwel, Tera, and Maradi) in Niger.

Figure 3.30 shows preferences of thin porridges prepared from naturally fortified formulations prepared by roasting method, using improved millet and legume varieties, and using micronutrient-rich plants (moringa, baobab fruit, carrot, pumpkin); these were compared to control formulations by food aid fortified blends (Misola:millet/cowpea/premix, WFP:maize/soy/premix). Results show that innovated porridge formulas had generally good scores in taste, texture, and color scores ($P<0.05$). Overall acceptability of the fortified products was good and better in some cases than the food-aid products as denoted in the box plot, and with lower variability among subject's response (Figure 3.35). This was thought to be due to formulations developed to target local preferences that gave good taste, creaminess and viscoelastic polysaccharide solid-like gel textures, and consumer preferred color characterized by high L^* and a^* values as well as lower b^* value compared to controls (food aid fortified blends). This was the first time these village consumers had been exposed to the innovated porridge formulas of the project and they liked them better than those food aid blends commonly distributed at rural health clinics. We predict that innovated porridge formulas will have better adoption, because they are made to appeal the palate of local children.

3.5 Conclusions

Innovated fortified porridge formulas were nutritious and had a creamy and viscoelastic solid-like gel texture, while food aid controls appeared watery and less viscous. This is the first time locally-developed fortified flours for making porridges were found more accepted by rural children than food aid blends in Niger. We reason that these fortified flours could have better adoption by rural communities in West Africa than food aid blends distributed at health centers and would support rural entrepreneurism and women processors.

Bioaccessibility of carotenoid, total provitamin A carotenoid, lutein, α, and β carotenes were higher in most innovated fortified porridges compared to their corresponding food aid control samples. Incorporation (10%) of natural fortificants, including, moringa, baobab fruit, carrot, or pumpkin, in the total composition of flours per of percentage formula, and location positively impacted bioaccessibility of total provitamin A carotenoid, total carotenoid, lutein, and α and β carotenes. Also, results indicate that the processing methods used, including extrusion, and roasting could have contributed to improved bioaccessibilty. The extrusion process used in making the instant flour formulas might have been responsible for the increase of their iron (Fe) and zinc (Zn) contents compared to the food aid control samples. Further studies are required to evaluate the sensory characteristics of both co-extruded and roasted-extruded blend fortified flours developed in this work.

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Table 3.1. Preliminary identification of best grain cultivars for thin porridge-making and percent incorporation of major ingredients into the formulation – 60% millet (variety) + 20% cowpea (v. TN378) + 15% peanut (v, 55437) by preference-based scoring.

Millet (variety)	Cowpea (variety)	Peanut (variety)	Mean Value (From 1 to 9 hedonic scale)
89305	TN378	55437	8.0
94206	TN378	55437	6.2
99001	TN378	55437	7.9
ICRI TABI	TN378	55437	3.9
MIL de SIAKA	TN378	55437	6.7
MIL LOCAL	TN378	55437	7.9
PPB-FALWEL	TN378	55437	5.8
PPB-SHERKIN HAOUSSA	TN378	55437	7.8
PPB-TERA	TN378	55437	8.2

A hedonic preference test was used with a 9-point numeric scale (from 9=like extremely to 1=dislike extremely). Values are means of panelist scores with higher scores, indicating, the most preferred millet-cowpea-peanut porridge combinations (P<0.05).

Table 3.2. Pasting values from Rapid Visco-Analyzer (RVA) analysis of fortified thin porridge roasted samples.

Sample	Peak Viscosity (cP)	Trough Viscosity (cP)	Breakdown Viscosity (cP)	Final Viscosity (cP)	Setback Viscosity (cP)	Peak Time (min)
RMiCP	413.50 [a]	392.50 [a]	21.00 [a]	1154.50 [a]	762.00 [a]	6.97 [a]
RMiCP +MB	292.50 [b]	282.50 [b]	10.0 [b c]	488.50 [b]	206.00 [c]	6.47 [a b]
RMiCP+CaB	309.50 [b]	302.50 [b]	7.00 [c]	561.50 [b]	259.00 [b]	6.63 [a b]
RMiCP +MPu	286.00 [b]	275.50 [b]	10.50 [b c]	553.00 [b]	277.50 [b]	5.67 [b]
Misola1	41.00 [c]	50.00 [c]	16.00 [a b]	28.00 [c]	30.00 [d]	6.13 [a b]
Misola2	59.50 [c]	25.00 [d]	9.50 [b c]	87.50 [c]	37.50 [d]	6.29 [a b]

Sample codes are described as follow: R=Roasted, Mi=Millet, C=Cowpea, Ca=Carrot, P=Peanut, Pu=Pumpkin, M=Moringa, B=Baobab (refer to Section 3.3.2.4 in Methods for more details). Values are means of triplicate determinations. Different superscripts within columns indicate significant differences (P<0.05, Duncan’s Multiple Range Test).

Table 3.3. Pasting values from Rapid Visco-Analyzer (RVA) analysis of fortified thin porridge co-extruded samples.

Sample	Peak Viscosity (cP	Trough Viscosity (cP	Breakdown Viscosity (cP	Final Viscosity (cP	Setback Viscosity (cP	Peak Time (min)
EMi	212.0 ^{a}	154.0 ^{a}	58.0^{a}	420.0^{a}	266.0 ^{a}	4.7^{b}
EMiMB	155.0 ^{b}	116.0 ^{b}	39.0^{b}	255.0 ^{b}	139.0^{b}	4.6^{bc}
EMiCaB	84.0 ^{d}	55.0^{d}	29.0^{c}	99.0^{d}	44.0^{c}	4.3^{c}
EMiMPu	131.0 ^{c}	101.0 ^{c}	30.0^{c}	206.0 ^{c}	105.0^{b}	4.5^{bc}
Food Aid	40.5 ^{e}	25.0^{e}	16.0^{d}	28.0^{e}	30.0^{c}	6.1^{a}

Sample codes are described as follows: E=Extruded, Mi=Millet, Ca=Carrot, Pu=Pumpkin, M=Moringa, B=Baobab (refer to Section 3.3.2.4 in Methods for more details. Values are means of triplicate determinations. Different superscripts within columns indicate significant differences (P<0.05, Duncan's Multiple Range Test).

Table 3.4. Color of fortified thin porridge samples made by roasting method.

Porridge Samples	*L*	*a*	*b*
RMiCP	54.94 [a]	2.12 [b]	13.28 [d]
RMiCP +MB	46.35 [b]	0.21 [c]	19.84 [a]
RMiCP+CaB	53.21 [a]	2.86 [a]	19.13 [b]
RMiCP +MPu	43.97 [b c]	0.42 [c]	18.21 [c]
Misola1	45.09 [b c]	3.27 [a]	12.98 [e]
Misola2	43.06 [c]	2.93 [a]	12.39 [f]

L=black (0) to white (100), *a*=green (-) to red (+), *b*=blue (-) to yellow (+). Sample codes are described as follows: R=Roasted, Mi=Millet, C=Cowpea, Ca=Carrot, P=Peanut, Pu=Pumpkin, M=Moringa, B=Baobab (refer to Section 3.3.2.4 in Methods for more details
Values are means of triplicate determinations. Different superscripts within columns indicate significant differences ($P<0.05$, Duncan's Multiple Range Test).

Table 3.5. Color of fortified thin porridges samples made by the co-extrusion method.

Porridge Samples	*L*	*a*	*b*
EMi	48.9^{b}	1.5^{b}	12.4^{e}
EMiMB	41.0^{c}	1.1^{c}	13.8^{c}
EMiCaB	55.6^{a}	2.8^{a}	15.5^{b}
EMiMPu	38.4^{d}	0.9^{d}	13.0^{d}
Food Aid	61.0^{a}	0.1^{e}	18.7^{a}

Sample codes are described as follows: E=Extruded, Mi=Millet, Ca=Carrot, Pu=Pumpkin, M=Moringa, B=Baobab (refer to Section 3.3.2.4 in Methods for more details. *L*=black (0) to white (100), *a*=green (-) to red (+), *b*=blue (-) to yellow (+). Values are means of triplicate determinations. Different superscripts within columns indicate significant differences ($P<0.05$, Duncan's Multiple Range Test).

Table 3.6. Color of fortified thin porridges samples by roasting and co-extrusion blending method.

Porridge Samples	*L*	*a*	*b*
EMi +RCP	51.2^{c}	1.9^{b}	13.3^{e}
EMi MB +RCP	42.5^{d}	1.0^{c}	14.1^{d}
EMi CaB +RCP	56.3^{b}	2.8^{a}	15.4^{b}
EMi PuM +RCP	41.0^{e}	1.0^{c}	14.4^{c}
Food Aid	61.0^{a}	0.13^{e}	18.7^{a}

Sample codes are described as follows: E=Extruded, R=Roasted, Mi=Millet, C=Cowpea, Ca=Carrot, P=Peanut, Pu=Pumpkin, M=Moringa, B=Baobab (refer to Section 3.3.2.4 in Methods for more details. *L*=black (0) to white (100), *a*=green (-) to red (+), *b*=blue (-) to yellow (+). Values are means of triplicate determinations. Different superscripts within columns indicate significant differences (P<0.05, Duncan's Multiple Range Test).

Table 3.7. Iron (Fe) content of fortified thin porridge samples.

Roasted Sample code	Fe (μg/g) Roasted	Co-extruded sample code	Fe (μg/g) co-extruded	*Extruded-roasted blends* sample code	Fe(μg/g) *Roasted-co-extruded*
RMiCP	70.6[c]	EMi	50.5[e]	EMi +RCP	30.5[d]
RMiCP +MB	57.0[d]	EMiMB	80.6[a]	EMi MB +RCP	77.1[a]
RMiCP+CaB	52.0[e]	EMiCaB	68.6[b]	EMi CaB +RCP	55.9[b]
RMiCP +MPu	71.0[b]	EMiMPu	56.5[c]	EMi PuM +RCP	55.9[b]
Misola1	48.1[f]	Food Aid	50.7[d]	Food Aid	50.7[c]
Misola2	101.9[a]				

Sample codes are described as follow: R=Roasted, Mi=Millet, E=Extruded, C=Cowpea, Ca=Carrot, P=Peanut, Pu=Pumpkin, M=Moringa, B=Baobab (refer to Section 3.3.2.4 in Methods for more details Values are means of duplicate determinations. Different letters within a column indicate significant differences (P<0.05, Duncan's Multiple Range Test).

Table 3.8. Zinc (Zn) content of fortified thin porridge samples.

Roasted sample code	Zn(μg/g) Roasted	Co-extruded sample code	Zn(μg/g) Co-extruded	*extruded-roasted blend* sample code	Zn(μg/g) *Roasted-Coextruded*
RMiCP	34.4[d]	EMi	40.5[c]	EMi +RCP	32.1[e]
RMiCP +MB	25.8[f]	EMiMB	61.8[b]	EMi MB +RCP	50.9[b]
RMiCP+CaB	34.8[c]	EMiCaB	37.6[d]	EMi CaB +RCP	34.2[d]
RMiCP +MPu	26.8[e]	EMiMPu	34.2[e]	EMi PuM +RCP	36.9[c]
Misola1	109.7[a]	Food Aid	69.7[a]	Food Aid	69.7[a]
Misola2	87.7[b]				

Sample codes are described as follows: R=Roasted, Mi=Millet, E=Extruded, C=Cowpea, Ca=Carrot, P=Peanut, Pu=Pumpkin, M=Moringa, B=Baobab (refer to Section 3.3.2.4 in Methods for more details Values are means of duplicate determinations. Different letters within a column indicate significant differences ($P<0.05$, Duncan's Multiple Range Test).

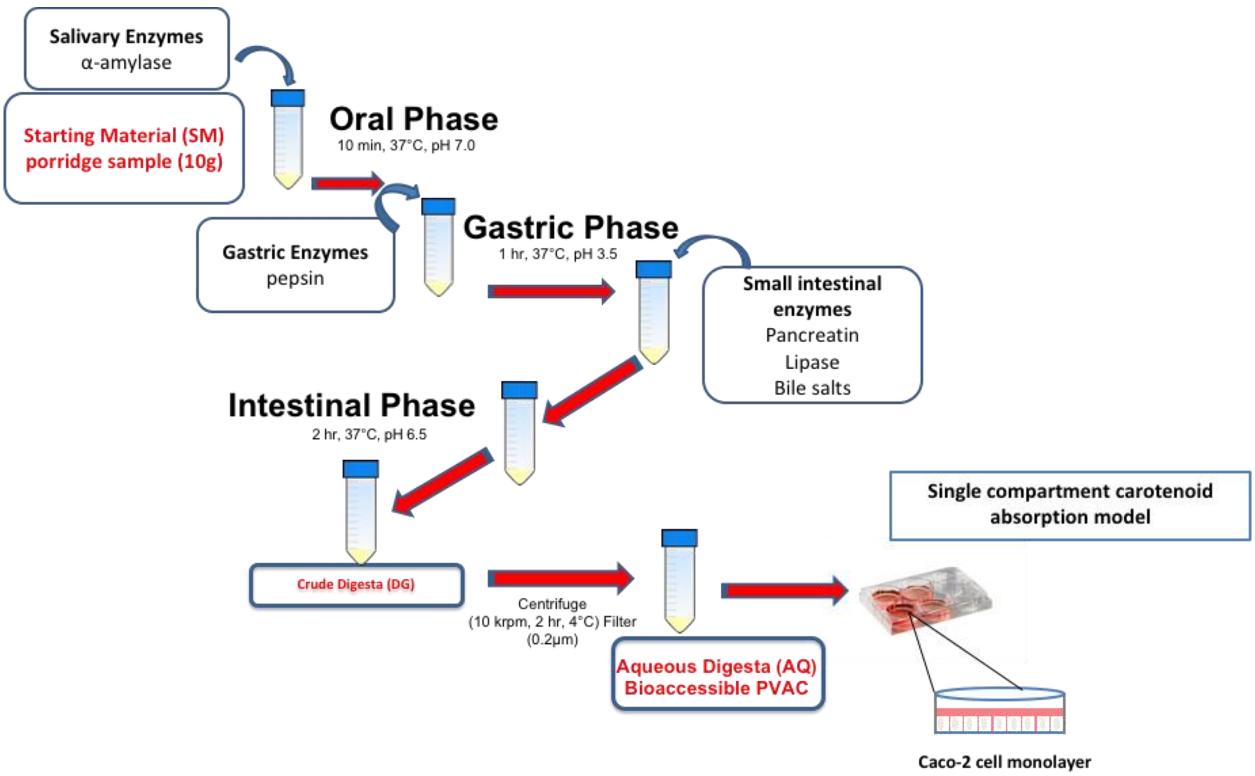

Figure 3.1. Protocol description by (Debelo et al., 2017, Lipke et al., 2013), at the Ferruzzi Laboratory, North Carolina State, University, USA.

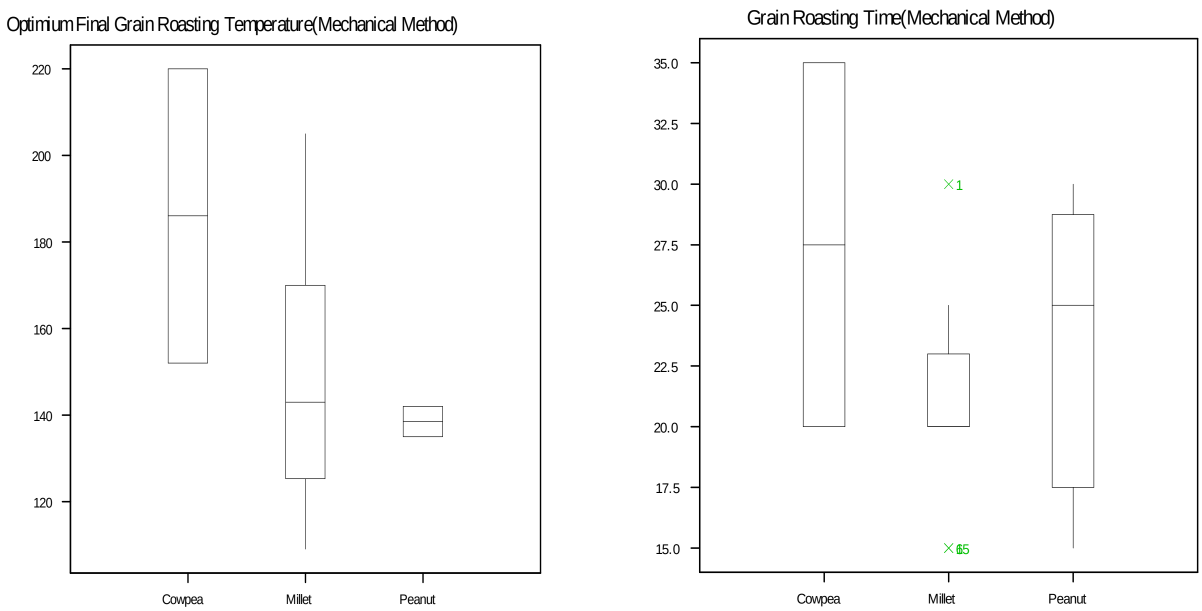

Figure 3.2. (a) Boxplot of grain roasting temperature (°C) and (b) Time(min), for testing of several millet varieties in process optimization of millet-legume (cowpea and peanut) blended flours for making fortified thin porridges in Falwel, Tera, and Sherkin Haoussa (Niger). Values are means of triplicate treatments.

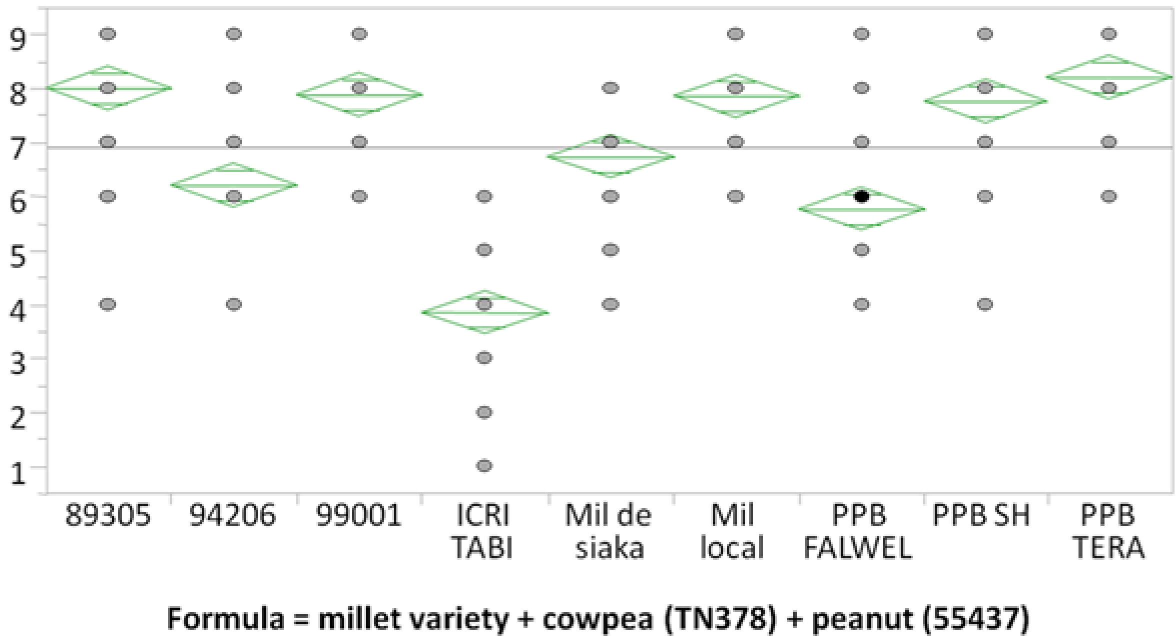

Figure 3.3. Consumer preference study of fortified thin porridge formulas conducted in Tera, Niger. Nine millet varieties were used with one cowpea and one peanut variety each. A hedonic preference test was used with a 9-point numeric scale (from 9=like extremely to 1=dislike extremely). Values are means of panelist scores.

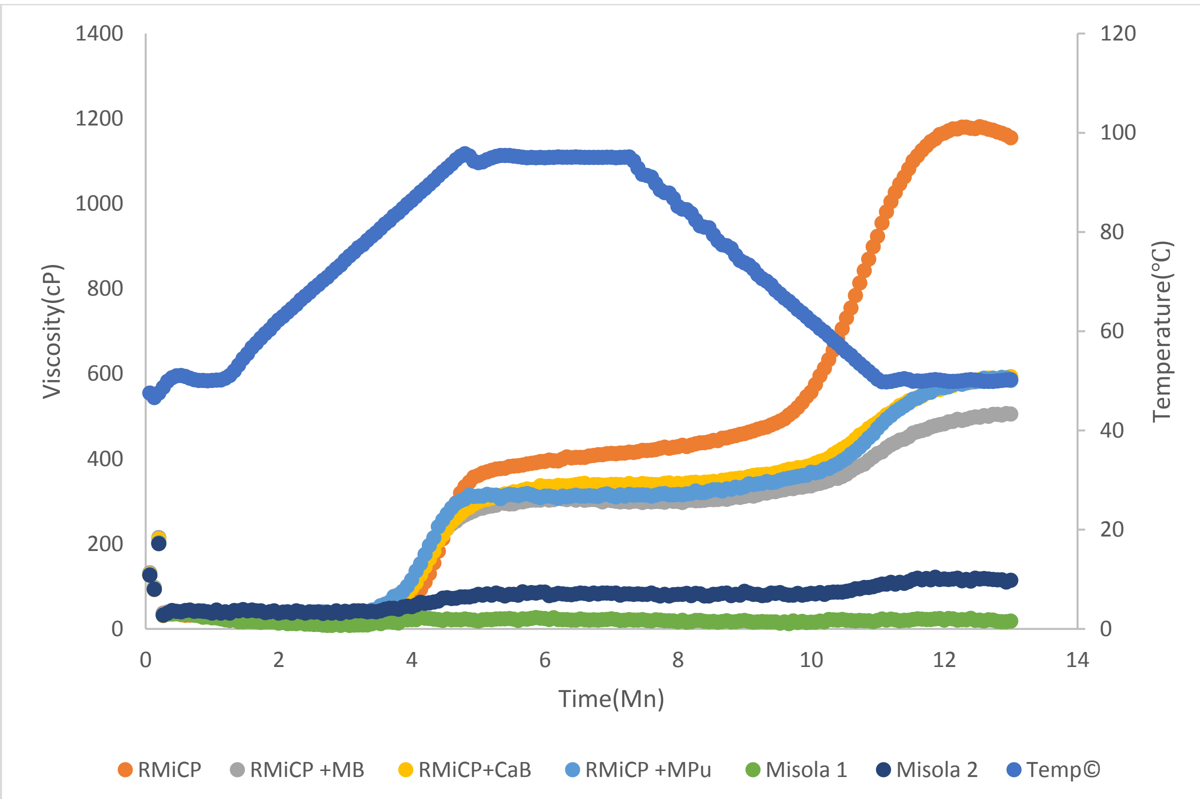

Figure 3.4. Rapid Visco-Analyzer (RVA) profiles of fortified thin porridge samples made using the roasting method versus local controls by Misola.

Values are means of triplicate runs. Sample codes are described as follows: R=Roasted, Mi=Millet, C=Cowpea, Ca=Carrot, P=Peanut, Pu=Pumpkin, M=Moringa, B=Baobab (refer to Section 3.3.2.4 in Methods for more details).

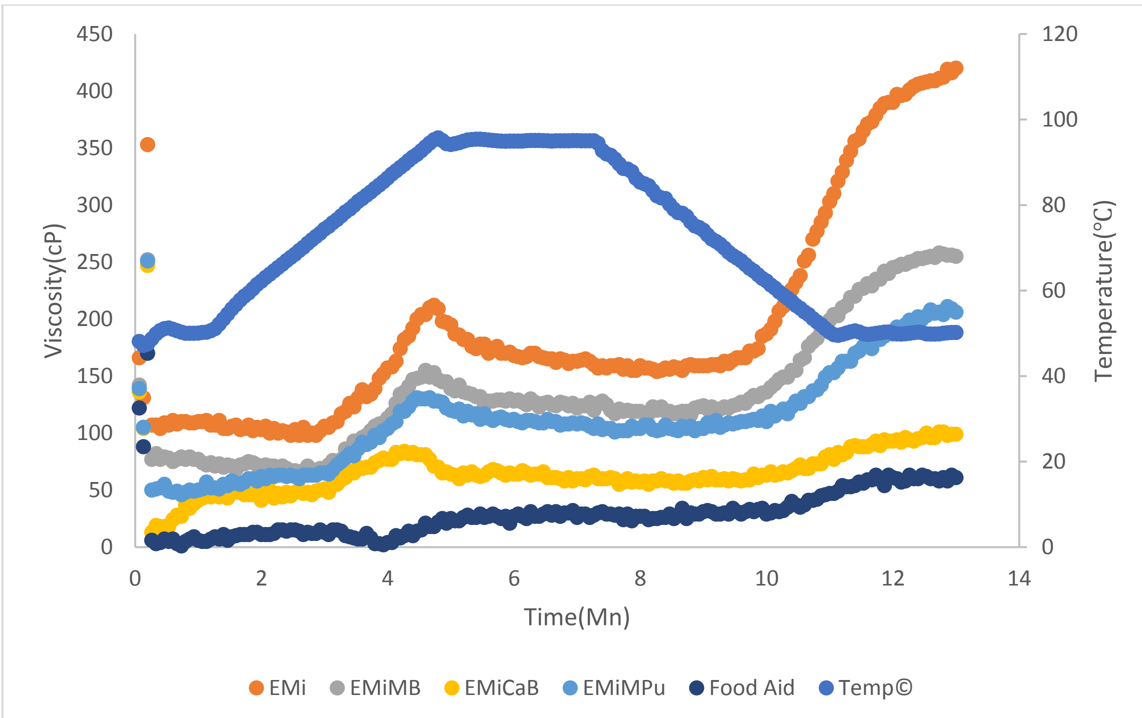

Figure 3.5. Rapid Visco-Analyzer (RVA) profiles of fortified thin porridges samples made using the extrusion method versus local food aid control.

Values are means of triplicate runs. Sample codes are described as follows: E=Extruded, Mi=Millet, C=Cowpea, Ca=Carrot, P=Peanut, Pu=Pumpkin, M=Moringa, B=Baobab (refer to Section 3.3.2.4 in Methods for more details).

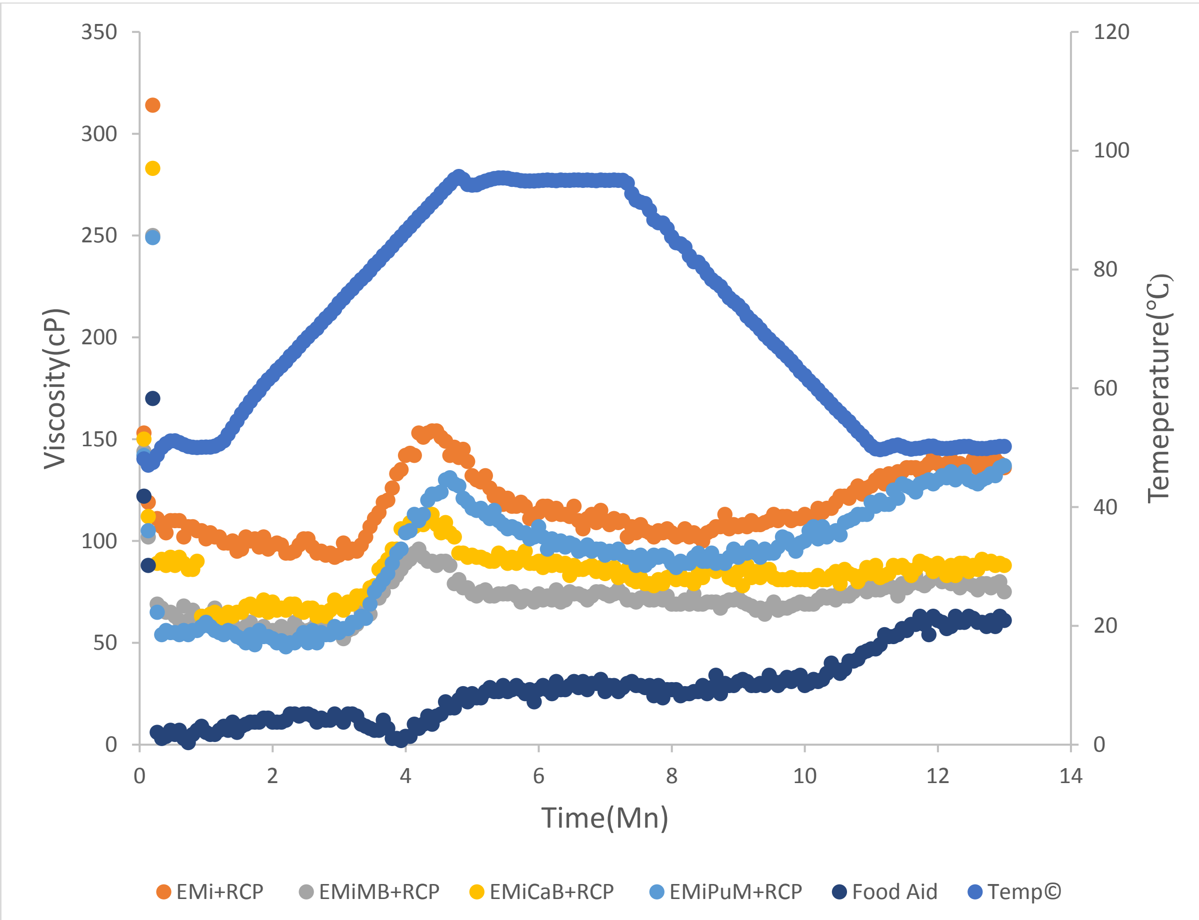

Figure 3.6. Rapid Visco-Analyzer (RVA) profiles of fortified thin porridge blended samples.

Values are means of triplicate runs. Sample codes are described as follows: E=Extruded, R=Roasted, Mi=Millet, C=Cowpea, Ca=Carrot, P=Peanut, Pu=Pumpkin, M=Moringa, B=Baobab (refer to Section 3.3.2.4 in Methods for more details).

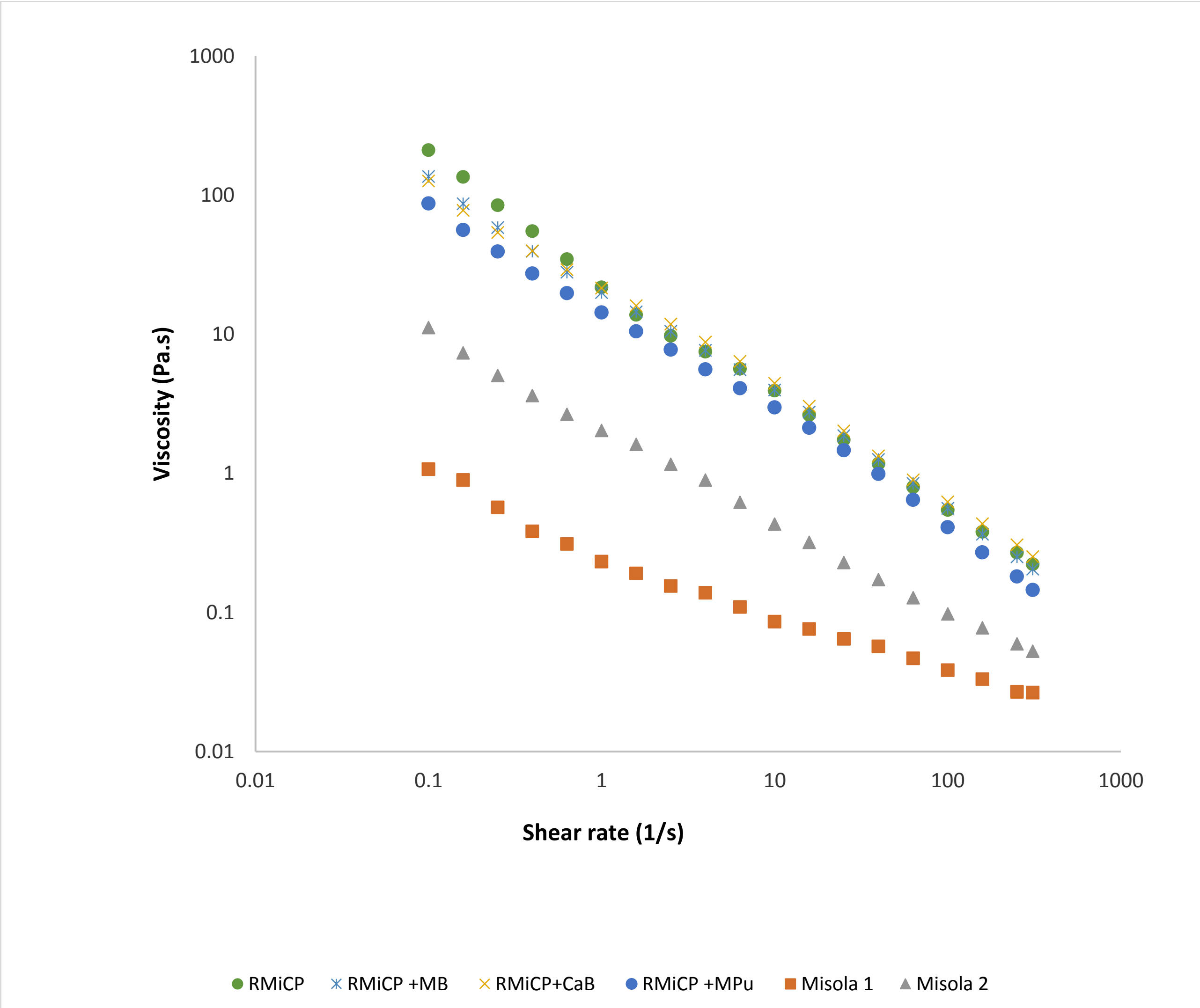

Figure 3.7. Steady shear measurement (viscosity versus shear rate) of fortified thin porridges samples made using the roasting method versus local controls by Misola.

Values are means of triplicate determinations. Sample codes are described as follows: R=Roasted, Mi=Millet, C=Cowpea, Ca=Carrot, P=Peanut, Pu=Pumpkin, M=Moringa, B=Baobab (refer to Section 3.3.2.4 in Methods for more details).

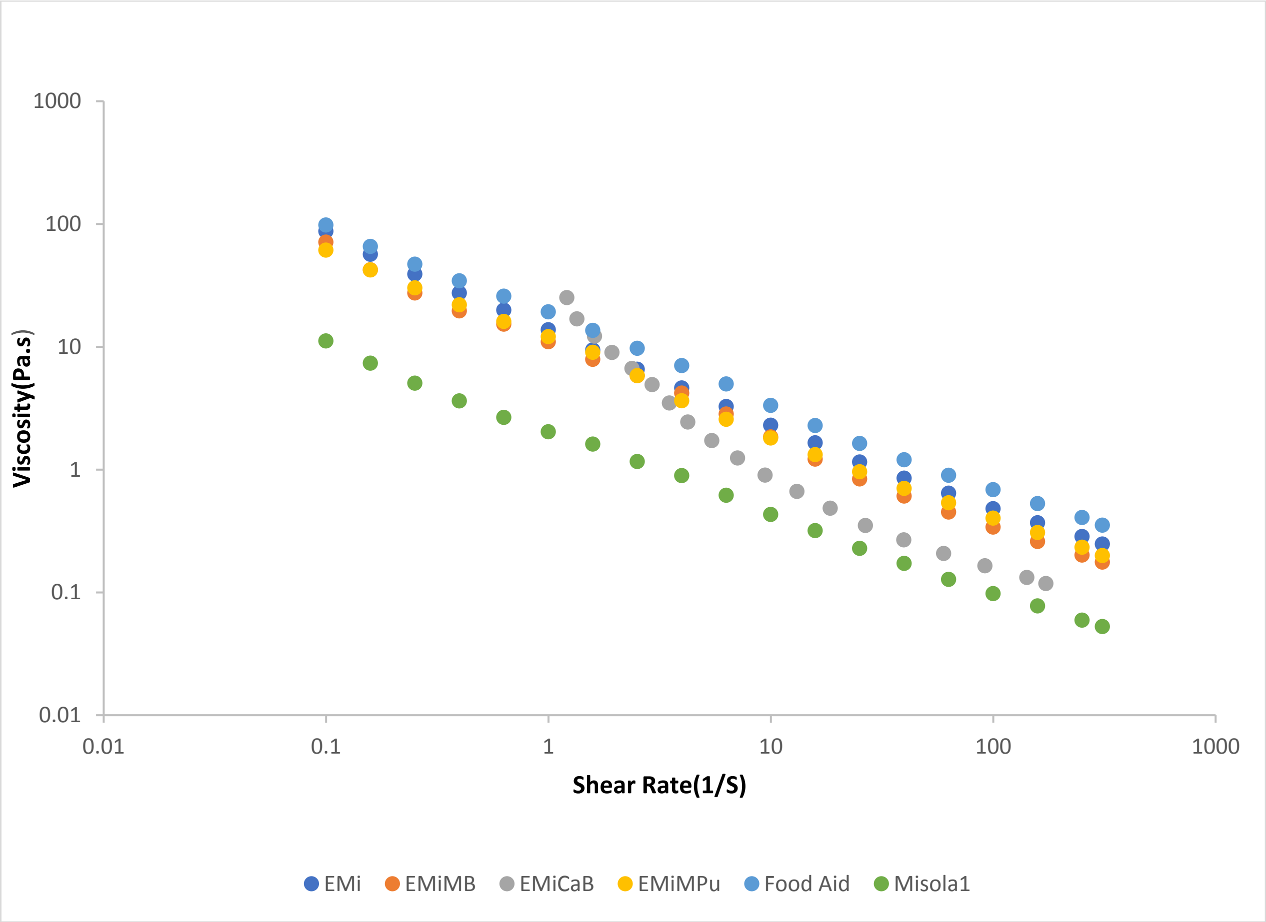

Figure 3.8. Steady shear measurement (viscosity versus shear rate) of fortified thin porridges samples made using the extrusion method versus local controls.

Values are means of triplicate determinations. Sample codes are described as follows: E=Extruded, Mi=Millet, Ca=Carrot, Pu=Pumpkin, M=Moringa, B=Baobab (refer to Section 3.3.2.4 in Methods for more details).

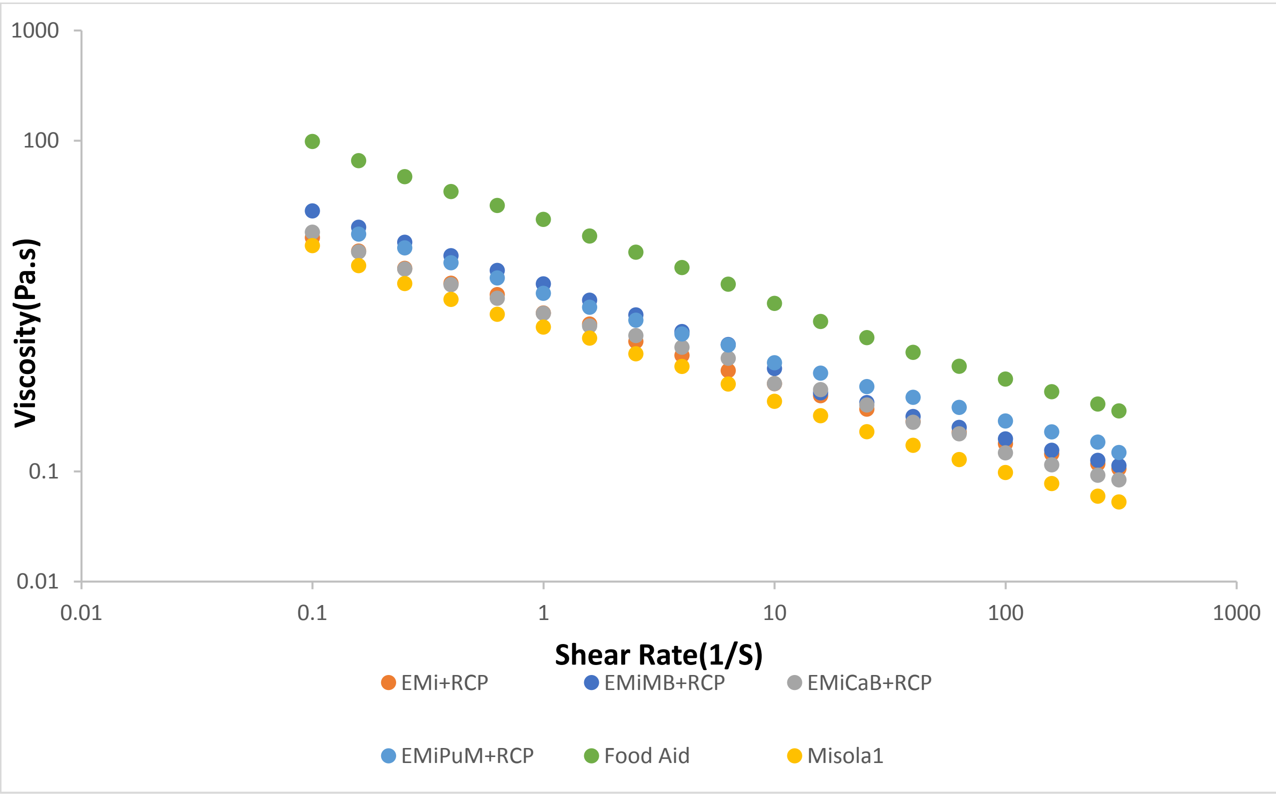

Figure 3.9. Steady shear measurement (viscosity versus shear rate) of fortified thin porridge blended samples made using the roasting and extrusion mixed methods versus local controls.

Values are means of triplicate determinations. Sample codes are described as follows: E=Extruded, R=Roasted, Mi=Millet, C=Cowpea, Ca=Carrot, P=Peanut, Pu=Pumpkin, M=Moringa, B=Baobab (refer to Section 3.3.2.4 in Methods for more details).

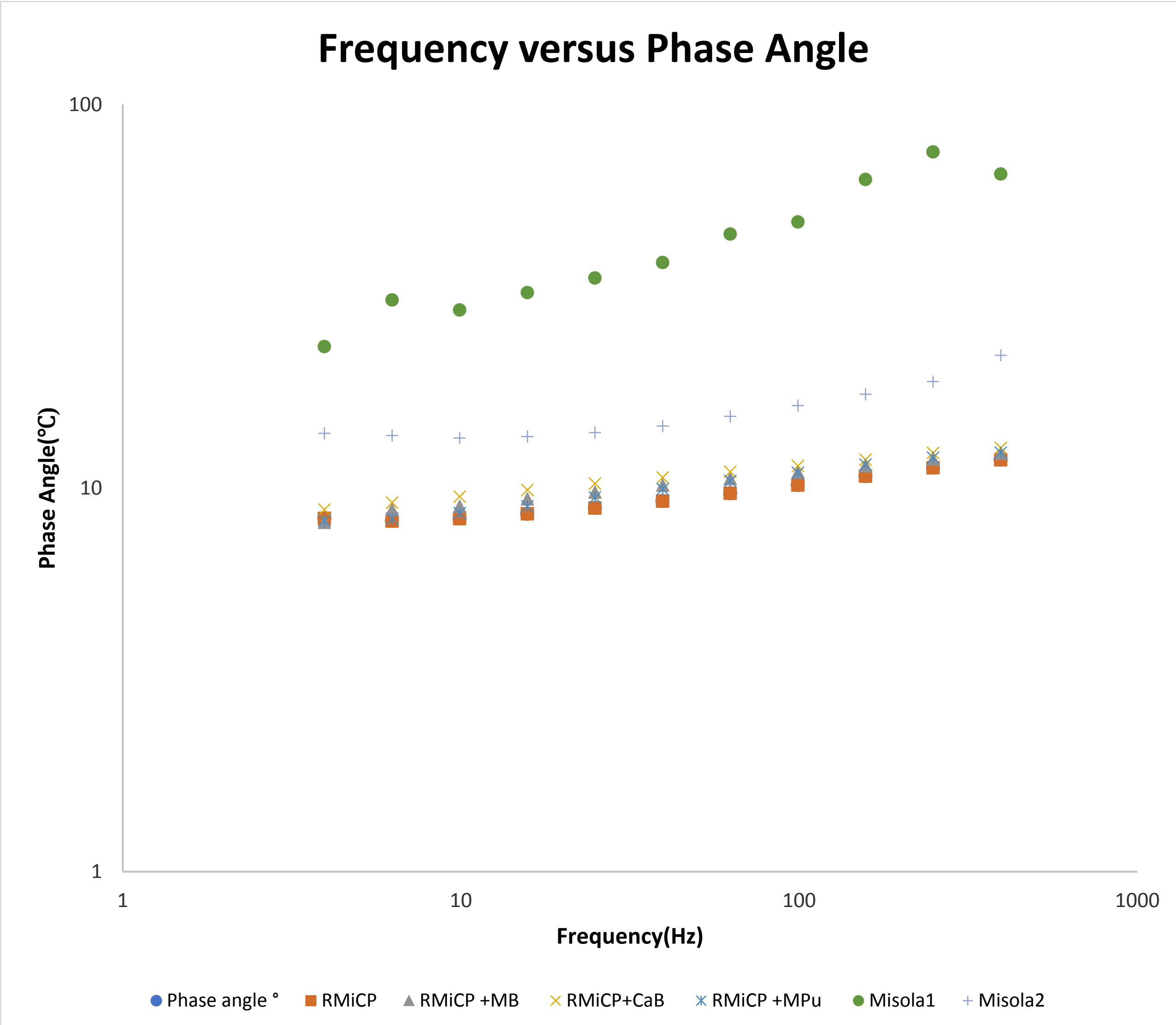

Figure 3.10. Phase angle measurement of fortified thin porridges samples made using roasting method versus local controls.

Values are means of triplicate determinations. Sample codes are described as follows: R=Roasted, Mi=Millet, C=Cowpea, Ca=Carrot, P=Peanut, Pu=Pumpkin, M=Moringa, B=Baobab (refer to Section 3.3.2.4 in Methods for more details).

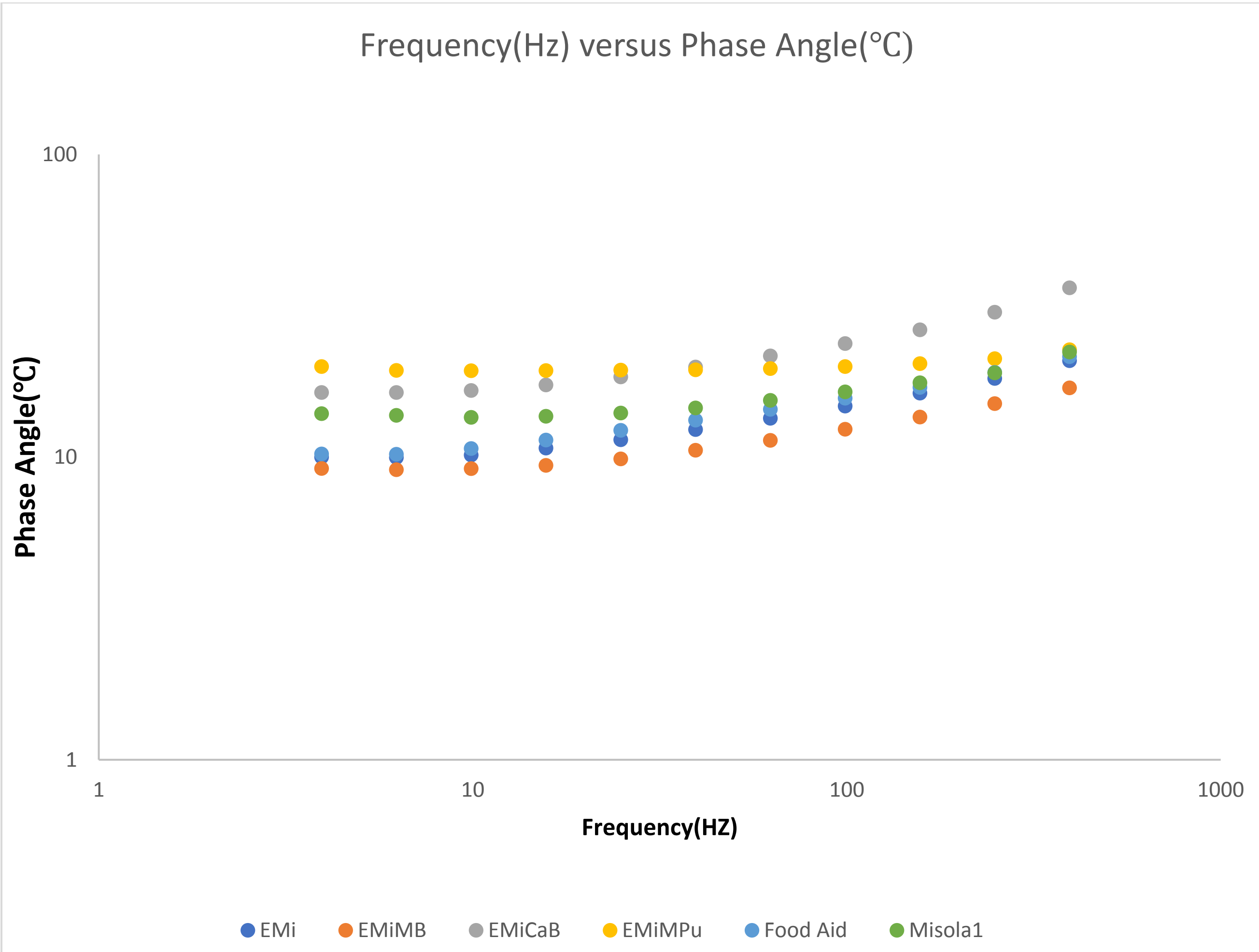

Figure 3.11. Phase angle measurement of fortified thin porridges samples made using the extrusion method versus local controls.

Values are means of triplicate determinations. Sample codes are described as follows: E=Extruded, Mi=Millet, Ca=Carrot, Pu=Pumpkin, M=Moringa, B=Baobab (refer to Section 3.3.2.4 in Methods for more details).

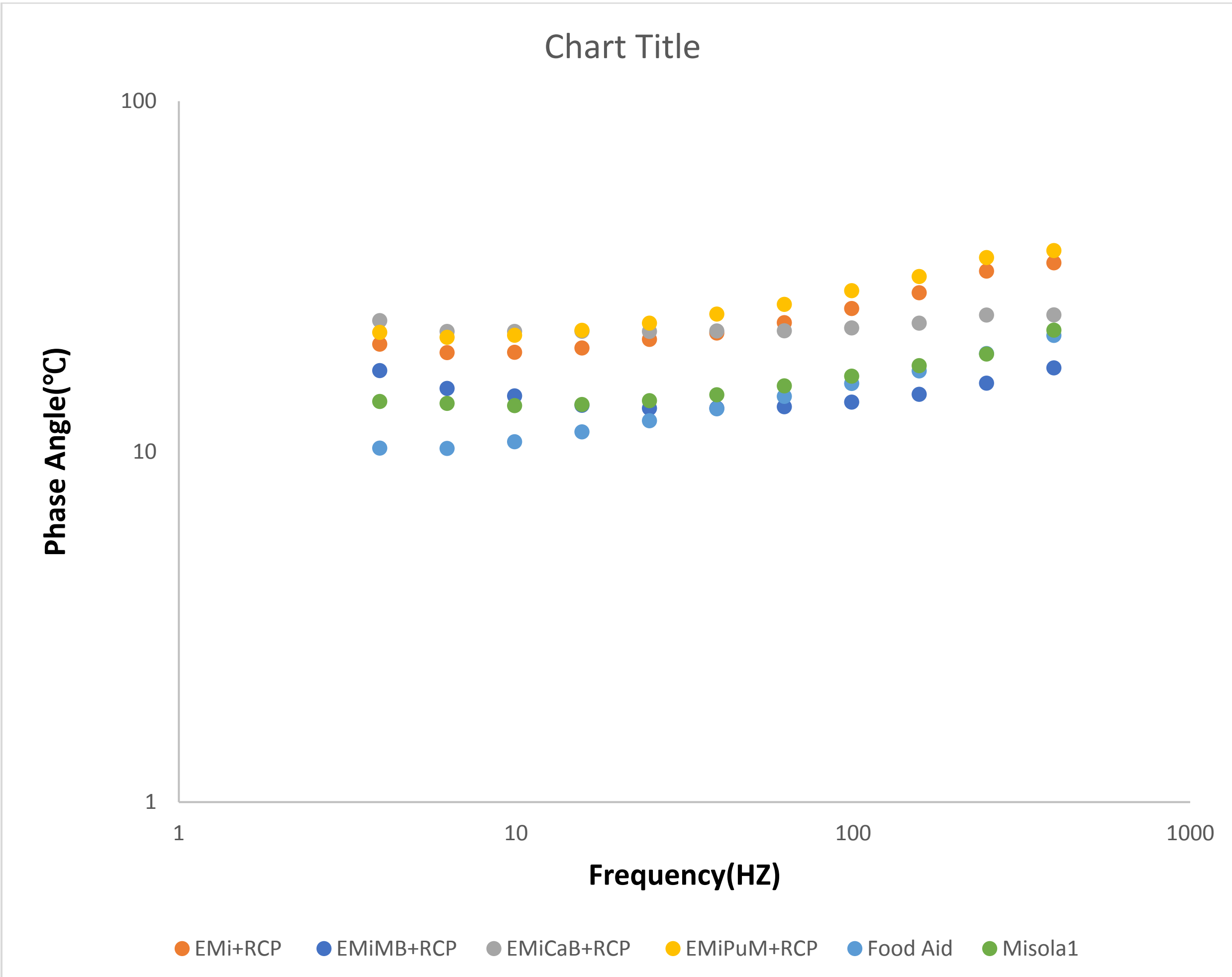

Figure 3.12. Phase angle measurement of fortified thin porridge blended samples made using roasting and extrusion mixed methods versus local food aid control.

Values are means of triplicate determinations. Sample codes are described as follows: E=Extruded, R=Roasted, Mi=Millet, C=Cowpea, Ca=Carrot, P=Peanut, Pu=Pumpkin, M=Moringa, B=Baobab (refer to Section 3.3.2.4 in Methods for more details).

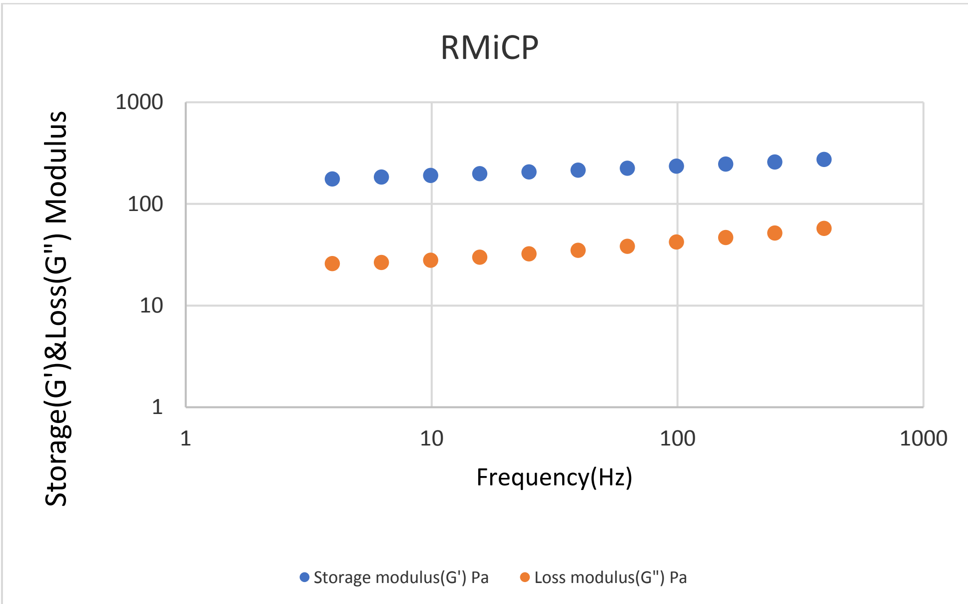

Figure 3.13. Dynamic oscillation measurement of fortified thin porridge sample, RMiCP made using the roasting method.

Sample codes are described as follows: R=Roasted, Mi=Millet, C=Cowpea, P=Peanut (refer to Section 3.3.2.4 in Methods for more details).

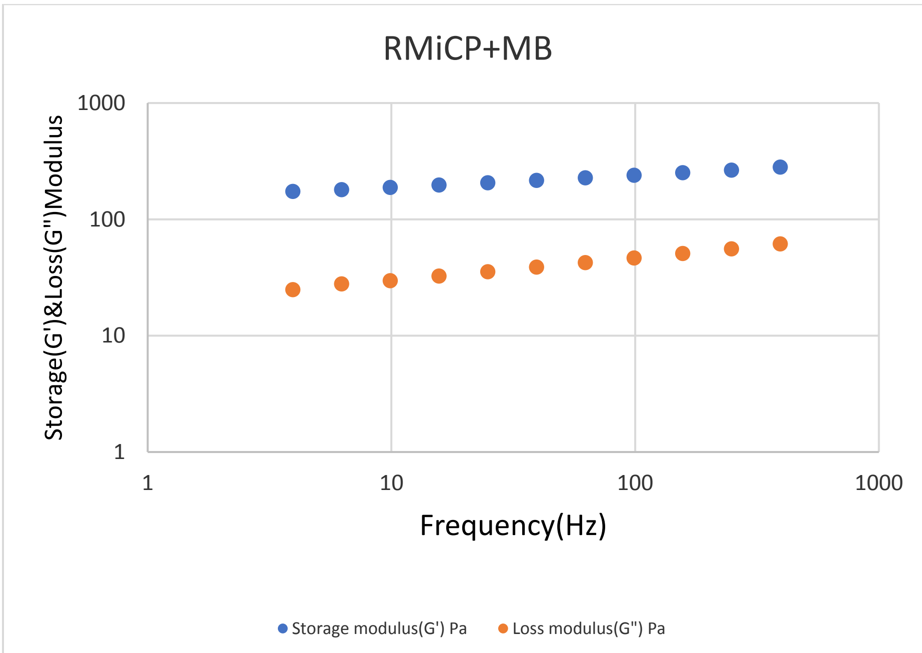

Figure 3.14. Dynamic oscillation measurement of fortified thin porridge sample, RMiCP +MB made using the roasting method.

Sample codes are described as follows: R=Roasted, Mi=Millet, C=Cowpea, P=Peanut, M=Moringa, B=Baobab (refer to Section 3.3.2.4 in Methods for more details).

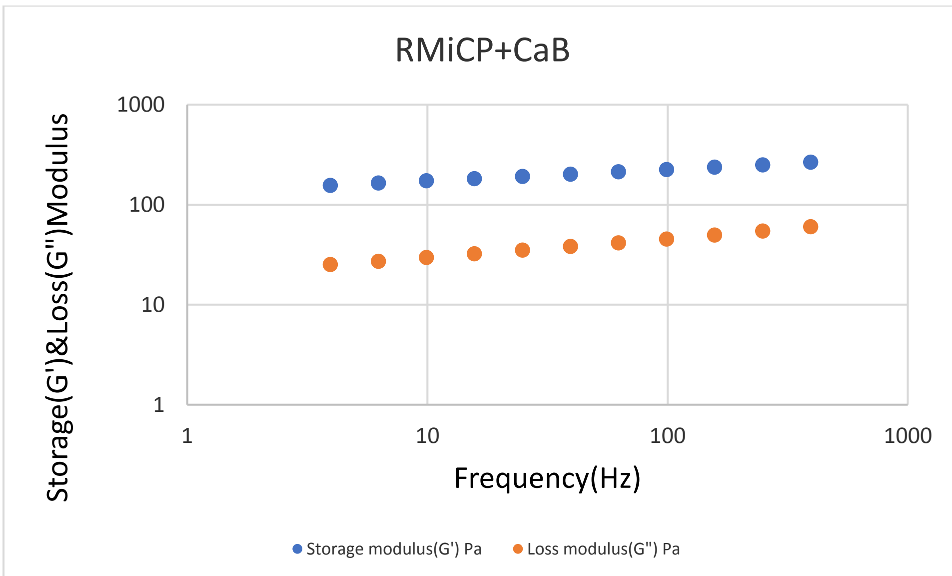

Figure 3.15. Dynamic oscillation measurement of fortified thin porridge sample, RMiCP+CaB made using the roasting method.

Sample codes are described as follows: R=Roasted, Mi=Millet, C=Cowpea, Ca=Carrot, P=Peanut, B=Baobab (refer to Section 3.3.2.4 in Methods for more details).

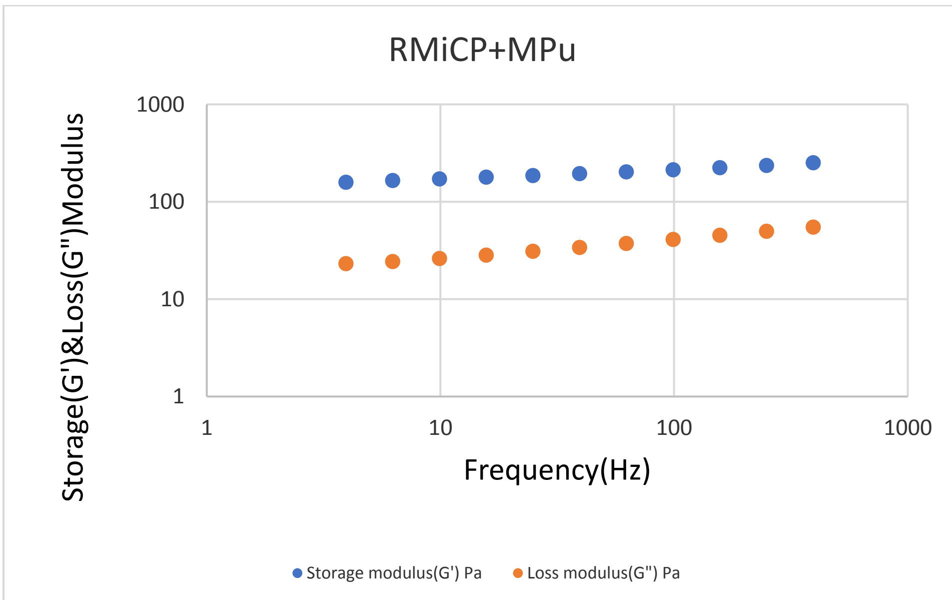

Figure 3.16. Dynamic oscillation measurement of fortified thin porridge sample, RMiCP +MPu made using the roasting method.

Sample codes are described as follows: R=Roasted, Mi=Millet, C=Cowpea, P=Peanut, Pu=Pumpkin, M=Moringa (refer to Section 3.3.2.4 in Methods for more details).

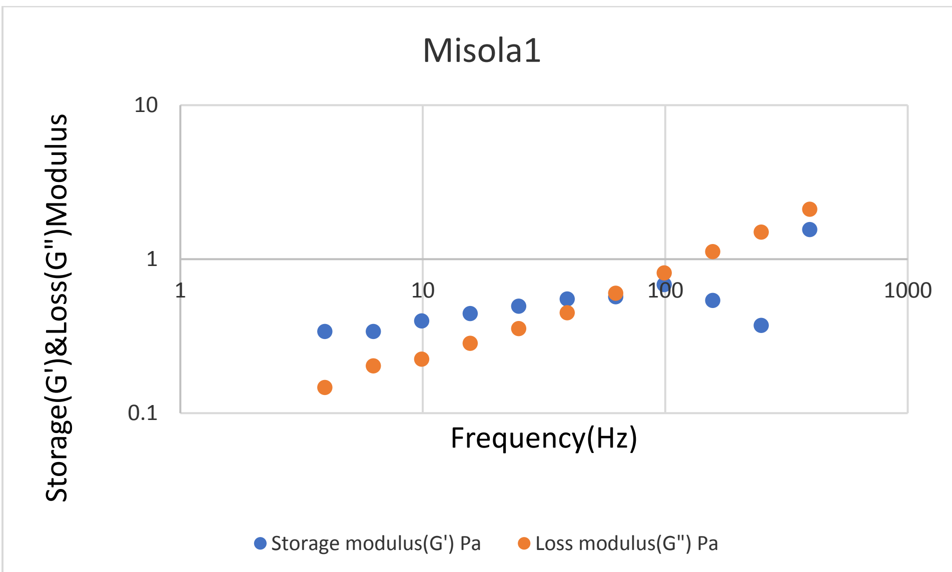

Figure 3.17. Dynamic oscillation measurement of fortified thin porridge control (Misola1) sample made using the roasting method.

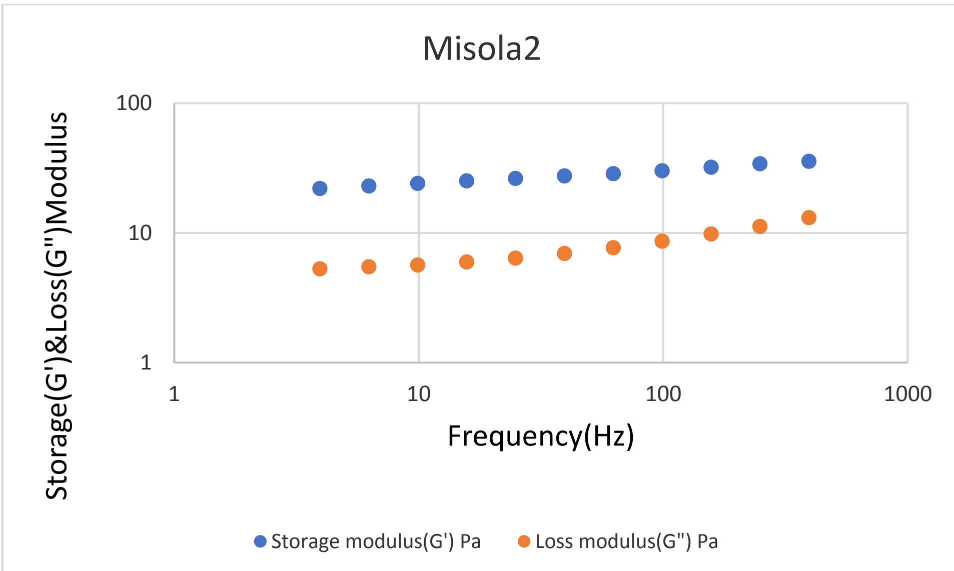

Figure 3.18. Dynamic oscillation measurement of fortified thin porridge control (Misola 2) sample made using the roasting method.

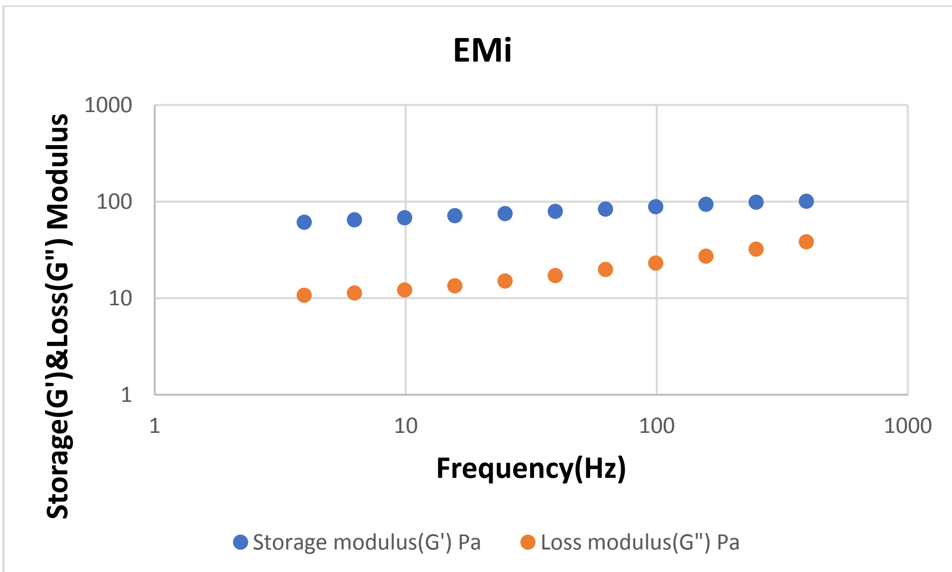

Figure 3.19. Dynamic oscillation measurement of fortified thin porridge sample, EMi made using the extrusion method.

Sample codes are described as follows: E=Extruded, Mi=Millet (refer to Section 3.3.2.4 in Methods for more details).

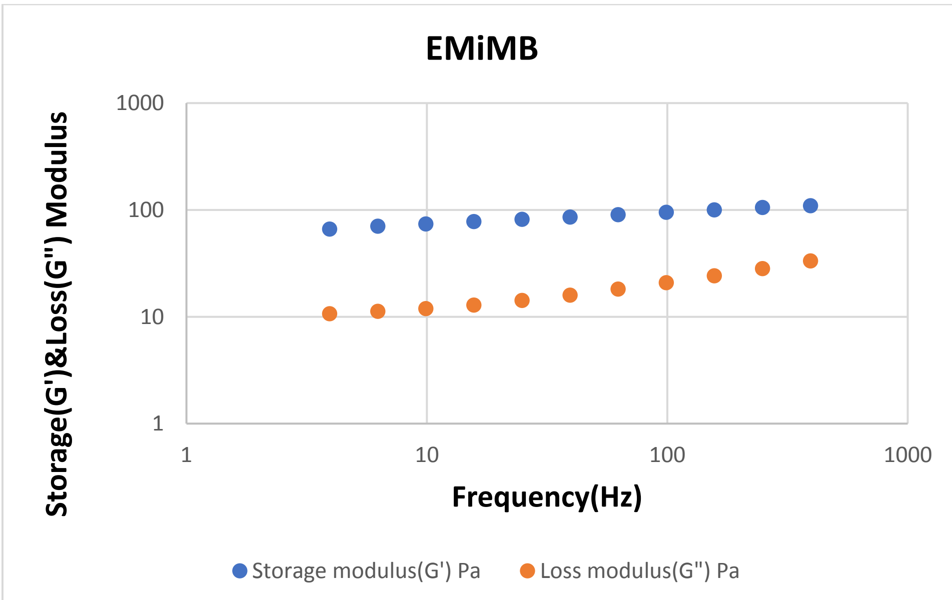

Figure 3.20. Dynamic oscillation measurement of fortified thin porridge sample, EMiMB made using the extrusion method.

Sample codes are described as follows: E=Extruded, Mi=Millet, M=Moringa, B=Baobab (refer to Section 3.3.2.4 in Methods for more details).

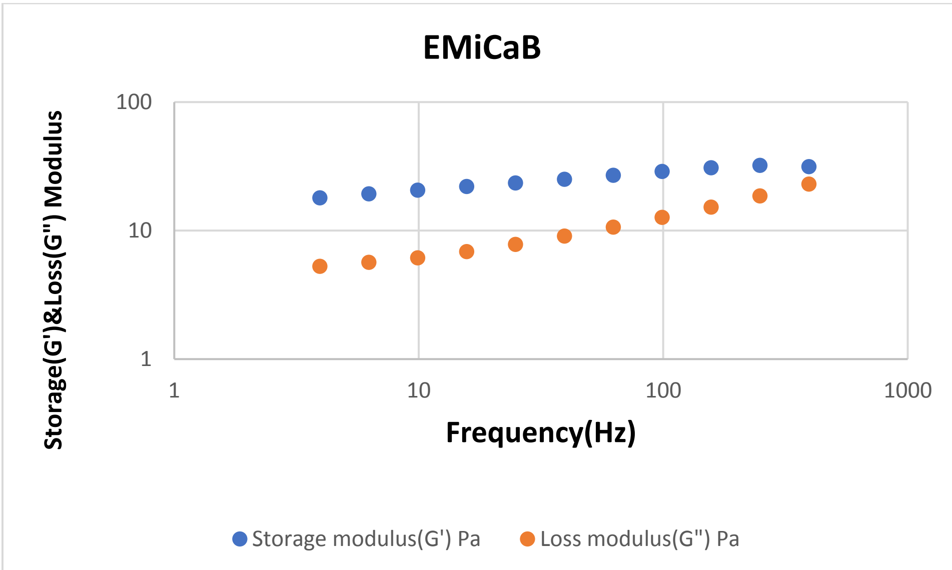

Figure 3.21. Dynamic oscillation measurement of fortified thin porridge sample, EMiCaB made using the extrusion method.

Sample codes are described as follows: E=Extruded, Mi=Millet, Ca=Carrot, B=Baobab (refer to Section 3.3.2.4 in Methods for more details).

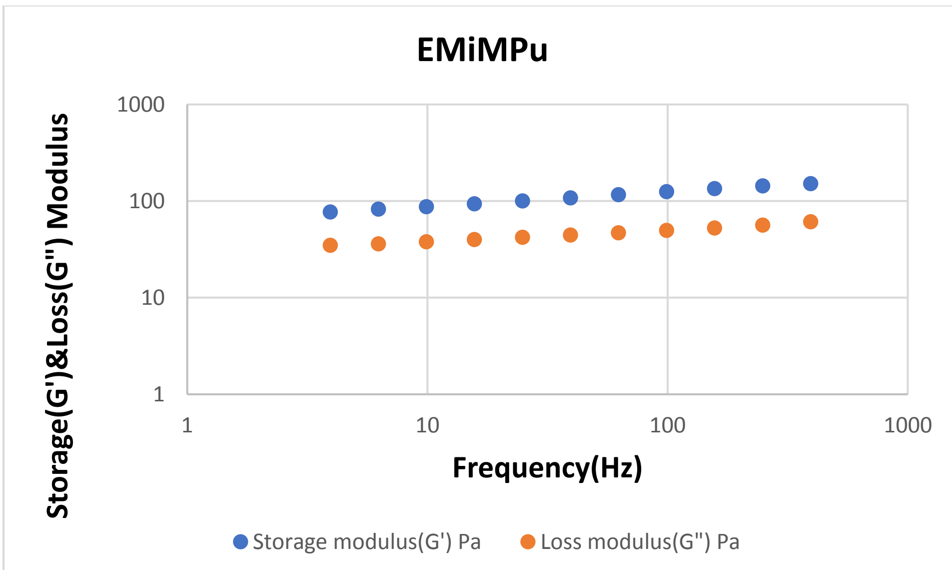

Figure 3.22. Dynamic oscillation measurement of fortified thin porridge sample, EMiMPu made using the extrusion method.

Sample codes are described as follows: E=Extruded Mi=Millet, M=Moringa, Pu=Pumpkin (refer to Section 3.3.2.4 in Methods for more details).

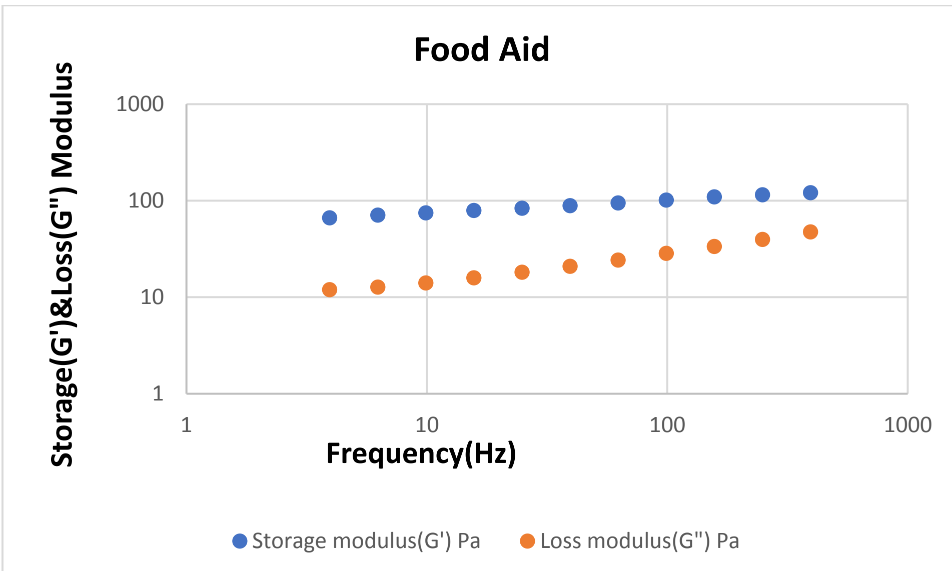

Figure 3.23. Dynamic oscillation measurement of the fortified thin porridge control sample (Food Aid).

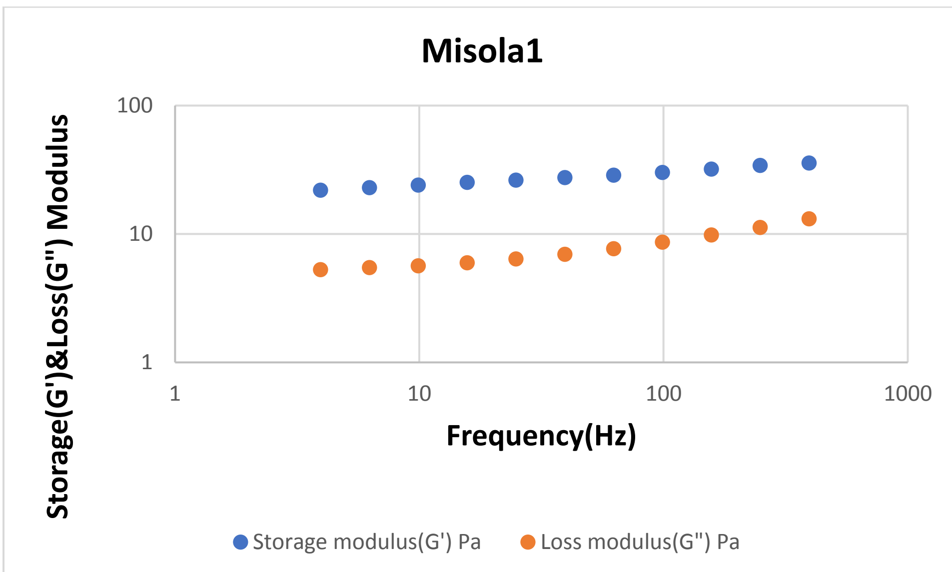

Figure 3.24. Dynamic oscillation of measurement of the fortified thin porridge control sample (Misola1).

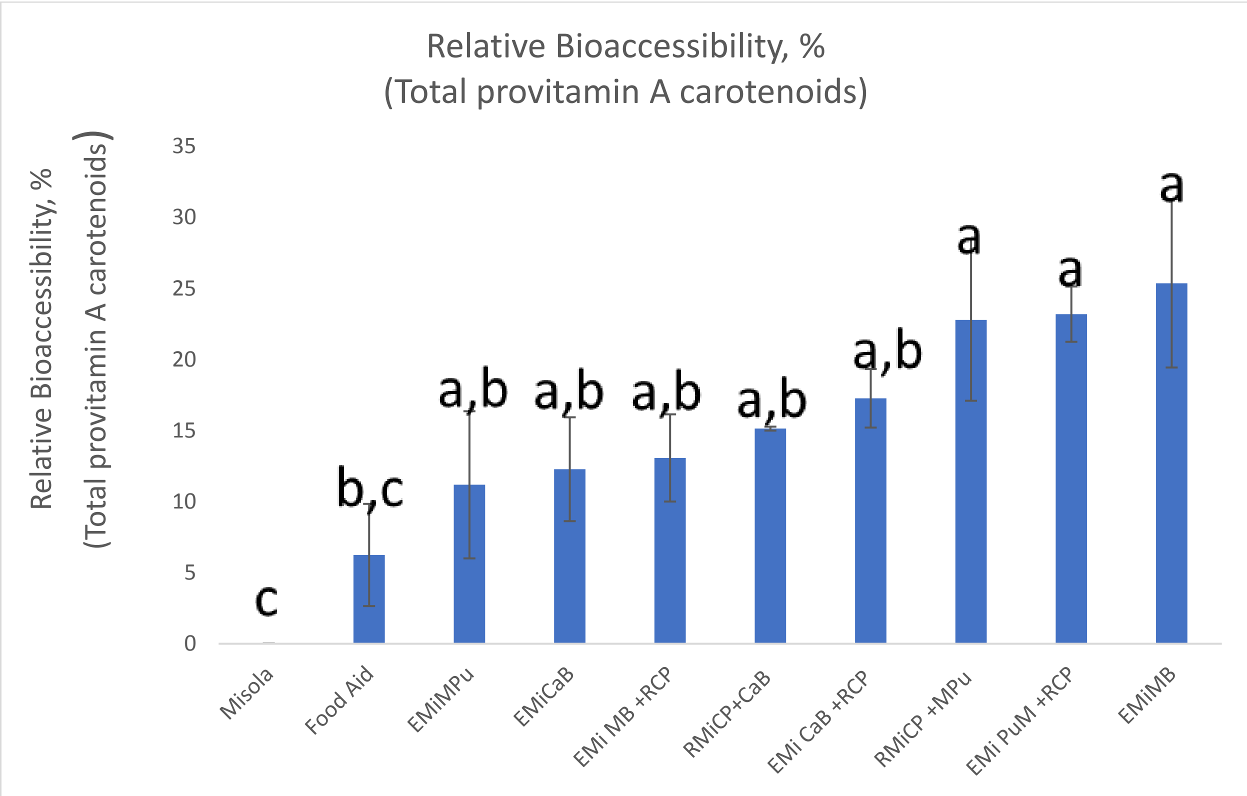

Figure 3.25. Relative bioaccessibility, % total provitamin A carotenoids. Values are means of triplicate determinations. Different superscripts among treatments indicate significant differences ($P<0.05$, Duncan's Multiple Range Test).

Sample codes are described as follows: R=Roasted, Mi=Millet, E=Extruded, C=Cowpea, Ca=Carrot, P=Peanut, Pu=Pumpkin, M=Moringa, B=Baobab (refer to Section 3.3.2.4 in Methods for more details).

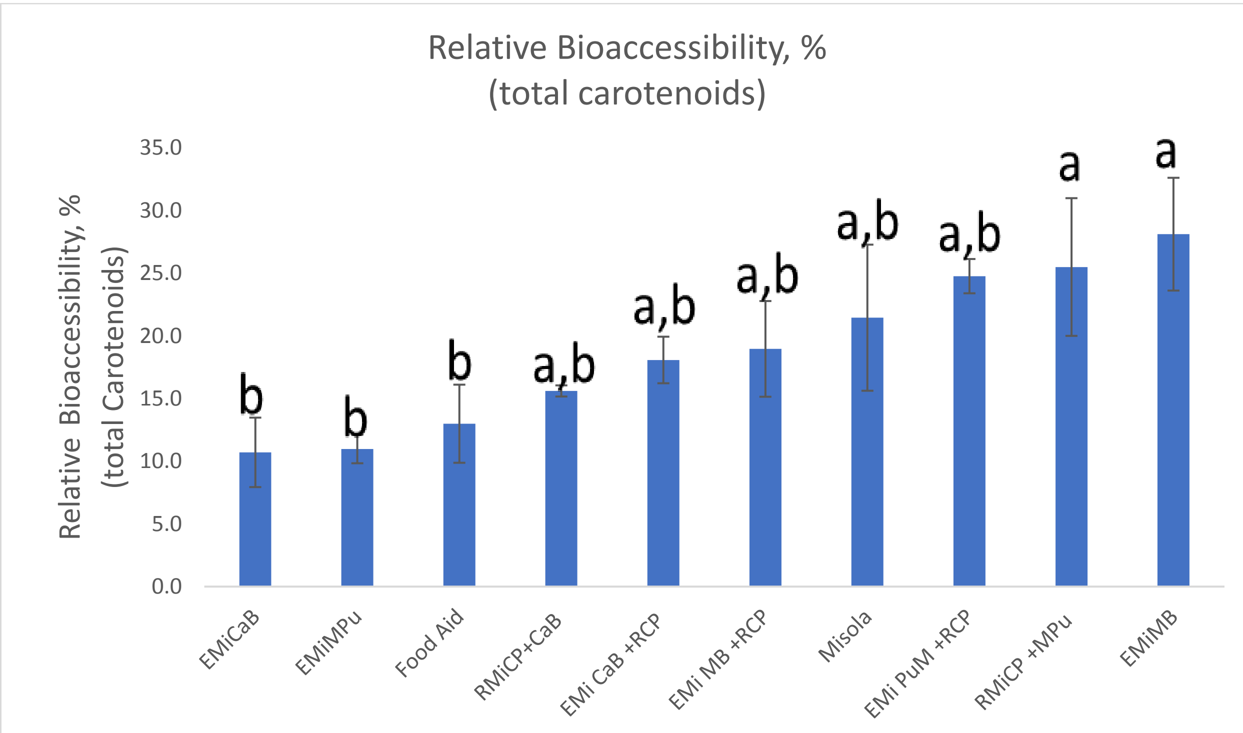

Figure 3.26. Relative bioaccessibility, % total carotenoids. Values are means of triplicate determinations. Different superscripts among treatments indicate significant differences ($P<0.05$, Duncan's Multiple Range Test).

Sample codes are described as follows: R=Roasted, Mi=Millet, E=Extruded, C=Cowpea, Ca=Carrot, P=Peanut, Pu=Pumpkin, M=Moringa, B=Baobab (refer to Section 3.3.2.4 in Methods for more details).

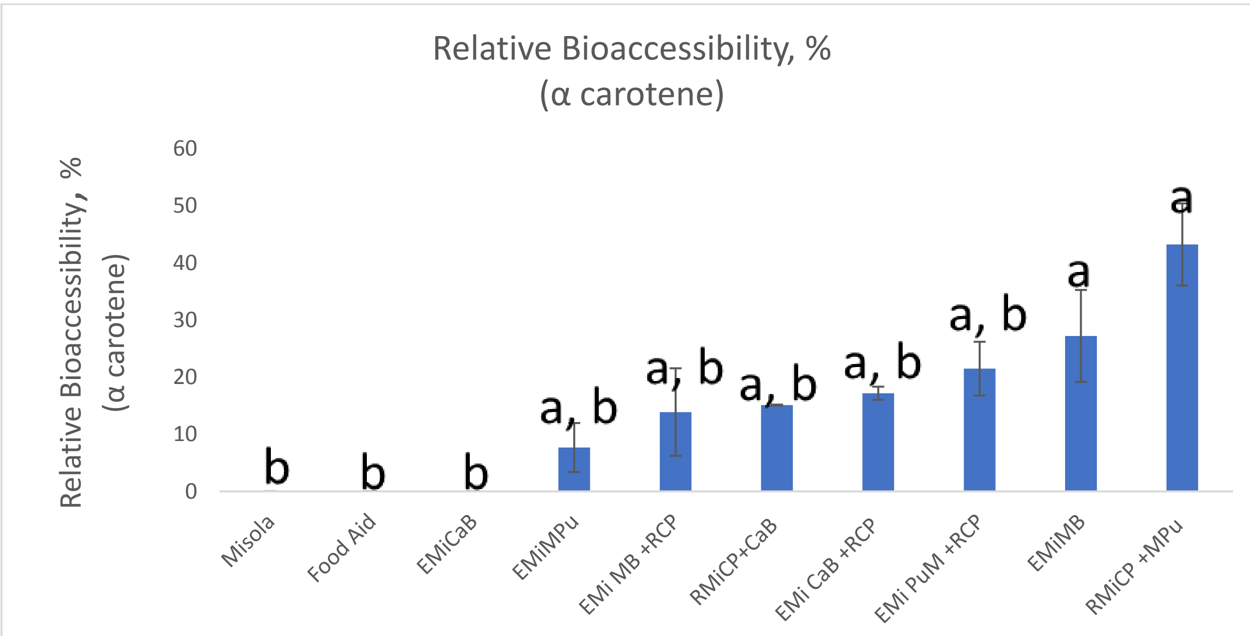

Figure 3.27.Relative bioaccessibility, % α-carotene. Values are means of triplicate determinations. Different superscripts among treatments indicate significant differences ($P<0.05$, Duncan's Multiple Range Test).

Sample codes are described as follows: R=Roasted, Mi=Millet, E=Extruded, C=Cowpea, Ca=Carrot, P=Peanut, Pu=Pumpkin, M=Moringa, B=Baobab (refer to Section 3.3.2.4 in Methods for more details).

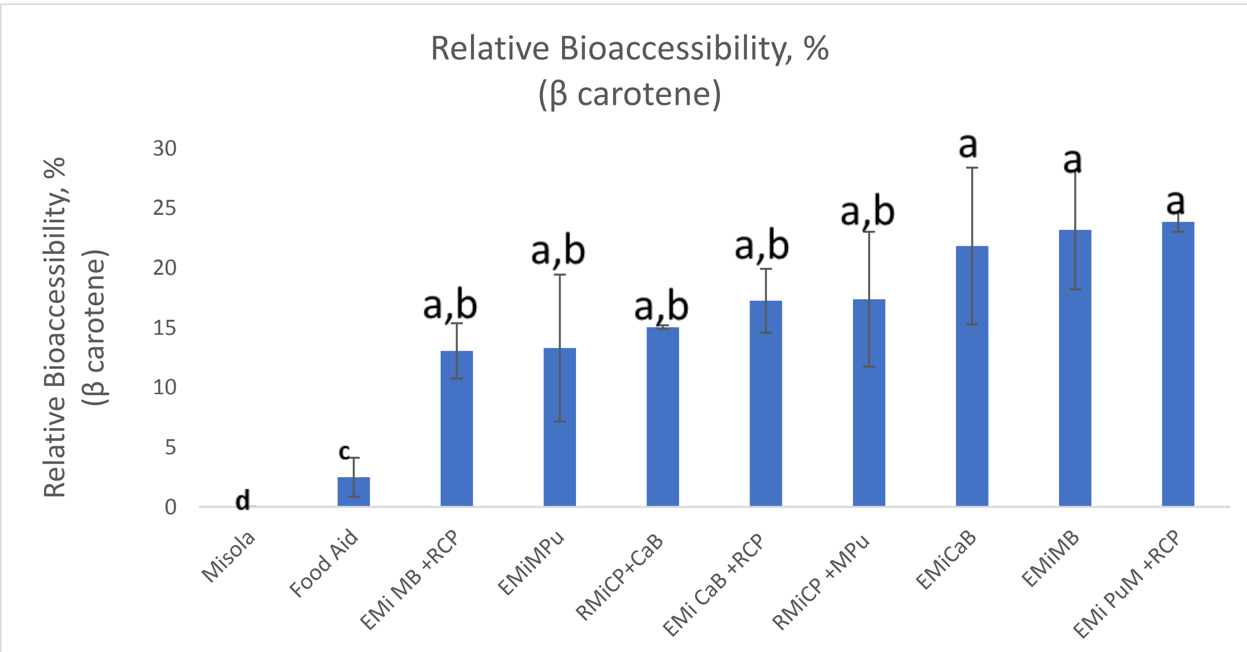

Figure 3.28. Relative bioaccessibility, % β-carotene**. Values are means of triplicate determinations. Different superscripts among treatments indicate significant differences (P<0.05, Duncan's Multiple Range Test).**

Sample codes are described as follows: R=Roasted, Mi=Millet, E=Extruded, C=Cowpea, Ca=Carrot, P=Peanut, Pu=Pumpkin, M=Moringa, B=Baobab (refer to Section 3.3.2.4 in Methods for more details).

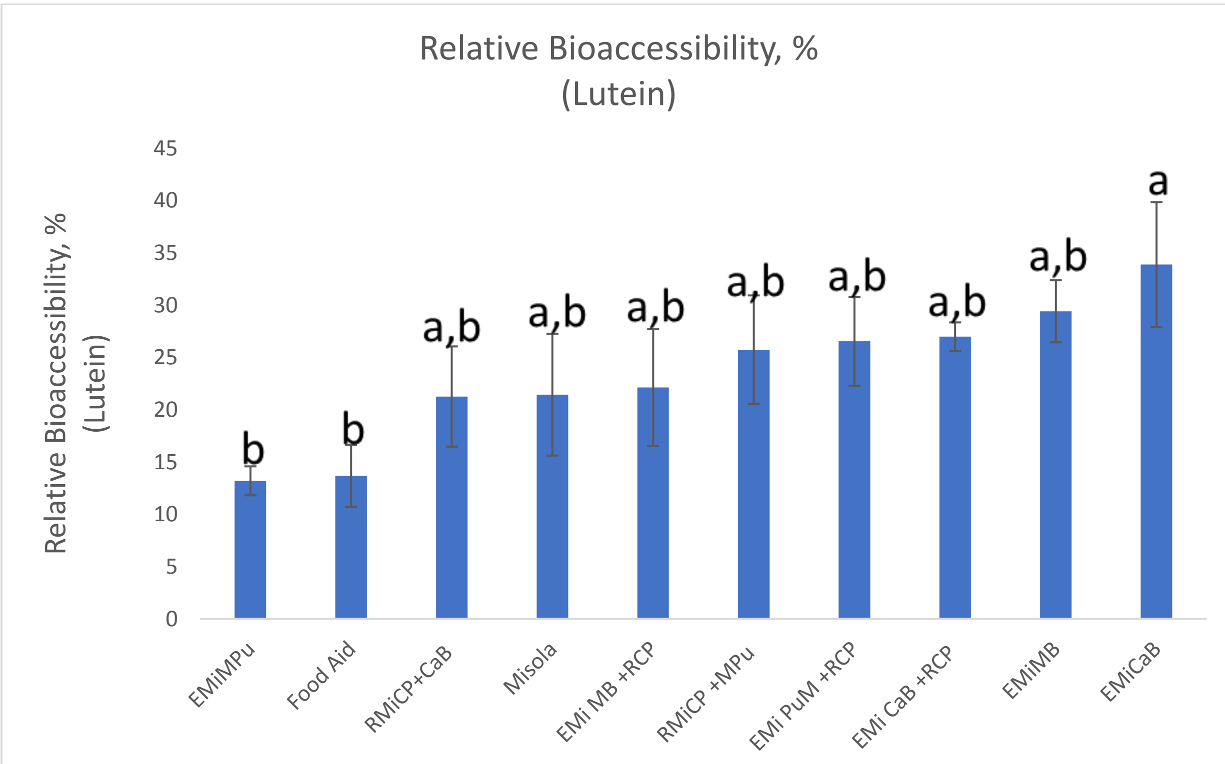

Figure 3.29. **Relative bioaccessibility, % lutein**.

Values are means of triplicate determinations. Different superscripts among treatments indicate significant differences ($P<0.05$, Duncan's Multiple Range Test). Sample codes are described as follows: R=Roasted, Mi=Millet, E=Extruded, C=Cowpea, Ca=Carrot, P=Peanut, Pu=Pumpkin, M=Moringa, B=Baobab (refer to Section 3.3.2.4 in Methods for more details).

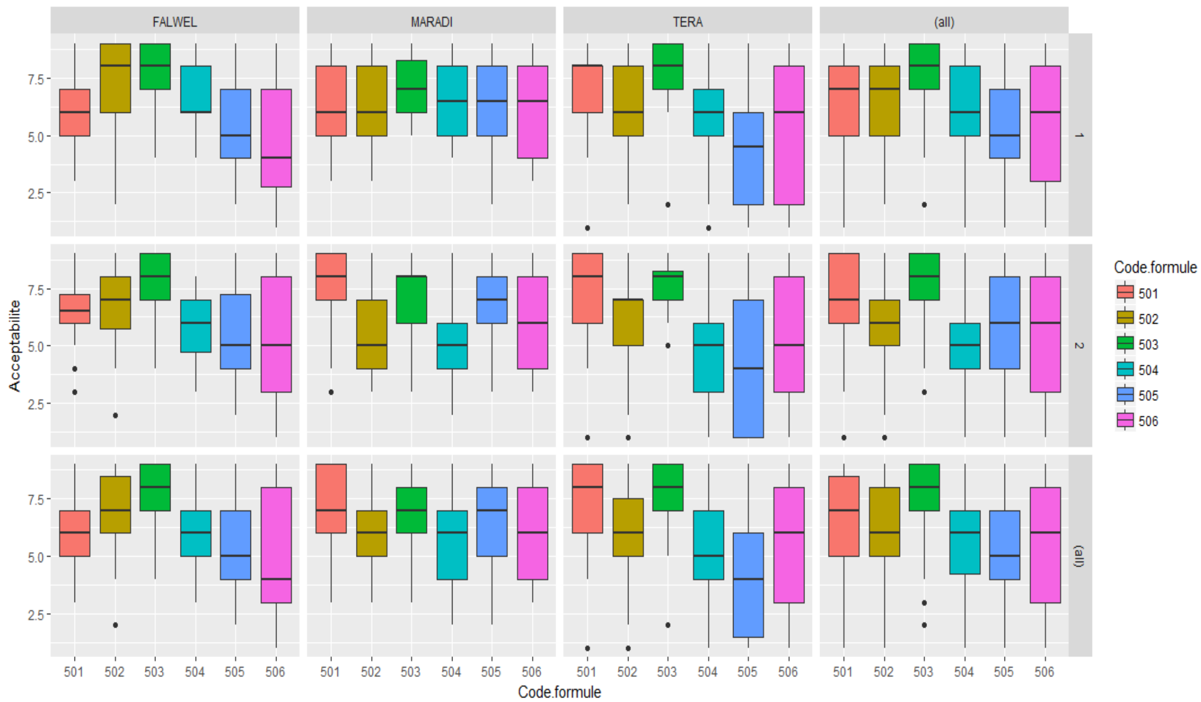

Figure 3.30. Boxplots of sensory preference testing of fortified porridge formulas made by the roasting method compared to food aid formulas in 8 villages in rural Niger (Falwel, Maradi and Tera). Values are means (n= 320, P<0.05).

Sample codes are described as follows: R=Roasted, Mi=Millet, C=Cowpea, Ca=Carrot, P=Peanut, Pu=Pumpkin, M=Moringa, B=Baobab (refer to Section 3.3.2.4 in Methods for more details 501-506 corresponded respectively to:

501: RMiCP = whole grain (Millet-89305)+cowpea (TN378)+peanut (5544);

502: RMiCP+MB = whole grain (millet-99001)+ cowpea (TN378)+peanut (5544)+moringa+baobab;

503: RMiCP+CaB = whole grain millet (PPBTera)+cowpea (TN378)+peanut (5544)+carrot+baobab;

504: RMiCP +MPu = whole grain (millet-local) +cowpea (TN378)+peanut (5544)+moringa+pumpkin ;

505: Food Aid = control1-food aid (maize-soybean+vitamin-premix blend);

506: Misola (millet-soybean-peanut-vitamin-premix).

CHAPTER 4. INNOVATIVE PROCESS OF MAKING INSTANT MILLET TUWO (THICK) AND FURA (THIN) PORRIDGES FOR THE WEST AFRICAN MARKET

4.1 Abstract

Thick and thin porridges are popular millet foods commonly consumed in West Africa. The traditional process of making instant *tuwo* and *fura* porridges is tedious, laborious, and time-consuming, and only produces small quantities of products. Processing conditions using a low-cost single screw mini-extruder were assessed and optimized to produce instant *tuwo* and *fura* porridge flours. The products have the advantage of short processing time with high daily throughput of ~200-300 kg. The instant *tuwo* and *fura* porridge flours were reconstituted by just adding hot or tap water. Laboratory analysis of the instant *tuwo* and *fura* products showed that instant extruded porridges had somewhat different paste and gel properties, with the thin *fura* porridge having higher viscosity and gel strength and better elasticity and shear thinning property compared to the traditionally-prepared *fura*. Color was also somewhat better for the instant *fura* product. The thick *tuwo* products were approximately the same in rheological properties, except that the instant *tuwo* had lower gel strength. In home-use-testing (HUT) of instant *tuwo* and *fura* porridges was conducted in Niamey, Niger. Results indicated good to very good overall consumer acceptability. Package label information included product size, weight, time, and mode of preparation and were also rated good to very good. In general, overall consumer acceptability and perception of the instant porridges were not strongly associated with level of education, work function, gender, location, or site of responders. The average willingness to pay mean for the instant *tuwo* and *fura* porridge was near 500 FCFA/500 g packet. In most cases WTP was not associated with level of education, work function, gender, or responder's site. A market sales study was conducted on the new instant *tuwo* (thick) and *fura* (thin) porridge flours in Niamey to explore, for the first time, their market potential. Porridge flours were sold by processor partners of the INRAN Food Innovation Center for 20 weeks in five locations and at 30 sale points to examine products' market behavior. A total quantity of 2.5 metric tons of instant porridge flours, including 1 metric ton of instant *tuwo* and 1.5 metric tons of instant *fura* porridge flour products were processed at INRAN. They were distributed to the sale points in Niamey by the six processors.

The two new instant porridge products to the Niamey market generated about 1/3 of the total sales of all the 35 cereal products sold by the processors in the 20-week period.

4.2 Introduction

Sorghum and millet crops are the staple foods for most people in the Sahelian region of West Africa (>80% smallholder's farmers in Niger). The adaptation of sorghum and millet to different agro-ecological zones and suitability for a large myriad of foods confers on them a leading role in the region's food security. Annual grain production in this region for millet and sorghum averaged 9,131,313 and 12,662,916 metric tons respectively (FAO, 2019). They are the major source of carbohydrates and provide more than 50% of the total calories in the diet (FAO, 2019; FAO, 2017). Millet and sorghum grains have considerable potential to develop new processed foods.

Millet foods include think and thick porridges, agglomerated products (e.g. *couscous*, *degue*) beverages, and cookies and baked products, and are popular in many African countries **(**Aboubacar et al., 2006; Moussa et al., 2011; Taylor et al., 2006). Millet porridges, in particular, are widely consumed as staple foods. In Niger, the most common porridges types are *tuwo* (thick) and *fura* (thin) porridges, as well as another thin porridge (*kounou*)**.**

Tuwo (thick) and *fura* (thin) millet porridges are commonly consumed in diets in Niger and northern Nigeria, in West African Sahelian region. The difference between them is the concentration of the flour and methods used in their preparation. *Tuwo* (thick) porridge is solid-like and stiff, and can be eaten with the hand, while *fura* (thin) porridge is fluid- or semi-fluid-like and is made by grinding millet or sorghum grain into flour, then wetted and rolled into large balls, parboiled, and liquefied into a watery paste with fermented milk. It is intended for drinking in a glass or cup. In addition to fermented milk, other flavorings or food items such as fruits, lemon, tamarind, or spices are added to *fura* (Obadina, et al, 2016; Moussa et al., 2011). Both products are made by women and sold on the street, though *fura* is more commercialized.

Thick porridge is consumed as the starchy staple food at meals, while thin porridges are consumed in the morning as breakfast, or during the day as a snack-type food. The quality of porridges can vary significantly due to methods of preparation and a wide range of genetic variation inherent in millet and sorghum crops, which results in porridges of different colors, flavors, and textures. Product characteristics including texture and color are considered the most important quality attributes that affect consumer acceptability of millet and sorghum foods (Cissé et al., 2018; Moussa et al., 2011; Aboubacar et al, 2006; Ndjeunga and Nelson, 2005; Scheuring, et al.,1982).

While they are popular, preparations of millet *tuwo* and *fura* porridges are manually intensive and laborious processes and have low efficiency. Production can take up to 2 days and is generally limited to household use. As mentioned, it is also prepared by women and sold on the street and in neighborhoods, thus market penetration is modest. At the same time, with growing urban populations, pressure on time for food preparation, and increasing income of the middle socioeconomic class, there is the potential for demand for high-quality processed convenient-to-prepare products.

In previous work at INRAN, Niger, in collaboration with Purdue University, and with support from SMIL-USAID, we have shown the potential of processing sorghum grain by a twin screw continuous processor (high shear, high temperature, low pressure extruder-type processor) to produce instant flours for making sorghum *tuwo* and *kounou* (thin) porridges. Our finding showed either a parity or preference in consumer preference scores for instant sorghum *tuwo* and *kounou* porridges compared to traditionally-prepared porridges in different varieties tested (Moussa et al., 2011). The continuous twin-screw extruder was an expensive piece of equipment and, later, the project switched to using a low-cost single screw extruder developed by Purdue University engineers and commercialized by Technochem, Inc. A single screw extruder was purchased and placed at INRAN, Niger and experiments were performed using single screw extrusion to make instant flours for thick and thin porridges.

Exploring the potential of using the single screw extruder, as optimized in Niger to process high-quality instant millet porridges, can be perceived as a way to expand millet markets and thereby boost local millet production by farmers in Niger and other parts of West Africa. In addition, we anticipate that single screw extrusion of instant or fast-cooking millet porridges with improved organoleptic properties will contribute to market expansion, particularly directed towards urban consumers. A further aim of the project is to facilitate scaling up of food processing innovation centers in West Africa to support the emergence, of small- and medium-scale entrepreneur processors who can compete well in the marketplace. The increased use of the single screw extruder for making instant millet porridges can catalyze an increase in demand for millet grains, and strengthen linkages to smallholders' farmers to the market, and be a stimulus for producing surplus millet grains by local farmers.

The objectives of this study were:

(1) To explore the potential of the single screw extruder to process a) instant *tuwo* (thick) porridge and b) instant *fura* (thin) porridge, and determine differences in physicochemical characteristics between the instant and traditional thick and thin porridges, and consumers acceptability in Niger.

(2) To evaluate urban consumer's sensory preference/acceptability of instant *tuwo* (thick) and b) instant *fura* (thin) porridges through a modified Home Use Testing (HUT), and determine whether the instant porridge products are acceptable to consumers compared to traditional porridges.

(3) To market test instant *tuwo* (thick) and b) instant *fura* (thin) porridges, for determination of product marketing behavior (frequency of sales) in the Niamey, over a 20-week period, and compared to similar existing and related cereal-based foods.

4.3 Part A Extruder processing of instant millet *tuwo* (thick) and *fura* (thin) porridges

4.3.1 Materials and methods

4.3.1.1 Materials

One (1) improved millet variety (*99001*) was selected, from several others tested from study presented in Chapter 3, and one (1) local variety (*Hainikire*) of millet were used for the study. The millet grains were provided by ICRISAT and INRAN scientists and grown on farms in Sherkin Haoussa. Maradi, Niger by the Fuma Gaskiya farmer group during the summers of 2017 and 2018.

4.3.1.2 Methods

4.3.1.2.1 Extrusion

Preliminary experiments were conducted to determine instrumental settings necessary to produce good quality products with the single screw mini-extruder (Technochem International, Inc. Boone, IA, USA). Process variables included rotating speed, temperature, and moisture content of feed flour. Prior to the extrusion process, the improved millet variety (99001) grain was decorticated to achieve between 75-80% extraction rate (grain separation from bran, removal of 20-25% grain weight). Decorticated millet grains were then washed and milled to grits of desired particle size ranging between 600-700 µm.

Samples were then equilibrated to a feed moisture content of 35% for 30 min at ambient temperature. The single screw extruder was appropriately set up to a temperature that varied between 115-140^{0} C, and a frequency of 50 Hz. Speed was adjusted between 700-900 rpm. Equipment was then run to produce the millet extrudates samples to be used for the preparation of instant flours for making thick and thin porridges.

4.3.1.2.2 Preparation of instant flours samples for making thick and thin porridges

Extrudates were first cooled, then cut into pieces, and dried to <10% moisture content in a gas drier (locally fabricated, Niamey, Niger). Dried samples were milled to desired particle sizes depending on the product type and described below.

a) For the instant flour sample for making *tuwo* (thick) porridge, extrudates were milled to a fine flour of particle sizes ranging between 200-500 µm and stored in polyethylene bags at room temperature.

b) For the instant flour sample for making *fura* (thin) porridge, the extrudates were milled to a medium particle size flour ranging between 700-1000 µm and stored in polyethylene bags at room temperature.

4.3.1.2.3 Preparation of traditional *tuwo* and *fura* porridges used as controls

The traditional *tuwo* (thick) and *fura* (thin) porridges used as controls were prepared by conventional cooking methods according to the procedures described by (Cissé et al., 2018; Obadini et al., 2016; Moussa et al., 2011; Aboubacar et al.,2006; Ndjeunga et al., 2005)

4.3.1.2.4 Pasting properties of porridge samples using RVA

The pasting properties of porridge samples (10.7% solids, 3 g in 25 ml water) were determined using a Rapid Visco Analyzer (RVA, Newport Scientific Pty. Ltd., Narabeen, Australia). Standard method 1 (short temperature profile) was used. The mixtures were first stirred at 960 rpm for 10 s and then at 160 rpm for the rest of the testing period. The temperature profile was a hold at 50^{o}C for 2 min, heating to 95^{o}C in 6 min, hold at 95^{o}C for 4 min, cooling to 50^{o}C for 6 min, and a hold at 50^{o}C for 4 min. From the pasting curve, the following values were obtained: initial pasting temperature and peak viscosity (P) (the maximum hot paste viscosity), holding strength (H) (trough at minimum paste viscosity), final viscosity (C), and viscosities of setback from trough (C-H), and of breakdown (P-H) as described (Moussa et al., 2011; Vamadevan and Bertoft, 2014).

4.3.1.2.5 Dynamic oscillatory testing and steady shear rheometry of porridges samples

Dynamic oscillatory measurements on porridges were performed using a rheometer (ATS, TA Instruments, Inc., NJ, USA) using a parallel plate geometry. After warming the instrument, a strain sweep was carried out to determine the viscoelastic linear region of strain for dynamic measurement of porridge samples. Frequency sweep measurements were made at a strain of 1% (0.01), which was within the linear region. Dynamic oscillatory measurements were taken on the porridge samples loaded on the plate at a constant strain of 1%, in a frequency range of 0.4 to 10 Hz, and at a temperature of 30ºC.

Viscosity characteristics of the porridge samples were determined from the flow curve obtained. After warming the instrument, a small portion (about 0.5 g) of porridge sample was loaded onto the parallel plates and viscosity was determined up to shear rates of 310/s at 30ºC, according to the procedure described by Moussa et al., 2011.

4.3.1.2.6 Color of porridge samples

Porridge color was determined using a Hunter Lab Colorimeter (Model D25, Hunter Associates Lab, Inc., Virginia, USA), as described by others (Moussa et al, 2011; Aboubacar et al., 2006). After calibration of the colorimeter with standard black and white tiles, porridge samples were placed in a 5.5 cm cell with an optically transparent glass bottom and L, a, b, readings taken. The parameters determined were L*, a*, and b* (L* value as the lightness, a* value the red-greenness, and b* value the blue-yellowness). The greater, the L*, a*, and, b* values, the lighter, redder, and more yellow, were the samples.

4.3.1.2.7 High Performance Size Exclusion Chromatography – Refractive Index (Varian HPSEC-RI)

(The method used was originally from Dr. Mario Martinez, and, was recently revised by Anna Hayes, Purdue University, 2019)

Step 1: Sample purification and dissolution

Porridge flour samples (9.0 mg) were transferred (equivalent to 4 mg dry starch) into a 2 mL microcentrifuge (Eppendorf) tube, mixed with 0.5 mL protease in tricine buffer (2.5 units/mL) using a vortex mixer, and incubated at 37°C for 30 min. Samples were mixed well, centrifuged at 4000 x g for 10 min, and the supernatant was discarded (as much as possible was removed using pipette). To the precipitate was added 0.5 mL sodium bisulfite solution (0.45%) using a vortex mixer, and the mixture was incubated at 37°C for 30 min. Samples were mixed well again, and centrifuged at 4000 g for 10 min, and the supernatant was discarded. The precipitate was then suspended in 1.5 mL pure DMSO and was inverted by hand to make a homogeneous mixture. Samples were then heated in the thermomixer at 80°C with 350 rpm for 24 h and were inverted by hand occasionally to ensure homogeneity of the mixtures.

Step 2: Sample purification and continued dissolution (DMSO and insoluble materials were removed)

Samples were mixed well using stir bars and were centrifuged at 4000 x g for 10 min and the supernatant were collected in a 15 mL centrifuge tube (this was done to remove insoluble materials, mostly non-starch polysaccharides and lignin). Absolute ethanol (10 mL) was added to samples and mixed well (this was done to precipitate the starch in the supernatant), and non-starch soluble materials, mostly lipids and protein, were also removed). Samples were centrifuged in a horizontal rotor, at 4000 x g for 10 min, and supernatants were discarded (this was done to remove non-starch soluble materials, mostly lipid and protein). Another 10 mL of absolute ethanol was added to samples and mixed well. Samples were centrifuged at 4000 g for 10 min, supernatant was discarded (this was done to remove residual DMSO/LiBr). The ethanol wash was repeated two or three more times to complete sample purification. The last trace of ethanol was removed by inverting tubes on a paper towel for about 2 min and dried overnight in vacuum desiccator.

Step 3: Sample preparation for injection

Approximately 5 h before injection, 3 mg/mL solution of dried starch pellet was prepared with boiling water (3 mg starch, 1 mL water) by heating with mixing in a thermomixer (95°C at 350 rpm) for 4 h. Solution was filtered through a 5.0 µL nylon syringe filter (into vial with a cap), and was immediately injected into a chromatograph (Varian HPSEC-RI) for separation on Superdex 200 and 30 SEC columns connected in series (Amersham Biosciences, Piscataway, NJ) with flow rate of 0.4 mL/min.

Step 4: Analysis sample data from HPSEC-RI

Data were normalized according to initial value and maximum value readings per sample run. Resulting values were expressed as Normalized RI.

4.3.1.2.8 Statistical analyses

Mean values for physicochemical and sensory testing measurements, as well as process performance data, were determined and compared to local controls using ANOVA in statistical software packages GMP (14 edition, SAS, 2019) and SPSS (26.1 edition, 2019) (significance level of 5%).

4.3.2 Results and discussion

4.3.2.1 Dynamic oscillatory rheometry of thick and thin porridges

Figures 4.1 and 4.2 show profiles of shear rate (1/S) versus frequency (Hz) using a plate rheometer instant *tuwo* (thick), and *fura* (thin) samples made using the extrusion method versus traditionally-prepared porridge samples. Results revealed shear thinning behavior showing significant differences in viscosity termed as resistance to flow between instant and traditional porridges (local controls). Figure 4.1 were approximately equal for the instant *tuwo* compared to traditionally-prepared *tuwo*, with latter having somewhat greater shear thinning effect. In contrast, Figure 4.2, at low shear rate, the instant *fura* sample had higher viscosity than the traditionally-prepared *fura*, followed by a more rapid drop in viscosity for the former. This might translate to a higher shear thinning property for instant *fura* in the mouth, which could be desirable for the consumer.

Figures 4.3 and 4.4 show profiles of phase angle (°) versus frequency (Hz) of instant *tuwo* (thick) and *fura* (thin) porridges versus the respective traditional porridges. Results in Figure 4.3 show that instant thick *tuwo* had a higher phase angle than the traditionally-prepared *tuwo*, with increasing frequency applied over the testing time. Therefore, instant *tuwo* can be considered to have lower elasticity than the corresponding control thick porridge. On the other hand, the instant fura (thin) porridge sample, was had a lower phase angle, indicating higher elasticity compared to the traditionally-prepared thin porridge control.

Figures 4.5 and 4.6 show profiles of storage (G´) and loss (G´´) moduli versus frequency (Hz) of instant and traditionally-prepared *tuwo* (thick) porridges, by extrusion and conventional methods. Results show that instant *tuwo* had lower storage (G´) and loss (G´´) moduli, values than those obtained for traditionally-prepared tuwo. In both instant and traditionally-prepared thick porridges, G’, and G” values were parallel, and therefore independent of the applied frequency. The instant and traditionally-prepared *tuwo* porridges were strong viscoelastic gels as indicated by the higher G’ than G” values.

Figures 4.7 and 4.8 show differences in storage (G´) and loss (G´´) moduli profiles between instant and traditionally-prepared *fura* thin porridges, by extrusion and conventional methods. For instant *fura*, higher storage (G´) than loss (G´´) moduli suggest a gelled or strong paste structure, however the traditionally-prepared fura had overlaid G’ and G” profiles suggesting a non-gelled structure. This supports the above finding (Figure 4.2) that at low shear rate instant fura had higher viscosity than the control, adding that it had higher shear thinning property.

4.3.2.2 Color of porridge samples

Table 4.1 gives color values of *tuwo* (thick), and *fura* (thin) porridges. There were significance differences ($P<0.05$) for *L** values, and somewhat similar *a** and *b** values among samples. The instant *tuwo* and *fura* porridges had higher L* values compared to corresponding traditionally-prepared porridges (control samples). While little differences were observed for *a** and b* values among samples, the instant fura had a* significantly lower a* value. Variation in *L** values among samples can be attributed not only to differences in processing methods (i.e. long cooking time of traditionally-prepared *tuwo*), but also to variation in millet cultivars used in making the various porridges. Thus, the instant porridge products were whiter and, in case of fura, more red than green. Color values were closed to those obtained generally for cereal based thick and thin porridges (Moussa et al., 2011, Aboubacar et al., 2006).

4.3.2.3 High Performance Size Exclusion Chromatography-Refractive Index

Figure 4.9 and 4.11 give size-exclusion chromatography patterns of porridges samples. Instant *tuwo* (thick) and *fura* (thin) porridges appeared to be somewhat fragmentated, as indicated by the slight shift to the left of the chromatograms of the instant flour starches compared to the corresponding control traditional porridges. The chromatograms in Figures 4.9 and 4.10 represent amylose and show its slight fragmentation. (refer to table in Appendix E on amylose molecular size results of samples).

4.3.3 Conclusions

Laboratory analysis of the *tuwo* and *fura* instant products generally showed that instant extruded porridges had somewhat different paste and gel properties, with the thin *fura* porridge having higher viscosity and gel strength and better elasticity and shear thinning property compared to the traditionally-prepared *fura*. Color was also somewhat better for the instant *fura* product. The thick *tuwo* products were approximately the same, except that the instant *tuwo* had lower gel strength.

Interestingly, as shown in Part B below, the instant *tuwo* and *fura* porridges were sometimes better accepted by consumers in the HUT and market tests study compared to the traditionally-prepared thick and thin porridges (Appendix I).

4.4 Part B Home Use Testing (HUT) study of instant millet thick ('tuwo'), and thin ('fura') porridges

4.4.1 Introduction

Home-use testing (HUT) is technic that enables a product to be used at home, and to allow consumers to explore it, and elucidate their perception and overall acceptability. It can also help consumers to estimate their willingness to pay for a commercial product, and to assess the potential market for that product under study. Consumer's perception and acceptance of new or innovated products is essential for processors and other technology end-users to take decisions as to whether accept or reject adoption of technologies generated, and other related research findings (DeGroote et al., 2014; Gunaratna et al., 2016).

Associated affective tests, specifically consumer's acceptance testing using hedonic rating scales, and experimental auctions have been used to obtain willingness-to-pay (WTP) of urban consumers for different rice cultivars and processing methods (Demont et al., 2012; Demont et al., 2013). WTP testing for new consumer products in West Africa is relatively recent (De Groote et al., 2017; Demont et al., 2013; Demont et al., 2012), as is the use of HUT, and other techniques to investigate consumer's perception and acceptance, and marketing of innovative millet and sorghum and other cereal products.

4.4.2 Material and Methods

4.4.2.1 Materials

About three (3) tons of two (2) improved millet varieties (*ICMV IS 8930 and 99001*) were selected from several others utilized in the previous two years' work. Seeds were provided by ICRISAT and INRAN scientists and grown on farms in Falwel, Tera, and Sherkin Haoussa in Niger by Moribeen and Fuma Gaskiya farmer groups during the summers of 2017 and 2018.

Additional supplies, including Purdue Improved Crop Storage (PICS) bags, plastics films, and labels were supplied and prepared for storage and packaging of extrudates, and instant *tuwo* (thick) and *fura* (thin) porridges, at INRAN in collaboration with its local partners, including suppliers, women processors, and label designers prior to starting the respective studies.

4.4.2.2 Methods

4.4.2.2.1 Home Used Testing of a) instant *tuwo* (thick) and b) *fura* (thin) porridges in Niamey, Niger

The method used for HUT was originally from DeGroote et al. (2014), adapted for this study by the project team at Purdue University and Kansas State University, and INRAN, and experts in research methods at the University of Reading (UK), through partnering of the SMIL and McKnight Foundation projects. The HUT method was used to evaluate urban consumers in Niamey on perception/acceptability of instant a) *tuwo* and b) *fura* porridges. It was designed to determine whether the instant porridge products are acceptable to consumers compared to traditionally-prepared non-instant porridges in terms of consumption (overall consumer acceptance), time for preparation, ease of preparation, and characteristics of households or individuals that affect overall acceptance of each product. Consumers' perception and acceptance of the characteristics of packaging used, and consumers' WTP for these instant porridge products (e.g. price as a whole, and as function of overall consumer acceptability, and individual characteristics).

Panelists selected in households were regular consumers of millet *tuwo* and *fura* porridges, responsible for cooking the family meals, and frequent buyers of cereal-based processed foods in sales stores in 15 districts randomly selected, in the five (5) fixed counties in Niamey.

At each household involved in the test, one (1) household member (the person responsible for cooking, the wife of the household head) was selected for the preparation of the porridge. The selected person was asked to cook the porridge, in her own kitchen using regular utensils, and using the mode of preparation described on the package label (see Appendix H), which was developed for each instant product by the research team. Following consumption of the product at a meal, a follow-up questionnaire was administered to evaluate the selected person and other household individuals who consumed the meal for perception/acceptability of the product for a limited number of characteristics described above and asked to express their WTP and cost of sale of unit product of 500 g packaging and labeling. Evaluation was performed mostly using a 5-level hedonic scale score, varying from 1=very bad to 5=very good, and also by 1=Yes, 2=No for other parameters (refer to questionnaire in the Appendix F). Other information was collected as well, on household characteristics, including household size (N), gender distribution, and total expenditures (CFA)/week for cereal-based foods (rice, maize, sorghum, millet, wheat) and millet thick porridges.

After signing a consent agreement to participate to the test, and accepting to follow all required conditions and guidelines, a training was administered to the selected panelists to brief them about the study objectives, methodology, expectation, and on appropriate procedures needed to prepare/reconstitute instant *tuwo* and *fura* porridges.

a) HUT of instant *tuwo* (thick) porridge

Two (2) packets of 500 g of the instant tuwo product were given to 188 households, randomly selected, and making a total of 188 kg of products distributed. The person selected in each respective household was asked to cook the porridge, as previously described.

Each packet of 500 g of the instant *tuwo* porridge flour, described above, was reconstituted at using a ratio of 1:2 flour to water in boiling water to produce the thick porridge. More specifically, 1000 ml of water was boiled in a cooking pot and 500 g of the instant *tuwo* flour of was added in small increments to the boiling in the pot. After each addition, the heated mixture was vigorously stirred with a flat wooden spoon, ensuring that no lumps remained, and then left on low heat to cook for 10 min. The thick porridge meal was served with the sauce of choice. Following consumption of the meal, a follow-up questionnaire was administered to evaluate their perception of the product, and information was collected on parameters as described above (Appendix F).

b) HUT of the instant fura (thin) porridge

Two (2) packets of 500 g of the instant *fura* product was given to 191 households randomly selected and making a total of 191 kg of products distributed. The person, selected at each respective household, was asked to cook the porridge as previously described. Each packet of 500 g of the instant *fura* flour was reconstituted at a ratio of 1:7.4 flour to water in room temperature water (500 g of instant thin porridge flour was mixed in 3700 ml of water). Before, consuming the *fura* meal, varying amount of milk and sugar were added depending each household's preference. Following consumption of the meal, a follow-up questionnaire was administered to evaluate their perception of the product, and the same type of information was collected from households as previously described (Appendix F).

4.4.2.2.2 Statistical analyses

Mean values for consumers perception/acceptability of products, and household characteristics were determined, and compared via statistical descriptive analysis and summary statistics using ANOVA by GMP (14 edition, SAS, 2019, statistical software packages at the 5% significant level).

4.4.3 Results and discussion

Household size of respondents was 5-6 persons in most locations in Niamey, with slight variation observed. Gender distribution of the population was ~69% female, and ~31% male (Figure 4.11). Greater than 70% of household's respondents were married (Figure 4.12) and in general, most had a minimum level of education (Figure 4.13). The work function of household respondents varied with the largest percentage (32%) in business or trade (Figure 4.14). Aggregated mean household weekly expenditure for cereal foods was ~4,500 FCFA (Figure 4.15) and did not appear to be associated with respondents' gender or level of education.

Household weekly expenditure averaged ~2,000 FCFA for *tuwo* (thick) porridge made from non-millet cereals (sorghum, rice, and maize) (Figure 4.16), ~1,600 FCFA for millet *tuwo* (Figure 4.17) and ~1600 FCFA for millet *fura* (thin) porridge (Figure 4.18). Wide variability was observed in weekly expenditures and were not associated with work function or gender.

Figure 4.19 shows boxplots of overall acceptability for instant *tuwo* (thick) porridge (n=188). Results show good to very good overall acceptability of the instant *tuwo* porridge. Greater than 90% of respondents said that the instant *tuwo* porridge was easier and faster to cook than the traditional thick porridge commonly used at household (Figure 4.20). Overall willingness to pay values of respondents was 400-500 FCFA/ 500g packet for the instant *tuwo* porridge (Figure 4.21).

Overall acceptability for instant *fura* (thin) porridge was also in the good to very good range (n=191**)** (Figure 4.22). About 89% of respondents found the instant *fura* porridge to be very easy to prepare (Figure 4.23). Respondents were willing to pay between 450-500 FCFA/500 g package of *fura* (Figure 4.24). Respondents liked the package label and information provided, scoring it good to very good for both the *tuwo* and *fura* (Figure 4.25).

4.4.4 Conclusions

Results of the in HUT of a) instant *tuwo* (thick) and b) instant *fura* (thin) porridges in Niamey, Niger good to very good overall consumer acceptability. Package label information included product size, weight, time, and mode of preparation and were also rated good to very good. In general, overall consumer acceptability and perception of the instant porridges were not strongly associated with level of education, work function, gender, location, and site of responders. The average willingness to pay mean for the instant *tuwo* and *fura* porridge was near 500 FCFA/500 g packet. In most cases, WTP was not associated with level of education, work function, gender, and responder's location, or site.

4.5 Part C Market testing of instant tuwo (thick), and fura (thin) porridges

4.5.1 Material and Methods

4.5.1.1 Materials

About 3 metric tons of two improved millet varieties (ICMV IS 8930 and 99001), selected from several others utilized in work during the previous two years, were used for a market study of instant *tuwo* (thick) and *fura* (thin) porridge flours. Seeds were provided by ICRISAT and INRAN scientists and grown on farms in Falwel, Tera, and Sherkin Haoussa in Niger by Moribeen and Fuma Gaskiya farmer groups during the summers of 2017 and 2018.

PICS bags, plastics films, and labels were used for storage and packaging of instant *tuwo* and *fura* porridge flours that were prepared at the INRAN Hub Food Innovation Center in collaboration with its local partners, including suppliers, women processors, and label designers.

4.5.1.2 Methods

4.5.1.2.1 Market testing of instant *tuwo* (thick) and *fura* (thin) porridge flours

A market sales study was conducted on instant *tuwo* (thick) and *fura* (thin) porridge flours for 20 weeks in Niamey to examine product behavior (frequency of sales) in local markets over an extended period of time. Sale data was assessed as a function of location, processor groups/enterprises involved, sale store type, and compared to similar existing products in the market. Sales data were collected using the questionnaire described in (Appendix G).

Six (6) entrepreneur processors (Multimetier, ETC, Columbe, Lakalkaney, Holare, EDEN) were selected for this study among the existing 15 units operating in Niamey, based on their experience in sales of millet-based foods, their relationship with sales stores managers in Niamey, and their association and collaboration with the INRAN Food Innovation Center. Sale store sizes varied with sampling at 30 sale points (varying from small to large sale stores) that were selected from 40 districts (sites), located in the five counties (sites) in Niamey. The selected six processors for the study had sales of their cereal products in these locations.

About 2.5 metric tons of instant porridge flours were produced by the INRAN Food Innovation Center, including 1 metric ton of instant *tuwo* (thick) porridge flour and 1.5 metric tons of instant *fura* (thin) porridge flour. The instant porridge flours were supplied to the selected sales stores every week by the six processors. In addition, about 6.5 metric tons of 33 other related and popular cereal (millet, sorghum, maize, and rice) processed products were distributed as usual by the processors over the 20 weeks duration of the study. Products included traditionally-prepared *fura*, flours for making thick and thin porridges, *degue*, *couscous*, and composite foods.

The instant millet *tuwo* (thick) and *fura* (thin) porridge flours were separately packaged each in 500 g bags. Bags were sold at 600 FCFA based on willingness to pay feedback from the home use testing (HUT) study and a consensus arrived at with processor groups. Log books were provided to each sale store manager for tracking weekly sales/frequency of all products provided by the six processors involved in the study.

Prior to the study, the selected processors, were invited to the INRAN Food Innovation Center to be briefed about the study objectives, methodology, expectations, and on appropriate procedures they needed to know before participating in the market test.

After signing an agreement to participate in the study and accepting to follow all required conditions and guidelines, a training was administered to them at the Food Innovation Center on the use of the single screw extruder operation for the production of instant *tuwo* and *fura* .

4.5.1.2.2 Statistical analysis

Frequency of sales of products placed in markets were estimated and compared using summary statistics by GMP (14 edition, SAS, 2019, statistical software package) at the 5% significant level.

4.5.2. Results and discussion

Figure 4.26 summarizes overall quantity of instant millet *tuwo* (thick) and *fura* (thin) porridge flours sold in the five locations in Niamey (I-VI). The highest sale volume products for both instant *tuwo* and *fura* flours were in Niamey I and IV sites, and then followed by sites II and III. The least amount of products sold was in Niamey VI.

ETC/Enterprise had the largest quantity of product sold over the 20-week study period, which approximated 550 kg of instant millet *tuwo* porridge flour and 600 kg instant millet *fura* flour, with average estimated sales of 660,000 and 720,000 FCFA, respectively. In rank order, sales of the next three processors from high to low were Multimetier, Lacolombe, and Lakalkaney with an estimated quantity of product sold of > 50 kg of instant *tuwo* that generated about 60,000 FCFA for each processor, and >90 kg of instant *fura* with an average of 100,000 FCFA for each processor. The smallest product quantity sold were by Holare followed by Eden with an estimated quantity of <50 kg, and sales value of <60,000 FCFA each for instant tuwoand fura porridge flours.

Figure 4.27 shows total sales achieved per week for each instant porridge product. Highest sales for instant *tuwo* (thick) porridge flour was in week 8 at 90,000 FCFA made, followed by weeks 9, 2, 7, 6, 10, 11, 15, 19, 17, 1, and 4. Lowest sales were observed in weeks 16 and 17 with >15,000 FCFA generated. Highest sales for instant fura (thin) porridge flour was realized in week 11 >100,000 FCFA made, followed by week 9 (100,000 FCFA), and week 1 with ~90 000 FCFA, and then weeks 10, 6, 7, 2, 4, 19, and 3. Lowest sales for instant thin porridge were in weeks 1, and 15 with 20 000 and 30,000 FCFA generated, respectively.

Figure 4.28 gives sales of instant millet *tuwo* and *fura* porridge flours achieved per product per processor group/enterprise and per week. ETC was ranked first with highest sales ranging between weeks 5-12 for both instant thick and thin porridges, with only slight variation between products. This was followed by Lacombe with top sale peak at week 1 and 18, and with minor variation between the two porridge products. Multimeter was ranked third with top sales peaks at weeks 11 and 13, also with little differences between products.

Figure 4.29 gives sales per product per sale stores type and per week. Highest sales were found at the larger district stores, followed by mini-markets, and then at enterprise/unit production facilities. Average or fair product sales were found at food marts, and face-to face/proximity sales. Lowest sales were realized at gas station stores.

Figure 4.30 revealed sales per location, per product and per week. Highest sales were achieved in Niamey I, with top peak sales at week 1, and from weeks 6-12 for all instant porridge flours. Niamey II was ranked 2nd with top peak sales at week1for instant thin porridge and from weeks 18-20, with slight variation between the two products. Niamey IV was ranked third with highest peak at week1for instant *fura* porridge product, and between week 6-12 for the combined instant porridges. Niamey V had the lowest sales for both instant thick and thin porridges.

Figure 4.31 summarizes sales of the two instant millet *tuwo* (thick), and *fura* (thin) porridge flours as compared to the other 33 related products sold by the processors including popular traditional cereal processed products made from millet, sorghum, maize, and rice grains (traditional *fura*, flours for making thick and thin porridges, *degue*, *couscous*, and composite foods). Between weeks

1-5, 5-9, 9-12, 12-16, and16-20, instant *tuwo* and *fura* porridge flours competed very well in the market against the other traditional cereal foods. Only one traditional food, *degue de mil*, had a higher sales volume. Among the other traditional products, except *couscous de riz*, the rest of the products, including *degue de sorgho, grumaux de mil, and grumaux sorgho,* sold equally or less sold than the instant porridge products.

Figure 4.32 summarizes overall sales of both the instant millet *tuwo* and *fura* porridge flours, and the 33 popular traditional cereal processed products made from millet, sorghum, maize and rice grains, per sales point. Thin *fura* porridge flour sold very well at certain sales points.

Over the 20-week study period, overall sales of the traditional food, *degue de mil*, was highest at about 3,200,000 FCFA among the total of 35 cereal products sold (33 + 2 instant flours). It was then followed by instant *fura* (thin) porridge flour ranked second with overall sales ~1,600,000 FCFA). *Couscous de riz* was ranked third with total sales of ~1,590,000 FCFA. Instant *tuwo* (thick) porridge flour ranked fourth among the 35 products and had a total sale ~1,200,000 FCFA). Traditional *grumaux de mil* (like fura) was the fifth product in terms of total sales at ~700,000 FCFA.

4.5.3 Conclusions

A market sales study was conducted on instant tuwo (thick) and fura (thin) porridge flour products, which are new to the Niamey market. Porridge flours were sold by processor partners of the INRAN Food Innovation Center for 20 weeks in five locations and at 30 sale points to examine products market behavior. A total quantity of 2.5 metric tons of instant porridge flours, including, 1 metric ton of instant *tuwo* and 1.5 metric tons of instant *fura* porridge flour products were processed at INRAN, that were distributed to the sale points in Niamey by six processors. Both instant flour products were all sold out over the 20 weeks and generated about 2,833,550 FCFA in sales, comprising 1,628,150 FCFA for the instant *fura* and 1,205,400 for the instant *tuwo* porridge flours (Table 4.2). The two new instant porridge products to the Niamey market generated about 1/3 of the total sales of all the 35 cereal products sold. According to local processor groups, the instant porridges are considered well received and promising new products in their market channels. The processors are currently very interested in the scaling of the extrusion technology, and many of the participating sales store owners in the project are requesting for the instant products.

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Table 4.1. Color of *tuwo* (thick) and *fura* (thin) porridge samples.

Porridge Samples	*L**	*a**	*b**
Instant *tuwo* porridge	57.7^{a}	1.14^{ab}	9.99^{a}
Traditional *tuwo* porridge (local control)	53.5^{b}	1.35^{a}	10.15^{a}
Instant *fura* porridge	51.6^{c}	0.52^{c}	9.06^{b}
Traditional *fura* porridge (local control)	47.2^{d}	0.94^{b}	9.30^{b}

*L**=black (0) to white (100), *a**=green (-) to red (+), *b**=blue (-) to yellow (+).
Values are means of triplicate determinations. Different superscripts within columns indicate significant differences (P<0.05, Duncan's Multiple Range test by 26.1 SPSS Inc., Windows software package, Chicago, Illinois).

Table 4.2. Overall total sales of the combined two instant millet *tuwo* (thick) and *fura* (thin) porridges versus 33 other popular traditional-related cereal processed products made from millet, sorghum, maize, and rice grains.

Product type	**Quantity produced (kg)**	**Quantity sold in 20 weeks (FCFA)**
Instant *fura* (thin) porridge	1,452	1,628,150
Instant *tuwo* (thick) porridge	1,005	1,205,400
Total instant porridges	2,457	2,833,550
Other related products	6,634	7,051,650

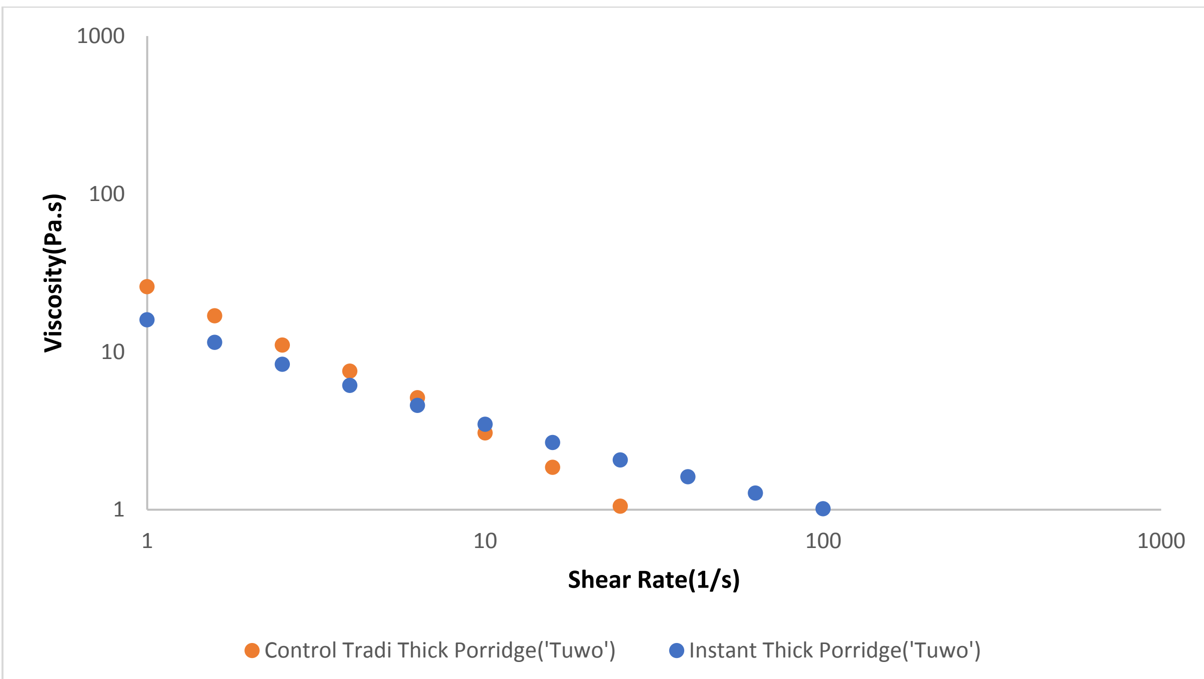

Figure 4.1. Steady shear measurement (viscosity versus shear rate) of instant *fura* (thin) porridge sample versus traditional *fura* porridge. Values are means of triplicate determinations ($P<0.05$).

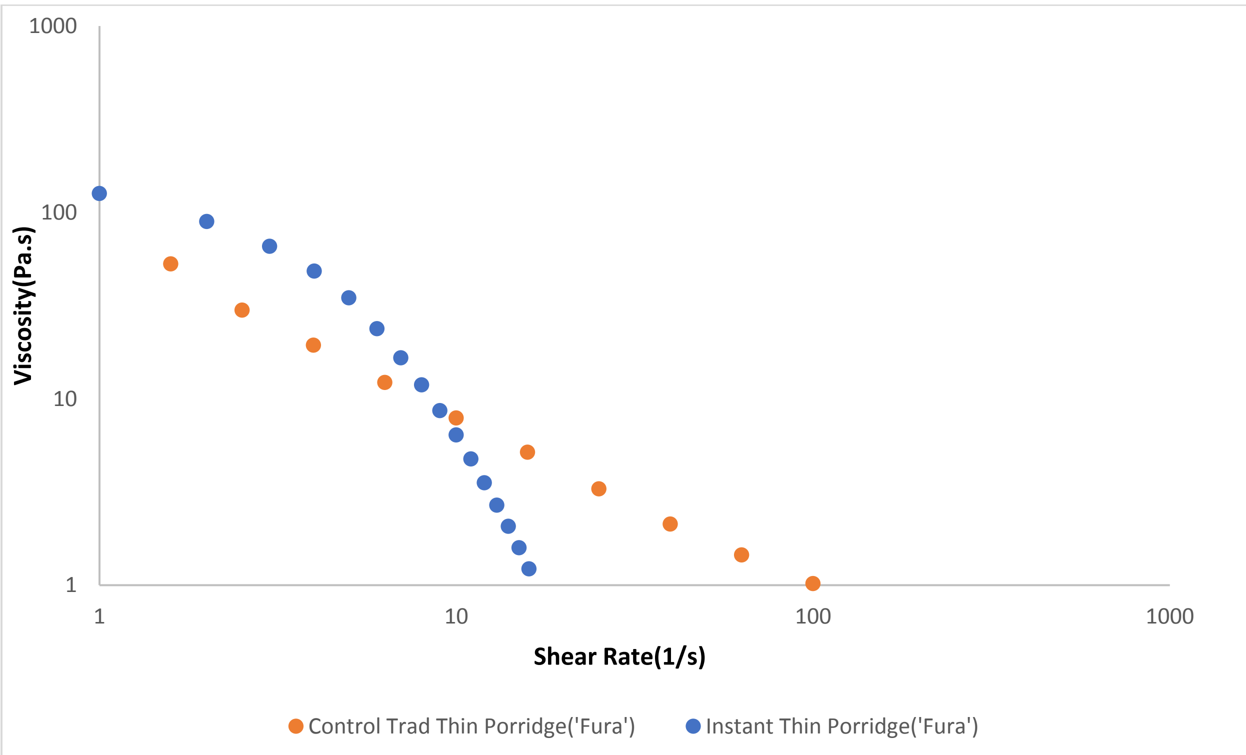

Figure 4.2. Steady shear measurement (viscosity versus shear rate) of instant *fura* (thin) porridge versus traditional *fura* porridge. Values are means of triplicate determinations ($P<0.05$).

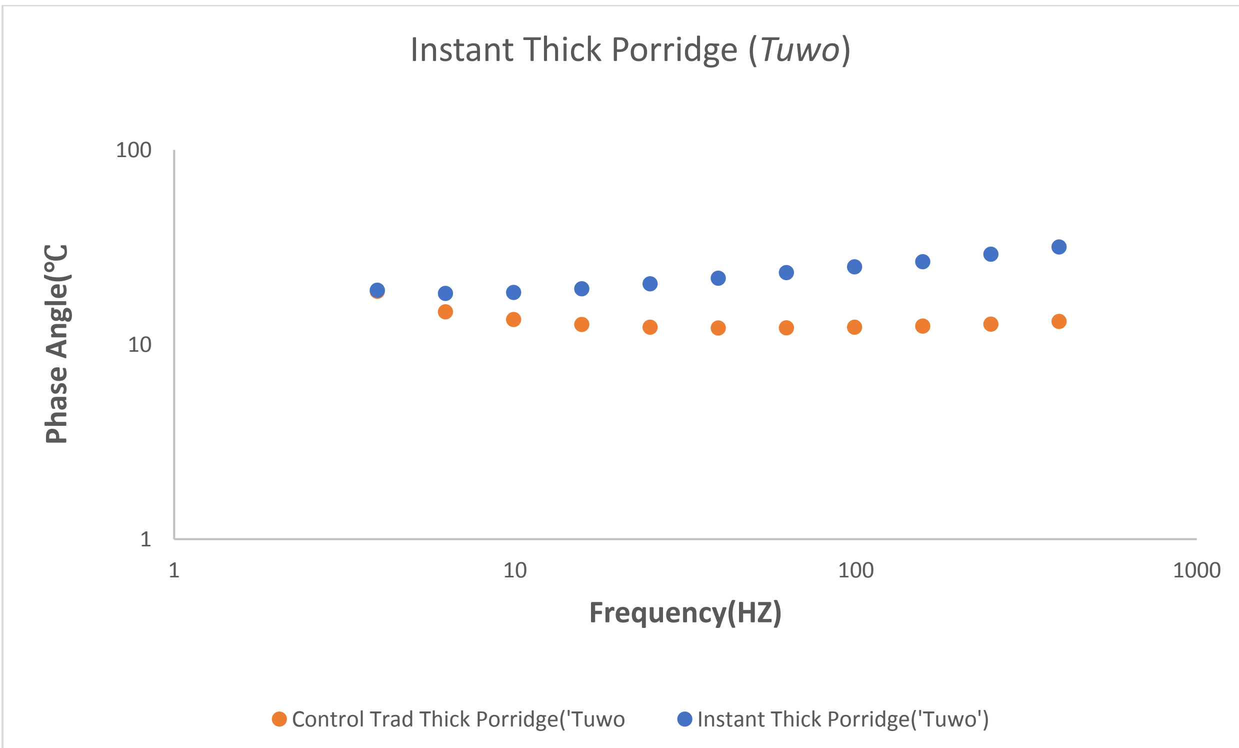

Figure 4.3 Phase angle measurement of instant *tuwo* (thick) porridge versus traditionally-prepared *tuwo*. Values are means of triplicate determinations (P<0.05).

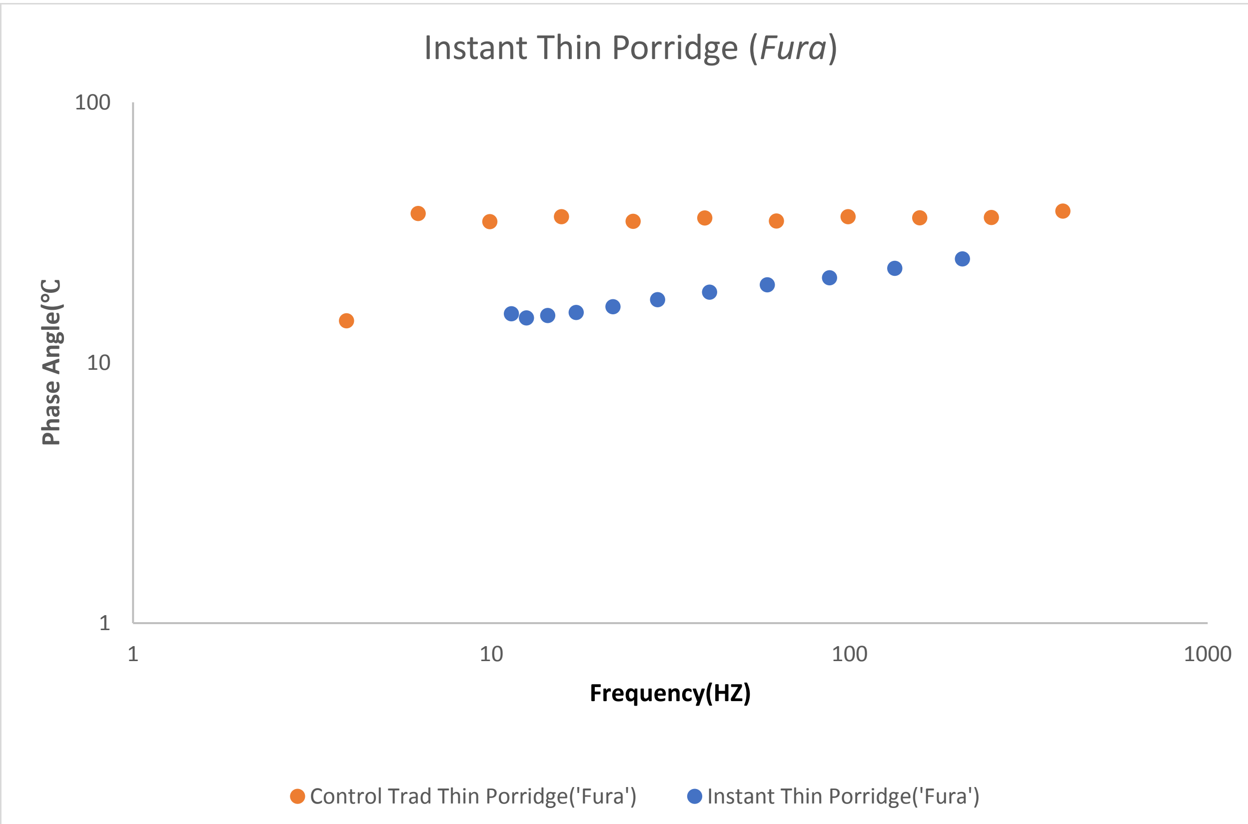

Figure 4.4. Phase angle measurement of instant *fura* (thin) porridge versus traditionally-prepared *fura* porridge. Values are means of triplicate determinations ($P<0.05$).

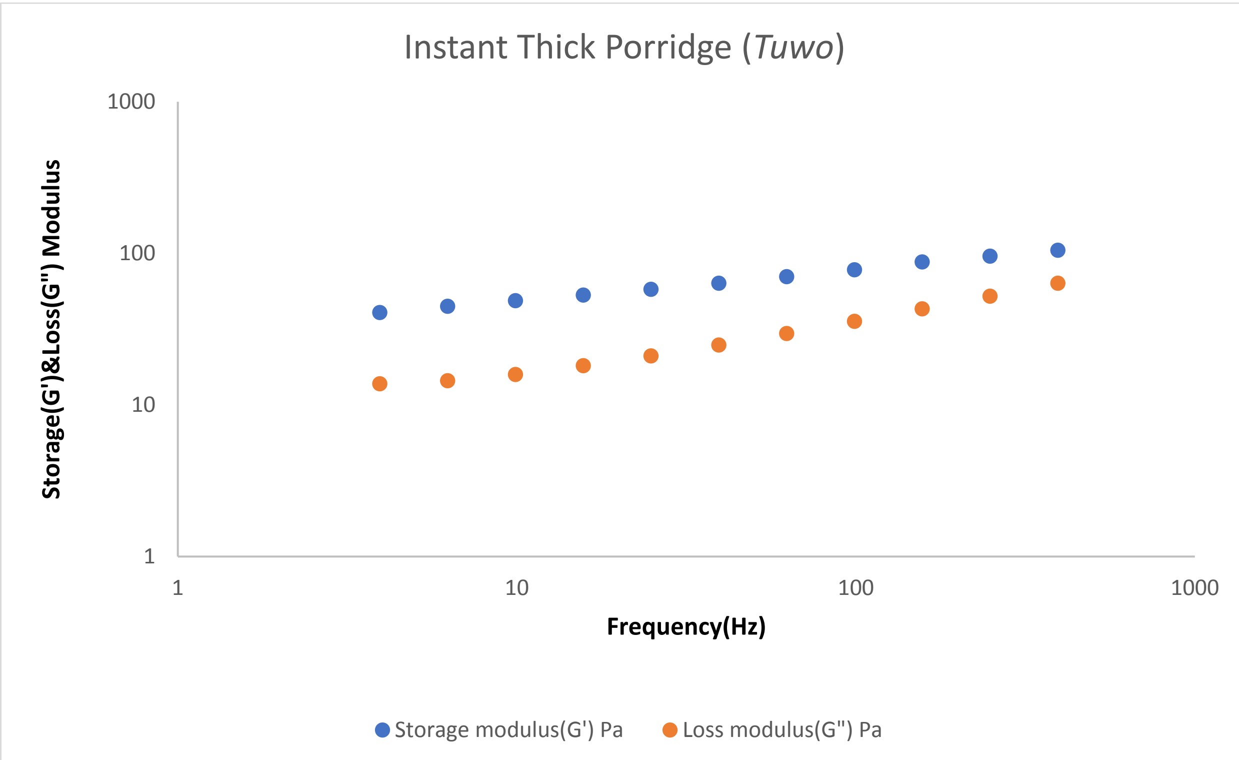

Figure 4. 5 Dynamic oscillation measurement of instant *tuwo* porridge**. Values are means of triplicate determinations (P<0.05).**

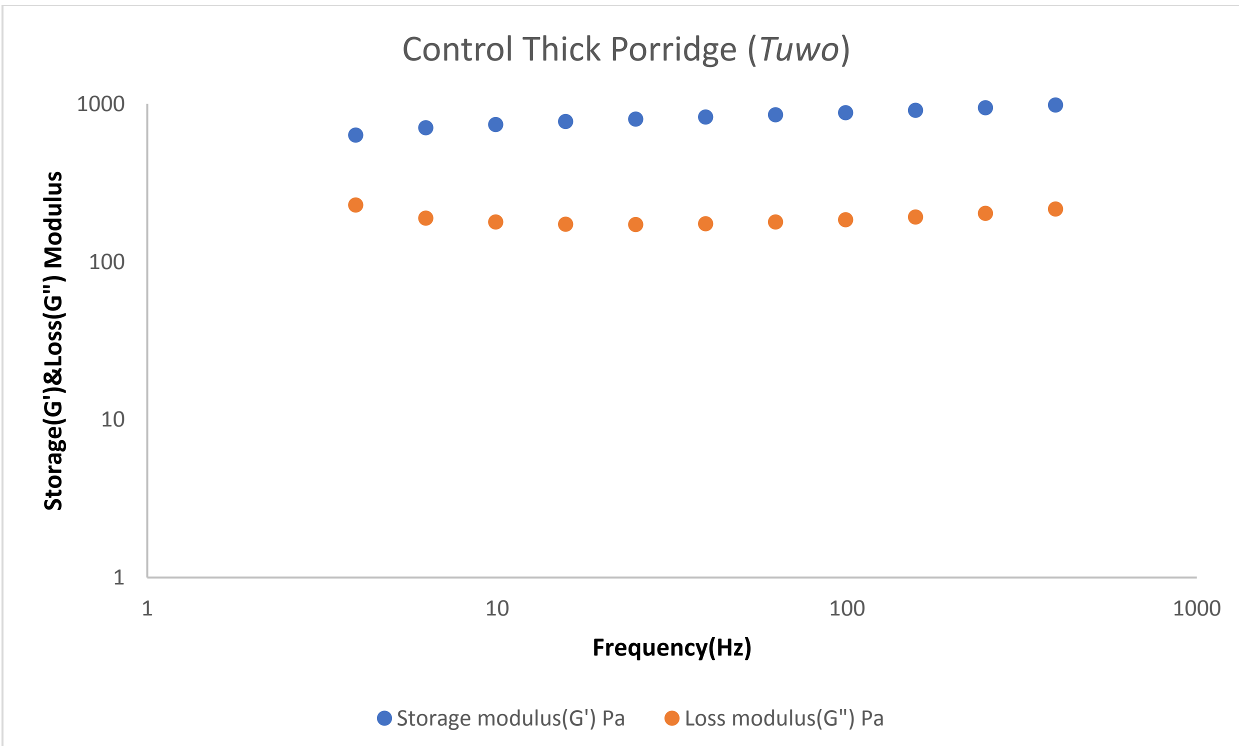

Figure 4.6. Dynamic oscillation measurement of traditionally-prepared *tuwo* porridge (local control). Values are means of triplicate determinations (P<0.05).

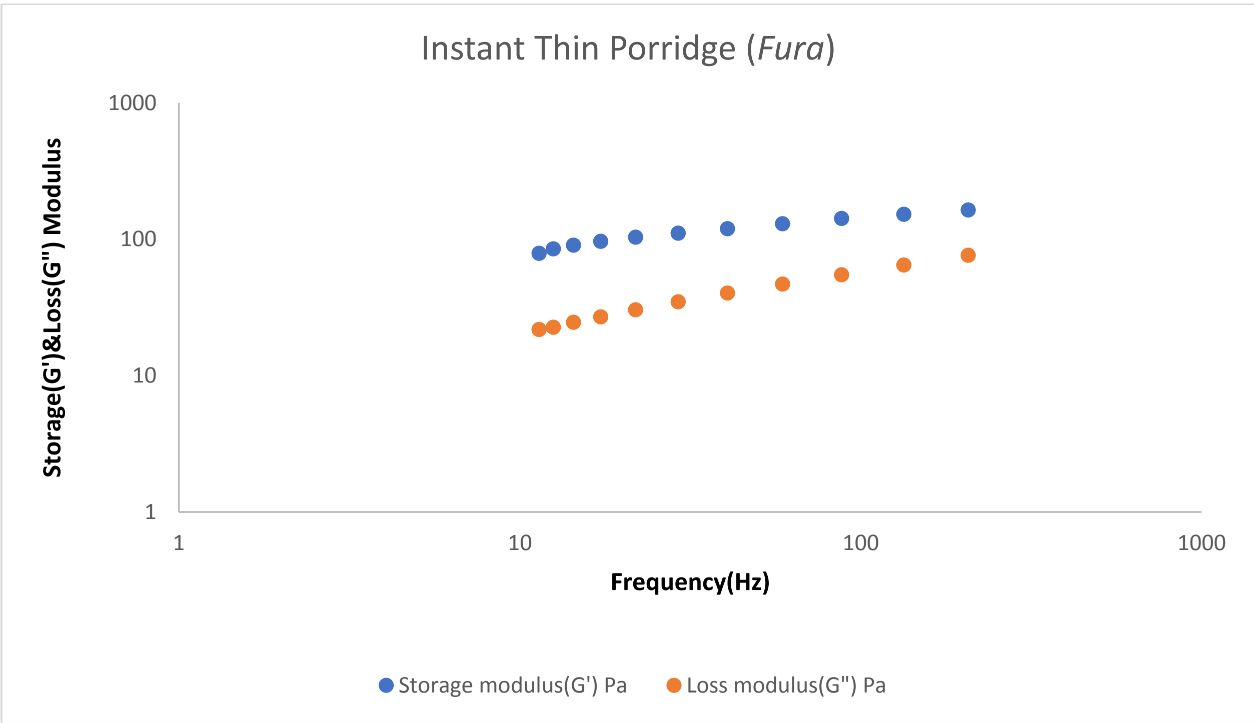

Figure 4.7. Dynamic oscillation measurement of instant *fura* porridge. Values are means of triplicate determinations (P<0.05).

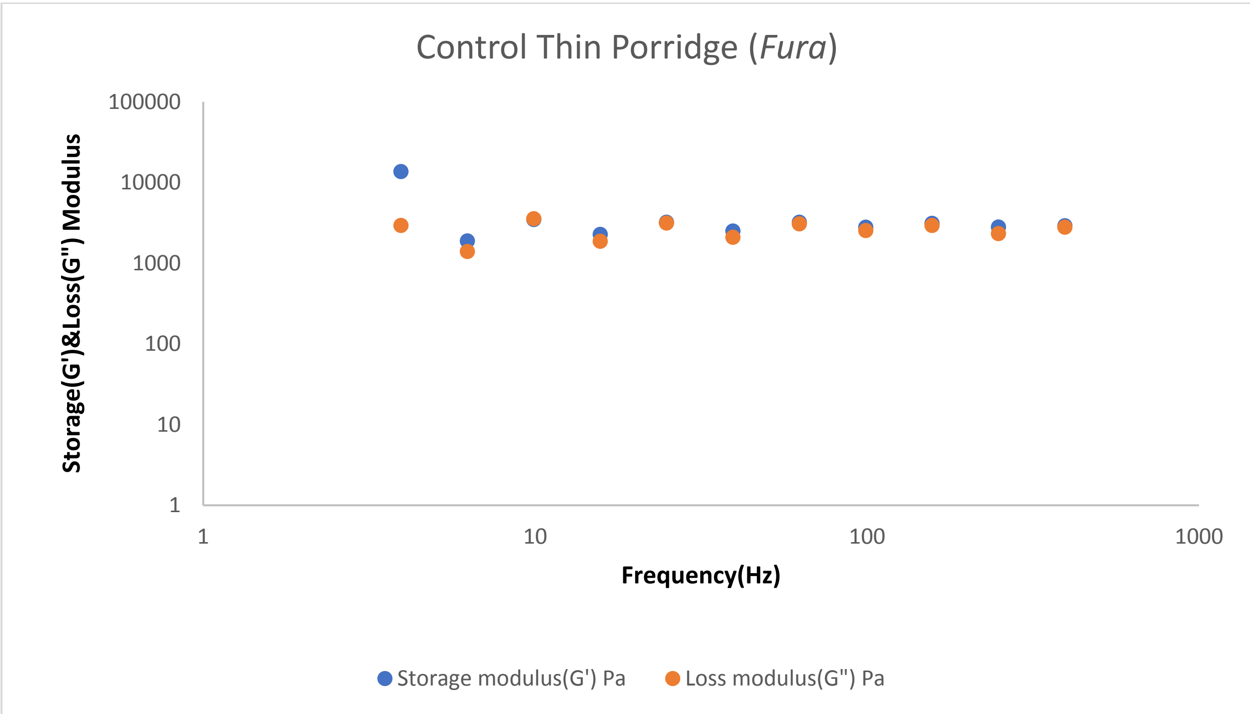

Figure 4.8. Dynamic oscillation measurement of traditionally-prepared *fura* porridge (local control). Values are means of triplicate determinations (P<0.05).

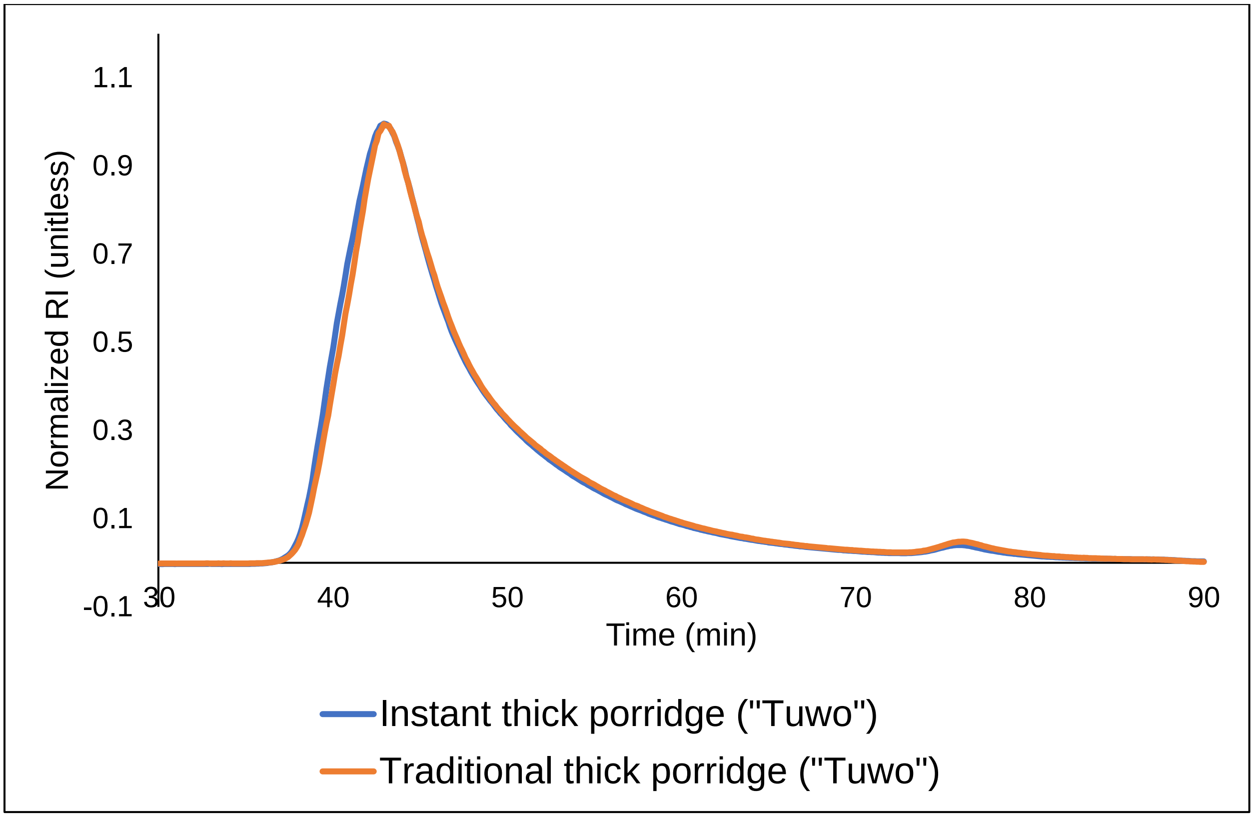

Figure 4.9. **High Performance Size Exclusion Chromatography – Refractive Index (Varian HPSEC-RI) of instant *tuwo* (thick) porridge versus traditionally-prepared *tuwo* porridge**. Values are means of triplicate determinations ($P<0.05$).

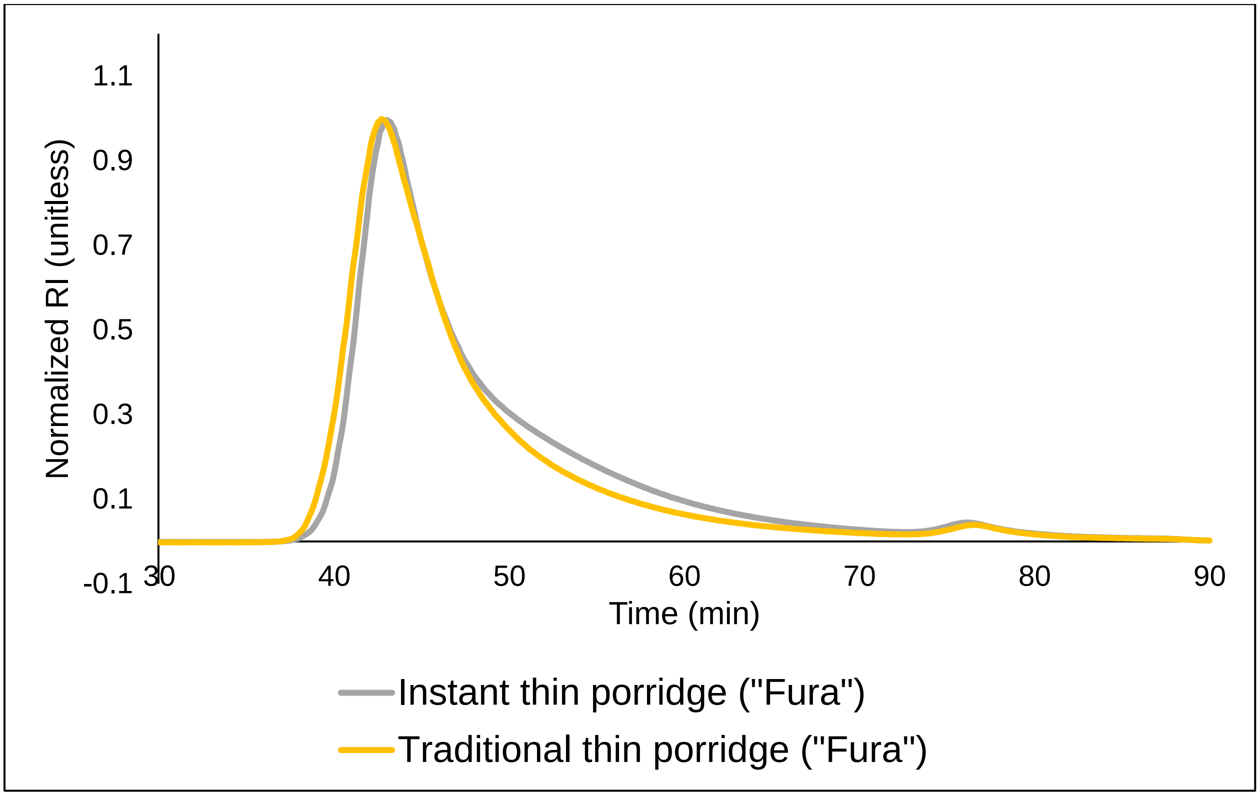

Figure 4.10. High Performance Size Exclusion Chromatography – Refractive Index (Varian HPSEC-RI) of instant *fura* (thin) porridge versus traditionally-prepared *fura* porridge. Values are means of triplicate determinations (P<0.05).

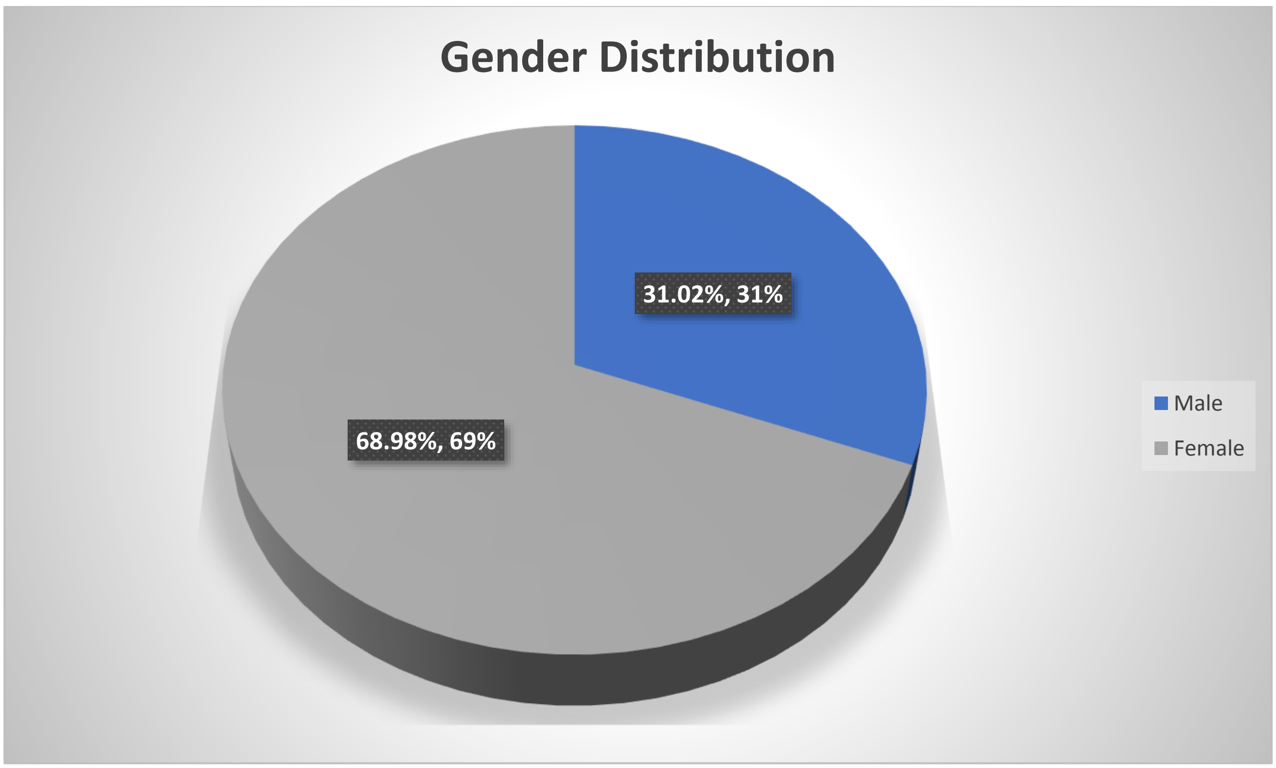

Figure 4.11 Gender distribution of households, in Niamey, Niger. Mean values for gender were different at $P<0.05$ (n=188).

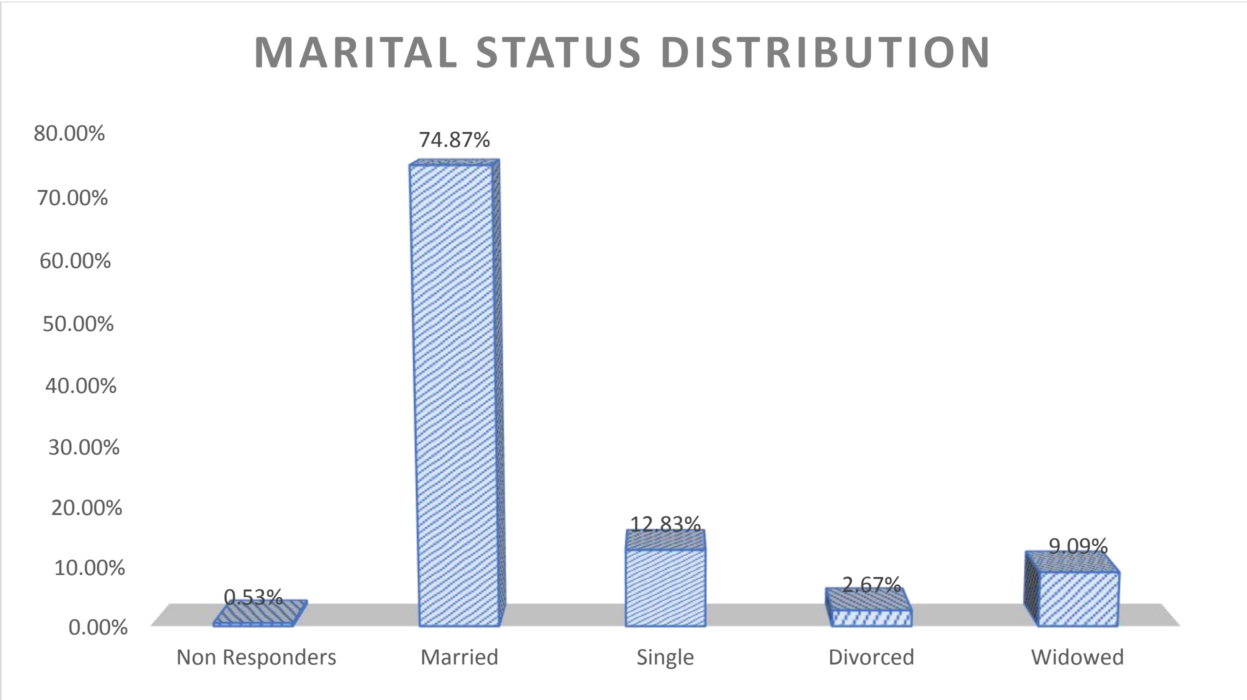

Figure 4.12. Distribution of marital status of households surveyed in Niamey, Niger. Legend used 0= Non-Responders, 1=Married, 2=Single, 3=Divorced, 4=Widowed (n=188).

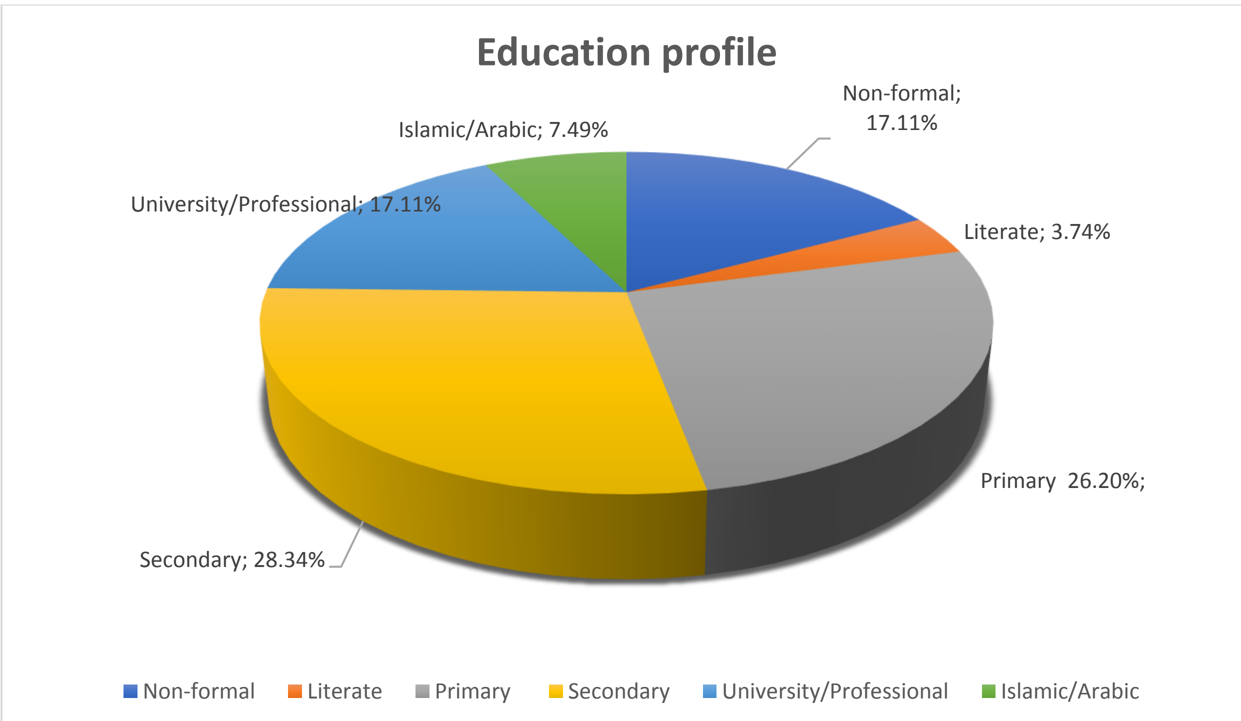

Figure 4.13. Education profile of households' responders surveyed, in Niamey, Niger. Legend 1 = Non-formal education, 2= Literate, 3=Primary school, 4= Secondary school, 5=Universities/professional schools, 6=Islamic/Arabic education. Values are means.

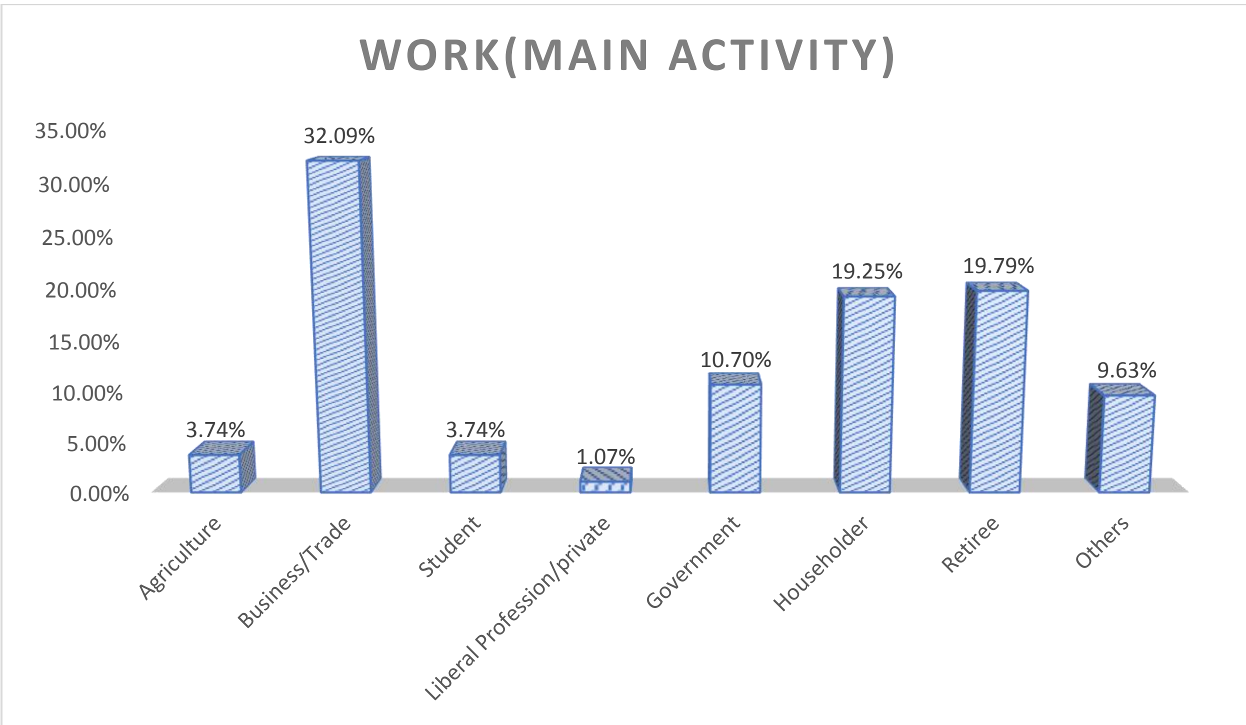

Figure 4.14. Work function of household respondents surveyed in Niamey, Niger. 1=Agriculture, 2= Business/trade, 3=Student, 4= Liberal profession/private, 5= Government, 6= Householder, 7=Retiree, 8=Others. Values are means determination using ANOVA by JMP14 (n= 188, $P<0.05$).

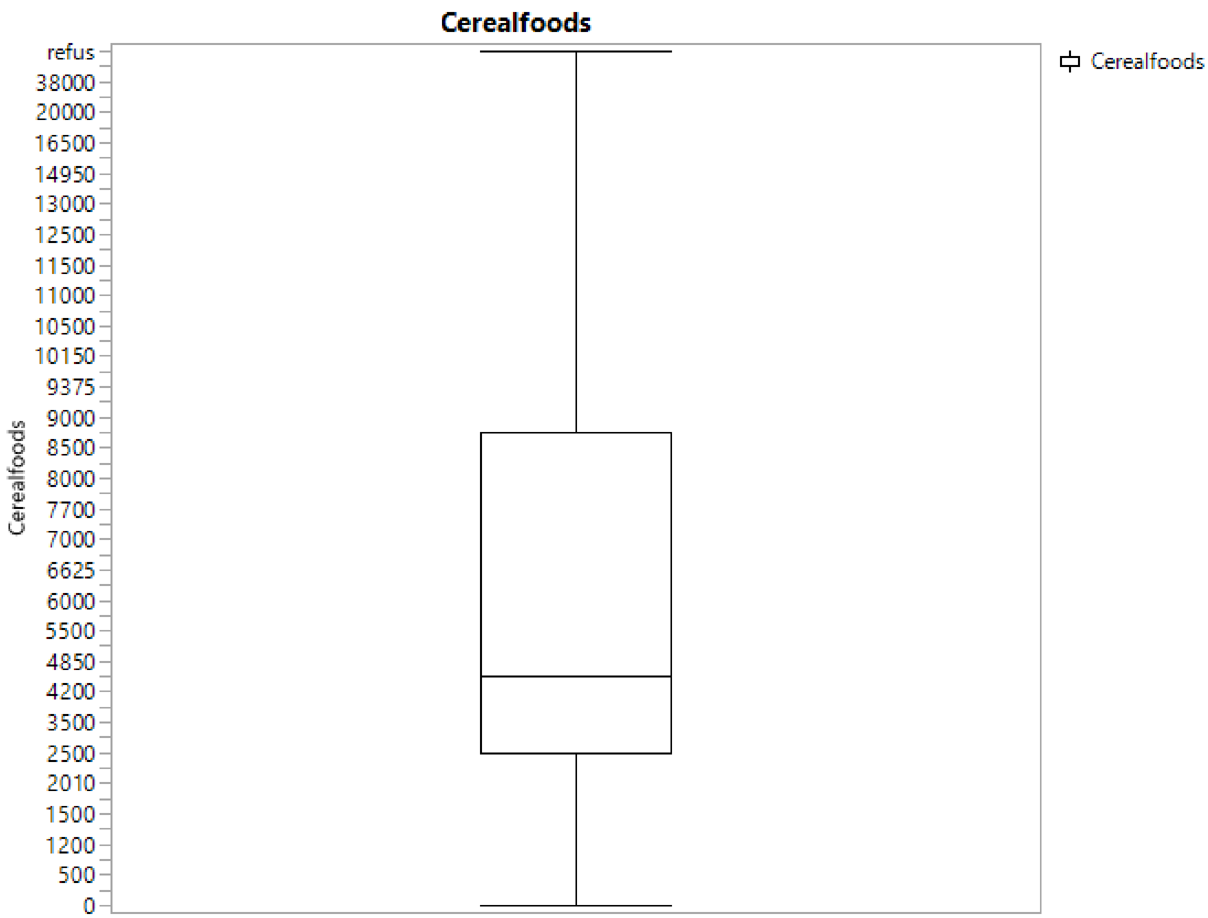

Figure 4. 15 Household expenditure (CFA)/week for cereal foods.

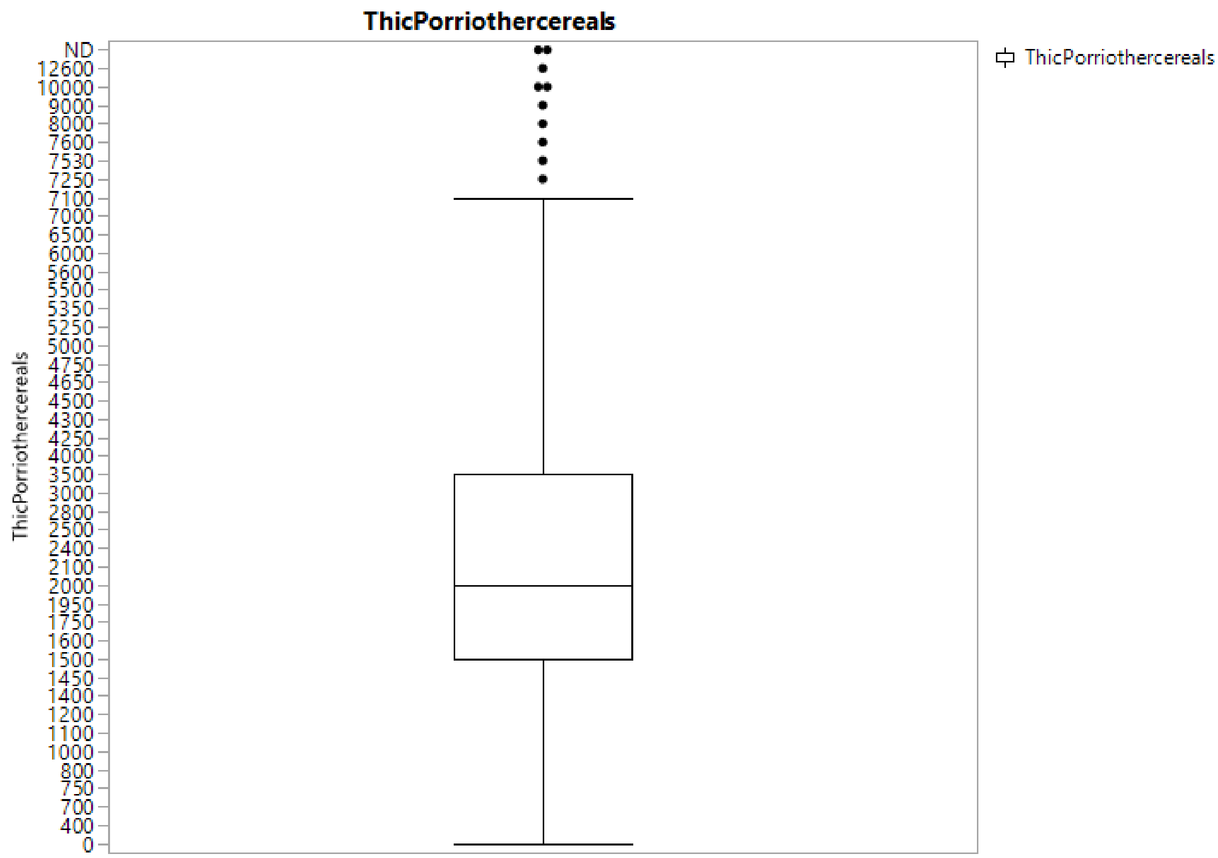

Figure 4.16. Household expenditure (CFA)/week for tuwo (thick) porridge from non-millet cereals (sorghum, rice, maize).

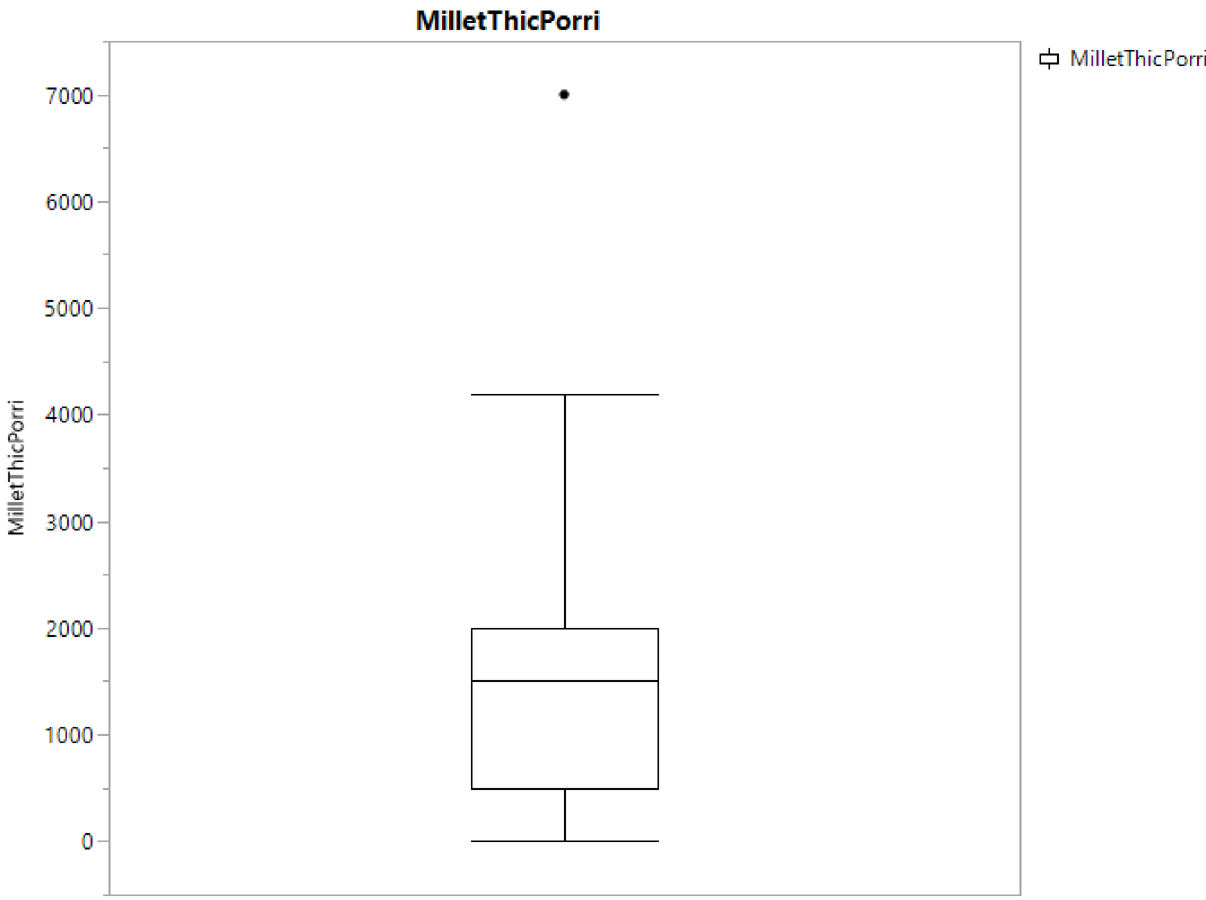

Figure 4.17. **Household expenditure (CFA)/week for millet *tuwo* (thick) porridge**.

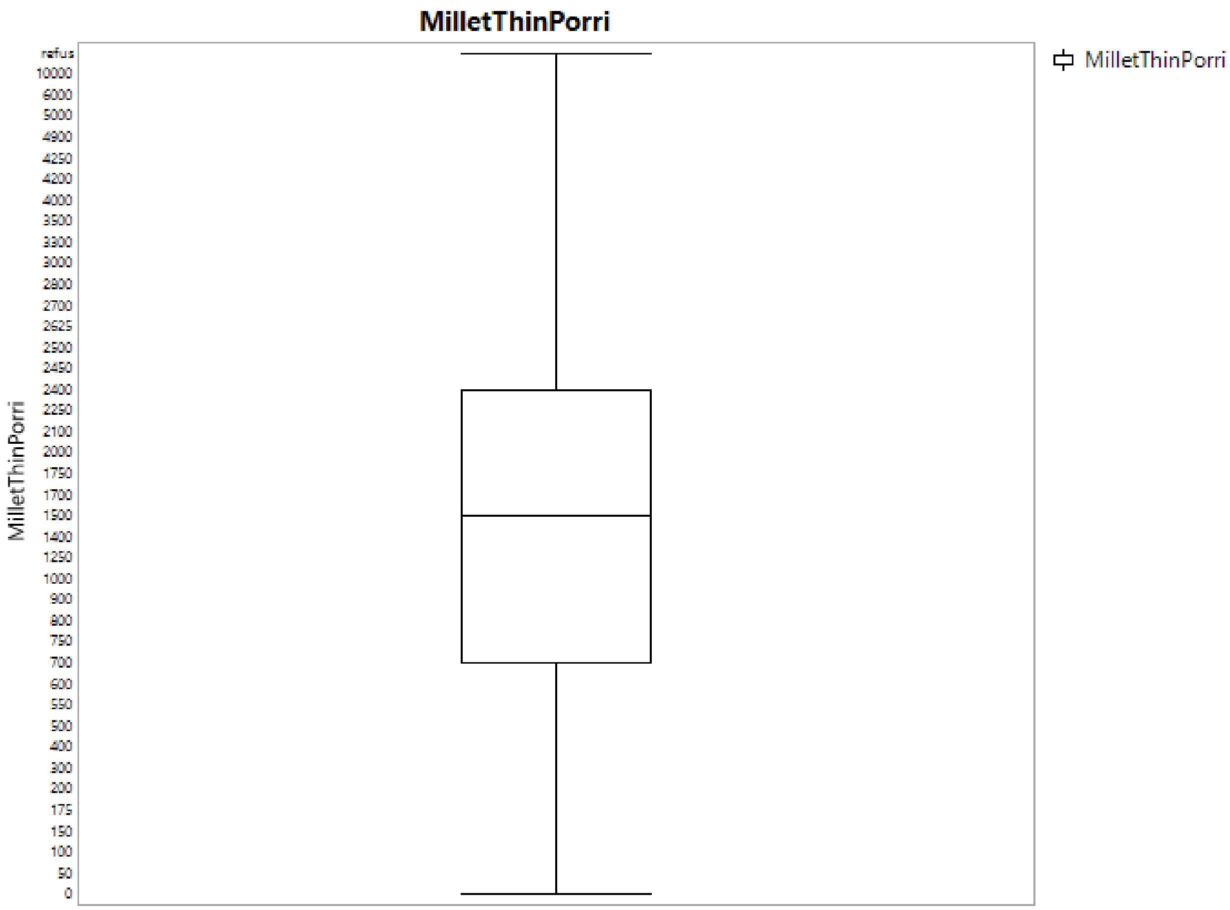

Figure 4.18. Household expenditure (CFA)/week for millet *fura* (thin) porridge.

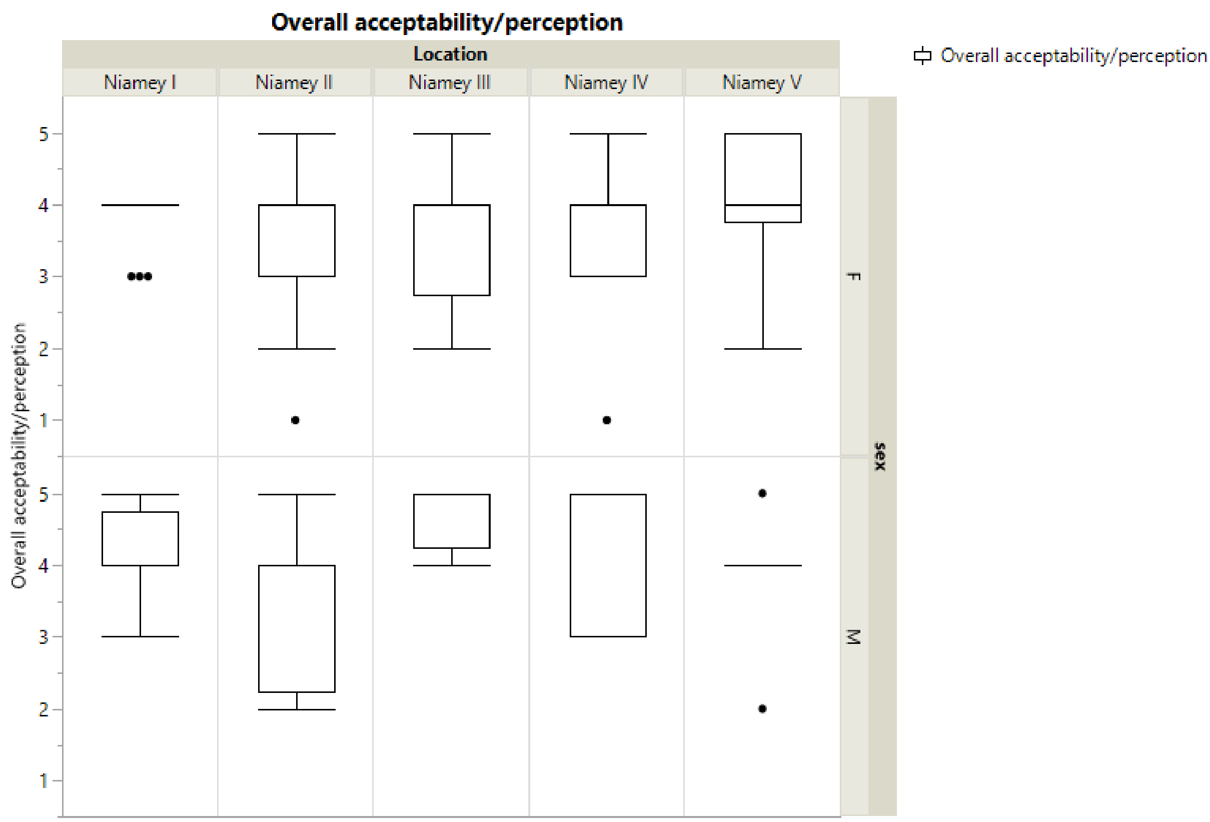

Figure 4.19. Overall acceptability of instant *tuwo* (thick) porridge per location (county) and per gender in Niamey. Hedonic 5-point scale score. 5= Excellent, 4= Very good, 3= Good, 2=Acceptable, 1= Bad). (F=Female, M=Male). Values are means.

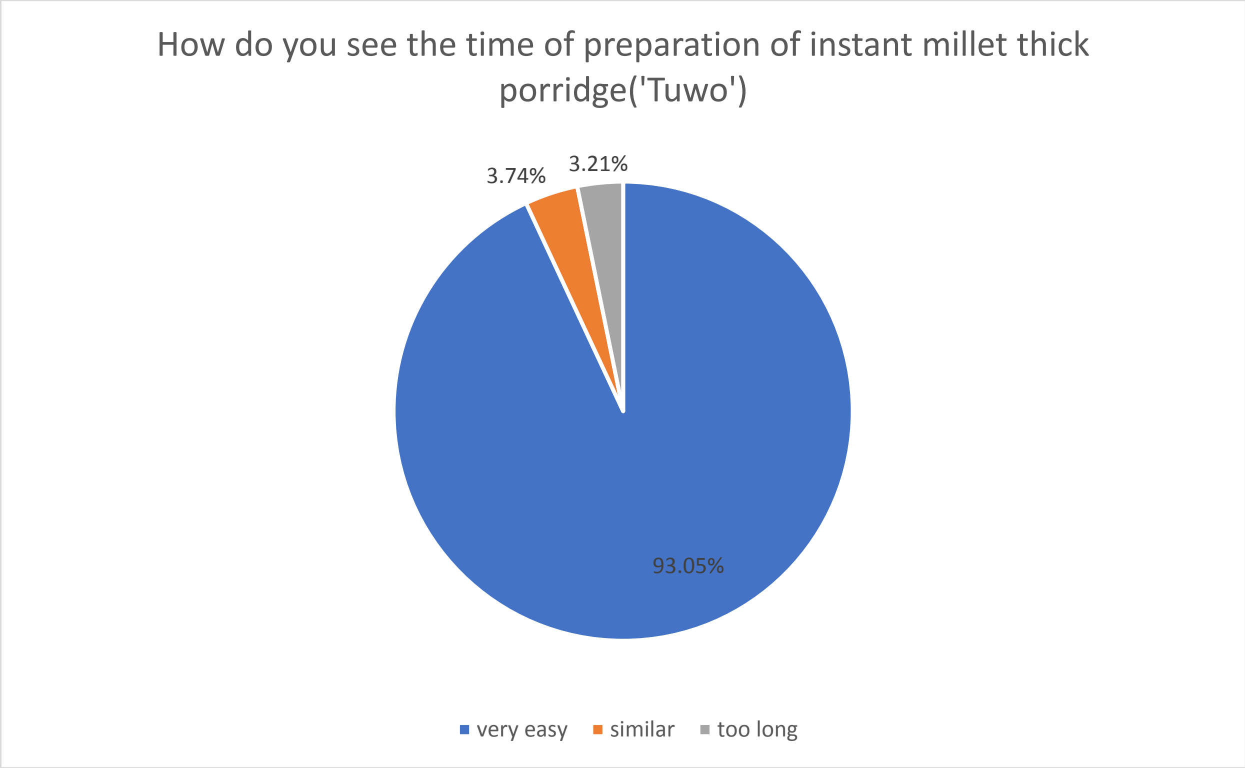

Figure 4.20. Overall perception of time of preparation of instant *tuwo* (thick) porridge in Niamey. Hedonic 3-point scale score. 1=very easy, 2=similar, 3=too long. Values are means.

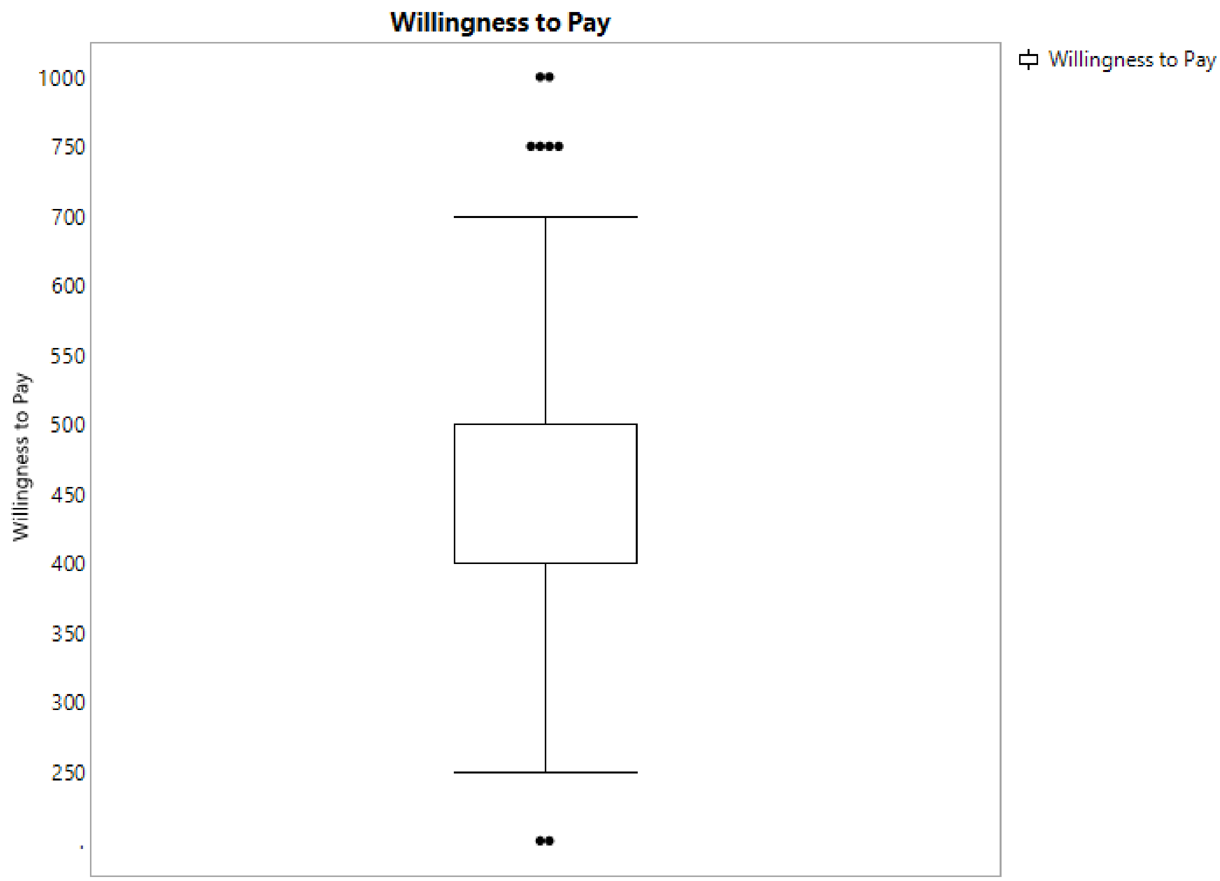

Figure 4.21. Willingness to pay (expressed in FCFA) of instant *tuwo* (thick) porridge.

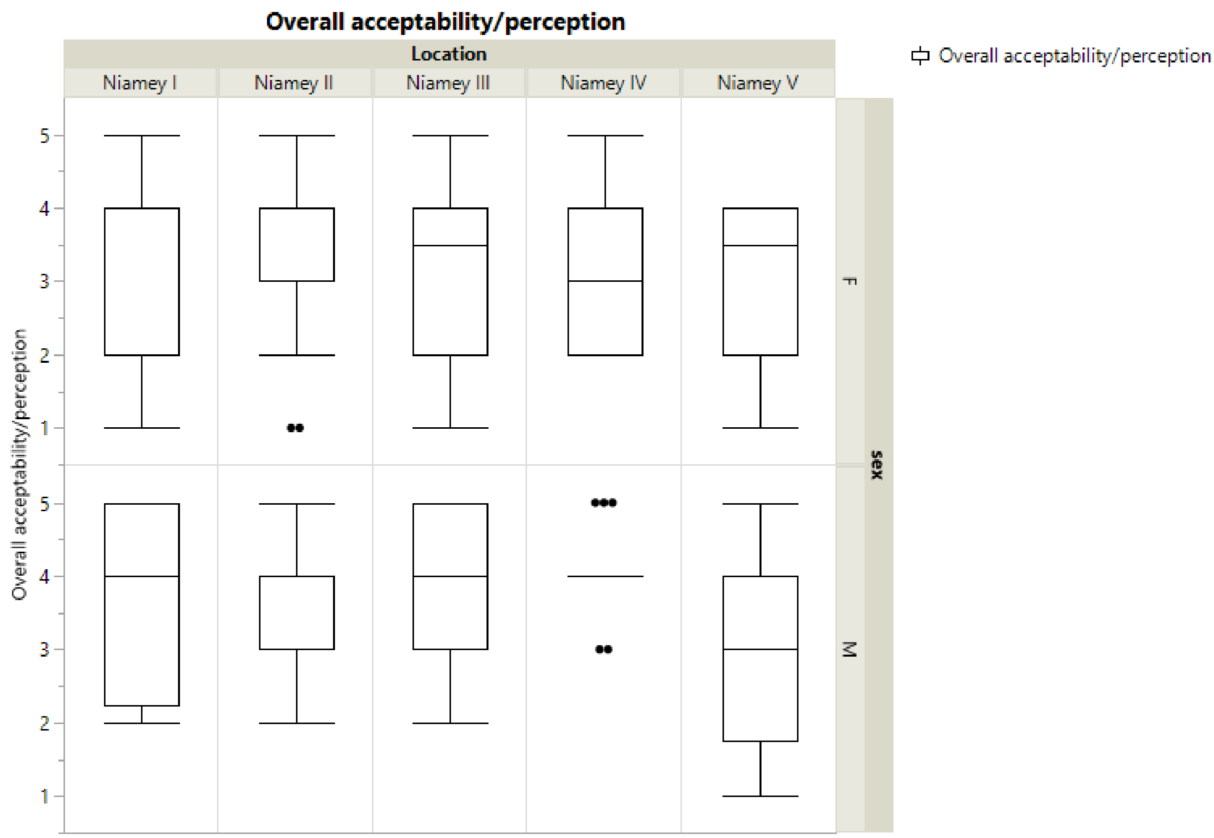

Figure 4.22. Overall acceptability instant *fura* (thin) porridge per location (county) and per gender in Niamey. Hedonic 5-point scale score. 5= Excellent, 4= Very good, 3= Good, 2=Acceptable, 1= Bad). (F=Female, M=Male). Values are means.

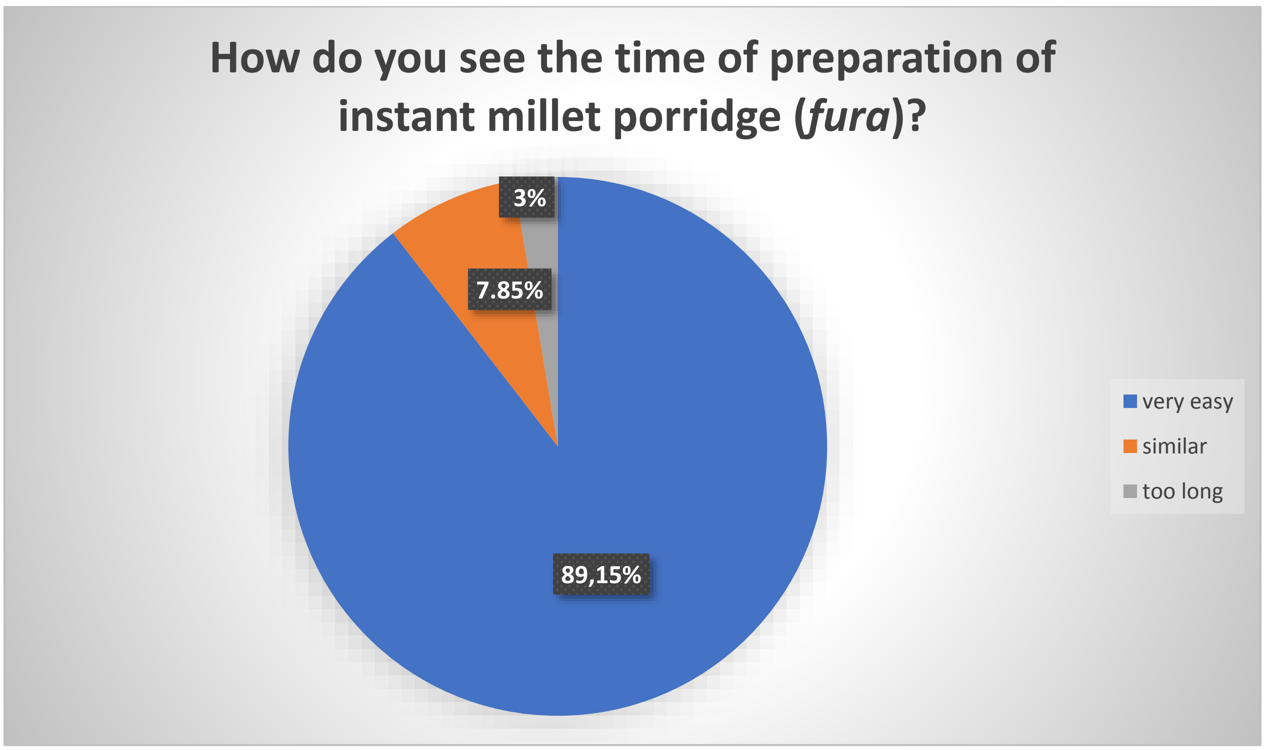

Figure 4.23. Overall perception of time of preparation of instant *fura* (thin) porridge, in Niamey. Hedonic 3-point scale score. 1=very easy, 2=similar, 3=too long. Values are means.

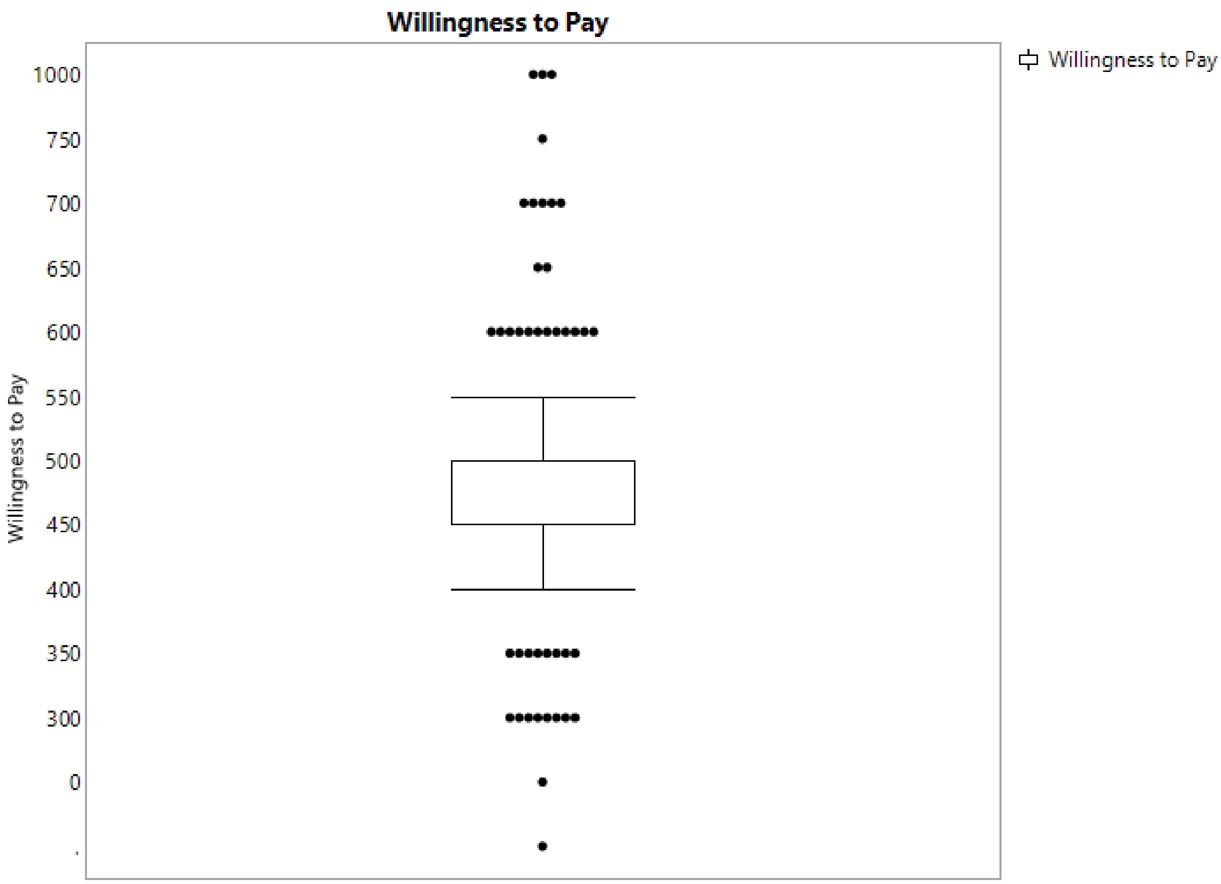

Figure 4.24. Willingness to pay (expressed in FCFA) of instant *fura* (thin) porridge.

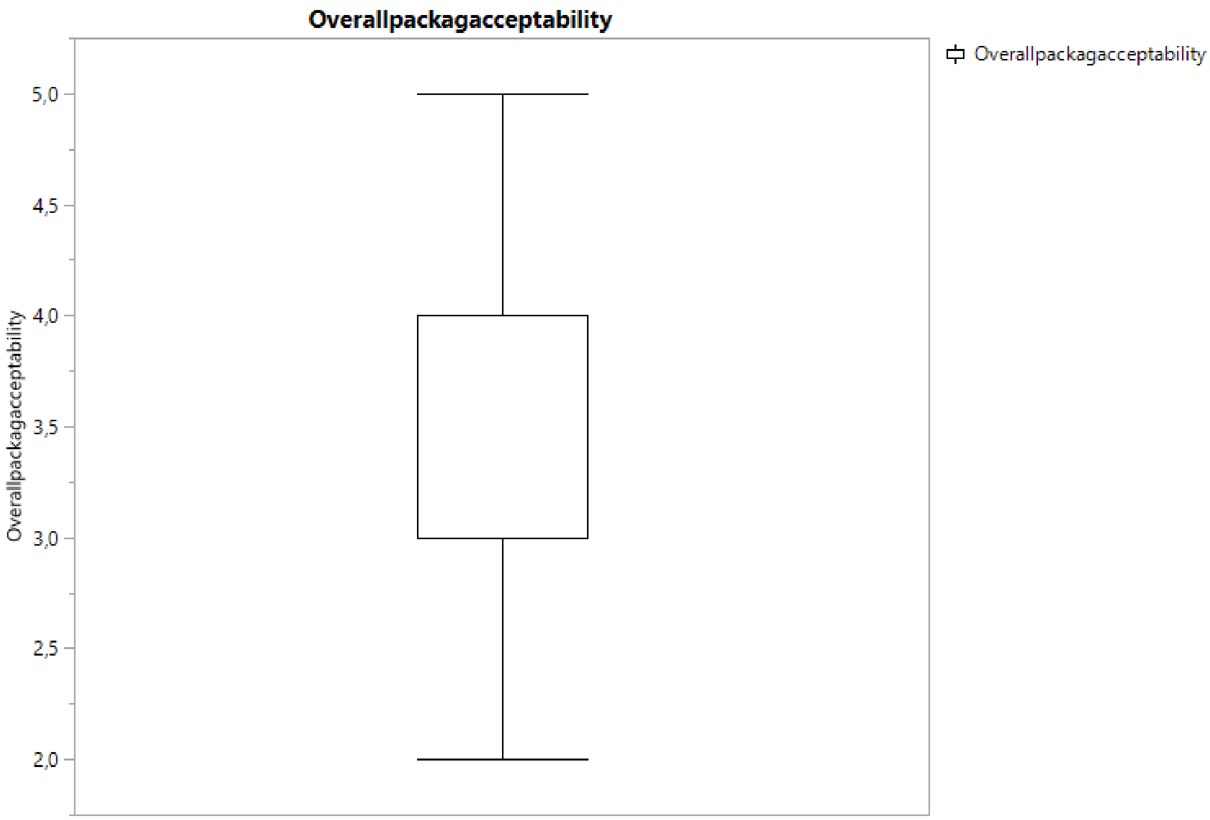

Figure 4.25. Overall package acceptability of instant of *tuwo* (thick) and *fura* (thin) porridges. Hedonic 5-point scale score. 5= Excellent, 4= Very good, 3= Good, 2=Acceptable, 1= Bad).

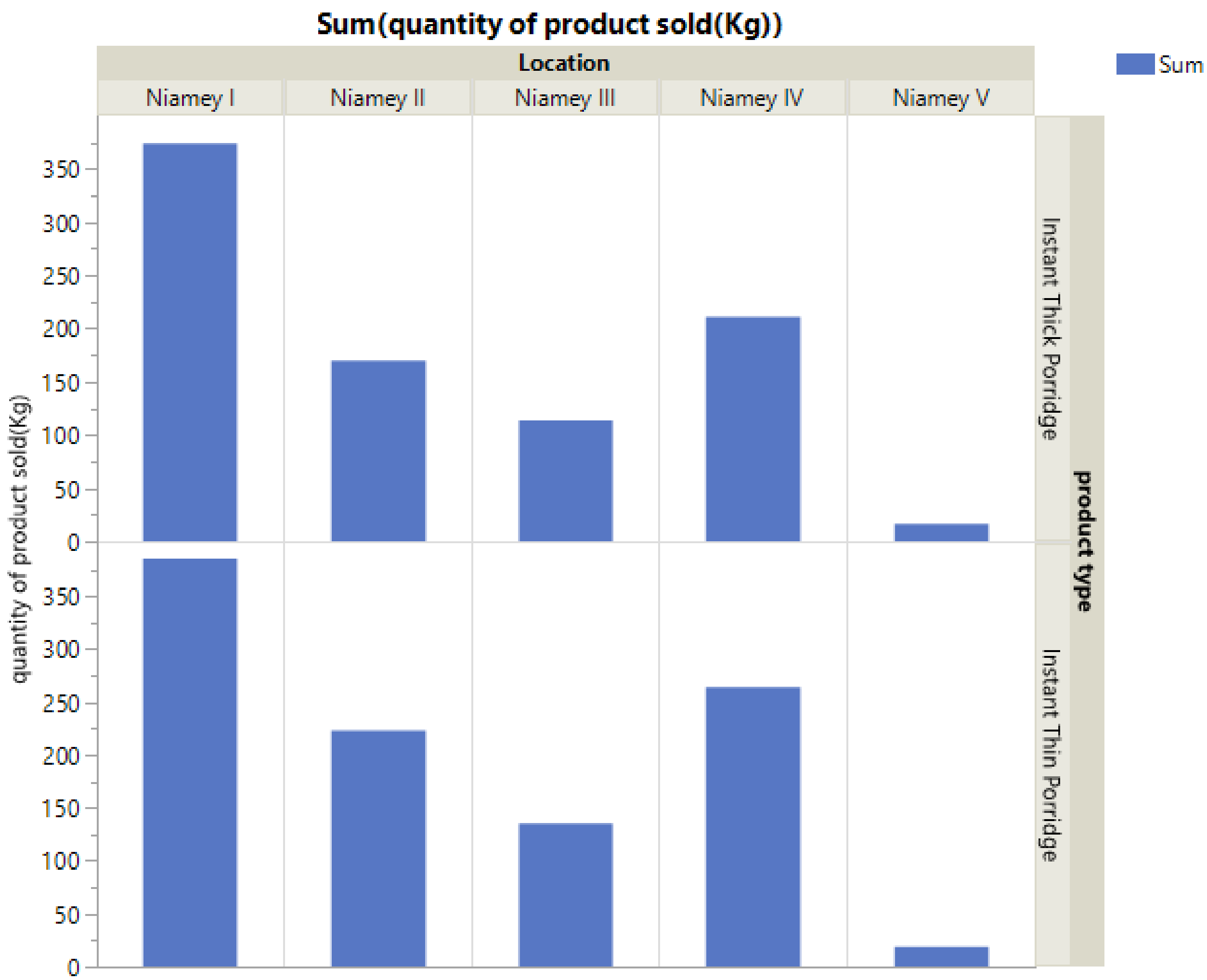

Figure 4.26. Summarized overall quantity of instant millet *tuwo* (thick), and *fura* (thin) porridge flours sold in the 5 locations/counties Niamey I-VI.

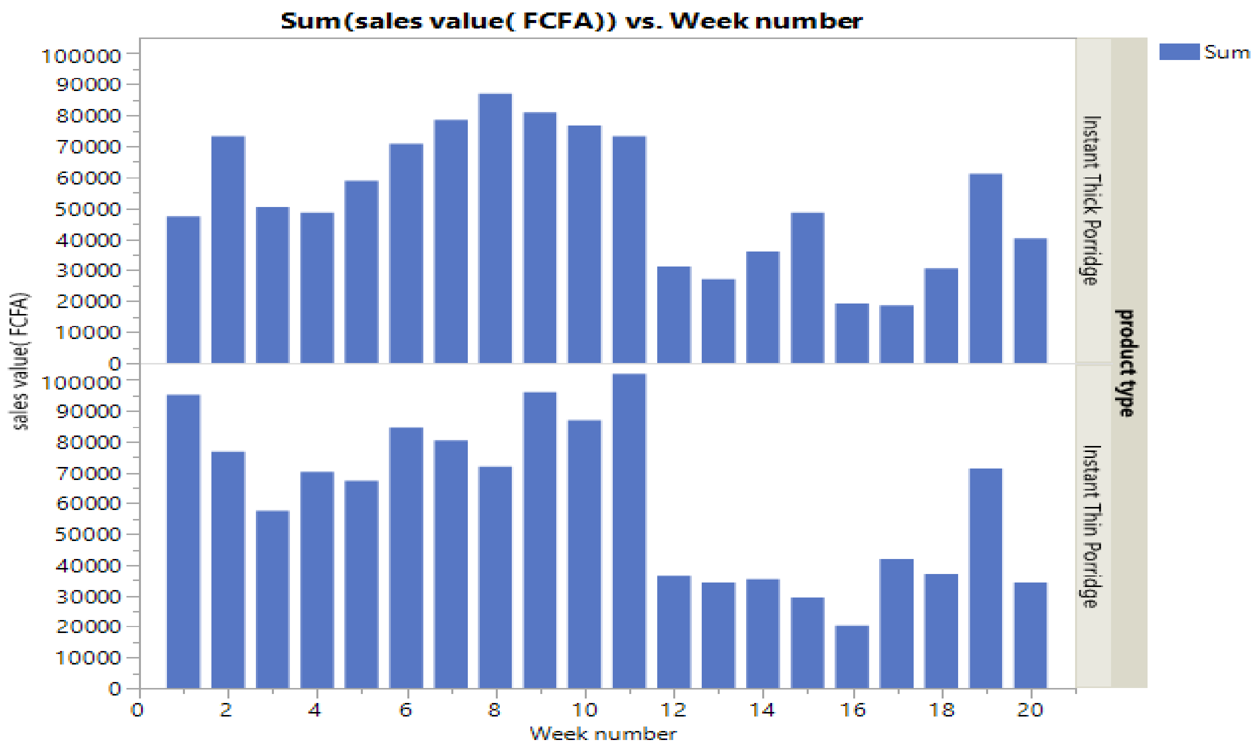

Figure 4.27. **Total sales achieved per week for millet *tuwo* (thick) and *fura* (thin) porridges**, 1USD=550 FCFA. Note that decrease in sales value at week 12 onwards was influenced by lesser availability of supply to market.

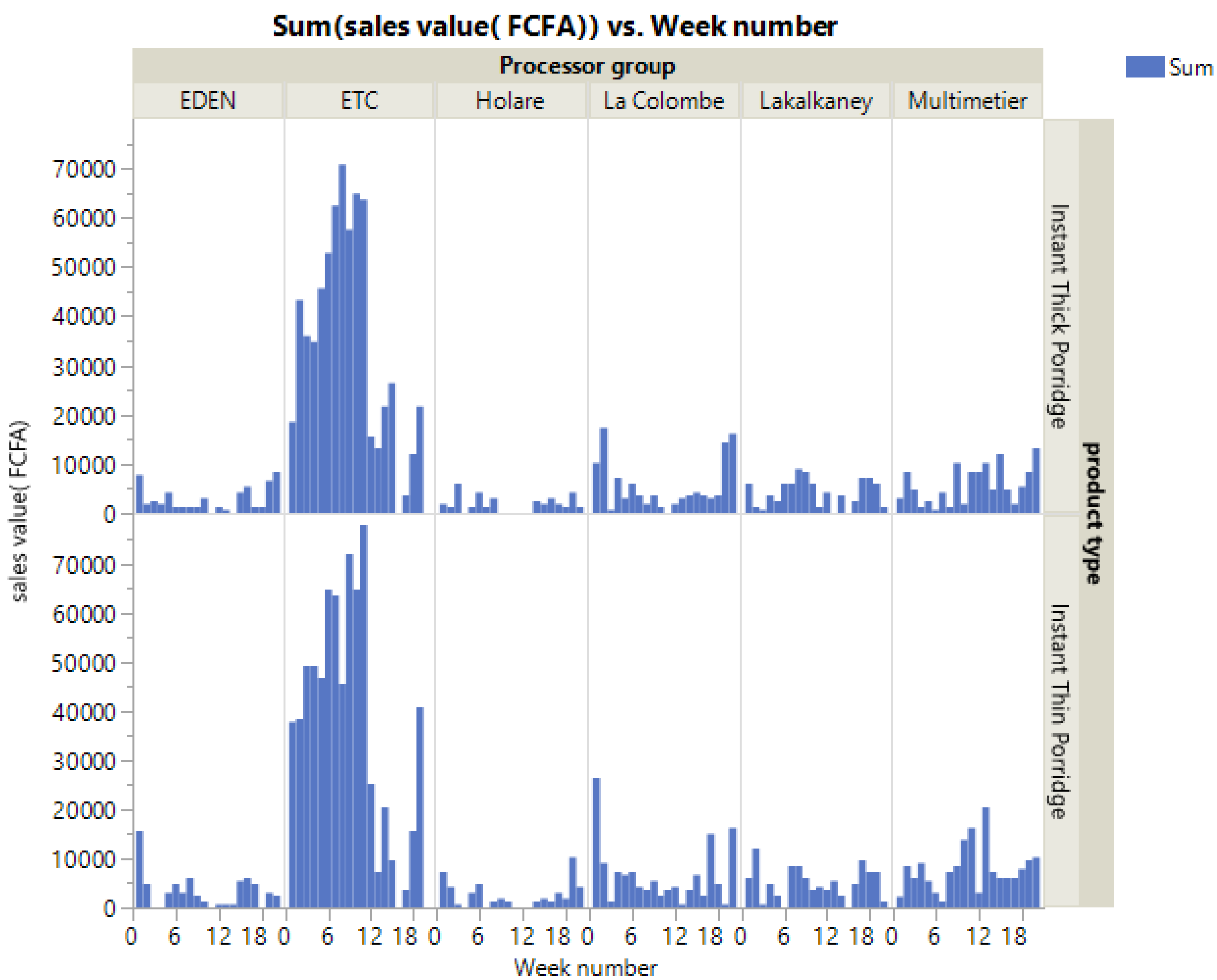

Figure 4.28. Sales achieved for instant millet *tuwo* (thick) and *fura* (thin) porridges per processor group/enterprise and per week, 1USD=550 FCFA.

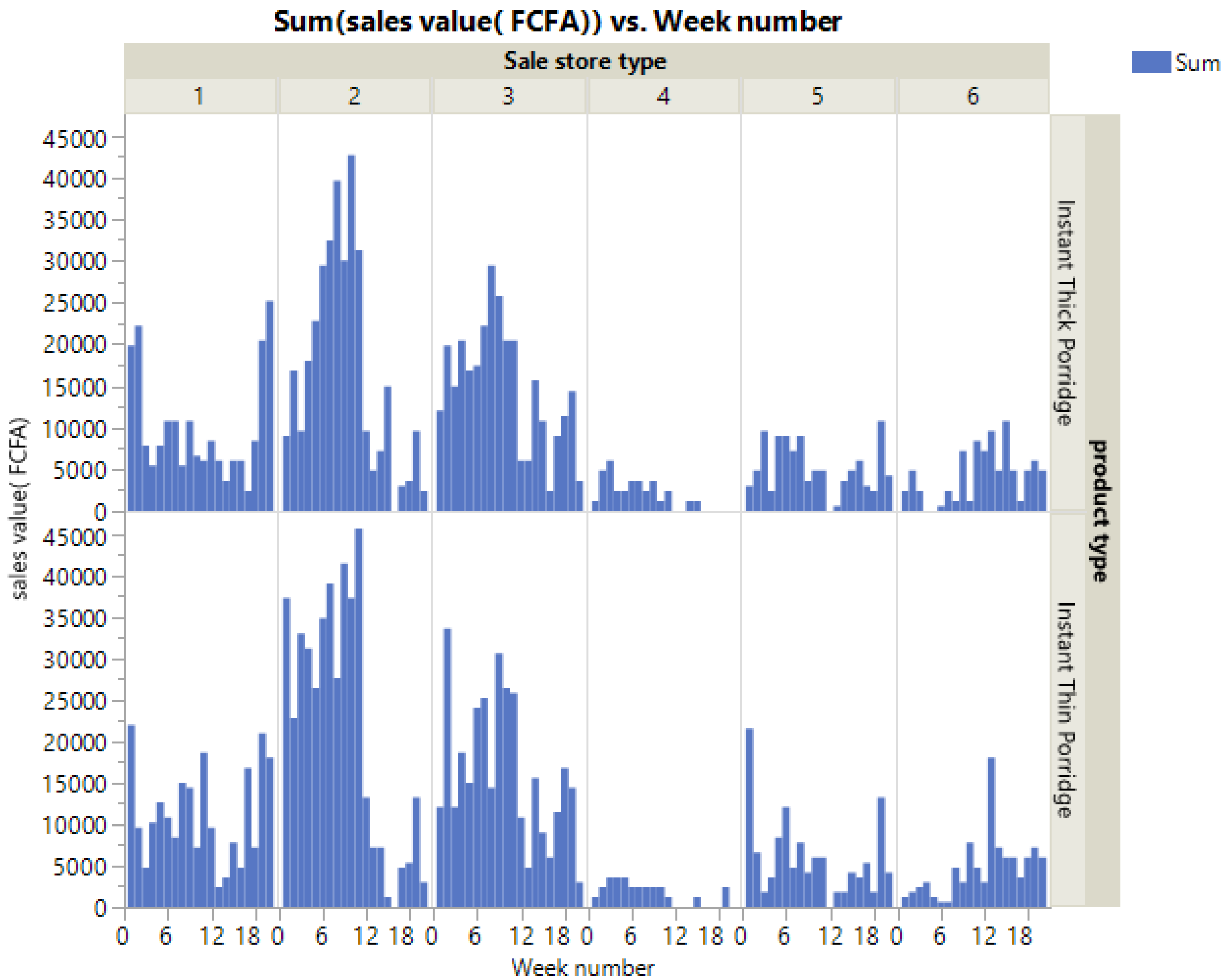

Figure 4.29. Sales achieved for millet *tuwo* (thick) and *fura* (thin) porridges per processor group/enterprise per sale store type and per week, 1USD=550 FCFA. Legend of sale stores type: 1 = Enterprise/unit production site, 2 = District store, 3 = Mini-market, 4 =Gas station store,5 = Food mart, 6 = Other (proximity, face-to-face sale).

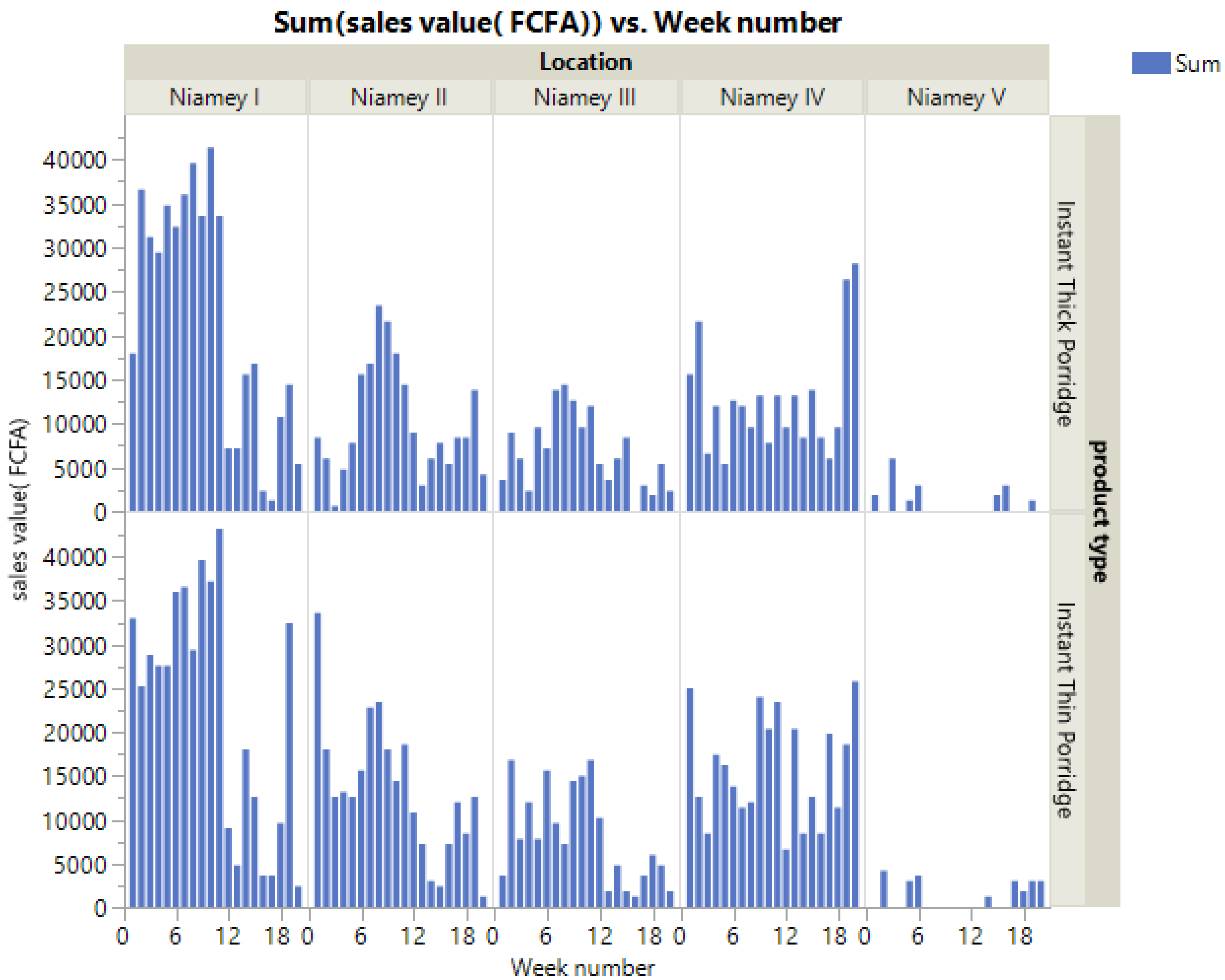

Figure 4.30. Sales achieved for millet *tuwo* (thick) and *fura* (thin) porridges per location, per product type, and per week, 1USD=550 FCFA.

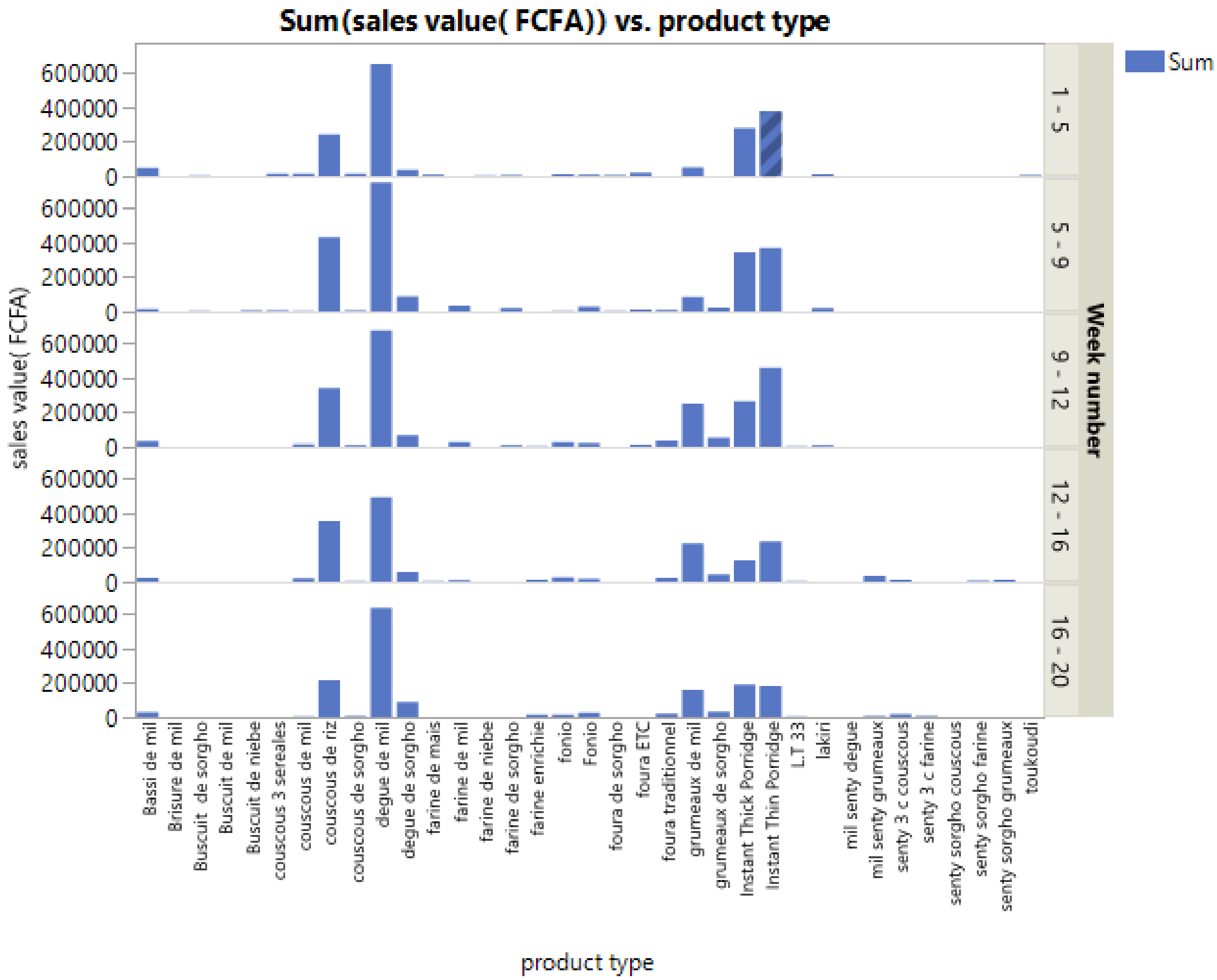

Figure 4.31. Overall sales of the instant millet tuwo (thick) and fura (thin) porridges versus 33 other popular traditional cereal processed products made from millet, sorghum, maize and rice grains, per week range (1-5, 5-9, 9-12, 12-16, and 16-20), 1USD=550 FCFA.

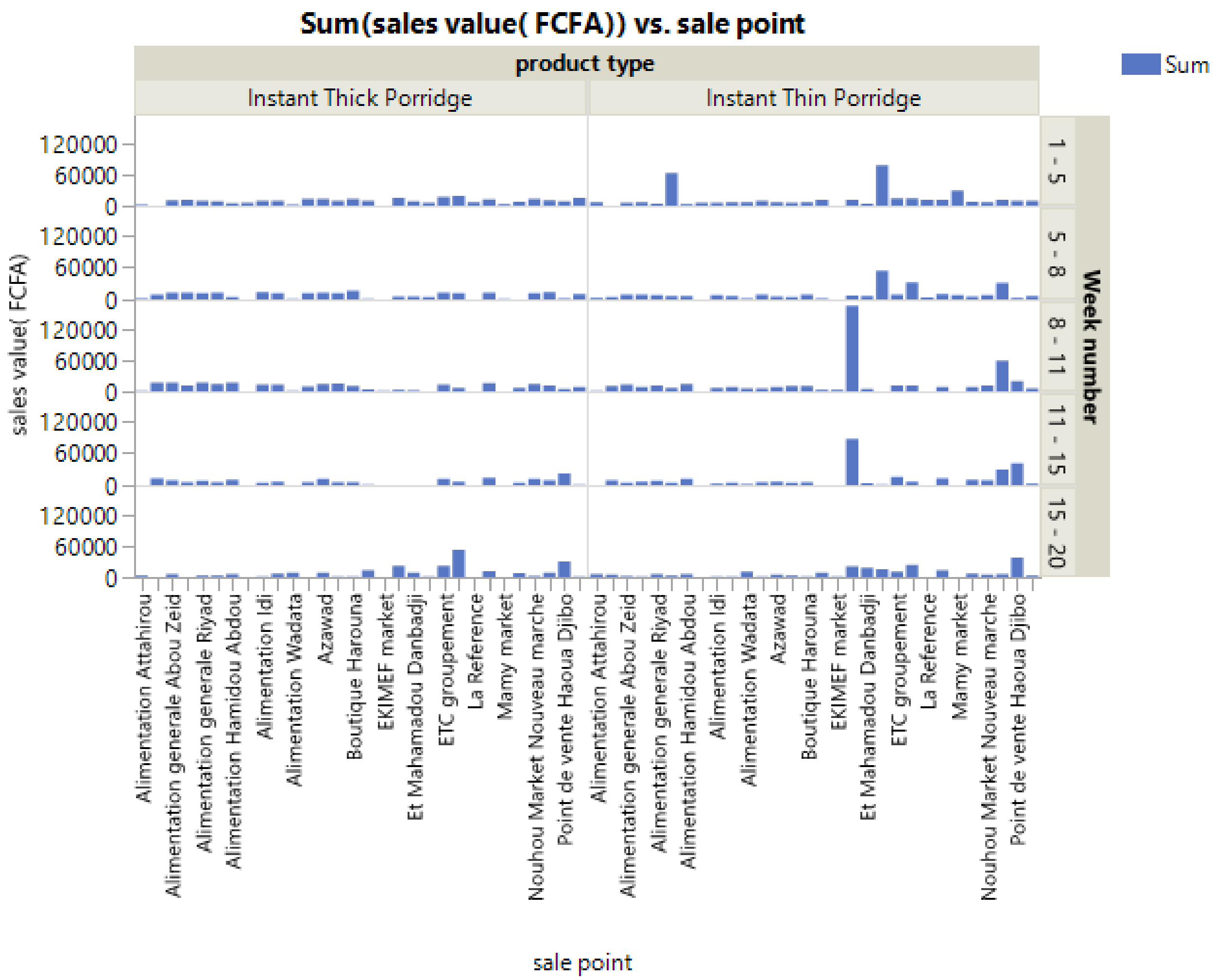

Figure 4.32. Overall sales of the instant millet tuwo (thick) and fura (thin) porridges, per sale point, and per week range (1-5, 5-9, 9-12, 12-16, and 16-20), 1USD=550 FCFA.

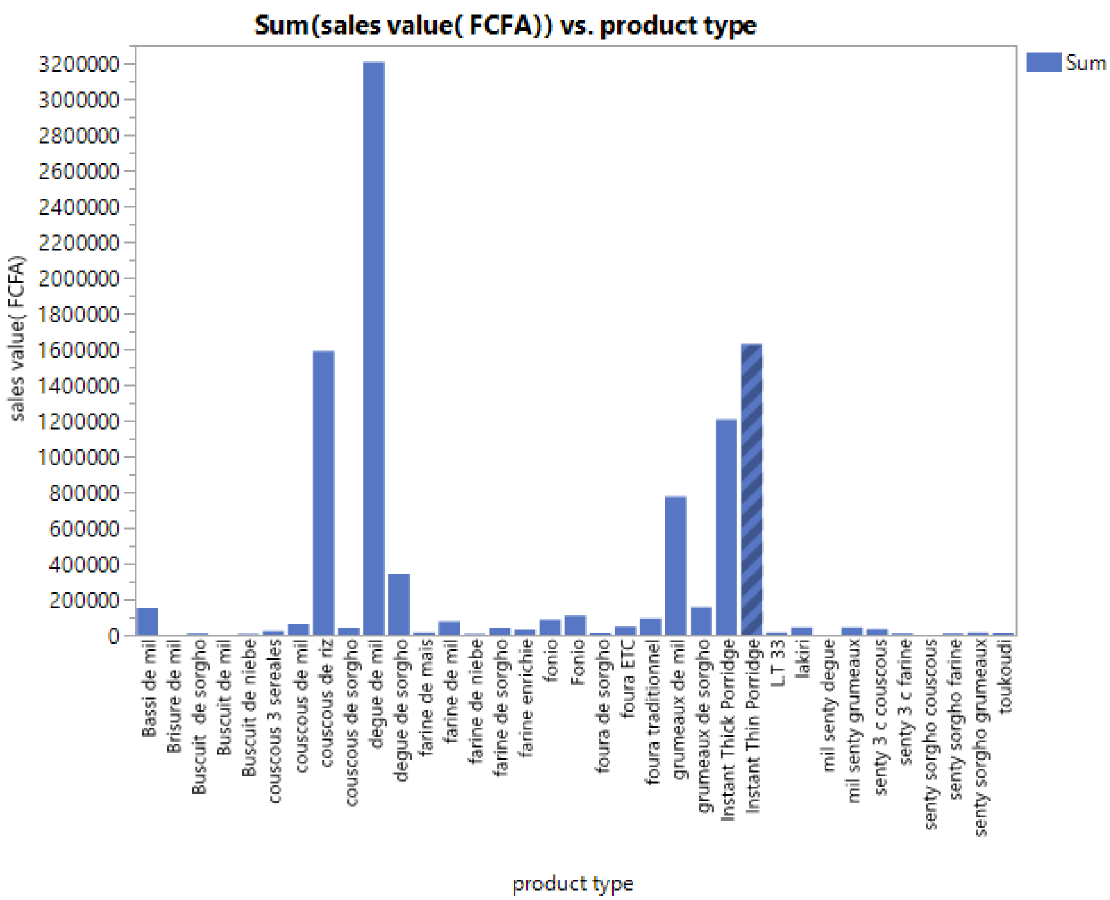

Figure 4.33. Overall total sales of the two combined instant millet tuwo (thick) and fura (thin) porridges versus 33 other popular traditional-related cereal processed products made from millet, sorghum, maize, and rice grains.

CHAPTER 5. OVERALL CONCLUSION AND FUTURE DIRECTIONS

5.1 Overall conclusion

We can conclude that if the use of low-cost single screw extruder is coupled to a well-designed process, and to a proper choice of options including optimum process parameters setting, and varieties with better food making ability, it will lead to a better technology innovation for the West African Sahelian Region. Therefore, integrating, a constant monitoring and understanding of the context of the use of the single screw extruder, can contribute to improve innovation and co-creation efforts, contributing to improve millet foods, and nutrition of local community, and expand market for millet grains, and fostering better development of emerging grain entrepreneurship in West Africa.

It is well established, and understood that food security, nutrition, and economic growth are among the top development priorities of West African Sahelian populations. At the same time, change in food style, growing of urban populations in Africa have increased pressure on time for food preparation and increases in the middle socioeconomic class are predicted to increase demand of cereal-based foods. In contrast, little work has been done to add more value to local grains through processing. In addition to that, preparation of millet and sorghum foods are known to be labor-intensive and time-consuming.

This thesis work was conducted with the goal of developing competitive and innovative processes to make high quality and high-yielding extruded *couscous*, and fortified instant, or fast cooking, millet food products to improve markets for smallholders' farmers, improve nutrition, and to meet the changing demands of local consumers in West Africa. The products that were designed, optimized, and tested in this work were found to shorten processing time for production of several products with appealing appearance, good taste, and texture, and designed for the preferences of local consumers. The products can be simply reconstituted by adding hot or tap water.

Results of the first study on a newly developed extruded *couscous* indicated that consumers, in general, accepted the extruded product and found it to be smoother in texture than the traditionally-prepared *couscous*. *Couscous* production by extrusion had 10x the daily yield as *couscous* typically prepared for commercial sale by women in a processing unit.

In the second study, the extruder was used to make instant porridge flours, and a locally available roasting process was optimized to make a fast-cooking porridge flour. Each flour was formulated using natural and locally-obtained plant fortificants to nutritionally enhance cereal-legume-fortified flours.

Results of consumers sensory tests and textural characterization by RVA and dynamic oscillatory rheometry of fortified porridge samples revealed that the innovated formulas had better viscosity, taste, and flavor and were more preferred by children and their mothers than food aid vitamin-mineral premix fortified flours distributed at rural government health centers. Bioaccessibility of provitamin A carotenoid and lycopene derivatives, including lutein, α- and β-carotenes, using an *in vitro* digestion system coupled with a HPLC-C30SHORT column, shown that the formulated fortified flour samples had good bioaccessibility values of provitamin A carotenoids, lutein, and α- and β-carotenes.

In the third study, rheological results indicated that instant *tuwo* (thick) and *fura* (thin) porridges had better viscosity and textural attributes (creamy, elastic, gelling) compared to traditional corresponding porridges.

In the fourth study, a home use testing (HUT) of instant *tuwo* and *fura* porridges in Niamey, Niger indicated that overall consumers' acceptability was good. In a market test conducted in Niamey over 20 weeks, in collaboration with local cereal processors and distributors, showed repeat purchases with good frequency of sale of instant *tuwo* and *fura* porridges that have generated about 1/3 in total sales of 35 products related millet and cereal based foods in the period.

We anticipate, more understanding of this innovative model could catalyze and boost demand and diversification of uses of millet grains, to develop market-driven nutritious and healthy grain-based foods, to benefit smallholders' farmers, and favor growth of small- and medium-scale entrepreneur processors in West Africa.

5.2 Future Directions

1. Explore scaling-up of the production and commercialization of the instant *tuwo* and *fura* porridges.
2. Test the market for the extruded millet *couscous*.
3. Test consumer preferences of the new, nutritionally enhanced- and co-extruded formulas.
4. Investigate bioaccessibility in iron, and zinc of both the co-extruded and roasted formulas generated though this work.
5. Conduct a feeding study to evaluate the impact of the fast-cooking nutritionally enhanced formulas versus the food aid one on young children < 5 years by monitoring changes in anthropometrics, including BMI, micronutrients (iron, and zinc) status, and perhaps calcium outcomes on selected children at the respective project village sites benefiting from being fed by the formulas from this thesis, and produced by the respective food innovation centers in Niger.
6. Continue exploring new plants varieties including millet and sorghum, and natural fortificants (moringa, baobab, pumpkin, carrot), and other plants species with potential in provitamin A.
7. Explore the potential of making new millet whole foods using the single screw extruder.
8. Conduct a nutritional survey and baseline study in Niger to determine traditional lifestyle diets and porridge thickness preferences both in villages and cities to understand how differences in the thickness of thick porridges, and particle size of *couscous*, both made using traditional methods and the single screw extruder, affect responses in feelings of satiety, gastic emptying, and blood glucose glycemic response of human subject groups residing in cities and villages in Niger.

APPENDIX A. ABSOLUTE BIOACCESIBILITY OF EXTRUDED, CO-EXTRUDED, AND ROASTED *COUSCOUS* SAMPLES

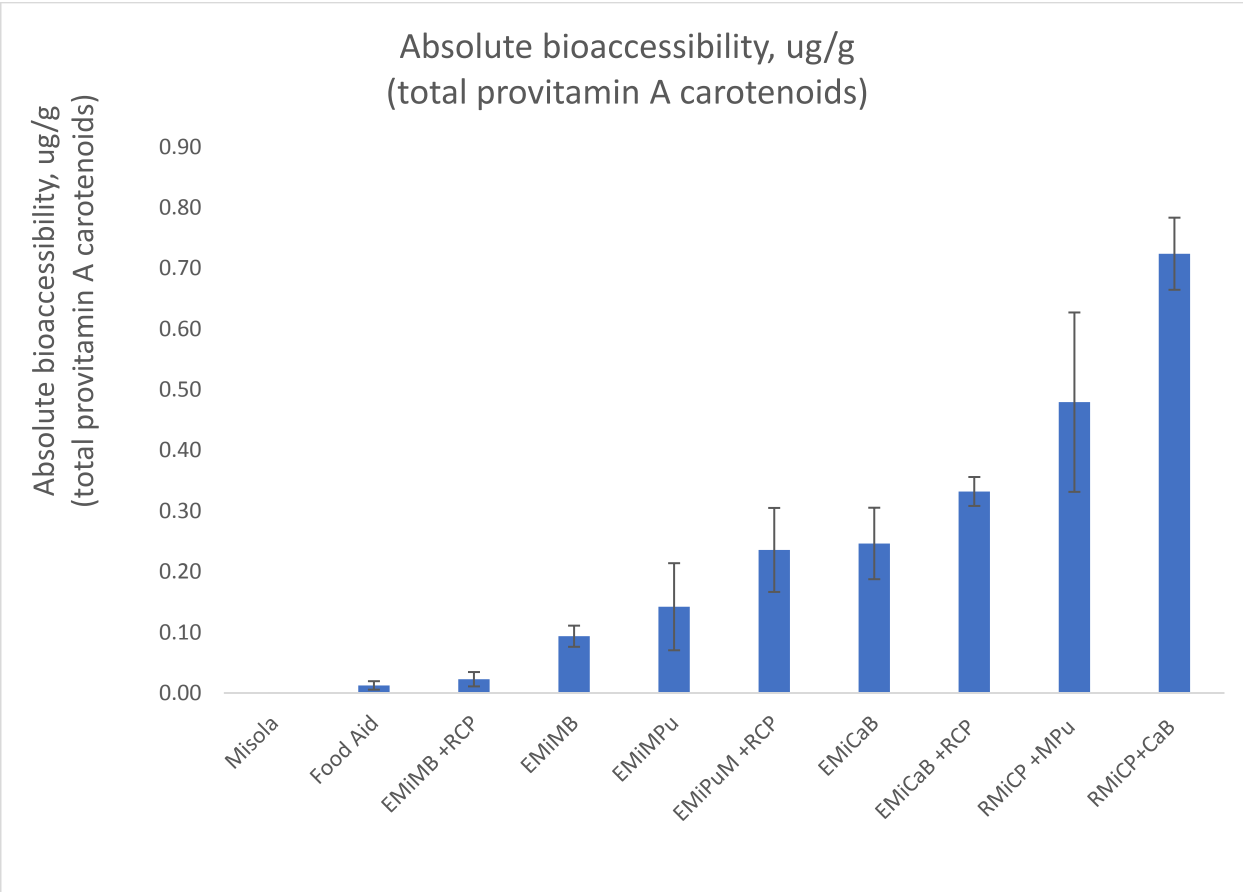

Figure A.1. Absolute bioaccessibility, μg/g (total provitamin A carotenoids. Values are means of triplicate determination.

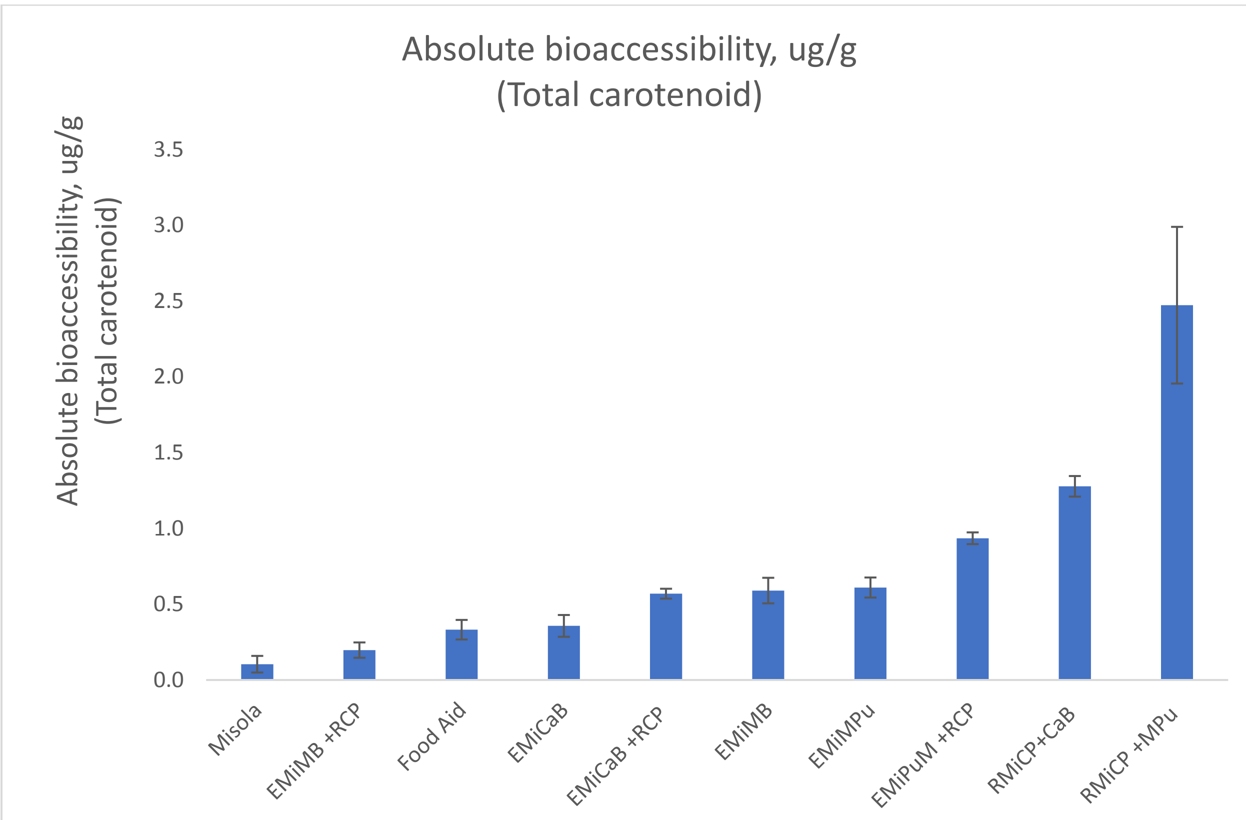

Figure A.2. Absolute bioaccessibility, µg/g (Total carotenoids). Values are means of triplicate determination.

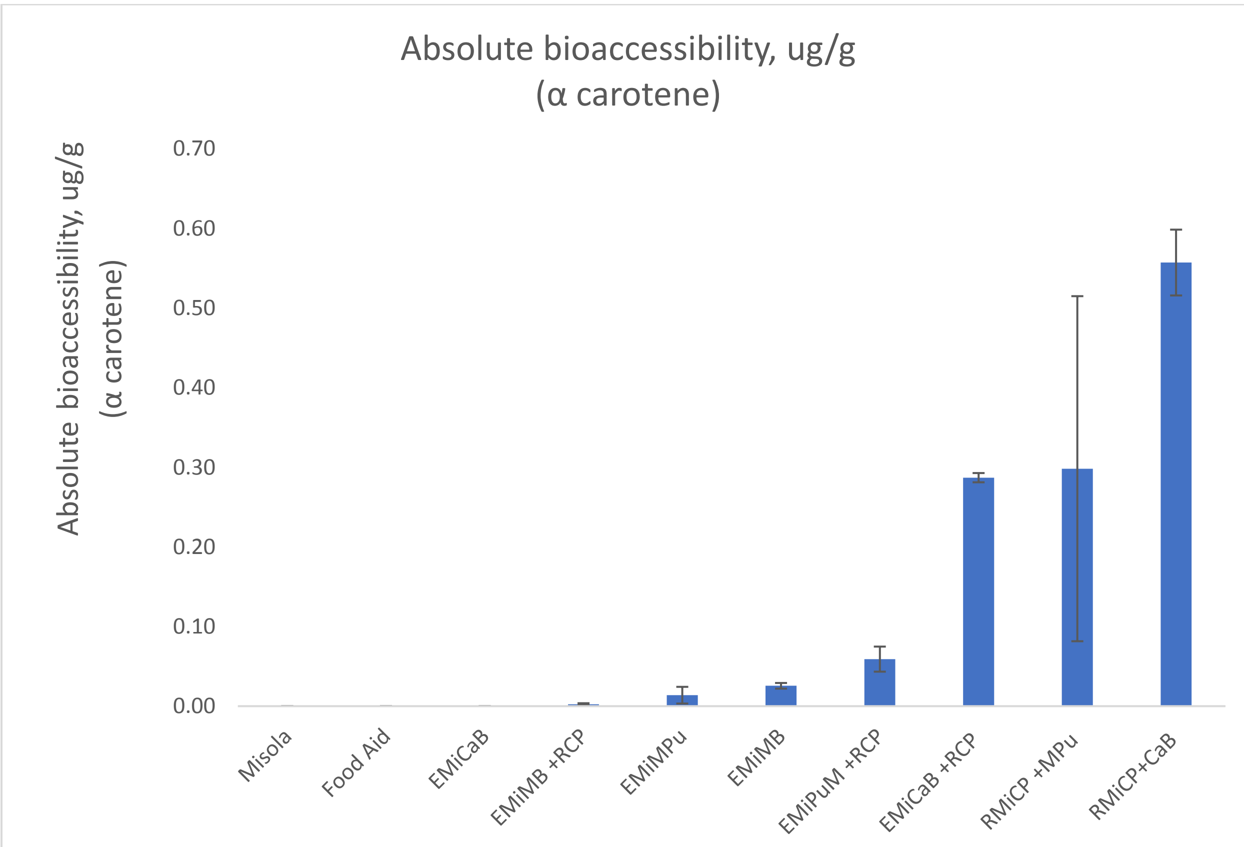

Figure A.3. Absolute bioaccessibility, μg/g (α carotene). Values are means of triplicate determination.

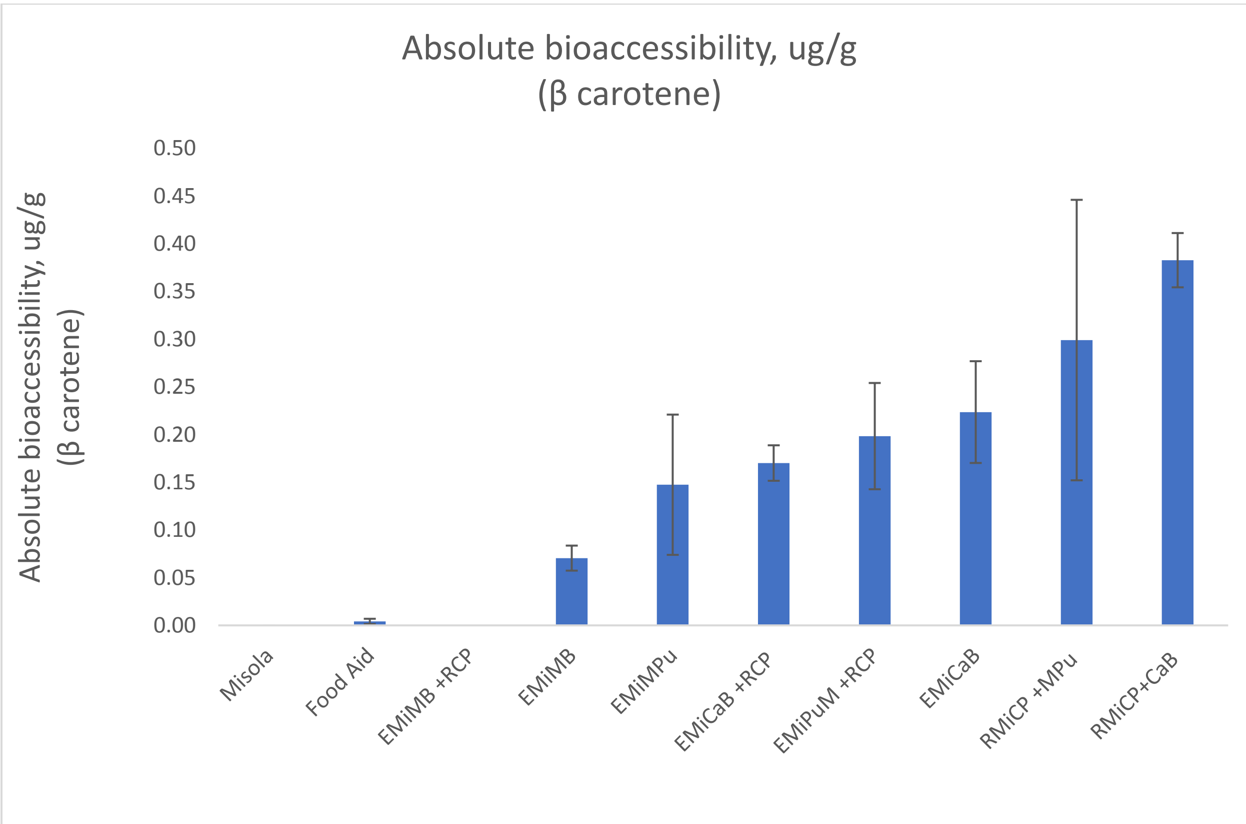

Figure A.4. Absolute bioaccessibility, μg/g (β carotene). Values are means of triplicate determination.

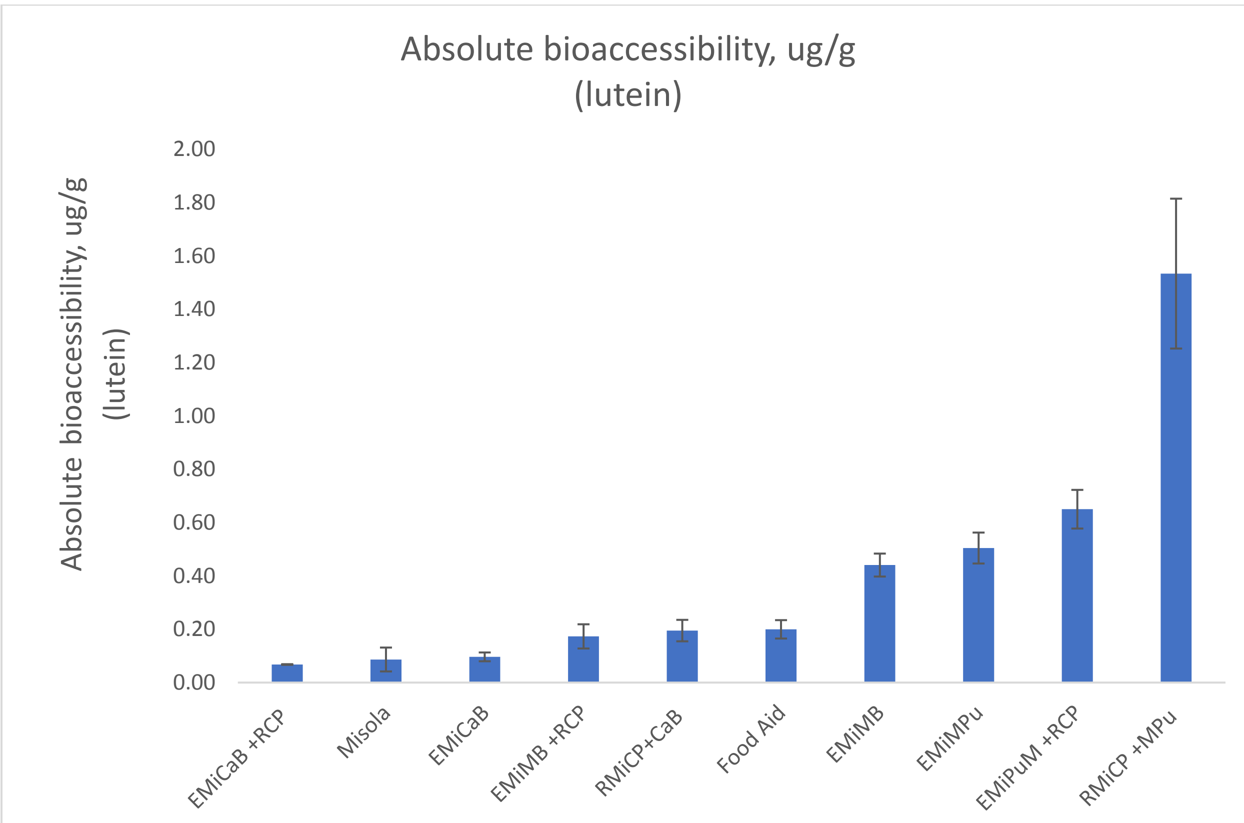

Figure A.5. Absolute bioaccessibility, µg/g (lutein). Values are means of triplicate determination.

APPENDIX B. RESULTS OF OBSERVATIONAL PERCEPTION SURVEYS FROM 16 RURAL MOTHERS WHO FED THEIR CHILDREN WITH FORTIFIED MILLET-BASED FORMULAS MADE BY RURAL WOMEN PROCESSORS AT FOOD INNOVATION CENTERS IN TERA, FALWEL, SHERKIN HAOUSSA, GANDA IYA, VILLAGES IN NIGER

Perception/observational data were also collected from 16 mothers (4 per location x 4 locations) who fed their children with formulas made by food innovation centers versus food aid blends. Numeric scores scale used varied from 1 to 6, depending on type of information collected, and included the following: child acceptability of fortified formula (6=excellent, 2=dislike, 1=dislike Much); child treatment duration/effect (4=rapid 3=acceptable, 2=slow,1=no effect); and accessibility of fortified products in location (3=accessible, 2=often accessible, 1=not accessible). Other information collected included number of weeks after which a malnourished child recovered (4-12 weeks) and the amount of fortified formula required to treat (feed) a malnourished child [number of packets (500g) administered to child/week]. Mothers were selected based on their residence in the village and affiliation with the community health center in their location. They must have had a malnourished a child of age that varies between 6 months and <5 years old under their care (either their own child, or an orphan under their cares).

Results and discussion

Innovated millet/legume formulas were assessed versus food aid maize-soy blends in relation with rural health centers. Data collection included perception/feedback responses from 16 mothers who purchased and fed their malnourished children with innovated millet/legume formulas. Below is summarized in (Figures B1 and 3) results from 4 locations (Falwel, Tera, Gadan Iya, Sherkin Haoussa), in Niger, indicating that mothers who tested the innovated blend perceived it to improve health of their children, and is more preferable, and accessible than food aid maize-soy blend. Figures B4 and B5 show that about 500 g per week of innovated millet/legume flour formula were enough for their children to improve health. Duration of treatment varied from 4-8 to 12 weeks depending on location and malnutrition severity. Figure B6) elucidates the number women trained from 2014 to 2018. Figures (B 7 and 8) show geographical locations of Food Innovation Centers in Niger and Burkina Faso. Figures B9 and 10 give a similar representation and the number of health centers and village markets benefiting from fortified formulas in Niger. Figure B11 gives the sales of fortified formulas in Tera, Gadan Iya, and Lebda.

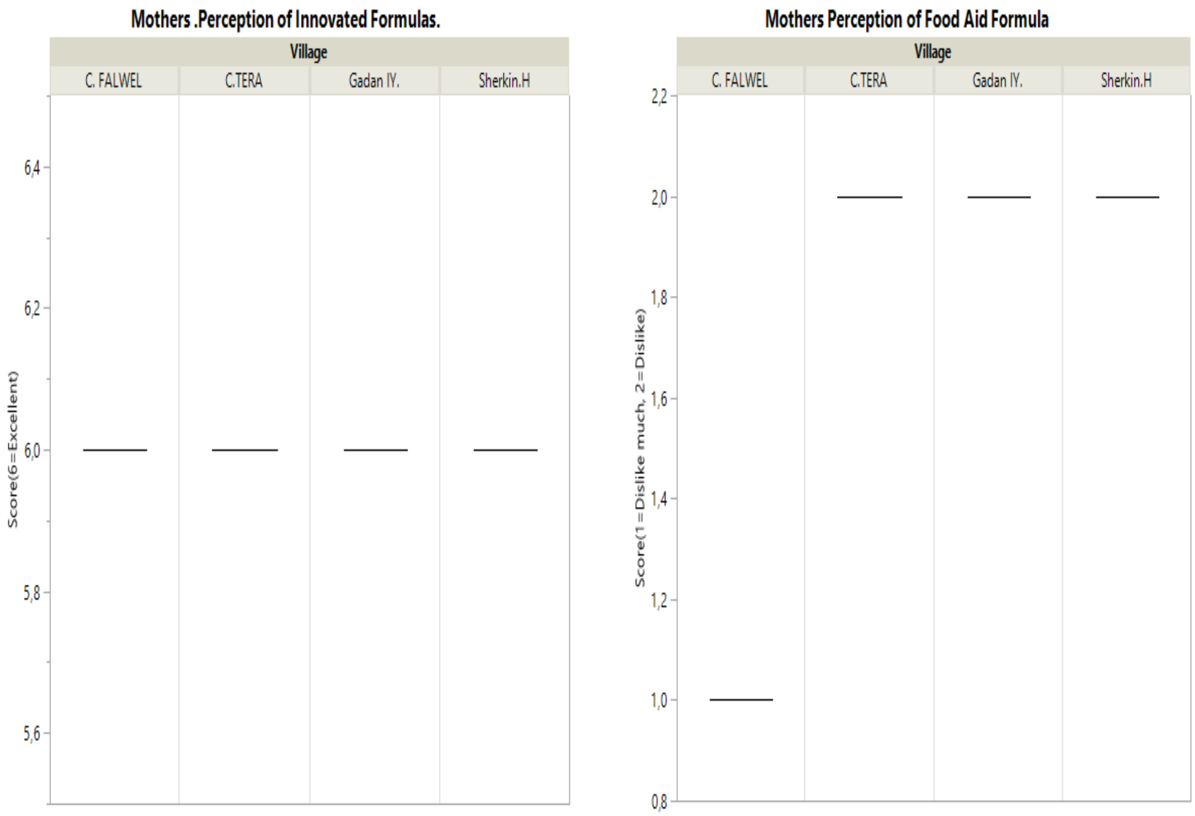

Figure B.1. Mothers' perception of their children's acceptability of innovated formulas made at the rural Food Innovation Centers versus food aid formulas provided by health centers in Niger. Children's acceptability of fortified formula was based on a 6-point scale rating (6=excellent, 2=dislike,1=dislike much). Values are means of four replicate determinations compared to local food aid controls ($P<0.05$).

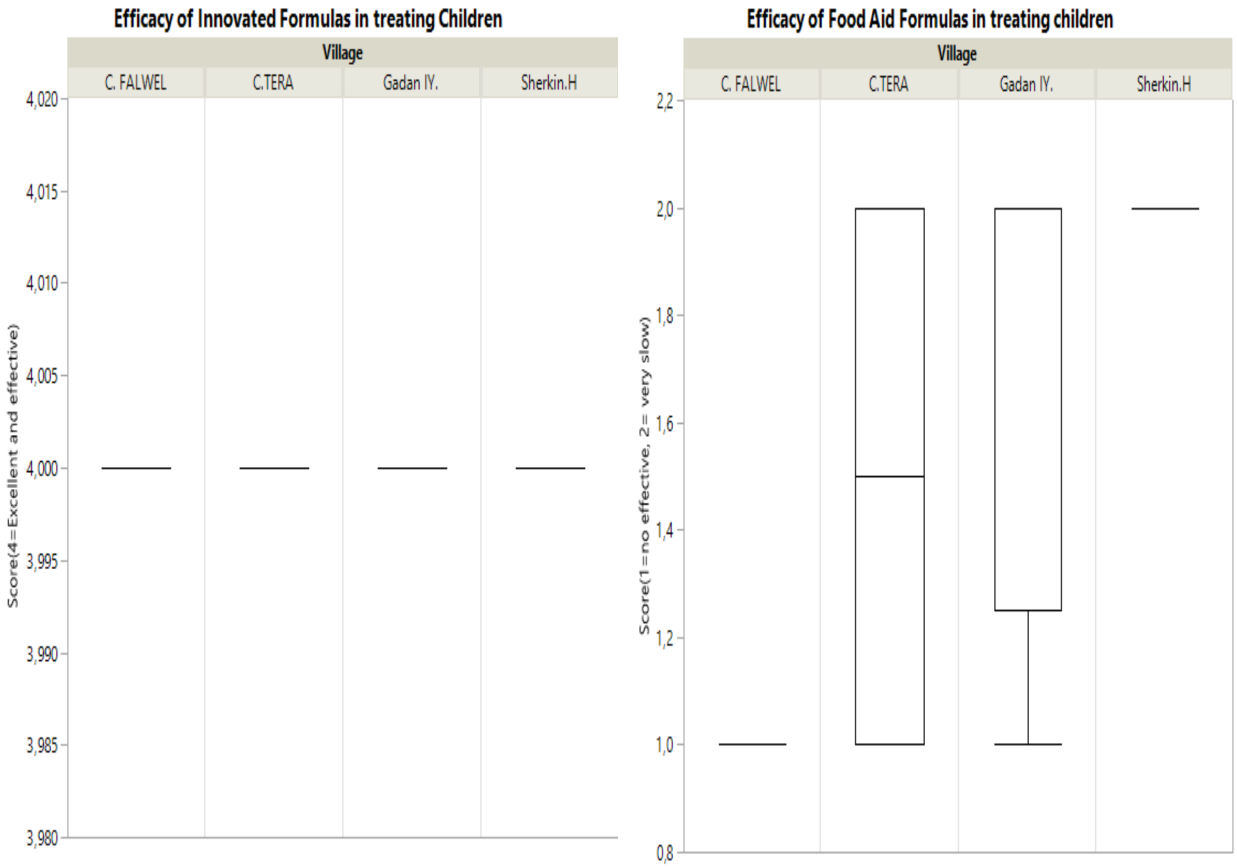

Figure B.2. Mothers' perception of efficacy of innovated formulas made at food innovation centers in treating children versus food aid formulas provided by health centers. Mothers' perception scores of efficacy were based on a 4-point scale (4=excellent and effective, 2=very slow effect,1=not effective). Values are means of four determinations compared to local controls.

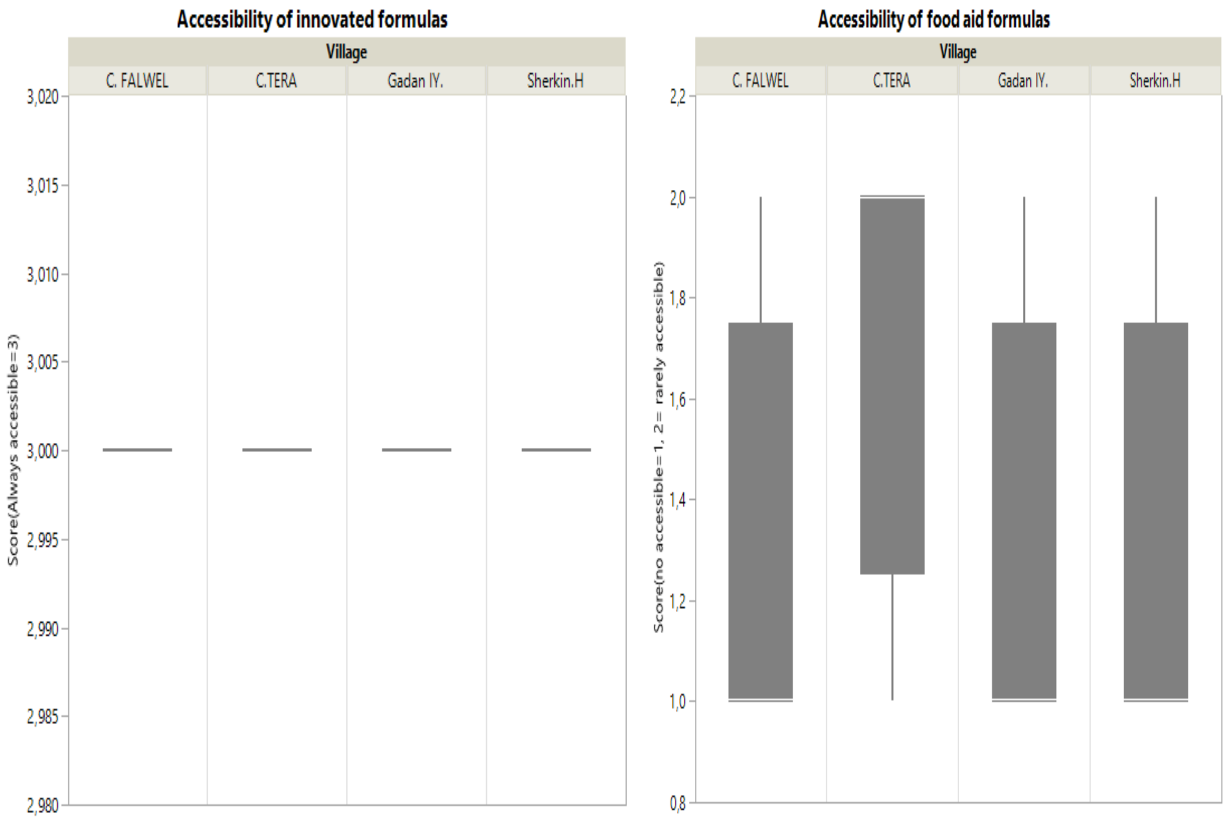

Figure B.3. Mothers' perception of accessibility/availability of innovated formulas made at Food Innovation Centers in location/village versus accessibility of food aid formulas at health centers. (3=always accessible, 2=rarely accessible,1=not accessible). Values are means of four determinations compared to local controls.

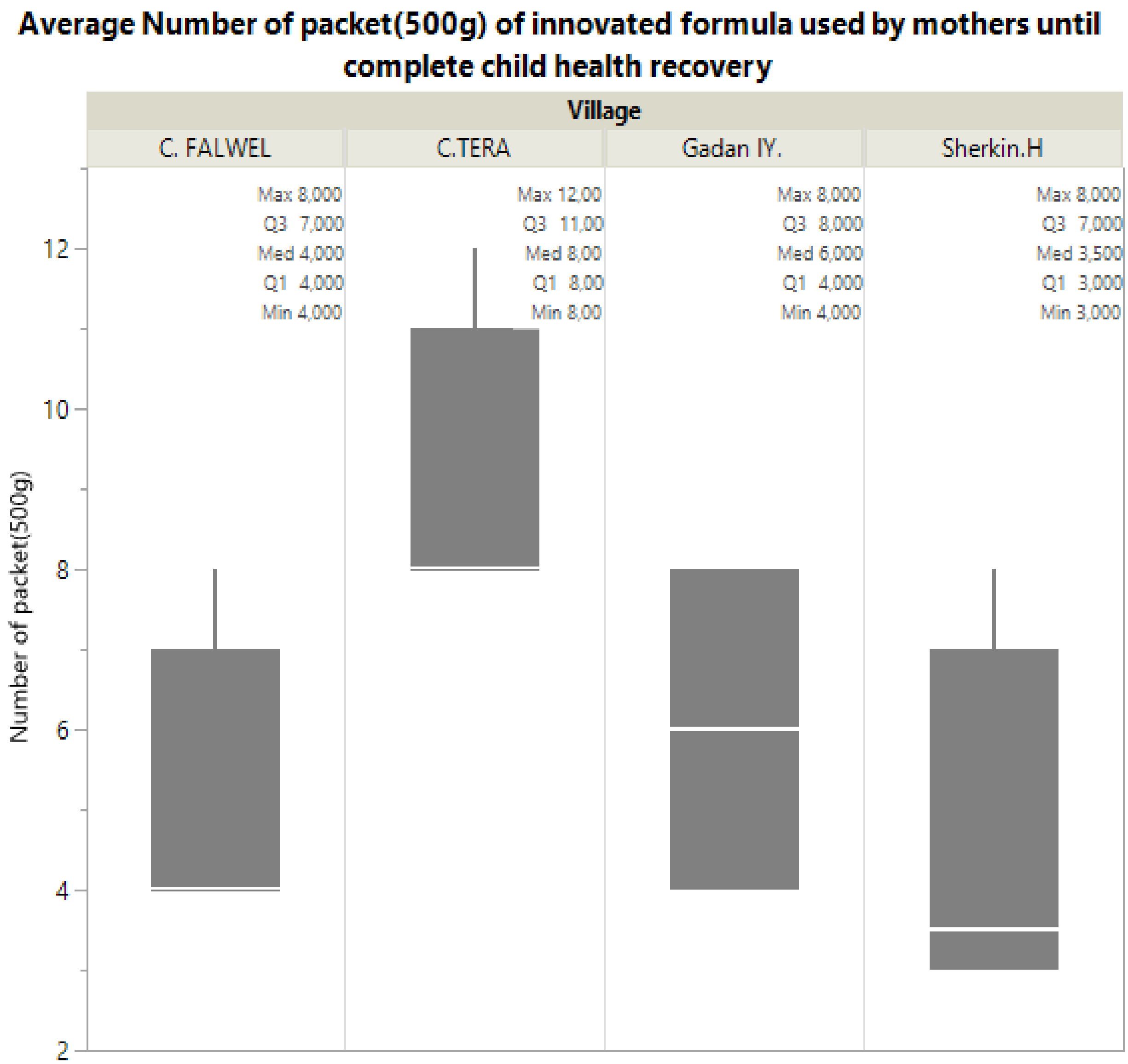

Figure B. 4 Average number of packets (500 g) of innovated formulas made at Food Innovation Centers administered to children by mothers until complete health recovery by location**. Values are means of four determinations.**

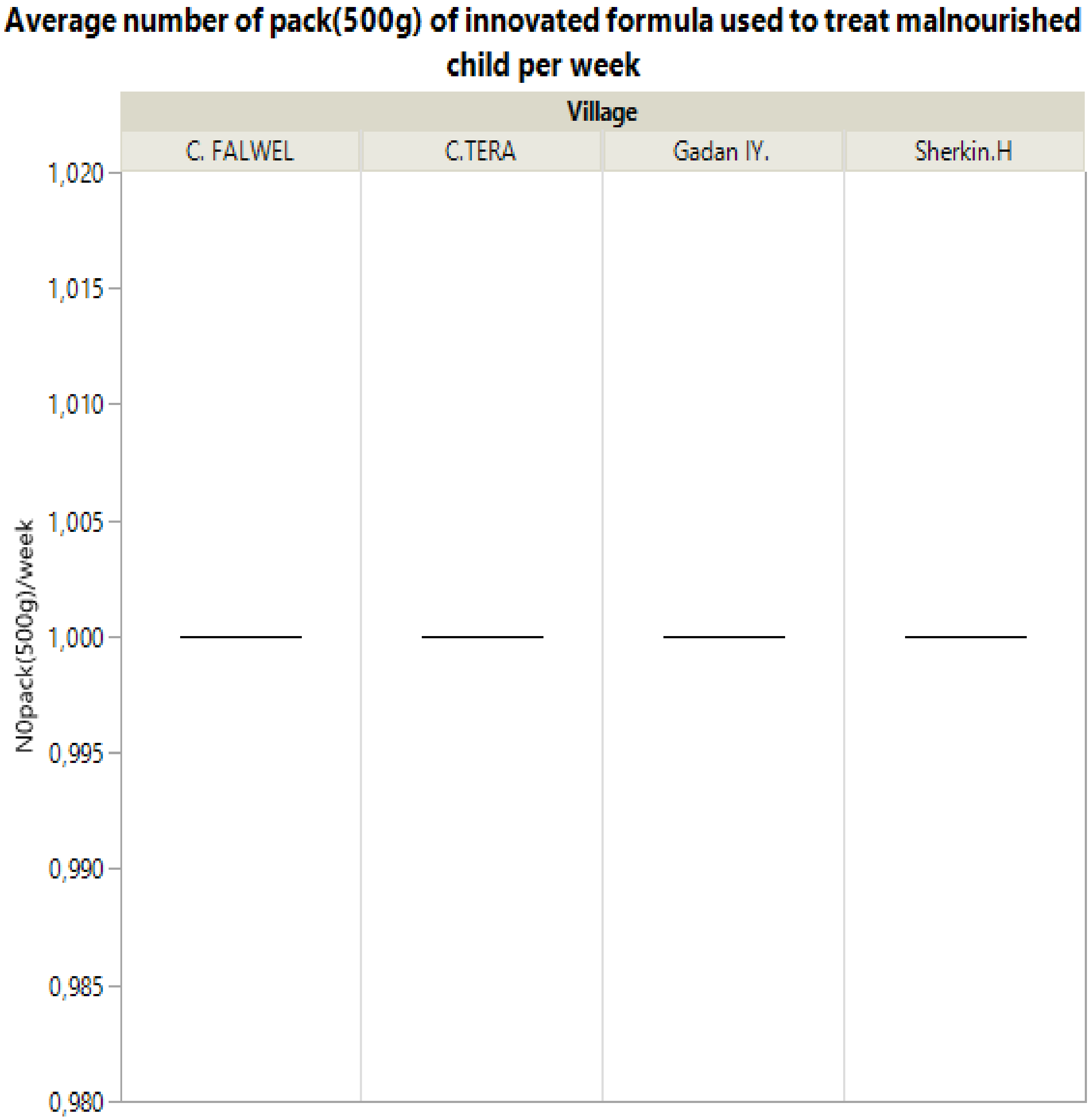

Figure B. 5 Average number of packets (500 g) of innovated formulas administered to child per week**. Values are the means of four replicate determinations.**

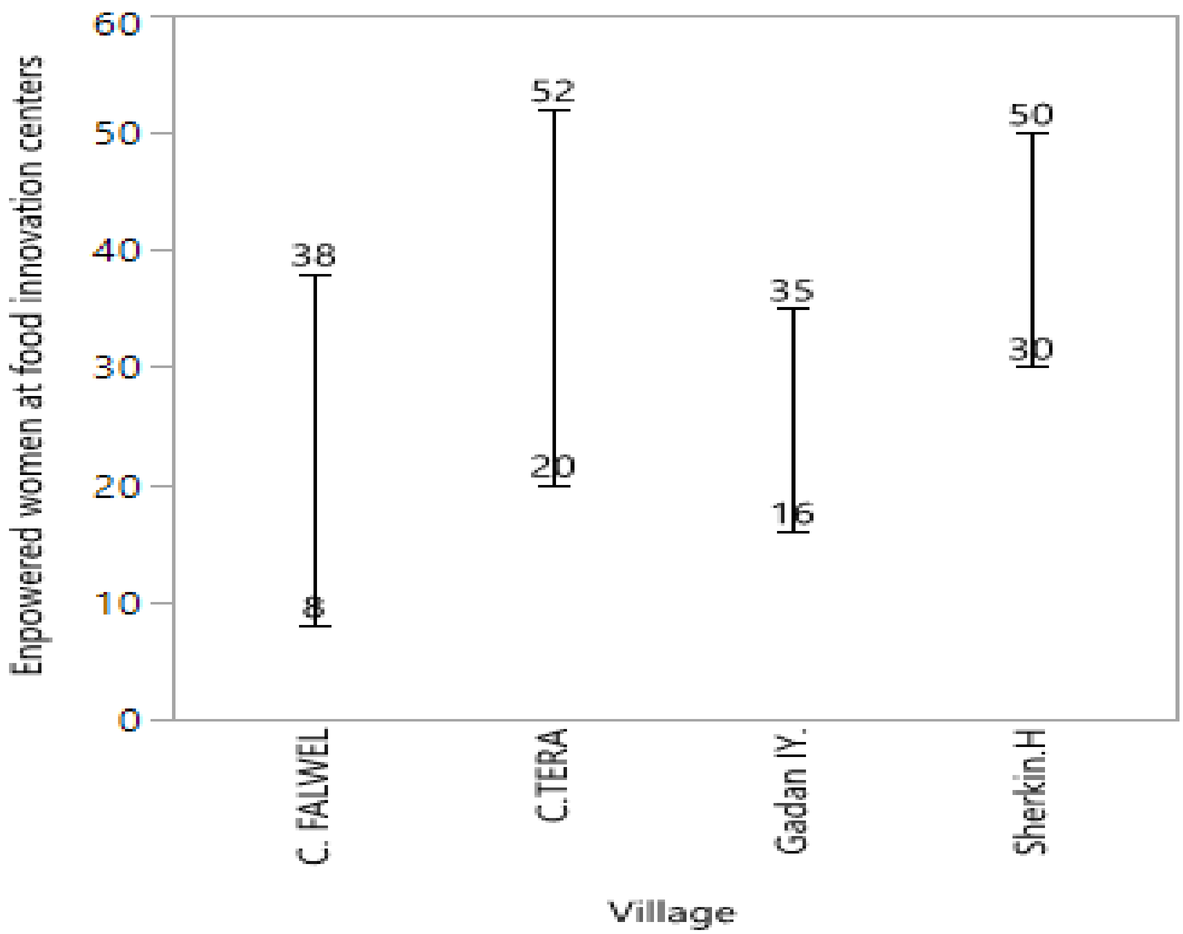

Figure B.6. Number of women operating at rural Food Innovation Centers in Niger from 2014 (low) to 2018 (high).

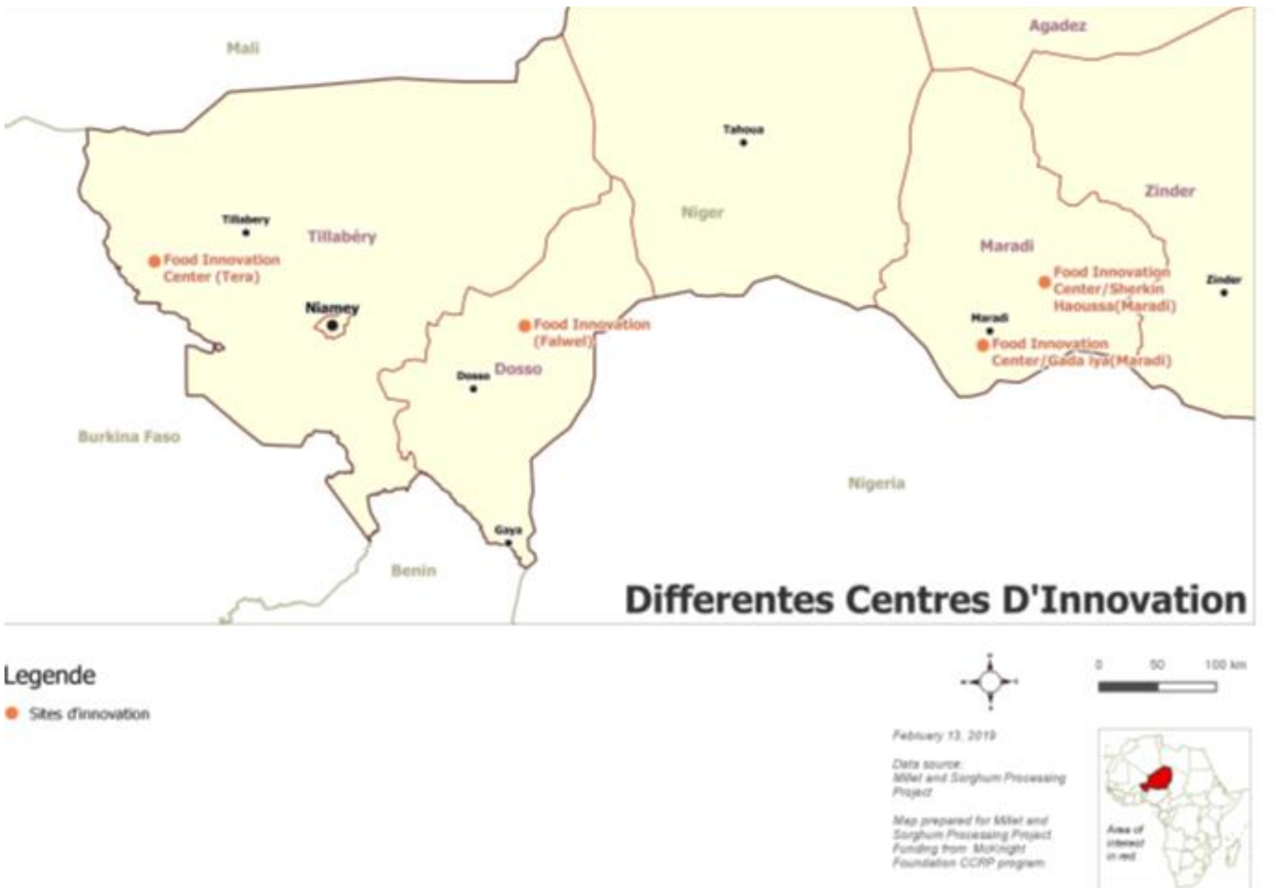

Figure B.7. GIS mapping of Food Innovation Centers implemented in Falwel, Gadan Iya, Sherkin Haoussa, and Tera villages in Niger.

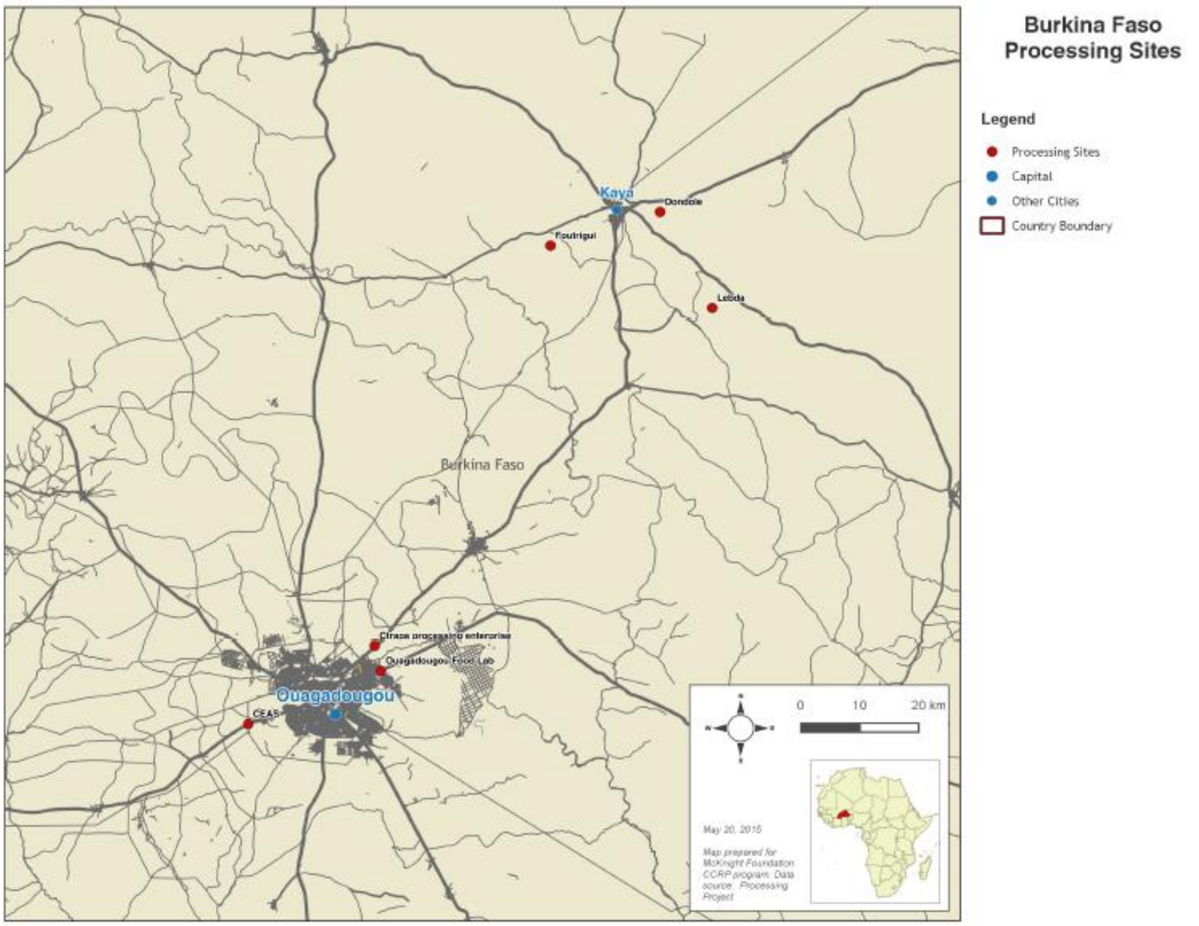

Figure B.8. **GIS mapping of Food Innovation Center implemented in Lebda/Kaya village in Burkina Faso**.

Figure B.9. GIS mapping of Food Innovation Centers implemented in Falwel, Gadan Iya, Sherkin Haoussa, and Tera villages, as well as affiliated/partner health centers in Niger.

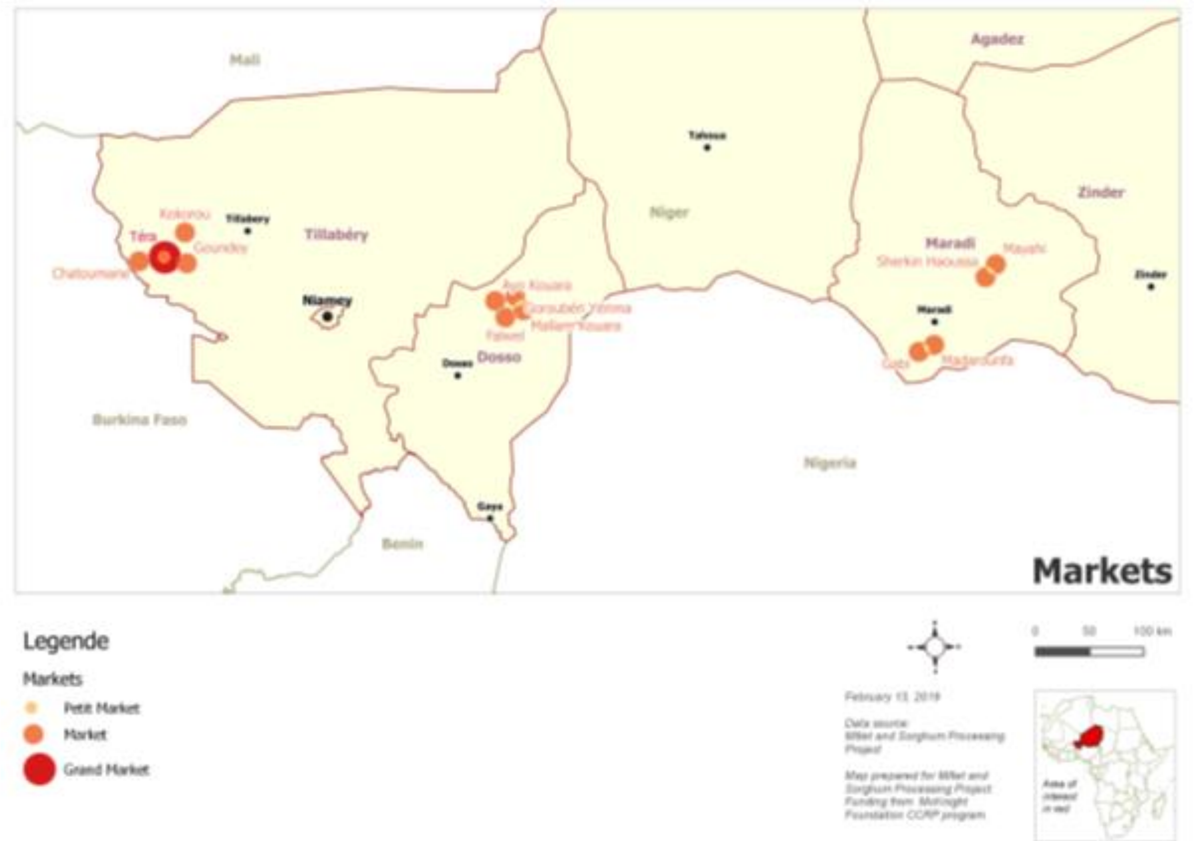

Figure B.10. GIS mapping of food innovation centers implemented in Falwel, Gadan Iya, Sherkin Haoussa, and Tera villages, as well as affiliated /partner weekly rural markets in Niger.

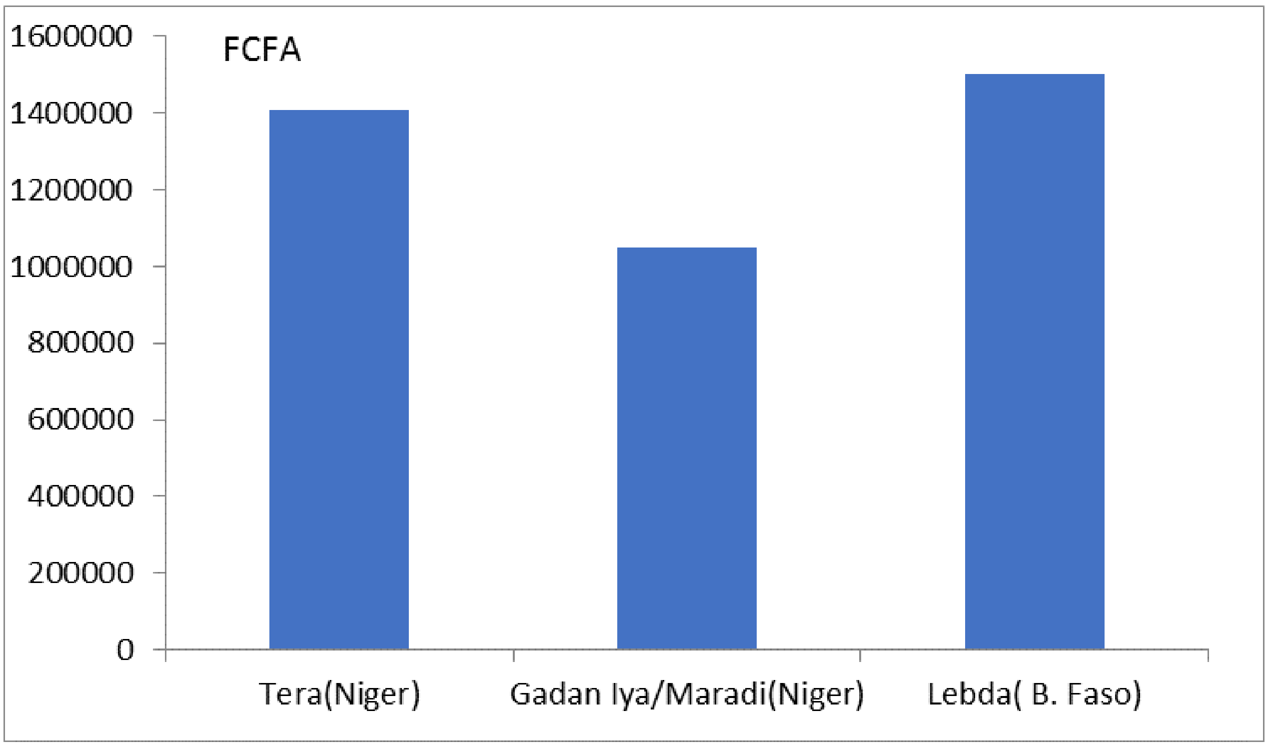

Figure B.11. Sales of fortified foods in 2018 in Tera, Gandan Iya, villages in Niger, and Lebda (Burkina Faso).

APPENDIX C. COMMENTS FROM 16 VILLAGE MOTHERS ON THE USE OF FORTIFIED PRODUCTS MADE AT THE FOOD INNOVATION CENTERS IN TERA, SHERKIN HAOUSSA, GADAN IYA, AND FALWEL VERSUS FORTIFIED PRODUCTS PROVIDED BY RURAL COMMUNITY HEALTH CENTERS FOR THE NUTRITIONAL RECOVERY OF MALNOURISHED CHILDREN

Witness N ° 1: mother of child, Age: 40 years, Téra
"My child had signs of malnutrition. That's how I have started giving her the flour (food aid one) from the community health center. However, with that flour, I did not observe an improvement in my child's health and then, I started feeding her with the flour I bought from Tera, food innovation center. Following the various feeding catches with that new flour, my child immediately recovered. She gained weight and is now in good health, while initially I fed her with the food aid blended product, that was provided by the community health center, it caused her vomiting and diarrhea.
My child now only prefers the porridge made with the fortified flour from Tera innovation center more than any other porridges. She only wants this porridge now. I bought the fortified flour from Tera innovation, 7 to 8 times for a value of about 4000 FCFA, to be able to treat my child, who is now very heathy and gained weight."

Witness N ° 2: Mother of child, Age: 24 years old, Téra
"My child was stunted and was thin, and that's when I started giving him porridge made from food aid blended flour with premix. But the effect of that flour on my child was very slow and when I knew about fortified flour made at Tera food innovation center (with millet, cowpea, peanut, and other ingredients), I started to give it to him too and I saw that the effect of the latter flour made at Tera Food Innovation center, was much better before even finishing the first packet of 500 g . The condition of the child has now improved. I gave him a packet of 500g every week and it has been 3 months since I gave him this, and now my child life was really saved by this new flour made at Tera food innovation. Thank you so much."

Witness N ° 3: Mother of child, Age: 27 years old, Tera
"I had a child under 2 years, malnourished to whom I gave the local porridge sold in town. There was no improvement in his health. Since, when I started giving him the enriched flour, made at Tera Food Innovation center (with millet, cowpea, peanut, and other ingredients), the child's condition has improved with weight gain. I'm now always buying the innovated flour from the food innovation center and feeding my child with it, and his health is now better"

Witness N ° 4: Mother of child, Age: 20 years old, Sherkin Haoussa
"I used 3 packets of (500g each) of fortified flour made from Sherkin Haoussa, food innovation center (with millet, cowpea, peanut, and other ingredients) to my child. I used one packet per week, and then, his health condition begins to improve from the first week.
After 3 weeks, I noticed that, he was very well. Now I always buy this flour and used it to feed my child. flour. It is also accessible any time, while the flour provided by the health centers is not always accessible, and my child does not like it at all"

Witness N ° 5: Mother of the child, Age: 35, Sherkin Haoussa
"When I started to notice signs of malnutrition in my child. I bought three bags (500g each) of the infant flour made (with millet, cowpea, peanut and other ingredients) from Sherkin Haoussa, food innovation center and gave it to my child. I noticed change after two weeks, even before the child finishes eating the 3 bags. After 3 weeks he was healthy. I did not use the flour (food aid) from the community health centers, because we only look for it when the child is very sick and most of the time, it is not accessible."

Witness N ° 6: Mother of the child, Age: 35, Sherkin Haoussa
"When I noticed signs of malnutrition on my child, I then started administering him the fortified flour made from Sherkin Haoussa, food innovation center (with millet, cowpea, peanut, and other ingredients). I used it for 4 weeks at a rate of 1 packet (500g) per week. After two weeks, my child had become very well and has gained weight."

Witness N ° 7: Name of the mother of the child, Age: 35, Sherkin Haoussa
"I started feeding my child with the fortified flour made from Sherkin Haoussa, food innovation center (with millet, cowpea, peanut, and other ingredients) when I saw signs of malnutrition on him. Then, I bought 8 to 10 bags, from the food innovation center, and after 8 weeks, I noticed that my child became normal and healthy."

Witness N ° 8: Mother of child, Age: 25 years old, Gadan Iya, Safo
"At first, I have started used 4 bags (250g) of the infant flour made at Gadna Iya, food innovation center (with millet, cowpea, peanut, and other ingredients) for my child. After, 1 month, I have observed a marked improvement in the health condition of my child. Then, I have continued to buy the flour for my child: I bought, 8 other bags (250g each) for the next two months, then 4 others after.
The flour(food aid one) from the community health centers is not accessible, and I did notice that, my child refused to drink the porridge made from that flour from the health center, he did not want it most of the time'' Now, I always buy, the flour made from Gadan Iya, food Innovation center (with millet, cowpea, peanut, and other ingredients), because my child like it very much, and it has improved his health"

Witness N ° 9: Mother of the child, Age: 20 years, Gadna Iya, Safo
"I noticed a change in the child as I gave him the infant flour produced at Gadan Iya, food innovation center. When I first fed him with 4th bag (250g), I have started noticing change in his health, and that's how I have decided to buy, 10 more bags and continued to give it to him for two months. At the end of the 10 bags I bought another 10 bags for the rest of the year. This flour is very good and has improved much the health of my child, and he likes it too much."

Witness N ° 10: Mother of the child, Age: years, Gadan Iya, Safo
"I have noticed a change in the child health, after two weeks of consuming 4 bags of infant flour made from Gadan Iya, food innovation center. He gained weight and he is much better than before. I have used a total of 8 sachets (250g) for him and he is completely relieved from his stunting''
The infant flour (food aid one) provided by the community health centers, is very rare. You can go to the health center without finding it. It is not easily accessible, and many children in the village do not much like that flour."

Witness N ° 11: Mother of child, Age: 25 years old, Gadan Iya, Safo
"I very quickly did notice a change in my child when I started giving him the children's flour produced at Gadan Iya, food innovation center. He has completely recovered from his stunting, after 4 weeks of consuming, 4 bags(500g) of the infant flour made at Gadan Iya.
After the treatment, he only likes to drink that porridge at home, and he is doing very well now. I am not used to the infant flour (food aid one) provided by the community health centers, but I hear that many children do not want to drink it, and that it is not accessible."

Witness N ° 12: Guardian mother of the child, Age: 28, Innovation Center: Falwel
"The child, I'm taking care of, is an orphan of 6 months. Initially, I fed him with the traditional porridge, made at home, but he did not like that porridge, and refused to drink it. That's how, I came across, the flour made at Falwel, food innovation center (made with millet, cowpea, peanut, other ingredients). After, 2 weeks of feeding him with the porridge made from this new infant flour, I began to observe a change in the child health. I noticed that, he was gaining weight, and is getting better. Since then, he did not like l the local porridge anymore. Every, two weeks, I fed him with 1 kg (2 bags of 500g) of the fortified millet flour produced at Falwel, food innovation center. It is now, almost one year that I feed him with the porridge made from this flour.
Currently, the child is doing well and is healthier despite the absence of his mother.
I am not used to the infant flour (food aid one) provided by the community health centers."

Witness N ° 13: Tutor mother, Age: 40, status: grandmother and guardian of two twin children, Falwel
"I'm not used to the infant flour provided by from the community health centers. At first, I gave, the traditional local porridge to my twin small children, and I observed that, they did not like it much. That's how I started giving them the porridge prepared from the baby flour made at Falwel food innovation center (made with millet, cowpea, peanut, and other ingredients). Subsequently, I found that the effect of this new porridge on the twin is more than beneficial and very fast. The children gained weight and their health was better than before.
Every month, I buy from the food innovation center at Falwel, 4 packets of the baby flour, and I did use 1 packet of 500g / week for each child."

Witness N ° 14: Mother of the child: Age: years, Falwel
"When, I saw signs of stunting on my child, I first started use for my child, one packet of 500g of the infant flour produced at Falwel, food innovation center (made with millet, cowpea, peanut, and other ingredients). After, the first week of feeding him with porridge made from this new flour, I have started to notice a better change in my child health. It's been 7 months now that I give him the porridge from this new flour, and I observed that, his health is much better, and he gained more weight."

Witness N ° 15: Mother of child, Age: 26 years old, Falwel
"I have a child, who was 4 years old, and still did not start walking, and was malnourished. Initially, I was feeding him with infant flour (food aid one) provided by community health centers, but I did notice that, the flour from the health center was causing him to have diarrhea. Then, I tried the infant flour produced at Falwel, food innovation center (with millet, cowpea, peanut, and other ingredients). I started to notice a change from the first week, I gave him the flour. My child health has now completely recovered with the porridge made from the infant flour from Falwel, food

innovation center.
It has been a year since I gave him the flour from the center. He gained weight now, and his health is much better.
His is 5 years old, he is doing well, and he is now even walking while when he was 4 years old, he could not walk and was malnourished. This new flour is very good, and my child like to drink every day."

Witness N ° 16: Mother of child, Age: 30 years old, Falwel
"Since, I start giving him the infant flour produced at Falwel, food innovation center (with millet, cowpea, peanut, and other ingredients). I did use, 1 kg (500 g/per week) of the infant flour from the food innovation center, and it last for 2 weeks''. My child likes to drink only that porridge, now he has recovered from his stunting, gained weight, and he is doing well!"

APPENDIX D. SENSORY EVALUATION QUESTIONNAIRE USED IN THE TESTING OF PORRIDGE SAMPLES

Questionnaire Hedonic Sensory Evaluation of Fortified Thin porridge Formulas, in Niger

Numerator Name: Date: Location:

Village:

Name of panelist (mother): Age:

Sensory Characteristics of fortified flour formulas: Place and "X" in the box to record your answer.

1-Color

Question # 1

Please indicate how much you like the color of each sample.

Degree of Acceptance	**Sample Formula 501**	**Sample Formula 502**	**Sample Formula 503**	**Sample Formula 504**	**Sample Formula 505**	**Sample Formula 506**
Like Extremely						
Like Very Much						
Like Moderately						
Like Slightly						
Neither Like nor Dislike						
Dislike Slightly						
Dislike Moderately						
Dislike Very Much						
Dislike Extremely						

2-Taste

Question # 2

Please use water to rinse your mouth before and after tasting each sample.

Please indicate how much you like the taste/flavor of each sample.

Degree of Acceptance	**Sample Formula 501**	**Sample Formula 502**	**Sample Formula 503**	**Sample Formula 504**	**Sample Formula 505**	**Sample Formula 506**
Like Extremely						
Like Very Much						
Like Moderately						
Like Slightly						
Neither Like nor Dislike						
Dislike Slightly						
Dislike Moderately						
Dislike Very Much						
Dislike Extremely						

3-Texture

Question # 3

Please use water to rinse your mouth before and after evaluating each sample.

Please indicate how much you like the texture of each sample in the mouth.

Degree of Acceptance	**Sample Formula 501**	**Sample Formula 502**	**Sample Formula 503**	**Sample Formula 504**	**Sample Formula 505**	**Sample Formula 506**
Like Extremely						
Like Very Much						
Like Moderately						
Like Slightly						
Neither Like nor Dislike						
Dislike Slightly						
Dislike Moderately						
Dislike Very Much						
Dislike Extremely						

4-Odor

Question # 4

Please smell and indicate how much you like the odor of each sample.

Degree of Acceptance	**Sample Formula 501**	**Sample Formula 502**	**Sample Formula 503**	**Sample Formula 504**	**Sample Formula 505**	**Sample Formula 506**
Like Extremely						
Like Very Much						
Like Moderately						
Like Slightly						
Neither Like nor Dislike						
Dislike Slightly						
Dislike Moderately						
Dislike Very Much						
Dislike Extremely						

5-Overall acceptability

Please look, touch, smell, and taste, each sample from you left to your right as indicated on your answer sheet, and indicate, your overall acceptability of each sample.

Degree of Acceptance	**Sample Formula 501**	**Sample Formula 502**	**Sample Formula 503**	**Sample Formula 504**	**Sample Formula 505**	**Sample Formula 506**
Like Extremely						
Like Very Much						
Like Moderately						
Like Slightly						
Neither Like nor Dislike						
Dislike Slightly						
Dislike Moderately						
Dislike Very Much						
Dislike Extremely						

Comments/Observations (optional):

APPENDIX E. AMYLOSE MOLECULAR SIZE DISTRIBUTION DERIVED FROM STARCH MOLECULE FRAGMENTATION OF INSTANT MILLET THICK (TUWO), AND THIN (FURA) PORRIDGES SAMPLES VERSUS CORRESPONDING TRADITIONAL MILLET PORRIDGES SAMPLES BY HPSEC-RI CHROMATOGRAPHY.

Table E.1. Estimation of amylose molecular size distribution of instant millet thick (*Tuwo*), and thin (*Fura*) porridges samples versus corresponding traditional millet porridges samples by hpsec-ri.

Amylose Molecular Size results of samples from HPSEC-RI:			
Peak	**Time (min)**	**Approximate size (Da)**	**Approximate size in scientific notation (Da)**
Instant thick porridge ('Tuwo') - Peak 1	43,01	Larger than 642000	>6.42x10^5
Instant thin porridge ('Fura') - Peak 1	43,10	Larger than 642000	>6.42x10^5
Traditional thick porridge ('Tuwo') - Peak 1	43,51	Between 337000-642000	3.37x10^5-6.42x10^5
Traditional thin porridge ('Fura') - Peak 1	42,77	Larger than 642000	>6.42x10^5
Instant thick porridge ('Tuwo') - Peak 2	75,95	About 7000	~7x10^3
Instant thin porridge ('Fura') - Peak 2	76,16	About 6100	~6.1x10^3
Traditional thick porridge ('Tuwo') - Peak 2	76,34	Slightly less than 6100	<6.1x10^3
Traditional thin porridge ('Fura') - Peak 2	76,46	Slightly less than 6100	<6.1x10^3

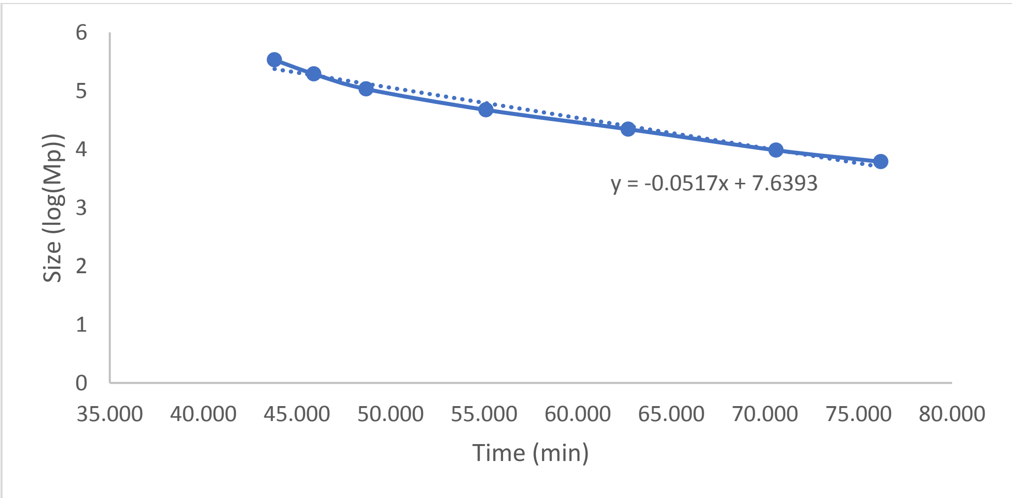

Figure E.1. Calibration curve using pullulan standards for high performance size exclusion chromatography – refractive index.

APPENDIX F. QUESTIONNAIRE USED IN THE HOME USE TESTING STUDY CONDUCTED IN NIGER

Modified In Home Use Testing (HUT) of Instant *Tuwo* and *Fura* porridges in Niamey, Niger

Identification Number :……………………………………………………………………

First, and second name of respondent (Lead household):

Are you the main buyer of foods in your household? Yes, No. Circle ☐

1-1. Demographic Characteristics

Age Category (Years)	Men	Women	Total
0 - 17			
18 - 60			
Over 60			

1-2. Socio-Economic Characteristics/and Demographic of Household

Household Member	Age (years)	Sex (Code A)	Marital Status (Code B)	Education Level (Code C)	Work (Main Activity) (Code D)	Household expenditure (CFA/week) on cereal foods	Household expenditure (CFA/week) on millet *tuwo* (thick), and *fura* (thin) porridges
Head of household							
		Code A 1=Male 2=Female	**Code B** 0= Non-Responders, 1=Married, 2=Single, 3=Divorced, 4=Widowed	**Code C** 1 = Non formal education, 2= Literate, 3=Primary school, 4= Secondary School, 5=Universities/professional Schools, 6=Islamic/Arabic education	**Code D** 1=Agriculture, 2= Business/trade, 3=Student, 4= Liberal profession/private, 5= Government, 6= Householder, 7=Retiree, 8=Others		

<u>2-Overall Acceptability/ perception of</u> instant millet *fura* (thin) porridge, and *tuwo* (thick) porridges, versus traditional millet *fura* thin and *tuwo* thick porridges

2-1. What is your overall acceptability/Perception of the product? (please circle)

Excellent	Very Good	Good	Acceptable	Bad

Provide details for your appreciation:

………………………………………………………………………………………………

2-2. What do you think about the mode of preparation? (Please circle)

Very easy	Similar	Tedious

2-3. What do you think about its time of preparation? (please circle)

Very easy	Similar	Too long

2-4. During, the preparation of your the product, did you respect the time, and water quantity to use, as indicated on the package?

Indicator	Yes	No
Time of preparation		
Quantity of water to use		

If no, why ? :
………………………………………………………………………………………………

2-5. If yes, give some advantages, and disadvantages related to the product :

Product Under Test	**Avantages**	**Disadvantages**
Instant millet *fura* thin porridge or Instant millet *tuwo* thick porridge	1- 2- 3-	

3- How do you appreciate the package of this product, compared to packages of other existing product commercialized in local markets ? (Circle your choice)

Attribute	Excellent	Very Good	Good	Acceptable	Bad
Information					
Package weight/size) (500g)					
Sealability					
Color (s)					
Readibility					
Package film transparency					
Overall package acceptability					

4- Willingness to pay

Identification Number:…………………………………………………………………………
Respondent first, and last
name :……………………………………………phone………………………………

Project team ‘’We plan to sale this product at 600 FCFA/500g. At which price, you can buy a packet of 500g ?(please circle your price choice.

Willingness to pay	**(Packet of 500g)**
>700 FCFA	
700 FCFA	
650 FCFA	
600 FCFA	
550 FCFA	
500 FCFA	
450 FCFA	
400 FCFA	
350 FCFA	
300 FCFA	
< 300 FCFA	

APPENDIX G QUESTIONNAIRE USED FOR THE MARKET TEST STUDY

Market Test of a) instant *tuwo* (thick) and b) instant *fura* (thin) porridges

Questionnaire Sales Point

I. <u>Identification of sales point</u>

Name of sales point…………………………………………………………………………

Sale store type (***Code* below*)***: …………………………………………………

Location……………………………………………………………………………………

Address/contact:……………………………………………………………………………

Identification number of sales points

(Coding description of Sale store type**)**:

1=Processing unit/Enterprise, 2=District store, 3= mini-market, 4= Gas station store, 5= Food Mart, 6= Other (proximity, face-face sales)

Weekly monitoring sales sheet of sales of millet and sorghum foods, at sales point.

Products coding: from 1-35, starting with ,1 = Instant millet *fura* (thin) porridge

Product supply date	Product type	Quantity (kg) of Products supplied (in packet of 500g)	Number of packets supplied	Follow up date of sales, at sales point	Unit price (FCFA/packet of 500g)	Quantity (kg) of products sold	Sales value (FCFA)	Quantity (kg) of products unsold	Number of packets unsold (in 500g)
…./…./2019	1-			…./…./2019					
…./…./2019	2-			…./…./2019					
…./…./2019	3-			…./…./2019					
…./…./2019	4-			…./…./2019					
…./…./2019	5-			…./…./2019					
…./…./2019	6-			…./…./2019					
…./…./2019	7-			…./…./2019					
…./…./2019	8-			…./…./2019					
…./…./2019	35			…./…./2019					

2= Instant millet *tuwo* (thick) porridge, 3=Traditional *fura*, 4=Traditional l *abdourou*, traditional flours(5= of millet ; 6= of sorghum, 7= of maize), and others (up to 35)
Instant millet *fura* thin porridge
Instant millet *tuwo* thick porridge

APPENDIX H. PACKAGE LABEL, INCLUDING PRESENTATION, AND MODE OF PREPARATION OF THE INSTANT MILLET *TUWO* (THICK) AND *FURA* (THIN) PORRIDGES PRODUCTS THAT WERE MARKET TESTED IN URBAN, CITY OF NIAMEY, NIGER

APPENDIX I. CONSUMERS SENSORY ACCEPTABILITY OF INSTANT *TUWO* AND *FURA* PORRIDGES COMPARED TO THE TRADITIONALLY-PREPARED THICK AND THIN PORRIDGES, IN NIAMEY, URBAN CITY, NIGER

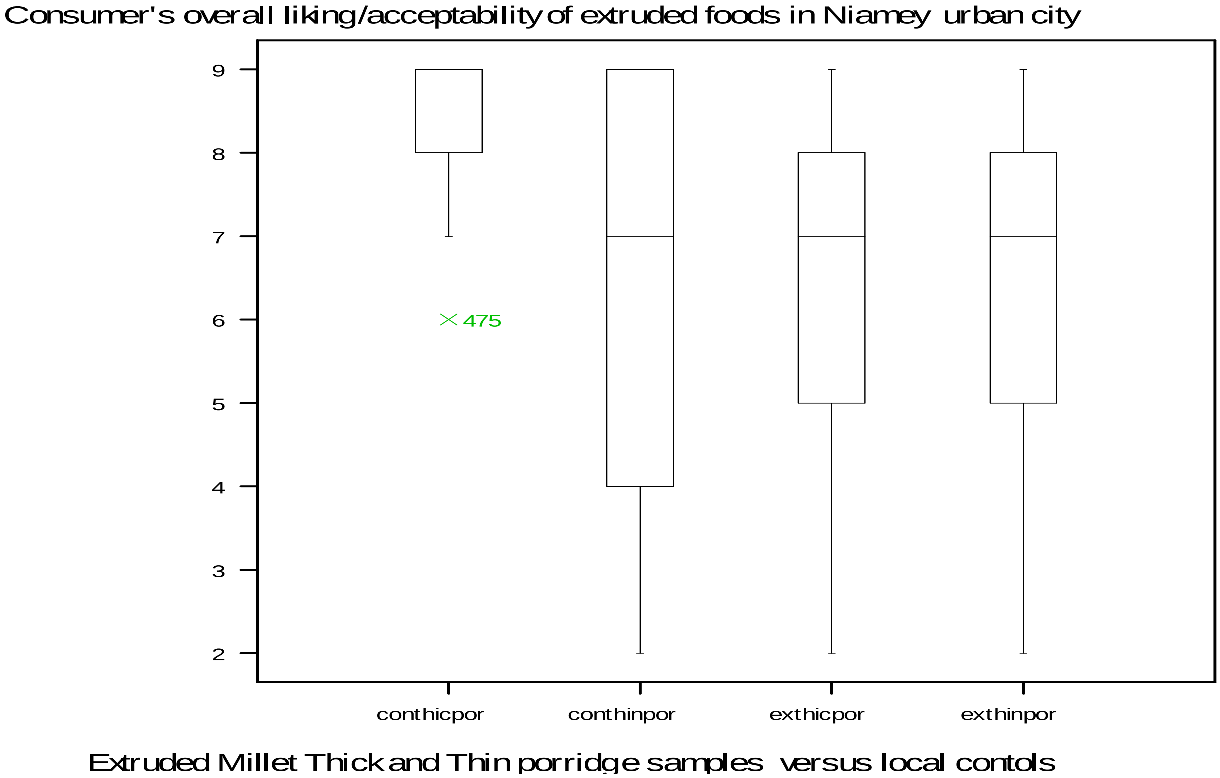

Figure H.1. Consumer’s overall liking/acceptability (taste, color, odor, texture) of decorticated millet extruded foods (thin and thick porridge) versus traditionally made thin and thick porridges in niamey.

A hedonic preference test was used with a nine-point numeric scale. (9=like extremely to 1=dislike extremely); N= 35 women processors; 6 millet samples and 1 control; 2 extruded products (thin and thick porridges). Values are means of panelist scores.

VITA

Moustapha Moussa,

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E-mail : mmoussa@purdue.edu; moustimou@purdue.edu, Mobile : 765 407 9483, +22796354140

1.EDUCATION & CERTIFICATIONS :

- **PhD ,** Food Science, Purdue University, W. Lafayette, IN, USA, October, 2019
- **Master's in Food Science, Purdue University**, W. Lafayette, IN,2004- 2007, Enriched with Professional Certifications in Food Safety, Hygiene; HACCP; ISO; Leadership& Man., Aseptic Proc. & Starch, and Organic Foods Production, Processing, Quality Monitoring& Inspection
- **Laboratory training, in Bio accessibility Determination,** Ferruzzi Laboratory, Institute of Plants for Health and Nutrition, **North Carolina State University, NC, USA, August 2019**
- **Norman Borlaug Fellowship; Washington State University, Pullman, WA, 2008**
- Certificate for Realizing Diagnostics to Restructure & Upgrade Agro-Food Enterprises & ISO 22000 & 94000 implementation in Niamey, Niger & UEMOA countries/West Africa, 2007-2010; and in **Food Manufacturing, Regulations, Quality, UNIDO, Tubikak, Turkey,2013**
- **Master's in Applied Chemistry, Usman D. Fodio Univ. Sokoto, Nigeria;1996**;
- **Baccalaureate in Natural Science & Mathematics (Lycee Isssa Kormobe),and awarded by University of Niamey, Niger,1988**

2.EMPLOYMENT

➢ **Food Research Scientist/Technologis**t, **from 2004-2007, and from 2016-2019, and Teaching Assistant (TA), 2019 to present;** Purdue University, and INRAN, 1997, to present

➢ **Projects Management/Coordination/& Monitoring**, on grain processing, Nutrition & agro-food business enterprises development for women/&youth in West African developing, 2009- to present

- USAID- funded projects (Country Coordinator, SMIL and INTSORMIL-USAID, 2011- to date);
- McKnigh Processing Project; HOPE/Bill Gate Foundations; 2011-to date);
- Promiso EU;2011-2012 UKAID; UNIDO & West African/PRMN-UEMOA projects/

➢ **Budget Managed & Coordinated, in Niger, and West Africa, Range of Projects Managed: $200 thousands-$1(one) Million, from 2009 to date**

➢ **Consulting Expertise/activities in Food manufacturing/Processing/Safety/Logistics/Evaluation/Monitoring:2009-date**:

- Rockefeller Hub-Spoke Processing Project on Maize and Mango crops in Tanzania& Kenya, August 2018-date,

- CARANA/SANA/GRM, Arlington, A, USA. Project: West African Food Market Diagnosis & Surveys UKAID/ Agribusiness Investment Potential Diagnosis in Niger, June 2015
- UNIDO/UEMOA Food Quality Program for auditing/upgrading Good Manufacturing Practices (GMP), Niger,2013
- Fintract, Food Analytics, Fintrac,1400 16th Street NW, Suite 400, Washington DC,20036 Project: Millenium Challenge Corporation (MCC)-Food& Agribusiness environment diagnosis in Niger, April 2015
- QED group, LLC, 1250 Eye Street, NW Suite 1100 Washington DC 20005. USA, (MCC) Project Diagnostic Analyses & Design of Niger Threshold Program, January 2012
- AMEX, international, Inc., Washington, DC, USA, Project :USAID/Pace Through Development Program in Africa/Niger project Mid Term Evaluation, September, 2010
- Euro Consultants S.A. Avenue Pasteur, 21 1300 Wavre, Belgium, Project: EU/UEMOA/UNIDO, January 2011
- PRMN/Niger/ICDE/Burkina Faso/: Project: UEMOA/. ONUDI program for realizing a strategic, Niger, october,2010
- DGSANCO: the European Directorate General for Health & Consumers: Project: program for Niger to help apply the EU's health & consumer protection laws, May 2009

- **Teaching Academic Experience/Short term training/Capacity building of Actors/End-users:**

National Institute of Public Health (ISP), Niamey, Niger, course taught Food Safety, & Hygiene

- **Specific Experience in the African region:**

(Niger, Mali, Burkina, Senegal, Ghana, Uganda, Kenya, and Ethiopia) , involved, in several projects, and participated to several conferences, on food processing, nutrition, market development for agricultural food commodities, in West African Sahelian Region

3.Recent Conferences attended:

- SMIL Phase II, inception workshop, in Niamey, Niger, March 2019, Review
- SMIL, CoP McKnight, Bamako 2019, Niamey, 2018, Wisler, 2019,
- West African Food Market (WAFM) Program, UKAID-Funded Project, West Africa Regional Wrap-up, Workshop, February 2019, Accra, Ghana, 2019,
- International Postharvest Scale up Conference hosted by Purdue University, Sept 2018
- West African Conveying Millet Workshop, Hosted by SMIL-USAID, Thies, Senegal, September,2018
- International Conference, Borlaug Fellowship Program, June 2018, Discovery Park/Entrepreneurship Building, Purdue University, W. Lafayette, IN, USA (
- Sorghum in the 21st Century Symposium & SMIL-USAID Workshop in Cape, Town, South Africa, 9-12 April 2018
- Borlaug fellowship, Summer Workshop for African Young Entrepreneurs, Purdue, June, 2018
- Whistler Center for Carbohydrate Research Annual Meeting, Purdue Univ, West

Lafayette,9-10 May, 2018

- McKnight Annual Regional CoP, Niamey, Niger, February 2018

High Level Ministerial Dialogue and Post Harvest Losses Reduction and Agro-Processing Flagship, 21-22 November, 2017, ADB Headquarter, Abidjan, Côte, D'Ivoire International SEMINAR on State Partnership Program (SPP) of INDIANA National Guard& NIGER, Indianapolis, IN, 11-13, August 2017/

- McKnight Annual Regional CoP, Ouadougou, Burkina Faso, April 2017

SMIL-USAID Annual Review Regional Workshop (in Saly, Dakar,6-9, March 2017

- International Conference, Mandela/Washington Fellowship, July 2017, Discovery Park/Entrepreneurship Building, Purdue University, W. Lafayette, IN, USA (

Film/Video: 17 Minutes film on sorghum and Millet Processing in Rural and Urban Niger(in completion, July, 2017

- **Other professional skills:**

- Excellent skills in Computer Microsoft Office;
- Statistical software packages (SAS & SPSS, GenStat& JMP,14)
- Excellent Languages Skills (French & English).
- Study abroad program in China supported by Purdue University: Areas of interests included Foods Manufacturing & Safety issues at Multinationals Food Companies (PEPSICO; OVODAN; DANISCO; ICI; NESTLE) in Beijing & Shanghai (China), Wuxi, Suzhou, & June 2006

- **Recent Articles/& Manuscripts under review & published:**

- M. Moussa, Bruce R Hamaker, et al. Innovative Way of Making Millet *Couscous* by Using a Single Screw Mini-Extruder for West African Market (in reviewing)
- M. Moussa, Bruce R Hamaker. A Technology Based Incubator Approach to support Food processing entrepreneurship in W. Africa (in reviewing for Technovation Journal, 2016
- M. Moussa, Bruce R Hamaker: et al ‘’High-quality instant sorghum porridge flours for the West African market using continuous processor cooking’’, International Journal in Food Science & Technology, 2011

- **Membership of professional bodies :**

- Member of American Association of cereal chemist (AACC-International), 2005 (to be updated)
- Member of Toast Master’s International, 2005
- Member of American Chemical Society, 1992