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The nutritive, rheological and sensory quality of selected indigenous complementary foods used for 6 – 24 months infants and young children in African communities

By

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Declaration

I, James Makame declare that the thesis, which I hereby submit for the degree PhD Food Science at the University of Pretoria, is my own work and has not previously been submitted by me for a degree at this or any other tertiary institution.

SIGNATURE: …………………………..

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Ethics statement

The author, whose name appears on the title page of this thesis, has obtained, for the research described in this work, the applicable research ethics approval [EC 180000086]. The author declares that he has observed the ethical standards required in terms of the University of Pretoria's Code of ethics for researchers and the Policy guidelines for responsible research.

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Dedication

To my family and children for their inspiration, to my Mom Esnath Makame for the enduring support, and to my late Dad Peter for having consistently shown love.

To God for His sufficient grace.

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Abstract

The nutritive, rheological and sensory quality of selected indigenous complementary foods used for 6 – 24 months infants and young children in African communities

by

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Co-Supervisor: Prof NM Emmambux

Child malnutrition remains a major public health problem in low-income African communities, caused by factors including the porridge rheology, poor oral texture quality and low nutritional value of mainly the indigenous/local complementary porridges (CPs), but also some commercially available complementary porridges (CACFs) fed to infants and young children. The flow properties (viscosity) of common indigenous/locally available African CPs (n = 8) plus CACFs (n = 23) were investigated at shear rates 0.001/s – 1000/s and 40 °C, using a rotational rheometer. The perception of the oral texture of the selected African CPs, Maize, Sorghum, Cassava, Orange-fleshed sweet potato (OFSP), Cowpea, and Bambara) and CACFs was investigated by a trained temporal-check-all-that-apply (TCATA) panel (n = 10). A simulated OP method (Up-Down mouth movements- munching) and a control method (lateral mouth movements- normal adult-like rotary chewing) were used. Energy densities of the flour were calculated from proximate analysis data using Atwater factors, and the solids (%) at which the porridge samples had viscosity of 3 Pa.s used to determine the porridges' energy and protein densities. Results showed a first-order exponential relationship between the apparent viscosity and solids (%) at all shear rates. Maize, sorghum and cassava porridges had very high viscosity profiles and consistency coefficients- K values (173.2; 134.7 and 105.9 Pa.s^n respectively) compared to a reference sample (4.7 Pa.s^n) and OFSP (3.5 Pa.s^n). The Cross model was able to predict the zer-shear viscosity of CPs, with maize, sorghum, cassava porridges (10 % solids), as well as some CACFs having very high zero-shear viscosity values. Some commercially available complementary foods (CACFs) also had high viscosity values and did not meet the WHO and Codex standards for energy and protein content. TCATA results showed that Maize, Cassava, and Sorghum porridges, and some CACFs were too thick, sticky, slimy, and pasty, and at the end not easy to swallow even at low solids content—especially by the Up-Down method, which simulates food oral processing in infants. Unsuitable oral texture limits nutrient intake in infants given their limited OP abilities, leading to protein-energy malnutrition. At very low shear rates estimates for infant oral processing, all indigenous complementary porridges, and some CACFs did not provide adequate energy to infants and young children (6 – 24 months), compared to OFSP. Further work is required to improve the viscosity and sensory properties of both African indigenous porridges and CACFs for optimization of infant nutrient intake. There is need to establish more precise shear rates applicable for in-mouth oral processing in infants and young children to assist in the design of infant foods of suitable oral texture.

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Abbreviations

CACFs	Commercially available complementary foods
CPs	Complementary porridges
OP	Oral processing
TMFs	Texture modified foods

1.0 Introduction

Child malnutrition is a persistent problem in many countries especially in sub-Saharan Africa (Keino et al., 2014). According to Grover and Ee (2009), the World Health Organization (WHO) defined malnutrition as the cellular imbalance between the supply of nutrients and the body's demand for them to ensure growth, maintenance, and specific functions. In child growth and development, it manifests as a deviation from the norm, affecting long term physical growth and reproductive health (Desalegn et al., 2015). A significant proportion of the world's malnourished children are stunted and fail to reach the normal international standard of height for their age (Keino et al., 2014). In South Africa, the NDoH; Stats SA; SAMRC; and ICF (2017) reported a stunting rate of 27% for children below 5 years in 2016. Stunted growth poses a major threat to human development.

Proper nutrition during the first 2 years of childhood is essential for good health and wellbeing (Black et al., 2017). Infants should be fed exclusively on breastmilk for about 6 months starting from birth (Solomons and Vossenaar, 2013). However, beyond 6 months, their requirements for energy and nutrients begin to exceed amounts from breast milk, and complementary foods should fill up the nutrient gap (World Health Organization, 2009, Parvin et al., 2014). Inappropriate infant foods at this stage may reduce nutrient intake leading to growth faltering and stunting (Dewey and Vitta, 2013). Complementary porridges must be high in energy and protein, ideally precooked, and have low viscosity with appropriate texture for easy consumption (WHO/UNICEF, 2003, GAIN, 2014). Current recommendations emphasize the inclusion of variety of vegetables and fruits to promote long-term healthy growth (Maier-Nöth et al., 2016).

However, home-prepared complementary foods in Africa are usually made from local staple cereals, roots and tubers of poor protein quality and high viscosity not suitable for children (Fasasi et al., 2007, Mbata et al., 2007). It is common practice for caregivers to dilute the porridge to a watery consistency, but this reduces its nutrient density (Carvalho, 2014). Infants must consume a large volume of this diluted porridge to acquire sufficient nutrition, yet their restricted gastric capacity (30 to 40 mL per kg body mass) limit how much they can take per meal (Tumwebaze et al., 2015, Dewey, 2016). Although commercial baby foods are thought to be nutritionally superior, they are often too expensive for poor families (Adhikari 2013). A

South African study reported that fortified commercial infant cereals were often diluted with water to make the product last, but this lowers nutrient density (Faber et al., 2016). Due to poverty, plant based complementary foods are the primary source of energy for many infants and young children in resource-poor African communities (Gibson et al., 2010).

Traditionally, infants are spoon-fed puréed foods and soft infant cereals as ‘first foods’. However recently, an alternative method of complementary feeding known as ‘Baby-Led Weaning’(BLW) has become popular in the UK, Canada, New Zealand and other countries (Cameron et al., 2012, Alpers et al., 2019). BLW is meant to introduce solid foods to infants, giving them more control of over the feeding process (Rapley, 2015, Dogan et al., 2018). In the conventional parents-led approach, feeding is guided by cultural and familial variations in foods preferences, as well as parental perceptions of children’s growth, health, appetite, and temperament (Black et al., 2017). BLW is initiated when infants are developmentally able to pick up and bring small pieces of food to their mouth, chew, and swallow, generally between 6 and 8 months of age (Wright et al., 2011). In practice however, BLW is often initiated in combination with parent-led complementary feeding (Black and Hurley, 2017), and simultaneously with continued breast-feeding (Alpers et al., 2019). The approach is designed to encourage infants to get conditioned to family mealtimes and to self-feed as much or as little as their appetite allows at each meal (Rapley, 2015). It is critical to note however, that both methods are affected by food access and availability and, do have their merits and demerits.

From an oral motor development perspective, optimal complementary foods should be well suited to infants’ chewing and swallowing abilities in order to provide a pleasant early feeding experience (Black et al., 2017). Yet that is not the case in many low-income communities. Most staple-based complementary foods in developing countries are starchy, forming a highly viscous porridge on cooking which may be difficult for infants to swallow (Tumwebaze et al., 2015). To this effect, Chen and Lolivret (2011) reported a strong positive correlation between the apparent shear viscosity of some commercial foods and the ease or effort required to swallow these, highlighting the potential role of shear deformation in food oral processing. Children’s eating skills develop gradually from sucking to munching, and then chewing (a more complex rotary pattern) (Nicklaus et al., 2015a). The ease of swallowing demands that the food bolus be readily deformable and flowable (Chen and Lolivret, 2011). This capacity to transform food into a safely swallow-able bolus influences food acceptability and nutrient intake, yet it is severely limited in infants and young children (Schwartz et al., 2018).

Laguna and Chen (2016) have argued that there is a lack of technical guidance in matching the rheological properties of foods with individuals' oral motor capabilities. In resource-poor African communities, inappropriate rheological properties of complementary foods may be a cause for inadequate nutrient intake among infants, eventually leading to child malnutrition. In an earlier study, Mushaphi et al. (2008) reported that 73 % of South African mothers fed their infants on soft maize porridge ('pap') by the 4th month from birth. This has important nutritional implications for infants and young children, considering that the ease of swallowing a food bolus is highly linked to its rheological quality (Gallegos et al., 2017).

The world committed to ending all forms of malnutrition by 2030, and to reduce stunting and wasting in children under 5 years of age by 2025 (De Onis and Branca, 2016). This study investigated the effect of flow properties (apparent viscosity) and sensory quality of indigenous/locally available complementary porridge samples as well as CACFs, on protein and energy density of the porridge samples. The aim was to establish how the stated properties of complementary porridge samples affect their capacity to meet the recommended nutrient intakes for infants and young children aged 6 – 24 months in African communities.

2.0 Literature Review

2.1 Protein-energy malnutrition in Africa

Protein-energy malnutrition (PEM) in children is a huge burden associated with poor health and physical functioning (Temba et al., 2016).The problem is manifested during the crucial transitional phase of weaning children from breast milk to semi-solid foods (Bazaz et al., 2016). In essence, PEM describes a range of pathological conditions arising from a lack of adequate protein and calories in the diet of young children (Ernest et al., 2013). It is a marker of diverse disorders associated with increased morbidity and mortality, loss of physical growth potential, reduced neurodevelopmental and cognitive function, and high risk of chronic disease in adulthood. According to the United Nations Children's Fund (UNICEF), PEM resembles the tip of an iceberg, with its deadly effects hidden from view (Grover and Ee, 2009)

Although the global stunting level for children under five years of age is declining (from 32.6% in 2000 to 22.2% in 2017), in Africa it is sadly increasing (Development Initiatives, 2018). About 33 % of stunting is in Africa, and among children, the statistic having risen by 1.4 million and 6.5 million in West and Central Africa, and in Eastern and Southern Africa respectively between 2000 and 2018(UNICEF, 2019). Stunted growth- the most prevalent form of child malnutrition, is when individuals fall 2 standard deviations (SD) below the median height-for-age of the WHO reference standard (De Onis and Branca, 2016). Worldwide, about 155 million children under 5 years (an estimated 22,9 % in 2016) are stunted (UNICEF, 2016). About 38 % of them reside in sub-Saharan Africa (Save the Children, 2017).

South Africa, despite being a middle-income country, is one of 34 countries with the highest stunting burden on a global level, at least 27% of its children are stunted (NDoH; Stats SA; SAMRC; and ICF, 2017). In Zimbabwe, around 650,000 children under 5 years (26 - 27 %) suffer from chronic malnutrition (ZIMSTAT and ICF International, 2016, USAID, 2018). Whilst stunting prevalence in Zimbabwe has declined from 33 % in 2010 to 26 % in 2018, it remains above the acceptable global threshold of 20 % (Food and Nutrition Council Zimbabwe, 2018). Only 4 % of children received a minimum acceptable diet in 2018- a sharp drop from 10 % in 2016 (Food and Nutrition Council Zimbabwe, 2018). The implications of stunting burden for Africa's human capital development are serious, accounting for around 10 % loss in gross domestic product per year (International Food Policy Research Institute, 2016).

Chronic undernutrition in the first 1000 days of a child's life is a leading cause of stunting (Save the Children, 2017). Its proximal drivers include inadequate complementary feeding, poor breast-feeding, infections, compromised maternal health and nutrition, household food insecurity, and poverty (Stewart et al., 2013, Save the Children, 2017). The number of undernourished children in sub-Saharan Africa continues to increase and the region has shown little improvement over the past decades (Baro and Deubel, 2006, Muhimbula and Issa-Zacharia, 2010). For low-income countries, where the daily average income is less than $2.80 per person, 37.8 million children are affected by stunting (Development Initiatives, 2018).

Although commercial fortified foods are often available on the market, they are generally too expensive for the poor families (Muhimbula and Issa-Zacharia, 2010, Abeshu et al., 2016). The vulnerability of infants to malnutrition during the complementary feeding period results from their high nutritional requirements, limited gastric capacity, compromised feeding abilities and lack of access to nutritious complementary foods (Black et al., 2017). A study done by (Mamabolo *et al*. 2004) in the Limpopo province of South Africa reported that only 4% of infants were still exclusively breastfed at 6 months of age, while 96 % were already fed on complementary foods in addition to breast milk.

To promote optimal child nutrition, the rheological, nutritional and sensory quality of a complementary diet must be optimal. The energy density of complementary foods is greatly influenced by fats, as its energy density (9 kcal/g or 37.8 kJ/g) is more than double that of protein and carbohydrate (4 kcal/g or 16.8 kJ/g) based on Atwater conversion factors (Development Initiatives, 2018). Additional determinants of the energy density include the water content, flour type, processing method, cooking method and ingredients (Development Initiatives, 2018). A higher water content reduces the energy density and increases the bulk of the food, negatively influencing energy intake (Development Initiatives, 2018).

Malnutrition holds back development with unacceptable human consequences. Yet the opportunity to end malnutrition has never been greater. Complementary feeding is one of the most effective interventions that can significantly reduce stunting during the first 2 years of life (Roy et al., 2007, Dewey and Adu-Afarwuah, 2008). The UN Decade of Action on Nutrition 2016–2025 and the Sustainable Development Goals (SDGs) provide global and national impetus to address malnutrition and expedite progress. The recommended daily energy and protein intake requirements from complementary foods at different ages for infants and young children (6 – 24 months of age) are shown in Table 1.

Table 1. *Total protein and minimum dietary energy density required to attain the energy level needed from complementary foods (CFs) per day for three age groups and level of breastmilk energy intake (BME)*[a].

	6-8 Months			9-11 Months			12-23 Months		
Energy	Low BME[#]	Average BME	High BME	Low BME	Average BME	High BME	Low BME	Average BME	High BME
Total energy required [kcal/day (kJ/day)] [b]	769.0 (3229.8)	769.0 (3229.8)	769.0 (3229.8)	858.0 (3603.6)	858.0 (3603.6)	858.0 (3603.6)	1118.0 (4695.6)	1118.0 (4695.6)	1118.0 (4695.6)
BME (kcal/day)/(kJ/day)	217.0 (911.4)	413.0 (1734.6)	609.0 (2557.8)	157.0 (659.4)	379.0 (1591.8)	601.0 (2524.2)	90.0 (378.0)	346.0 (1453.2)	602.0 (2528.4)
Energy required from CFs* (kcal/day)/(kJ/day)	552.0 (2318.4)	356.0 (1495.2)	160.0 (672.0)	701.0 (2944.2)	479.0 (2011.8)	257.0 (1079.4)	1028.0 (4317.6)	772.0 (3242.4)	516.0 (2167.2)
Total Protein (g/day)	9.1	9.1	9.1	9.6	9.6	9.6	10.9	10.9	10.9
Minimum energy density at - Specified meal frequency [c]									
1 meal/day	2.22 (9.3)	1.43 (6.0)	0.64 (2.7)	2.46 (10.3)	1.68 (7.1)	0.90 (3.8)	2.98 (12.5)	2.24 (9.4)	1.50 (6.3)
2 meals/day	1.11 (4.7)	0.71 (3.0)	0.32 (1.3)	1.23 (5.2)	0.84 (3.5)	0.45 (1.9)	1.49 (6.3)	1.12 (4.7)	0.75 (3.2)
3 meals/day	0.74 (3.1)	0.48 (2.0)	0.21 (0.9)	0.82 (3.4)	0.56 (2.4)	0.30 (1.3)	0.99 (4.2)	0.75 (3.2)	0.50 (2.1)
4 meals/day	0.56 (2.4)	0.36 (1.5)	0.16 (0.7)	0.61 (2.6)	0.42 (1.8)	0.23 (1.0)	0.74 (3.1)	0.56 (2.4)	0.37 (1.6)
5 meals/day	0.44 (1.8)	0.29 (1.2)	0.13 (0.5)	0.49 (2.1)	0.34 (1.4)	0.18 (0.8)	0.60 (2.5)	0.45 (1.9)	0.30 (1.3)

[a] Assumed functional gastric capacity (30g/kg reference body weight) is 249 g/meal at 6-8 months, 285 g/meal at 9-11 months, and 345 g/meal at 12-23 months. [b] Total energy - requirements are based on new US longitudinal data averages plus 25 % (2SD), based on WHO/UNICEF 1998. [c] Values in front of meal frequency represent daily energy - intake in kJ or kcal (in brackets). [#] Breast Milk Energy intake. Adapted from (Dewey and Brown, 2003)

Considering the low BME intake, infants require a total of about 3230 kJ, 3600 kJ and 4696 kJ per day for the age-groups 6 – 8; 9 – 11 and 12 – 24 months respectively. Complementary foods must provide 2318 kJ, 2944 kJ and 4318 kJ of energy (the energy gap) to infants and young children in these three age-groups respectively. For daily protein intake, the infants and young children must get a total of 9.1 g, 9.6 g and 10.9 g at 6 – 8; 9 – 11 and 12 – 24 months respectively. The amount of energy and protein required from complementary foods is the difference between the energy and protein contribution of breast milk and the total daily energy and protein requirement at each age interval (6 – 8, 9 – 11 and 12 - 24 months) (Van Der Merwe et al., 2007). With infants expected to grow from 3.5 kg at birth to 12 kg on the second birthday, the energy requirements are continuously escalating against a generally fixed energy and protein composition per volume human milk consumed (Solomons and Vossenaar, 2013). Optimal energy intake improves nitrogen balance by minimizing net protein loss through the inhibition of both proteolysis and the oxidation of amino acids (protein sparring effect) (WHO, 2007).

Dietary proteins provides precursor amino acids, peptides, and low-molecular weight substances for synthesis of biomolecules with enormous physiological importance in child growth and development (Wu, 2016). Protein is the most fundamental component of tissues in animals and humans (Reeds, 2000). Thus, the content, digestibility, and relative proportions of amino acids in dietary protein are the determinants of its nutritional value (Tomé, 2013). Inadequate protein intake from complementary foods is graphically indicated by metabolic disorders such as kwashiorkor (caused by a severe deficiency of protein) and marasmus (caused by the severe deficiency of both protein and energy) in many children of developing nations (FAO, 2013).

2.2. Infant food oral processing and the sensory quality of food

Physiological factors are especially important in shaping children's attitudes to food textures, because their ability to manipulate food in-mouth is limited by their oral development (Szczesniak, 1972). At the time of introducing complementary foods, the infant must be physically and physiologically able to cope with such foods (Black et al., 2017). During this period, infants move from consumption of ready for swallowing foods delivered to the back of the oral cavity where the swallow reflex is naturally triggered, to forming a semi-solid food bolus that must be actively moved from the front to the posterior of the oral cavity during oral processing (Morris et al., 2001, Rudolph and Link, 2002). With the development of teeth, onset of lateral jaw movements, and more sophisticated tongue movements, children also move from liquid to semisolids to solid foods that progressively require the involvement of these oral structures (Kim and Vickers, 2019). Infants will use different feeding skills at different growth stages, such as sucking, munching and graded bite prior to chewing capacity (Törölä et al., 2012, Nicklaus et al., 2015b, Sampallo-Pedroza et al., 2014). At the age of 4 – 6 months, food is mashed by the tongue through an upward/downward motion (Ross, 2017). As their oral feeding skills develop, they start to deal with more solid foods at 8 months (Schwartz et al., 2018). Chewing onset and efficiency increases as the tongue becomes more mobile and independent of the jaw, thus allowing control and manipulation of the food (Le Révérend et al., 2014). The transition from milk to first solids requires physiological changes and some learning influences to accommodate a new food texture (Cichero, 2017, Kim and Vickers, 2019).

Figure 1 compares the cross-sections of the head and neck regions in an infant and an adult person.

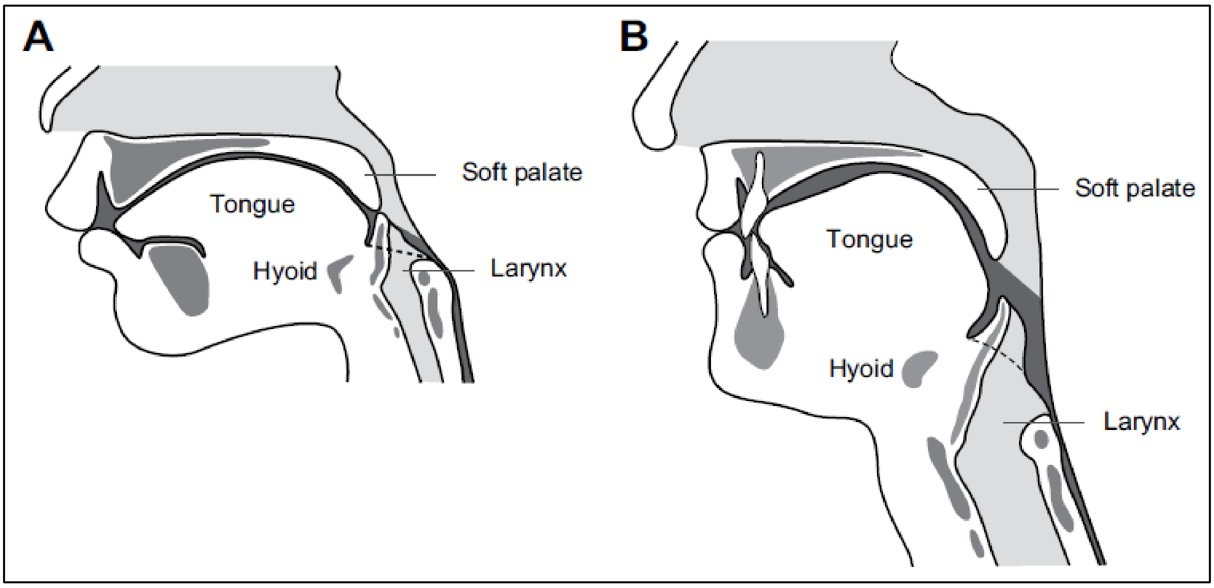


Figure 1. *Section of the head and neck in an infant (A) and an adult (B). The food passageway and the airway are shaded in dark grey and light grey, respectively (Matsuo and Palmer, 2008).*

It can be observed that in infants, the mouth volume, tongue and larynx sizes are much smaller compared to adults. Masticatory efficiency in infants is also limited due to limited dentition (Le Révérend et al., 2014). Schwartz et al. (2018) noted that mastication efficiency is influenced by dentition, occlusion contact area between the upper and lower teeth, bite force, ability to control masticatory muscles for efficient contraction, and soft tissues (tongue, lips and cheeks) to move the bolus and place it in the occlusion area. However, very little is known about the effect of bolus consistency on masticatory kinematics and how immature mandibular control can adapt to accommodate the progressive introduction of new food consistencies in young subjects (Le Révérend et al., 2014). Where literature is available, it is often inconclusive and in some cases contradictory.

The feeding progression during complementary feeding is influenced by advances in digestive and oral motor skills, hunger and satiety regulatory cues, and advances in cognitive, fine motor, and social-emotional development that facilitate interest in food, self-regulation, and self-feeding (Butte et al., 2004, Black et al., 2017). The emergency of molars is critical, for generating the shearing forces that break down the bolus and for providing a consistent point of occlusal contact (Black et al., 2017). As the child's oral motor function advances, s/he learns to stabilize the jaw, and to control the tongue first centrally with sucking and then laterally with munching (Meyer, 2000). One of the most important physiological factors of food oral processing efficiency and hence nutrient intake is the age of infants (Fucile et al., 1998). Evaluating the efficiency of oral motor performance in young children, Gisel (1991) in Delaney and Arvedson (2008) showed that 93 % of the 2-year-old children use slow, rolling tongue movements to lateralize the food. This means they cannot use oral shear to breakdown food and form a safe-to-swallow food bolus. Consequently, infants will reject foods with textures that are difficult to manipulate in the mouth (Szczesniak, 2002), due to their restricted eating capacity. The differences in developmental oral physiology and consequently food oral processing strategies may lead to differentiated food texture liking patterns in infants and young children, with implications for complementary food design and processing.

At present, evidence exist that too early solids introduction may increases the risk of choking, picky eating, food hypersensitivity, sudden infant death syndrome, and chronic diseases (Clayton et al., 2013). Alternatively, when the introduction of solids is delayed, a child may not learn to eat solid foods properly, become malnourished, develop iron-deficiency anaemia, and not follow the normal growth curve (Butte et al., 2004). From the foregoing, it is clear that optimal timing for the introduction of more challenging textures must be ensured. Figure 2 shows children’s progression in chewing efficiency from the level of beginners to advanced level chewers, indicating that infant oral physiology optimizes with age.

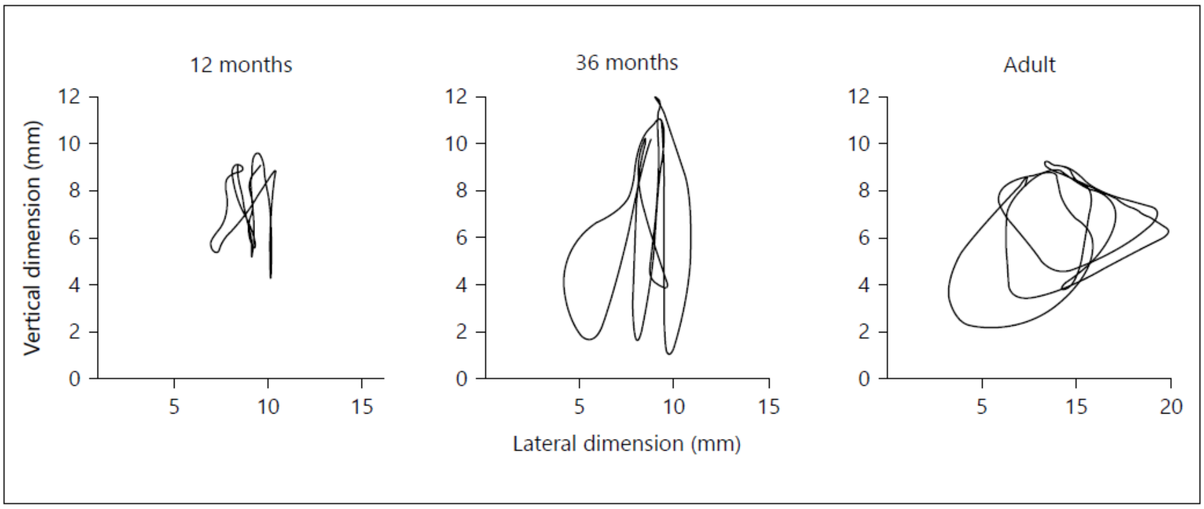


Figure 2. *Jaw movement trajectories during chewing recorded from a 12-month-old, a 36-month-old, and an adult (Black et al., 2017).*

Mature adult chewing motor skills are characterized by rhythmic oscillations of the jaw, driven by a consistent pattern of reciprocal activation among jaw depressor and elevator muscles (Black et al., 2017). Compared to infants at 12 months of age, experienced chewers/adults are particularly adept at chewing, adapting to different textures of foods, and exploiting elastic muscular forces to minimize the work done (Black et al., 2017). However, it is important to appreciate that each infant develops at his or her own rate (Special Supplemental Nutrition Program for Women and Children, 2008), and therefore their food oral processing behaviour may vary.

The main functional purposes of food oral processing are to transform non-swallowable food into a swallow-able bolus that can be transported smoothly from the oral cavity to the stomach (Laguna and Chen, 2016). Yet, for infants, little is known regarding the development of chewing motor skills, in-mouth mechano-sensations and how children learn to accommodate foods with varying textures (Black et al., 2017). Although complementary porridges should not be too thick as to compromise food intake, exposure to thicker and lumpier foods is important as this enables the development of oromotor skills for consumption of a range of food textures required to transition to family foods (Black et al., 2017).

2.3. Complementary feeding- porridge types available

Complementary feeding is ‘the process of introducing other foods to infants, in addition to breast milk to meet the nutritional requirements of infants (Du Plessis et al., 2013). It is a period of inherent vulnerability to nutrient scarcity and nutritional deficiency (Solomons and Vossenaar, 2013), due to disproportionately high requirements for metabolic processes, rapid developmental processes, and limited gastric capacity (Dewey, 2013, Black et al., 2017). Breastfeeding is the gold standard for infant feeding, encouraged for 2 years and beyond following birth (Black et al., 2017). However, at around 6 months of age, an infant’s requirements for energy, protein and other nutrients cannot be met by breast milk alone and complementary foods must be introduced (Dewey, 2013, Temesgen, 2013).

The pace of complementary feeding depends on the sensorimotor development of infants, cultural standards, available resources, and parental decisions based on a child’s perceived readiness (Black et al., 2017). According to The American Academy of Paediatrics (Kleinman, 2000), babies should not be fed solids until they reach several key developmental milestones (doubling of birth weight, adequate independent control of the neck and head, ability to sit up with minimal support, and ability to refuse food by pulling away or shutting the mouth). Optimal complementary foods should have good functional properties and be appropriately adapted to chewing ability, swallowed safely, and provide a pleasant oral texture for infant feeding (Black et al., 2017). Additionally, the porridges should be nutritionally adequate, safe, and appropriately fed in order to meet the young child’s energy and nutrient needs for adequate growth (GAIN, 2014). Infant complementary foods/porridges must have a low viscosity, recommended at 1.0 – 3.0 Pa.s, and be spoonable (Mosha and Svanberg, 1983, Thaoge et al., 2003, Onweluzo and Nwabugwu, 2009a). However in most African countries, the porridges prepared from maize, cassava or sorghum, tend to have high paste properties (exceeding 3000 mPa.s) with low protein-energy quality (Fasasi et al., 2007, Mbata et al., 2009). High viscosity porridge is usually unacceptable for infants as it makes feeding difficult and more energy demanding (Bazaz et al., 2016).

Complementary foods usually are of two types: commercially prepared infant foods on the market, and homemade complementary foods which are prepared at household level by the caregivers following traditional methods.

2.3.1 Commercial complementary foods

Commercial complementary food formulations can be milk-based (casein or whey), soy protein-based, protein hydrolysate-based, or amino acid-based (Klerks et al., 2019). Commonly available commercial infant foods include iron-fortified infant cereal (rice, oat, and barley, wheat), mixed-grain infant cereals, and infant cereal-fruit blends; infant juices, vegetable or fruit infant foods (purees) (Ng et al., 2012). For carbohydrate ingredients, only lactose, maltose, sucrose, maltodextrins, glucose syrup or dried glucose syrup, gluten-free pre-cooked or pre-gelatinized starch is recommended (Nasirpour et al., 2006). Infant cereals are defined as "processed cereal-based foods" that are divided into simple cereals for reconstitution with milk or other appropriate nutritious liquid, or cereals with an added high protein food for blending with water or another protein-free liquid (Klerks et al., 2019). Some of the important functions of infant cereals during the complementary feeding period are shown in figure 3.

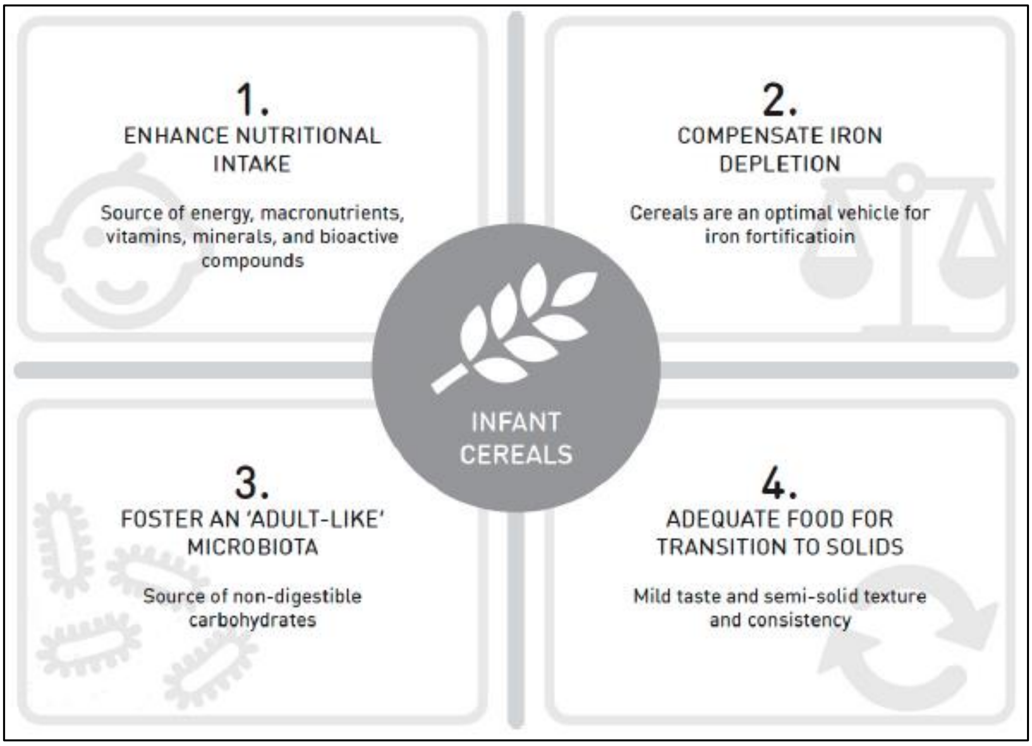


Figure 3. *Functions of infant cereals in infant nutrition (Adapted from Klerks et al. (2019).*

In the context of low-income African communities, one of the disadvantages of processed complementary foods includes the high cost (Van Der Merwe et al., 2007). The main ingredients of commercial baby foods are presented in Table 2.

Table 2. Major ingredients in commercial baby foods #.

Ingredient	Source or name
Protein sources	Non-fat dry milk, condensed skim milk partially demineralized whey, sodium and calcium caseinates, soy protein isolate and soymilk
Oils	Soy, corn, safflower, sunflower, colza, palm, copra
Carbohydrates	Lactose, starch, sucrose, corn syrup, and corn syrup solids
Minerals: Major	Calcium carbonate, mono-, di-, and tribasic calcium phosphates, dibasic magnesium phosphates, potassium citrate, magnesium chloride
Minerals: Minor	Potassium iodide, ferrous sulphate, manganous sulphate, cupric sulphate, zinc sulphate
Vitamins	A, E, K, C, B1, B6, B12, niacin, folic acid, pantothenic acid, biotin choline, inositol
Functional ingredients	Soy lecithin, mono- and diglycerides, starch, carrageenan

#Adapted from Nasirpour et al. (2006)

2.3.2 Home-prepared complementary porridges

These are infant foods prepared at household level by the caregivers following common traditional methods. According to Temba et al. (2016) , the most widely consumed cereals in Africa are maize, sorghum and millet. Such foods, when given as complementary porridge to infants- are typically made to a watery consistency, often consumed in very small quantities, and at sub-optimal meal frequencies per day (Dewey and Vitta, 2013). The advantages of home-prepared porridges for the low-income communities are that starchy cereals, roots and tubers are affordable, easy to prepare and culturally acceptable by locals as complementary food source (WHO/UNICEF, 2003). However, when starch is heated in water it swells, gelatinizes and pastes to form a thick gruel at relatively low solids content (Amagloh et al., 2013b) which is difficult for infants to eat. The poor sensory and nutritional quality of homemade complementary foods is a key driver of child malnutrition- when viewed in light of the restricted oral processing abilities of infants and young children (Dewey and Adu-Afarwuah, 2008, Du Plessis et al., 2013).

In Nigeria, complementary foods are made from maize (*Zea mays*), millet (*Pennisetum americanum*), or guinea corn (*Sorghum* spp.) (Abeshu et al., 2016), while in Ghana, the main complementary food is a traditional fermented maize porridge (*koko*) (Abeshu et al., 2016). Porridge made with maize meal is commonly used as complementary food by South African mothers (Mamabolo et al., 2004, Faber, 2005, Mushaphi et al., 2008, Faber et al., 2016). In

Zimbabwe, a maize-based complementary porridge (*bota*) is common (Cosminsky et al., 1993). Table 3 shows some of the indigenous complementary porridges used in African communities.

Table 3. *Common grain-based African traditional complementary foods.*

Complementary Foods (Age*)	Country	Flour prepared from	Remarks	Reference
Gruel (6)	Ethiopia	Teff, sorghum, barley, maize, wheat, emmer wheat, and enset	Not nutritious enough to-fill the calorie, protein gap	Abeshu et al. (2016)
Porridge (4 - 6)	Ethiopia	Teff, sorghum, barley, maize, wheat, emmer wheat, and enset	Thin and runny	
Fetfet (6)	Ethiopia	Teff, sorghum, barley, maize, broad beans, chickpeas, wheat field peas, lentil		
Kitta (6)	Ethiopia	Teff, sorghum, barley, maize, wheat, enset, chickpeas		
Dabo (6)	Ethiopia	Teff, sorghum, barley, maize, wheat, and emmer wheat		
Bota (6) (Gruel/porridge)	Zimbabwe	Maize, sorghum or millet. other grains and legumes Bulrush millet, rapoko (finger millet).	Salt, sugar, oil, margarine or peanut butter, milk may be added to the porridge, if available or affordable. Fed from a cup or bowl with a spoon or hands	Cosminsky et al. (1993)
Sadza (8 - 9) (Stiff porridge)	Zimbabwe	Maize, sorghum or millet. Bulruch millet, finger-Millet, (rapoko)	Eaten with a relish such as greens or other vegetables, peanut butter, fermented milk, or less frequently meat or soup.	Cosminsky et al. (1993)
Soft porridge (6)	South Africa	Maize	Thick for infant oral processing	Mamabolo et al. (2004) Faber et al. (2016)
Koko (6)	Ghana	Maize	Traditional fermented maize porridge, thin.	Abeshu et al. (2016)
Family foods (6+)		Starchy tubers, legumes vegetables.	May be difficult to chew	
Porridge (4 - 6)	Nigeria	Maize, millet, sorghum	Legumes rarely used, introduced much later due to indigestibility, flatulence and associated diarrhoea	Abeshu et al. (2016)
Gari		Fermented cassava grits		
Other family foods		Yam, rice, cocoyam		

**Age at which the complementary food is introduced to infants, reported in months.*

The information in Table 3 reveals that in different parts of Africa cereals and legumes are predominantly used in the preparation of common complementary foods for infants. However, maintaining a good balance between a porridge providing optimal nutrition for babies, and one that has the suitable in-mouth texture quality for easier consumption by young children is often problematic. Protein and energy are amongst the major "problem nutrients", showing greatest disparity between their content in African indigenous complementary foods and the estimated amounts required by the child (WHO/UNICEF, 1998). A recent Zimbabwean study reported that 16/19 of the interviewed mothers thought infants should be fed thin and watery porridges believed to be easy to swallow, rather than thick porridges (Desai et al., 2015), which may have better nutrient density. The challenge again is how thick should a porridge be for comfortable oral processing at a specific age-group? According to Cosminsky et al. (1993), foods that are not considered good for an infant are primarily those that are difficult to chew or digest.

2.4. Rheological properties of complementary porridges- role in child nutrition

Rheology is the science of deformation and flow properties of materials. One of the most important rheological determinants of energy and protein density in complementary porridge is viscosity (Tizazu et al., 2010). Viscosity refers to the resistance of a fluid to deformation and flow when a shear force is applied (Tiest, 2015). The viscosity and energy density of complementary porridges are inextricably linked, but studies investigating the two and their interrelationships are scarce (Kikafunda et al., 1997). A non-Newtonian fluid food subjected to a shear force (like in the mouth and throat during food oral processing) deforms continuously towards a lower viscosity (shear-thinning) (Sheffler et al., 2015). However, the shear conditions governing in-mouth food oral processing are yet to be fully comprehended. This has tremendous implications for optimal infant feeding. Viscosity influences not only the quantity of food a child can consume, but also the energy intake (Mosha and Svanberg, 1983), by restricting the solids content in a porridge of acceptable consistence for baby feeding.

Bolus flowability depends on both the oral physiological conditions of the consumer and bolus rheology itself, with regards to its chemistry and composition (Alsanei and Chen, 2014, Gallegos et al., 2017). The rheological characteristics of a food bolus are highly linked to the performance of the swallowing process (Newman et al., 2016). Food texture is a sensory perception derived from the structure of food at molecular, microstructure, and macroscopic levels (Chen, 2009). A desirable viscosity is one that allows ease of consumption while maintaining adequate solid content to achieve the recommended nutrient intake level (Kikafunda et al., 1997). When nutrient intake is limited, infants and young children become vulnerable to protein-energy malnutrition.

2.4.1 Shear-thinning flow behaviour of complementary porridges and the entanglement model.

Viscosity of a shear-thinning fluid food such as a porridge decreases with increasing shear rate, as shown in Figure 4.

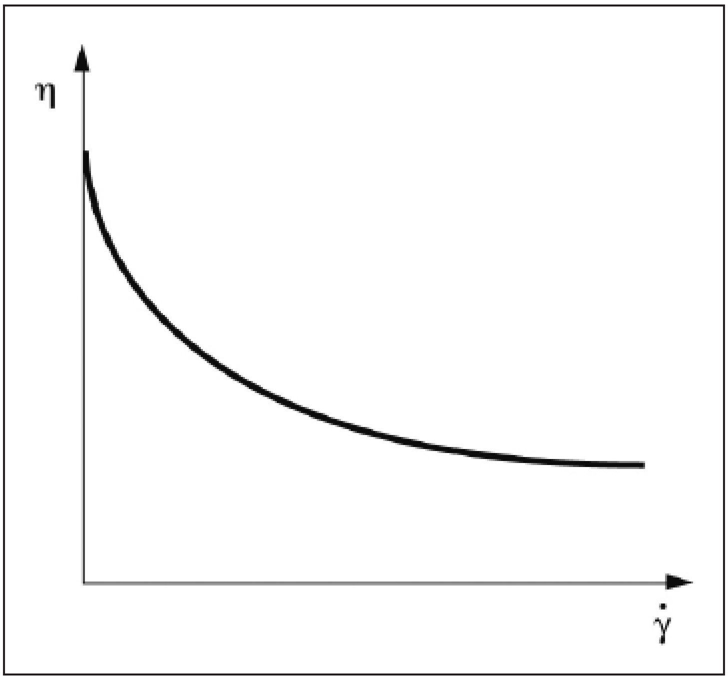


Figure 4. *Viscosity curve of a shear-thinning fluid (Mezger, 2014).*

The ratio of shear stress to shear rate varies with the shear load and the term “apparent shear viscosity” at the corresponding shear rate is used (Mezger, 2014). When measuring the viscosity of shear-thinning fluids, it is critical to state the specific shear conditions applicable, moreover, each viscosity value obtained represent a single point of the viscosity function only. The viscosity and flow behaviour of shear-thinning foods such as complementary porridges can be explained by the molecular entanglement model, which proposes that in a polymer melt or solution the relatively long molecules would entangle loosely with others many times

(Mezger, 2014). At rest, each individual macromolecule assumes the shape of a three-dimensional coil in the absence of any external load, as shown in Figure 5.

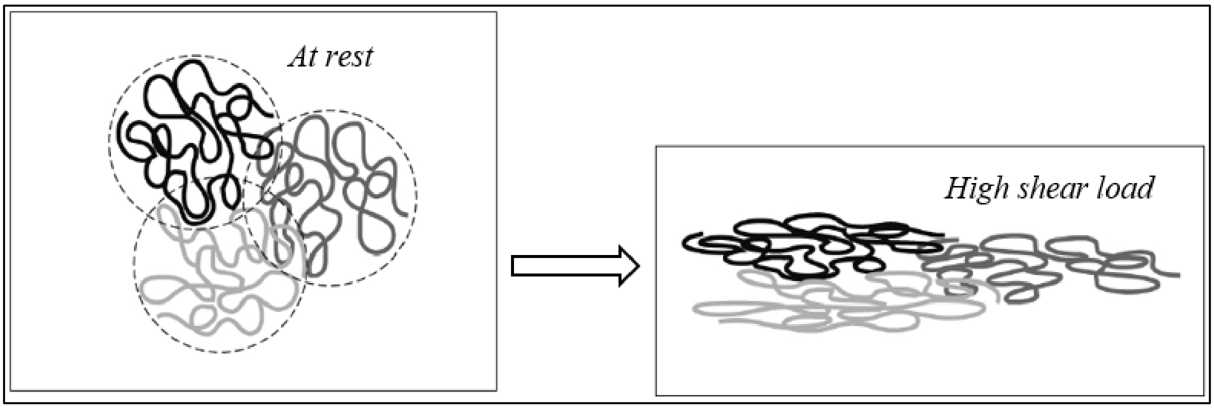


Figure 5. *Macromolecules (left) at rest showing the coiled and entangled chains, and (right) under high shear load showing oriented and partially disentangled chains (Mezger, 2014).*

At rest, each molecular coil is entangled many times with neighbouring macromolecules, but when a shear load is applied, the molecules move, orient in the shear direction and disentangle to a certain extent which reduces their flow resistance (Gina, 2016).

Figure 6 presents the viscosity function of a polymer displaying changes in apparent viscosity (η) with increasing shear rate (γ) on a double logarithmic scale.

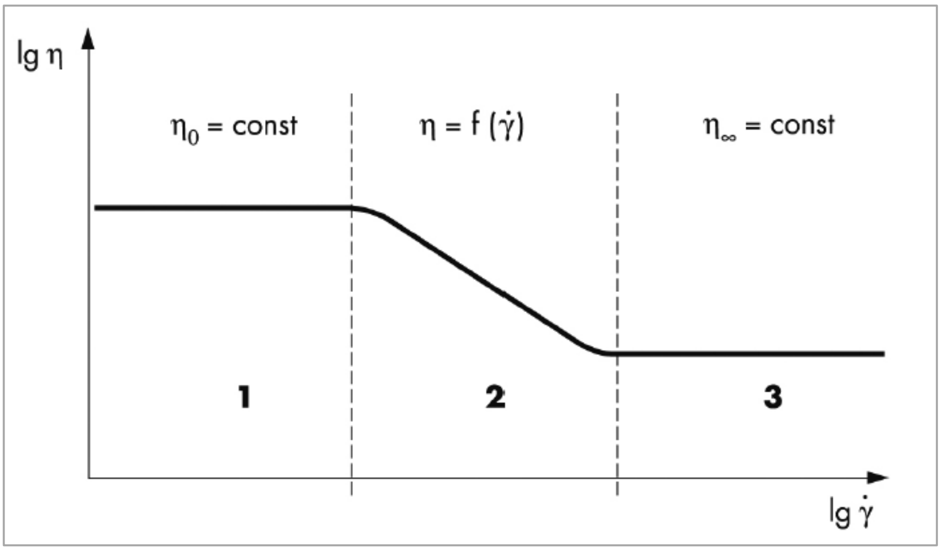


Figure 6. *The viscosity function of a polymer solution showing shear-thinning behaviour (Mezger, 2014).*

The graph shows three regions of the dependence of apparent viscosity on shear rate:

1. The first Newtonian range with the plateau value of the zero-shear viscosity **(**η_0) which represents a constant viscosity at increasingly low shear rates.
2. The shear-thinning, Non-Newtonian range: shear rate-dependent viscosity function ($\eta = f(\gamma)$), where the apparent viscosity decreases uniformly with increasing shear rate.
3. The second Newtonian range with the plateau value of the infinite-shear viscosity**(**η_∞), where the apparent viscosity remains constant at infinitely high shear rates.

For many polymers, the upper limit of this range occurs around the shear rate $\gamma = 1s^{-1}$ while for some it can be found already at $\gamma = 0.01s^{-1}$ or even lower. Shear force causes partial chain disentanglements and a consequential viscosity decrease. However at the same time, some macromolecules which had already dis-entangled are recoiling and re-entangling continuously, so increasing viscosity again (Gina, 2016). At low shear rates, polymer molecules in solution show visco-elastic behaviour due to the superposition between molecular disengagements and elastic recoil, effectively keeping viscosity constant (the zero-shear viscosity-η_0). The zero-shear viscosity is a constant limiting value of the viscosity function towards sufficiently low shear rates which are “close to zero-shear rate” (Mezger, 2014).

At increased shear rates, molecular chain disentanglements exceed re-entanglements, hence the polymer shows shear-thinning behaviour and the curve of the viscosity function $\eta(\gamma)$ therefore decreases continuously (shear range (2), Figure 6: the “flow range”). In the “high-shear range” (range 3), all macromolecules are almost fully oriented and disentangled, and flow resistance is reduced to a minimum value which cannot be decreased any further. For polymer solutions this may begin at around $\gamma = 1000s^{-1}$ - $10,000s^{-1}$ or beyond, and the value corresponds to the friction between the individual disentangled molecules gliding off each other. Viscosity is then recorded as a constant value which is referred to as the infinite-shear viscosity η_∞. Infinite-shear viscosity is occurring as a constant limiting value of the viscosity function towards sufficiently high shear rates which are “close to an infinitely high shear rate” (Mezger, 2014).

2.4.2 Dependence of the zero-shear viscosity (η_0) on polymer concentration, C

For a polymer solution in the low-shear range, the η_0 value is attained only when the polymer concentration C (g/dm^3) is high enough. At sufficiently high polymer concentrations, the molecule chains come together and begin to form entanglements, as shown in Figure 7 below.

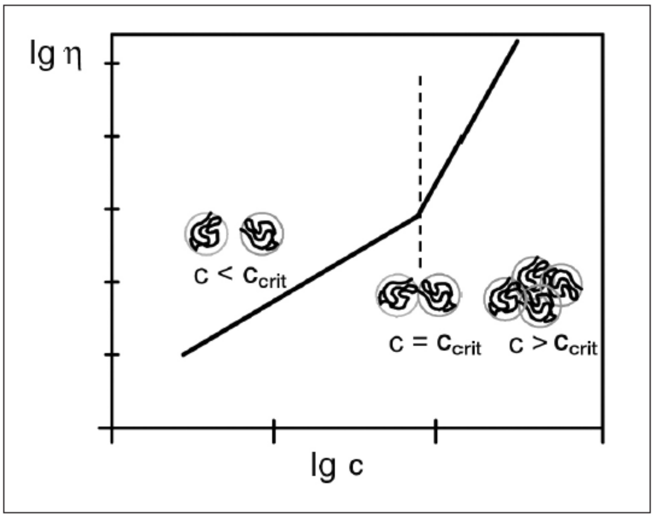


Figure 7. Dependence of low-shear viscosity on the polymer concentration. C_{crit} is the critical concentration (Mezger, 2014).

Concentrated solutions of polymer systems showing effective entanglements between the individual molecular chains indicate a zero-shear viscosity value in the low-shear range. However, low-concentrated polymer solutions having no effective entanglements between the individual molecule chains display ideally viscous flow behaviour (Mahmood et al., 2017). In this case, the viscosity value is directly proportional to the concentration (with the material-specific factor C_1).

For $C > C_{crit}$ *Equation 1*

With increasing concentration, there is a stronger increase of the η_0-value, indicated by the higher slope of the log η viz log C function in this concentration range.

2.4.3. Dependence of the zero-shear viscosity (η_0) on the average molar mass, M

A low molecular weight polymer has a molar mass, M (g/mol) which is below the critical molar mass, M_{crit}, required for the formation of effective entanglements between its macromolecules. Therefore such a polymer will not form effective entanglements and will display ideally viscous flow behaviour (Mahmood et al., 2017). Mathematically, this is shown in equation 2.

For $M < Mcrit, \eta/M = C_2 = Constant$ *Equation 2*

where C_2 is the material-specific factor, M is the molar mass (g/mol), and M_{crit} is the critical molar mass for the formation of effective entanglements between the macromolecules. Figure 8 below shows the effect of increasing molecular mass on the zero-shear viscosity, as well as on apparent viscosity in general.

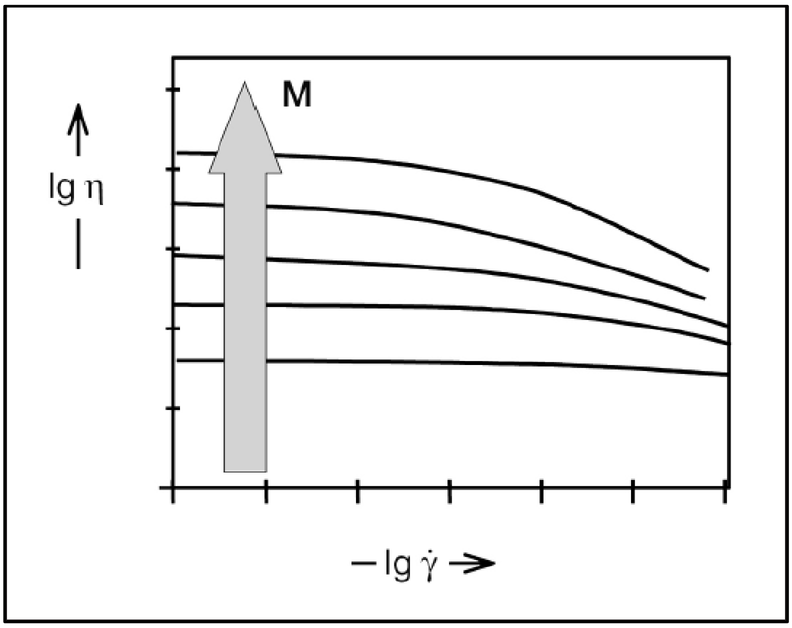


Figure 8. *Dependence of zero-shear viscosity (η_0) on the average molar mass, M (Mezger, 2014).*

However, as the magnitude of the molecular mass (M) increases beyond M_{crit}, the apparent viscosity increases, and a zero-shear viscosity region is observed. Polymers with high molecular mass (M) show effective entanglements between the individual molecular chains, hence they display a zero-shear viscosity in the low-shear range. Viscosity is now directly proportional to the molar mass, such that the higher the molar mass, the higher is the plateau value of η_0 (Mezger, 2014).

$For\ M > Mcrit: \eta_0 = C_2 \times M^{3.4}$ *Equation 2*

Knowledge of the effects of solids concentration, shear rate and molecular mass on the zero-shear, and on apparent viscosity in general is important to scientifically influence the production of infant porridges of acceptable texture and nutrient density. The proportionality of η_0 and M usually shows the exponent 3.4 to 3.5, a value approximately constant for all unlinked polymers (Mezger, 2014). The M_{crit} is a polymer dependent quantity (although often estimated as 10,000g/mol) that specifies a limiting value between materials showing a low molar mass (no entanglements) and polymers (entanglement formers).

2.4.4 A mechanism for shear-thinning behaviour

Figure 9 shows the shear-thinning behaviour in various food dispersion systems.

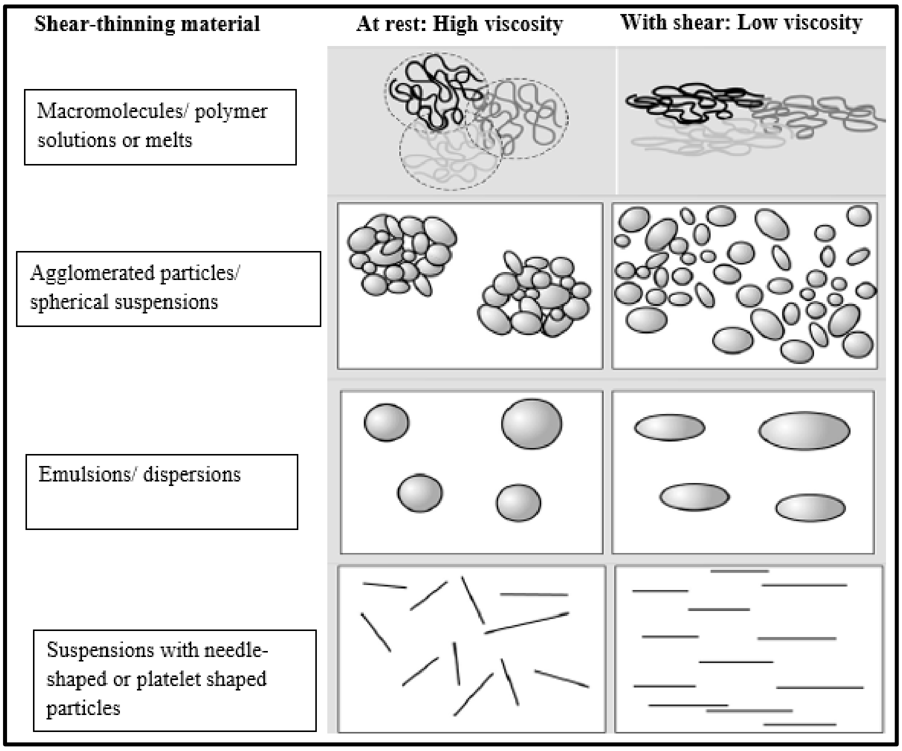


Figure 9. *Shear-thinning behaviour in different dispersions. Adapted from Gina (2016).*

The food industry involves a plethora of multiphase substances, structured as particle suspensions, regardless of how they are finally presented to the consumers (Mueller et al., 2009). Complementary porridges are typical examples in which a shear force may cause orientation of the dispersed particles in the flow direction. Shearing also causes disintegration of agglomerates into primary particles, making bound liquid free to flow again (Mezger, 2014).

The viscosity of fluid foods (such as complementary porridges) is influenced by the cohesive interactions in the food systems, which includes hydrogen bonds, hydrophobic interactions, Van der Waals and electrostatic interactions (Nasirpour et al., 2006, Sukkar et al., 2018). Electrostatic interactions occur between molecular species that possess a permanent electrical charge, such as ions and polar molecules; Van der Waals forces act between all types of molecular species, whether they are ionic, polar, or nonpolar; and hydrogen bonds occur between oxygen or nitrogen and hydrogen (Nasirpour et al., 2006). The various interactions described are illustrated in figure 10. Cohesiveness as a textural property of the food, can be defined as the strength of the internal bonds holding the sample structure together (Szczesniak, 1963, Sukkar et al., 2018).

Figure 10 illustrates different forces operational within fluid food systems.

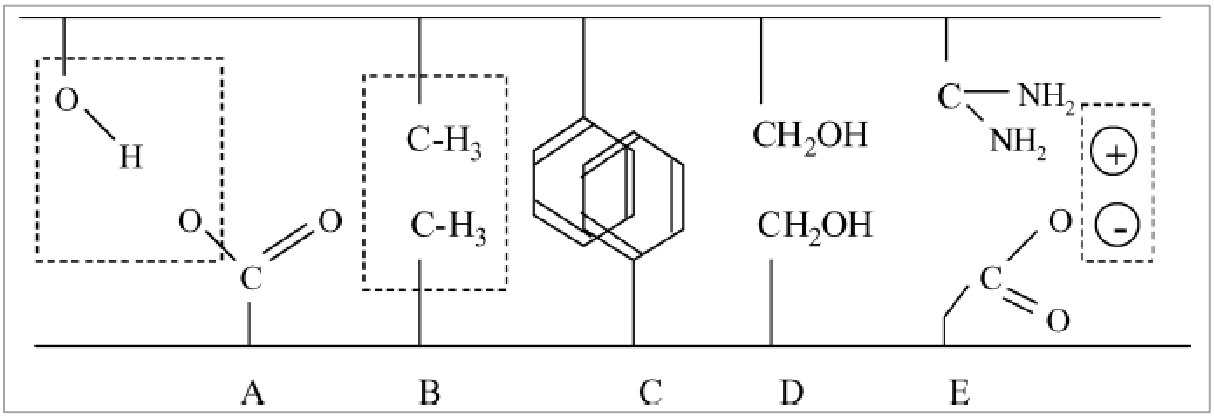


Figure 10. *Possible inter-molecular forces in protein interactions: A; Hydrogen bonds, B and C; Hydrophobic interactions, D; Van der Waals and E; Electrostatics (Nasirpour et al., 2006).*

With respect to the in-mouth viscosity of fluid foods, Wood (1968) explored the oral flow behaviour (thickness) of some soups and syrups using a sensory panel and concluded that a shear rate of $50s^{-1}$ was suitable for the evaluation of oral thickness. However, Stokes et al. (2013), perhaps relating to the concept of dynamic sensory perception, argued that a shear rate of $50\ s^{-1}$ can only be applied to the initial thickness perception and not to any other sensory attribute. Meanwhile, Nicosia (2013) emphasized that a single shear rate is impractical for measuring in-mouth viscosity, given that in-mouth shear tends to vary across the oral processing trajectory, but also with infant individual differences and age. The subject of whether a single shear rate or a range of shear rates and shear stresses are operational in thickness (viscosity) perception was also investigated by (Shama, 1973a) and (Shama, 1973b), as reported in (He et al., 2016). From oral viscosity analysis, la Fuente et al. (2019) estimated the shear rates applicable during swallowing to be around 5 - 1000 s^{-1}. In another study by Cutler (1983) in Steele et al. (2015), the perception of thickness was found to be highly correlated with instrumental viscosity at 10 s^{-1}.

Investigating the sensory perceptions of 5 food samples (thickened solutions prepared from xanthan and dextran), He et al. (2016) reported that mouthfeel perceptions were well correlated ($r^2 = 0.961$) to low shear viscosity (50 s^{-1}), with inclusion of high shear viscosity or extensional viscosity in the model parameters improving the predictive quality of the models for thickness, stickiness and mouth coating. These results are presented in Table 4.

Table 4. *Correlation between viscosity at low and high shear rate, extensional viscosity (η_e) and mouthfeel sensory scores* #.

			Correlation coefficient R^2		
	Initial thickness	Thickness in mouth	Stickiness on lips	Stickiness in mouth	Mouth-coating
Apparent Viscosity (η) at 50/s	0.961	0.952	0.890	0.884	0.911
Apparent Viscosity (η) at 10/s	0.556	0.577	0.670	0.688	0.663
Extensional Viscosity (η_e)	0.862	0.872	0.902	0.909	0.911

#*Adapted from (He et al., 2016).*

The foregoing findings strongly suggest that a range of shear rates from low to high might be important in predicting oral thickness perception. However, there is a general lack of consensus amongst researchers regarding the precise viscosity evaluation conditions. According to Steele et al. (2015), the actual shear rates in oral processing and swallowing depend on the rate and degree of pressures applied as well as the material properties of the fluids. Studying the effect of food bolus rheology on the ease of swallowing, Chen and Lolivret (2011) observed that apparent shear viscosity had a positive correlation with the sensed difficulty of swallowing, irrespective of the shear rate (Figure 11).

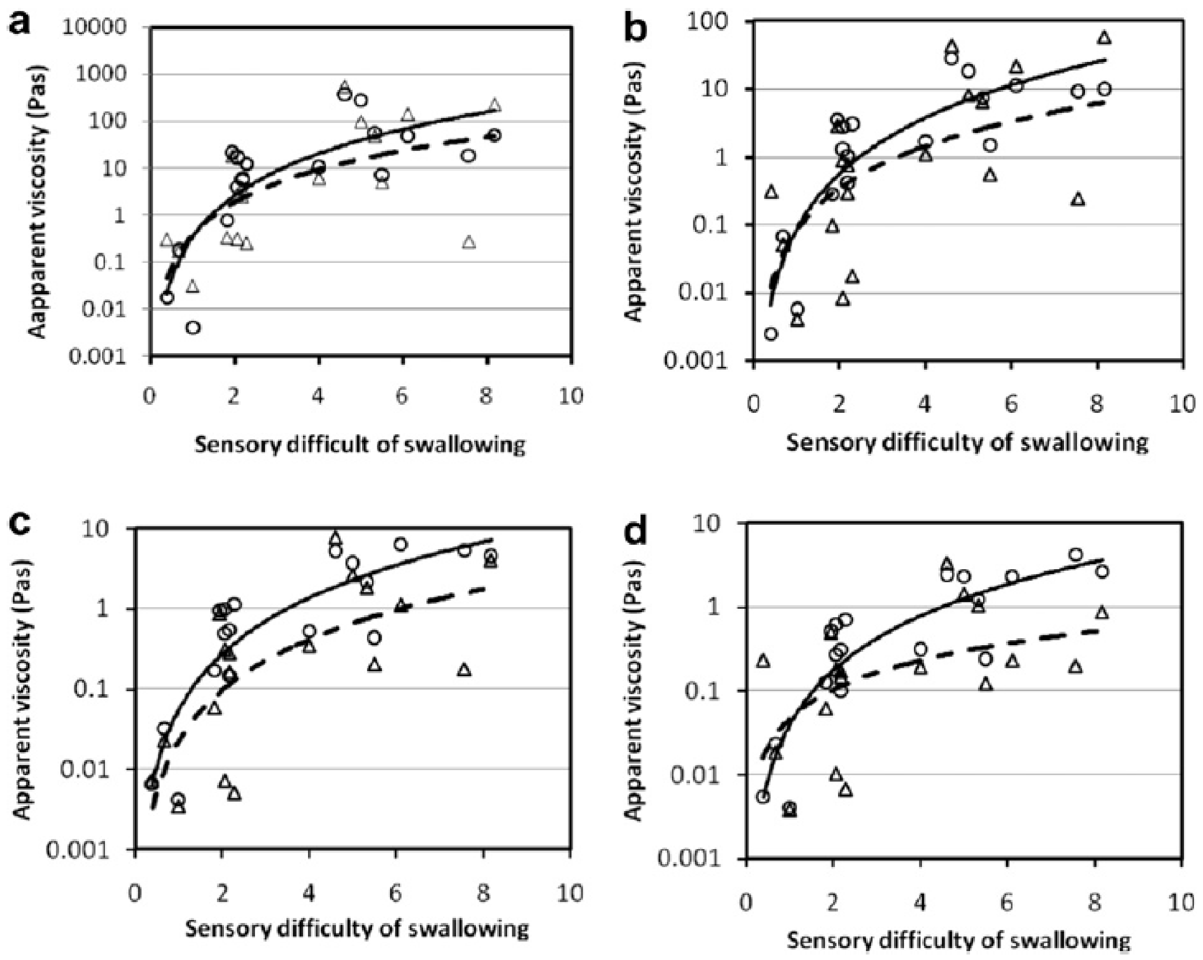


Figure 11. *Correlations between sensed swallowing difficulty and viscosity for some commercial foods analysed at shear rates of (a): 1/s, (b): 10/s, (c): 50/s and (d): 100/s. Open circles: no saliva mixing; open triangles: mixed with simulated saliva. Adapted from Chen and Lolivret (2011).*

In light of available literature, there is presently no consensus on the shear rates most representative of the mastication and swallowing processes, although 50 s^{-1} is commonly used (Newman et al., 2016, Sukkar et al., 2018). Hence until new research findings emerge, Steele et al. (2015) recommended that the apparent viscosities of fluid foods (e.g., for dysphagia clinical fluids, which may have similar flow properties to infant foods) should be reported across a range of shear rates (1, 10, 30, 50, and 100 s^{-1}) for reasonable comparison. Low shear rates are particularly more relevant because the oral motor deficits in compromised groups (infants, elderly and dysphagia) may affect abilities to generate the shear forces and physiological behaviours typical of healthy swallowing.

2.5. Instrumental measurement of viscosity

The rheological properties of complementary foods can be evaluated using instrumental or sensory methods. Table 5 shows a summary of some instrumental rheological measuring techniques used to analyse the flow behaviour of foods and non-food materials.

Table 5. *Rheological measurement techniques*

Categories	Definition	Instrumentation/Test	Advantages	Disadvantages
Fundamental	Measures rheological properties like viscosity and elasticity	Dynamic oscillator rheometer, Creep test Stress relaxation test	Parameters are physically well defined	Expensive equipment poor correlation with sensory data
Imitation	Mimic the conditions to which the food is subjected when eating or processing	Texture Profile Analysis Farinograph, Visco-Amylo-Graph	Closely duplicates mastication or sensory methods Good correlation with real situation	Measures parameters which are often poorly defined, but appear to relate to texture quality
Empirical	Simulates the conditions to which materials are subjected in practice	Puncture and Penetration tests Extrusion test, Bostwick or Adam consistometers	Good correlation with real situation, easy and fast, inexpensive	Measures parameters are poorly defined Arbitrary procedure

Adapted from Sukkar et al. (2018).

A common practice in many food laboratories is to measure viscosity with viscometers and rheometers, which registers the force necessary for moving a plate relative to another at a given speed, with the liquid between them (Tiest, 2015). A line spread test which measures the distance a fluid food flows across a flat surface can also be used to quantify a fluid food’s thickness or viscosity(Stanley and Taylor, 1998). The advantages of a line spread over rheometers and viscometers are simplicity, low cost and being more practical, making them applicable at the household level (Tumwebaze et al., 2015). Alternatively, a Bostwick consistometer can be used where simplicity is of prime concern. It is a simple bench device in which a fixed volume of fluid is released from a chamber to flow into an adjacent channel with markings, and the leading edge of the liquid when it comes to rest is recorded (Steele et al., 2014b). Bostwick consistency is expressed as distance flowed (cm) over a 30-s interval. A more recent simple instrumental method for measuring the viscosity of fluid foods is the gravity flow test, developed by the International Dysphagia Diet Initiative (IDDSI) (Sukkar et al., 2018). The test uses a 10 ml syringe as a practical objective measure to classify fluid foods based on their rate of flow (Figure 12).

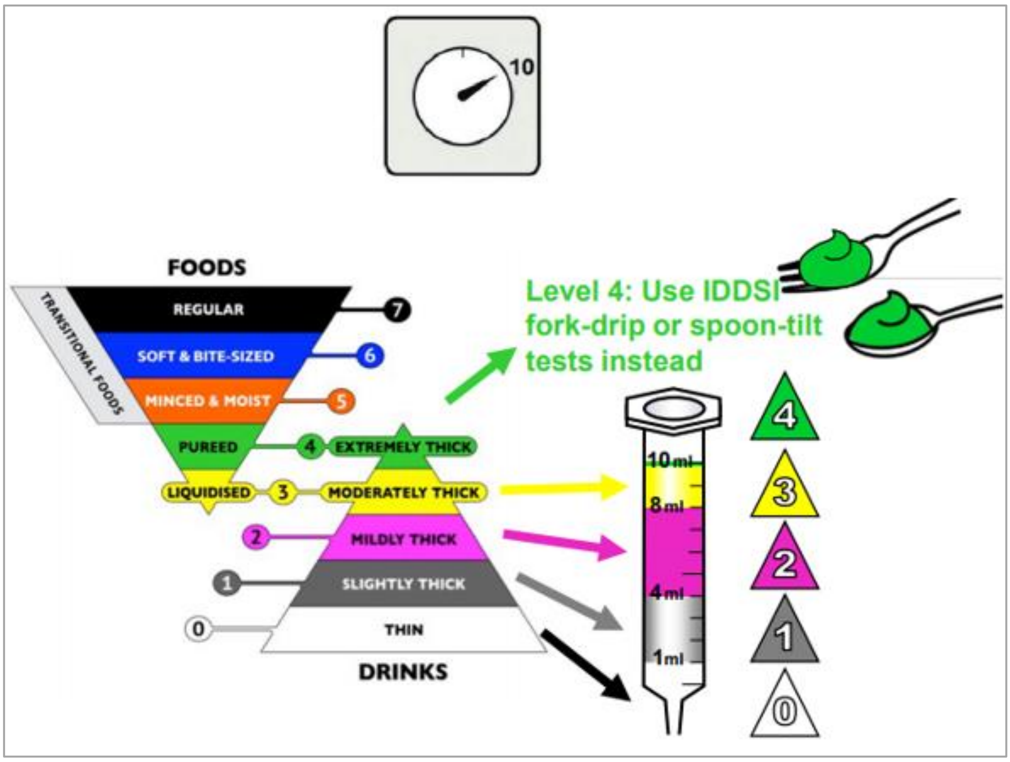


Figure 12. *The IDDSI gravity flow test measures how much fluid leaves the full syringe kept upright in 10 s. Level 0: the syringe completely drains, level 4, the syringe remains full. Adapted from the IDDSI (2017).*

According to Stokes et al. (2013), imitative, instrumental and fundamental rheological methods may be effective at predicting the key aspects of “texture” perception at the initial stage of oral processing. However, as the oral processing trajectory progresses, traditional rheological methodologies become inadequate and tribology becomes more significant. Nonetheless, instrumental texture evaluation methods cannot replace the sensory methods of texture perception.

2.6 The need for sensory measurement of porridge viscosity

Although instrumental methods produce robust and reliable results for texture characterization, the interpretation of the data is so complex as a result of the lack of causality between instrumental results and oral perception (Guinard and Mazzucchelli, 1996). Additionally, there are often poor correlations between instrumental characterization and oral perception (Aktar et al., 2015), perhaps due to the different scaling mechanisms between human beings and physical measurement instruments (van Vliet, 2002, Aktar et al., 2015). There is wide consensus among sensory scientists that various mechanoreceptors function collectively as sensory detectors to receive texture-related stimuli, relaying them to the brain for sensory analysis (Aktar et al., 2015).

Analytical sensory tests are objective methods that document the sensory profiles of products free from liking considerations (Schiano et al., 2017). Examples include descriptive sensory analysis tests, which are designed to reflect the total sensory profile of products being evaluated (Stone and Sidel, 2004). Analytical tests involve detection and description of qualitative and quantitative sensory aspects by trained panellists (Meilgaard et al., 2007). In discrimination tests, the aim is to identify whether a significant difference exists between 2 or more samples (Lawless and Heymann, 2010). They are concerned with the smallest difference in stimulus intensity that is still perceivable (i.e. Just Noticeable Difference, JND) (Tiest, 2015). Common sensory discrimination tests include paired-preference, duo-trio, triangle, tetrad , 2-AFC (alternative forced choice), A-Not-A and quantitative descriptive evaluation tests (Carlisle, 2014, Shin et al., 2016). A triangle test is a simple to use, robust psychophysical testing protocol for detecting just noticeable differences (JND) in sensory stimuli, in which participants are asked to identify one stimulus from a set of three, that is perceived to differ from the other two (Steele et al., 2014b).

Tactile oral processing capacity and texture of a food product are major determinants of liking and acceptability of foods (Coulthard et al., 2018). None-the-less, whereas the nutritional quality of (especially commercial) infant foods are fairly well researched, their texture profiles and acceptance levels have been rarely studied (da Costa et al., 2017) despite their highly prevalent usage. Identifying those sensory properties of infant foods which are the drivers of liking has long been an important challenge for the food industry (Laureati and Pagliarini, 2018). The capability to discriminate differences in viscosity and the subsequent perception is an important factor for food texture appreciation (Aktar et al., 2015), especially for infant foods.

Magnitude estimation scaling is another sensory method used to characterize the relationship between the physical intensity of a stimulus and its sensorial perceived intensity (Tiest, 2015). In oral viscosity determination, magnitude estimation can be used with fingers or the mouth for stimulus perception. A power function with an exponent of about 0.3 – 0.4 represents a good description of the relationship between physical and perceived viscosity, with oral methods (the lips, palate and tongue) generally yielding a higher perceived viscosity than non-oral methods (rod, fingers) for the same stimulus (physical viscosity) (Tiest, 2015). Generally, it has been found that using magnitude estimation (i.e., ordered ranking) techniques, a ten-fold increase in physical viscosity corresponds to an approximate doubling in orally perceived viscosity (Steele et al., 2014b). Aktar et al. (2015) and Tiest (2015) both reported that the ability of humans to discriminate a sensory property using the "just noticeable difference" (JND) was by percentage difference rather than by absolute amounts. This is represented by the theory of proportional threshold for sensory perception, often termed Weber's law:

"the magnitude of a just noticeable difference (JND) of a sensory feature (ΔI) is proportional to its own physical intensity (I)", mathematically stated thus:

$$\Delta I \propto I \qquad \text{OR} \qquad k = \frac{\Delta I}{I} \qquad\qquad \textit{Equation 5}$$

where k is a constant (the Weber's fraction, Weber's ratio or the viscosity ratio).

The JND values (hence Weber's ratios) will vary for different subjects, regardless of the sensory properties under study due to differences between the sensory physiology of individuals (the physiological factor), life experiences that shape an individuals' sensory capability (the psychological factor) or a combination of the two (Tiest, 2015).

Table 6 shows some Weber ratio examples obtained from studies of different selected stimuli.

Table 6. *Compilation of Weber's ratio results from various discrimination experiments from literature.*

Reference	**Stimulus**	**Range (mPa.s)**	**Method**	**Weber fraction**
Scott Blair and Coppen (1939)	Bitumen	10^{8}	Manual	0.3
Bergmann Tiest, Vrijling and Kappers (2013)	Silicon oil	200 - 16000	Manual	0.3 - 5
Smith et al. (1997)	Corn syrup	3 – 2240	Oral	~2
Steele, Van Lieshout and Goff (2003)	Apple juice	1000	Oral/Manual	0.7
				0.74 - 0.84
Withers, Gosney and Methven (2013)	Milk	45 – 130	Oral	0.74 - 0.84

Adapted from Tiest (2015).

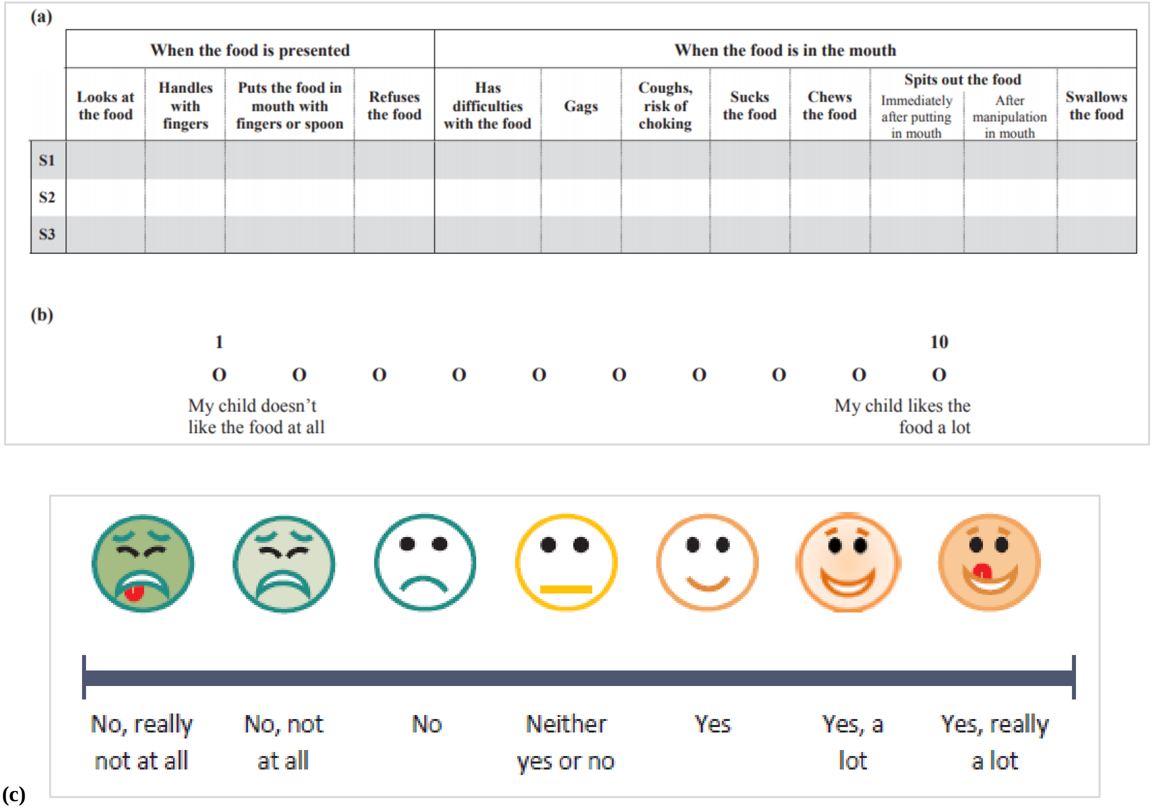
2.7. Challenges of Sensory evaluation with infants

The study of texture in infant complementary porridges presents great challenges for both researchers and food processors. Developing food products for infants and young children requires their input since their perceptions, sensory acuity, expectations, and likings differ from those of adults (Laureati and Pagliarini, 2018). The paediatric palate is different from that of the adult, and there are differences in oral physiology (Mennella and Beauchamp, 2008, Laureati and Pagliarini, 2018). These factors could result in the incongruent perception of texture between infants and adults (Rose et al., 2004), which can affect liking.

Although sensory evaluation with children directly appears to be the most obvious approach to developing potentially more palatable infant food formulations, this approach presents major feasibility difficulties (Mennella and Beauchamp, 2008). Children have limited cognitive, linguistic and attentional abilities, and they may focus their attention to one dimension of foods instead of simultaneous consideration of different sensory dimensions (multimodal) (Popper and Kroll, 2005).The limitations in children's abstraction power and metaphorical thinking may affect their capacity to successfully perform some analytical sensory tasks or provide objective and reliable responses (Issanchou, 2015). According to Mennella and Beauchamp (2008) young children are more prone to attention lapses and have shorter memory spans, and any method relying on sustained attention could yield spurious findings. Therefore, most sensory profiling research on infant foods has often been conducted by adult panellists, because of their ability to understand instructions and express their judgement and decision (Chanadang, 2017, Laureati and Pagliarini, 2018).

With regard to preference evaluation of baby foods, an effective way to evaluate children's (hedonic) responses is based on non-verbal cues, such as facial expression and body movements, and hedonic rating scales (Guinard, 2000, Mennella and Beauchamp, 2008). These indirect observational approaches use caregivers and mothers to assess children's acceptability of the food, by observing behaviours during feeding and translating them into a degree of liking score (Amegovu et al., 2014). Demonteil et al. (2019a) employed mothers to assess the evolution of food texture acceptance and feeding behaviours between 6 and 18 months, with a view to determine the optimal time for the introduction of diverse textures. In Burkina Faso, Iuel-Brockdorf et al. (2015) asked caregivers to evaluate their children's appreciation of baby foods by observing their reaction based on a 5-point hedonic scale.

Figures 13 shows some hedonic scales which may be used for preference studies with infants.



(a)

	When the food is presented				When the food is in the mouth							
	Looks at the food	Handles with fingers	Puts the food in mouth with fingers or spoon	Refuses the food	Has difficulties with the food	Gags	Coughs, risk of choking	Sucks the food	Chews the food	Spits out the food		Swallows the food
										Immediately after putting in mouth	After manipulation in mouth	
S1												
S2												
S3												

Figure 13. *Example hedonic scales for use in the evaluation of infant food preferences. Adapted from Lange et al. (2019) and Demonteil et al. (2019b)*

Observational and behavioural hedonic methods are certainly very important in understanding the liking and preference patterns for complementary foods. However, they are not part of the quantitative descriptive analytical sensory profiling tools, and therefore, do not give insights into the drivers of preferences. Analytical sensory tests are objective methods that document the sensory profiles of products free from liking considerations (Schiano et al., 2017). The drivers of preferences are specific product sensory attributes which are associated with increased liking scores for that product.

Very simple, intuitive methods which do not require scaling, such as the paired comparison test to investigate children's preferences, are also thought to be ideal with young children (2 – 3 years old) (Liem et al., 2004). Examples include the ranking method, requiring samples to be ordered according to increasing or decreasing preference or intensity of a sensory descriptor (Laureati and Pagliarini, 2018). However, this method cannot be used with infants, and even with older children it may require tasting several samples, which implies good memorization skills and sometimes the risk of fatigue (Liem et al., 2004, Laureati and Pagliarini, 2018).

Projective mapping or Napping is another non-verbal method based on perceptual distances amongst products, which can be advantageous for young children who may encounter difficulties in developing a sensory lexicon (Laureati et al., 2015). Like the ranking method, Napping works better with at least 8–12 samples evaluated simultaneously, which can be tricky for children, who may develop sensory fatigue and boredom much faster (Laureati and Pagliarini, 2018). Additionally, napping cannot be used with infants.

It is important to use appropriate methods considering the sensory, cognitive and social factors that may impact testing with children (Guinard, 2000, Popper and Kroll, 2005, ASTM, 2013). Delimont et al. (2017) used paired preference tests with mothers to observe their infants as they eat, to assess preferences for Fortified Blended Foods in Tanzania (Chanadang et al., 2018). During evaluation the caregivers employed behavioural methodologies (smiles, tongue movements, e.g., licking or attempting to move the porridge into the mouth, reaching arms and hands for more, wiggling to try and reach the cup when held in the care-givers' hand), to infer on children's liking of the product. Ambivalence, slapping at the cup, and frowning meant that the child did not like the product (Chanadang et al., 2018). Although Chanadang et al. (2018) used descriptive sensory analysis as a follow up on the preference testing of fortified blended foods (FBFs), the analytical methodology did not consider the differences in oral processing behaviours between infants and adults, as a result of developmental differences in their oral physiology.

2.8 A special descriptive sensory method for baby foods

It is very difficult to predict consumer food preferences without actual information from the target group (Laureati and Pagliarini, 2018). However, conducting sensory and consumer research with infants (6 to18 months) and toddlers (18 to 36 months) is a challenge (Chanadang et al., 2018), yet information regarding the type of food textures accepted by children at a given age is quite limited (Demonteil et al., 2019a). There are very few examples in literature, on the use of analytical descriptive sensory profiling with children, especially infants (Laureati and Pagliarini, 2018). To develop specialised and optimized infant food products, it is critical to use an appropriate methodological approach which enables identification of the "product sensory finger-prints", showing the key drivers of liking or otherwise (Laureati and Pagliarini, 2018).

Analytical sensory methods can provide both qualitative and quantitative descriptive sensory profiles of a food product. However, these methods are complex for young consumers due to their inability to use rating scales correctly, lack concentration and attention (Laureati et al., 2015). Finding a suitable and reliable methodology to identify important descriptive sensory properties of infant foods is still one of the biggest challenges for food companies and sensory and consumer research scientists (Laureati and Pagliarini, 2018). Understanding the drivers of children's food texture preferences could help in designing strategies to reduce both malnutrition and obesity (Laureati et al., 2015). For investigating the descriptive sensory profiles of infant complementary foods, an ideal methodology must address at least three key requirements:

a) it must be dynamic, because food oral processing is a temporal rather than static process (Dijksterhuis and Piggott, 2000),
b) it must use an adult panel, because of the discussed limitation associated with infants and young children; and
c) it must simulate the food oral processing kinetics in infants' mouths, as a result of their limited oral physiology which is different from adults.

Understanding the oral physiological differences between infants and adults helps in the development of an analytical sensory method suitable for infant foods evaluation. Currently there is no method for the oro-tactile analytical description of baby foods. Temporal Dominance of Sensations (TDS) and Temporal Check All That Apply (TCATA) (Castura et al., 2016), are the most used dynamic techniques which have recently been employed for the evaluation of different consumer products. TCATA is a rapid method where attributes are actively checked and unchecked to track the product-induced sensations over time, so that the checked words fully describe the sample at any given moment (Reyes et al., 2017).

Investigating infants and young children' oromotor readiness for different food textures, Utsumi et al. (2015) analysed mastication using a 3D motion capture system, to understand the acquisition of grinding movements by the molar teeth, with the aim of informing the design of infant foods. The work confirmed that the vertical, up-and-down chewing behaviour (munching) is observed at 6 months (Himmlova et al., 2007). By 12 months, munching is well-established and continues to optimize until 2 – 3 years (Le Révérend et al., 2014, Demonteil et al., 2019b). By 3 years children acquire the 3-D trimetric rotation (rotary chewing) accompanied by a grinding, sweeping motion (Himmlova et al., 2007). At this stage, the tongue gains the ability to transport food easily beyond the midline with increasing speed and dexterity (Fucile et al., 1998). During infancy, it is possible to perform chewing-like processing by smashing food with the gums (munching) before the eruption of teeth (Utsumi et al., 2015).

However, more research into oro-tactile sensation is needed to determine what types of adult sensory panels and which methods are most appropriate for characterizing infant foods and predicting product acceptance by paediatric populations (Mennella and Beauchamp, 2008). The need to adapt common sensory methods to the particularities of children has been emphasized since many years (Issanchou, 2015). One method that could be adapted for the analytical evaluation of infant foods is TCATA. TCATA is known to be cognitively demanding, as the evaluation is multi-modal (Jaeger et al., 2017). However, with an adult panel trained to simulate the limited oral capacity of infants, the method could be efficacious in predicting the dynamic oral texture properties of infant porridges. The texture properties and energy density of infant porridges are important in meeting the energy and nutrient requirements of infants (Usman et al., 2016). An ideal complementary food must be of a suitable consistency, nutrient-dense, and easily digestible (WHO/UNICEF, 2003). da Costa et al. (2017) observed that baby foods for infants had different texture levels in different countries, reflecting the current absence of regulation, and very limited guidance regarding the texture of baby foods (Nicklaus et al., 2015b). Development of a sensory methodology for baby foods can assist in the standardization of the sensory texture of infant porridges.

Despite progress in sensory science and food rheology, little has been reported in the literature about the temporal tactile interpretation of viscosity perception of African indigenous complementary porridges, and its link to nutrient intake in infants and young children. This study investigated the rheological, dynamic (temporal) sensory textural properties, protein and energy content of indigenous/ locally available complementary porridge samples, as well as commercial infant foods for 6 to 24 months old children in African communities. The aim was to optimize the rheological and sensory texture quality of CPs to enhance protein and energy intake among young children for an improved nutritional status.

3.0 Hypotheses and objectives

3.1 Hypothesis 1: Flow properties of common African indigenous/ locally available complementary porridge samples (Chapter 4)

The apparent viscosity values of some common African indigenous/ locally available complementary porridges measured at shear rates estimates for oral processing (0.001/s; 0.1; 1/s; 10.0/s and 50.0/s, and temperature of 40 °C), will be higher at much lower solids content relative to a commercial reference porridge. Consequently, their protein and energy content at the solids content enabling suitable optimal viscosities for oral processing by children of ages 6 - 8, 9 - 11 and 12 - 24 months, will be inadequate to meet the WHO recommended daily nutrient intake requirements.

Scientific rationale

The relative quantities of high molecular weight polymers (proteins and polysaccharides like starch) in complementary foods contribute to the viscosity (Funami, 2017). High viscosity is due to entanglement of polymer chains above a critical entanglement concentration (Mezger, 2014). Most staple-based complementary foods in developing countries are starchy (Amagloh et al., 2013b, Tumwebaze et al., 2015). The viscous nature of gelatinized starch is due to suspended swollen starch granules dispersed in a macromolecular solution created by amylose polymers (Alloncle and Doublier, 1991). Above the critical entanglement concentration the molecules are less mobile, start approaching each other forming entangled networks resulting in the system’s viscosity increasing (Mahmood et al., 2017).

An increase in the molecular weight of food biopolymers lowers the critical concentration required for chain entanglement (Mahmood et al., 2017), hence at low solids content such cooked suspension tend to have very high viscosity. Low molecular weight molecules tend to have no effective entanglements and they display ideally viscous flow behaviour (Mahmood et al., 2017). The nature of molecular interactions (hydrogen bonds, hydrophobic interactions, Van der Waals and electrostatic interactions) in the fluid foods affects the nature of dispersions, and particle aggregations formed in a food system, which influences viscosity (Nasirpour et al., 2006, Funami, 2017).

3.1.1 Objective 1: Effect of shear rate and solids content on flow properties of African indigenous/locally available complementary porridge samples

To determine the effect of type of African indigenous/ locally available complementary porridge and solids content on:

i) the flow properties (apparent viscosity), analysed at different shear rate estimates for food oral processing (0.001; 0.1; 1; 10.0; 50.0/s) and a viscosity of 3 Pa.s -

ii) the protein and energy content of the porridge at a viscosity of 3 Pa.s , -

with the aim of optimising porridge viscosity to improve protein and energy intake in young children for a better nutritional status.

3.2. Hypothesis 2: Effect of porridge type and oral processing method on oral texture perceptions of porridge samples (Chapter 5)

There will be significant differences in the perceived temporal oral (in-mouth) texture properties of indigenous/local and commercial porridge samples commonly consumed by infants and young children (ages 6-8, 9-11 and 12-24 months) in Africa. Common African indigenous/local porridges will be perceived as more challenging in oral texture relative to commercial porridges, especially when evaluated using a method that mimics/simulates the limited food oral processing capacity in infants and young children compared to a control method involving adult-like chewing.

Scientific rationale

Food oral texture perception and in-mouth flow behaviour depends on the rheology of the food bolus itself, as well as the oral physiological conditions (e.g., tongue pressure capability) of the consumer (Alsanei and Chen, 2014). The oral physiology of adults differs from that of infants (Matsuo and Palmer, 2008). At around 6 months and before the eruption of teeth, it is possible to perform chewing-like food oral processing by smashing food with the gums, using the vertical, up-and-down chewing behaviour (munching) (Utsumi et al., 2015). By 12 months, munching is well-established and continues to optimize until 2 – 3 years (Le Révérend et al., 2014, Demonteil et al., 2019b). By 3 years, the tongue gains the ability to transport food easily beyond the midline with increasing speed and dexterity (Fucile et al., 1998), and children acquire trimetric rotation (rotary chewing) which improves mastication efficiency (Himmlova et al., 2007). Such anatomical and physiological differences may lead to a differentiated oral texture perception.

Food oral texture is a measure of the strength of internal bonds (H-bonds, van der Waals, electrostatic, hydrophobic, and hydrophilic forces) making up the food matrix (Sukkar et al., 2018). The ability to efficiently chew and swallow a given food (oromotor readiness) (Black et al., 2017), determines the perceived oral texture. A more viscous and thicker texture (higher viscosity) results from entanglement of hydrocolloid polymer chains above a critical concentration (Mezger, 2014), forming a food matrix that is not readily deformable. The relatively higher shear force during food oral processing in adults causes shear-thinning (Gina, 2016), perceived as thin texture.

3.2.1. Objective 1: Effect of complementary porridge type

To characterize the dynamic (temporal) in-mouth textural attributes of common African indigenous/locally available complementary porridges and commercial baby foods for 6 to 24 months children, -

with the aim of optimising sensory texture for improved protein and energy intake in infants and young children.

3.2.2. Objective 2: Effect of oral processing method

To investigate the effect of oral processing method on the dynamic (temporal) in-mouth textural attributes of common African indigenous/locally available complementary porridge samples and commercial baby foods for 6 to 24 months children, -

with the aim of developing a reliable and convenient evaluation method to simulate infant oral chewing patterns to more accurately predict the oral texture of complementary porridges.

3.3. Hypothesis 3: Flow properties- Commercial complementary porridge samples (Chapter 6)

The apparent viscosity values of some commercial complementary porridges commonly used to feed babies of age 6 – 24 months in African communities measured at shear rates estimates for oral processing (0.001/s; 0.1; 1/s; 10.0/s and 50.0/s, at 40 °C), - will be within acceptable limits (≤ 3 Pa.s) at the applicable solids content and preparation instructions recommended by the manufacturer. Consequently, the protein and energy content of the porridges will be adequate to meet the WHO recommended daily nutrient intake needs for children of ages 6 - 8, 9 - 11 and 12 - 24 months.

Scientific rationale

The type of polymer and its hydrodynamic volume, charge density, chain rigidity, and properties of food system affect the viscosity of hydrocolloids (Mahmood et al., 2017). Infant cereals are "processed cereal-based foods", containing pre-cooked or pre-gelatinized starch as part of the major ingredients (Nasirpour et al., 2006, Klerks et al., 2019). If high molecular weight components such as proteins and starch polysaccharides are present in complementary foods, they can contribute to a much higher viscosity compared to low molecular weight ingredients such as maltose or protein hydrolysates (Funami, 2017). Most commercial baby foods are processed by technologies (e.g., pre-gelatinization, complete or partial hydrolysis, dextrinization) which break-down macromolecules to simple monomer fragments (e.g., protein hydrolysates, simple sugars) to improve on functional and nutritive properties (Nasirpour et al., 2006).

Processing techniques like extrusion cooking lead to depolymerization of macromolecules into smaller monomers, which reduces viscosity and allows more solids to be incorporated in a porridge (Muoki, 2013b). Dextrinization of starch during extrusion processing or drum-drying leads to a lower viscosity in the porridge (Nout and Ngoddy, 1997a). Viscosity is directly proportional to molar mass, and smaller molecule show increased solubility and do not form molecular entanglements (Mezger, 2014, Mahmood et al., 2017). At higher polymer molecular weight, the critical concentration required for entanglement is lower because macromolecules form coiled chains and entanglements even at rest (Mahmood et al., 2017). The viscosity of food is influenced by inter-particle interactions (hydrogen bonds, hydrophobic interactions, Van der Waals and electrostatic interactions) within the system, (Nasirpour et al., 2006).

3.3.1 Objective 1: Effect of shear rate on flow properties of commercial complementary porridge samples

To determine the effect of shear rate, manufacturer-declared solids content and declared nutrient density values on:

i) the flow properties (dynamic viscosity) of common commercial complementary porridges for infants and young children aged 6 to 24 months, analysed at different shear rate estimates for food oral processing (0.001; 0.1; 1; 10.0; 50.0/s) -

ii) the efficacy of common commercial complementary porridges for infants and young children aged for 6 to 24 months to meet the WHO recommended nutrient levels at the recommended oral viscosity of 3 Pa.s , -

with the aim of advising industry and policy makers regarding the rheological and nutritive quality of the porridges to improve protein and energy intake in young children.

3.4. Hypothesis 4: Effect of porridge type on energy and protein content (Chapter 4 & 6)

Common African indigenous and locally available commercial complementary porridges at the recommended oral viscosity limit of 3 Pa.s (Nout and Ngoddy, 1997a, Thaoge et al., 2003) measured at 40 °C, will not provide adequate protein and energy to meet the WHO recommended daily nutrient intakes (RNI) for infants and young children of ages 6 – 8 months; 9 – 11 months and 12 – 24 months. Commercial complementary porridges will not exceed the critical viscosity limit of 3 Pa.s when prepared according to the manufacturer’s instruction, and will be able to meet the recommended daily protein and energy intakes for infants and young children of ages 6 – 8 months; 9 – 11 months and 12 – 24 months.

Scientific rationale

Indigenous/local complementary porridges for young children in many developing countries are mostly prepared from readily available starchy staple foods (cereals and tubers) which when cooked, have high paste properties (above 3000 centipoise) at low flour concentration (Fasasi et al., 2007, Mbata et al., 2009). The viscosity and swelling characteristics of staple cereal-based porridges upon cooking are related to starch content (Singh et al., 2004). Starch is a high molecular weight polymer that forms a highly viscous paste when cooked (Saha and Bhattacharya, 2010). This high viscosity at low solids content in starchy indigenous complementary porridges limits the quantity of food ingested (hence protein and energy obtained from the meal) in infants (Tizazu et al., 2010, Abiose et al., 2015). The recommended energy intakes from complementary foods for children receiving low-breast milk energy intake (Low BME) at 6 – 8 months, 9 – 11 months and 12 – 24 months are 2318 kJ/day (552 kcal/day), 2944 kJ (701 kcal/day) and 4318 kJ (1028 kcal/day) respectively. In terms of protein intake, they should receive 5.2 g/day, 6.7 g/day and 9.1 g/day at 6 – 8 months, 9 – 11 months and 12 – 24 months of age respectively (Brown et al., 1998, Dewey and Brown, 2003).

3.4.1. Objective 1: Effect of complementary porridge type on the porridge samples' energy and protein content

To measure the energy and protein content of common African indigenous and locally available commercial complementary porridges at porridge viscosities ≤ 3 Pa.s, so as to evaluate their efficacy in meeting the RNI levels for infants and young children of ages 6 – 8; 9 – 11 and 12 – 24 months,-

with a view to better understand the reasons for protein-energy malnutrition in this age group and recommend on practices and policies for improving food and nutritional security.

3.5. The Experimental Design

The experimental design to investigate the relationships between the independent and the dependent variables for the study is shown below (Figure 14).

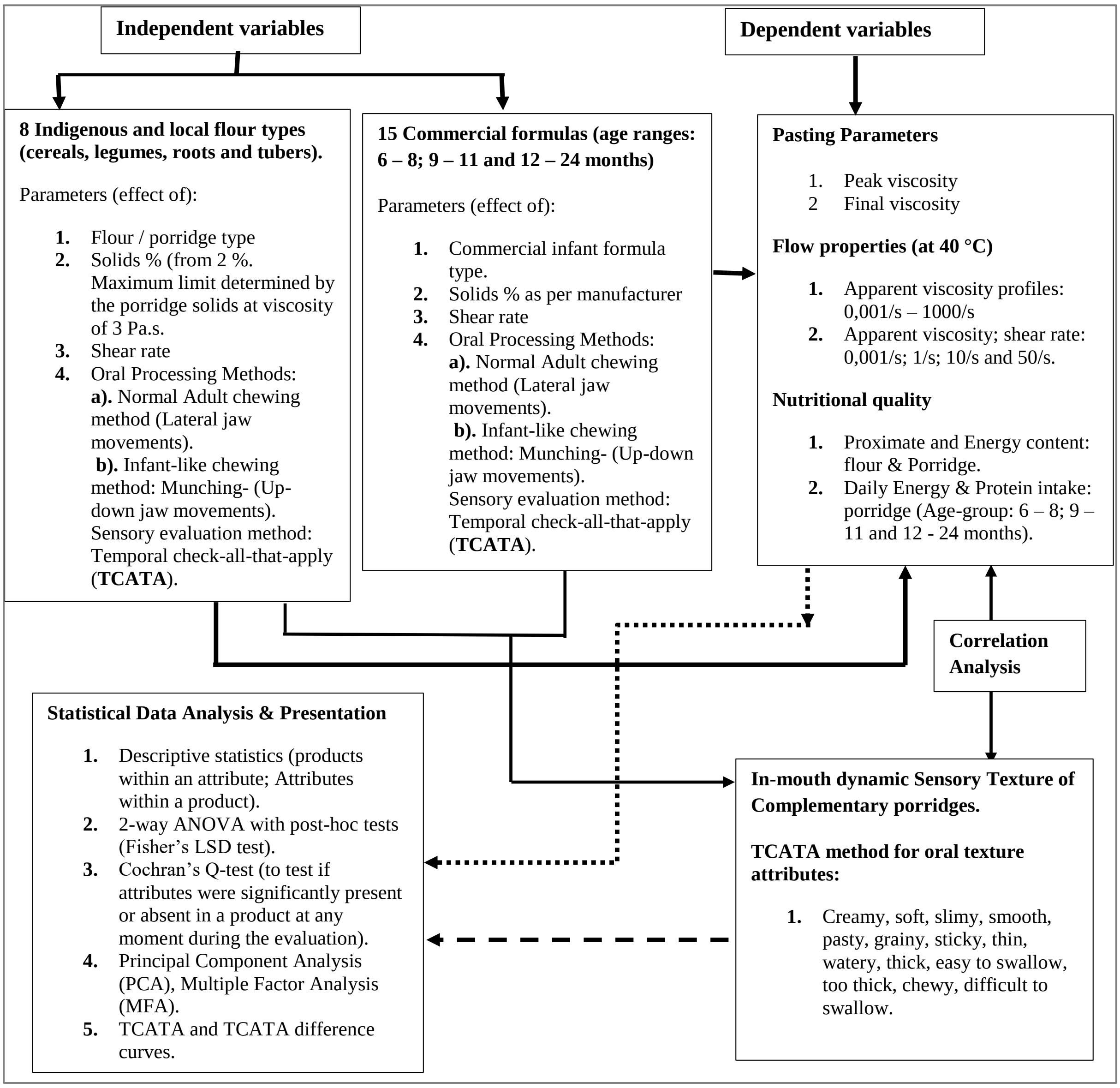


Figure 14. *Schematic study design for the rheological, sensory and nutritive quality of indigenous and commercial complementary porridge samples commonly used in African communities.*

4.0 Flow properties and nutrient density of common African indigenous/local complementary porridge samples

4.1. Introduction

Malnutrition in young children remains a serious public health problem in low-income African communities. When persisting, it can lead to stunted growth, morbidity or mortality, impaired intellectual development and working capacity (Michaelsen et al., 2009). Globally, about 155 million children under 5 years (an estimated 22,9 % in 2016) are stunted (UNICEF, 2016). Approximately 38 % of them reside in Sub-Saharan Africa (Rumsby and Richards, 2016). South Africa, although a middle-income country, is one of 34 countries with the highest stunting burden on a global level (Bhutta et al., 2013). It is estimated that at least 27% of South Africa's children are stunted (National Department of Health (NDoH), 2017). Chronic undernutrition in the first 1000 days of a child's life is a leading cause of stunting (Save the Children, 2017). Inadequate complementary feeding, insufficient breast-feeding, infections, compromised maternal health and nutrition, household food insecurity, and poverty are the key drivers for stunting (Stewart et al., 2013, Rumsby and Richards, 2016). Protein-Energy Malnutrition (PEM)- the most lethal form of child malnutrition, arises from inadequate protein and energy in complementary diets (Bazaz et al., 2016). Poverty limits access to quality complementary foods (Solomons and Vossenaar, 2013, Bazaz et al., 2016).

Indigenous and locally available starchy staples (cereals, roots and tubers) are considered as affordable, culturally acceptable, and convenient complementary food sources in developing countries (WHO, 2003). However, when starch is heated in water it swells, gelatinizes and pastes to form a thick gruel at relatively low solids content (Ratnayake and Jackson, 2006, Li et al., 2008, Amagloh et al., 2013b). At these critical solids concentrations (c*) of the porridge system, the gelatinized amorphous starch chains progressively approach each other and begin to overlap at the entanglement concentration (c_e) (Wool, 1993). This increases the shear resistance (viscosity) of the system, which is perceived by mechanoreceptors in the mouth as a thickness perception (Cook et al., 2005). In general, high molecular weight polymers display more effective molecular entanglements (Mezger, 2014, Gina, 2016), and are often perceived as more viscous compared to those with smaller molecules. The resulting viscous porridge is difficult to consume and swallow for infants due to their limited oromotor capacity (Cichero, 2017). For easier consumption, the porridge is normally diluted with water up to about 90 %

(9 parts water: 1 part solids) (Walker, 1990) or more. In this diluted form, both the energy and protein content are critically limited (Muoki, 2013a, Carvalho, 2014, Tumwebaze et al., 2015). Young children must consume large volumes of this porridge for adequate nutrient intake, but their gastric capacities (about 249 g, 285 g and 345 g/meal for ages 6 - 8, 9 - 11 and 12 - 24 months, respectively) restrict how much they can consume (Dewey and Brown, 2003, Dewey, 2016). The high viscosity of indigenous/local complementary porridge can be a limiting factor for adequate energy and protein intake in infants and young children, leading to malnutrition and stunting (Parvin et al., 2014).

In-mouth viscosity is probably the most important rheological factor for comfortable oral processing of complementary porridge, influenced by infants' oral physiology and the porridge's physical properties (Engmann and Burbidge, 2013, Alsanei and Chen, 2014). Despite that, clear scientific specifications for the determination of complementary porridge flow properties (dynamic viscosity) have not been well established. A viscosity cut-off of 3 Pa.s - commonly measured at a shear rate of 50/s and eating temperature range of 30 – 40 °C (Kikafunda et al., 1997) has been suggested for an easy-to-swallow, semi-liquid consistency porridge suitable for children below 3 years (Nout, 1993, Thaoge et al., 2003, Newman et al., 2016). However, the viscosity of complementary porridge is shear rate dependent (non-Newtonian) and presently, there is no consensus on the shear rates most representative of the mastication and swallowing processes during infant oral processing (Steele et al., 2015, Sukkar et al., 2018). Actual shear rates depend on the age, oral pressure exerted and the porridge properties. When studying porridge properties, application of a single shear rate may not be practical since the oral physiology and shear capacity of infants evolve with growth (Nicosia, 2013).

In Africa, various commercial complementary foods are available, yet stunting rates remain high. These commercial complementary foods are too expensive and most poor families cannot afford them (Anoma et al., 2014). Good quality complementary porridge should be appropriately adapted to the chewing ability of the infant or small child to provide for pleasant early feeding experiences (Black et al., 2017). Infants' oral-motor deficits may impact on their ability to generate the shear forces and physiological behaviours typical of matured oral processing and swallowing. Complementary foods should be adequate in energy (at least 3.3 kJ/g to 4,2 kJ/g), proteins and essential amino acids for healthy infants' growth and development (Dewey and Brown, 2003, Solomons and Vossenaar, 2013, GAIN, 2014).

This study explored how the viscosity at different shear rates of various indigenous/locally available complementary porridge samples in Sub-Saharan African communities affect the protein-energy density to meet the recommended nutrient intakes for infants and young children aged 6 - 8; 9 - 11 and 12 - 24 months, respectively. Such information will be of value in designing appropriate foods and to inform science-based policy formulation for enhancing the quality, safety and appropriateness of indigenous/local complementary foods to improve child nutrition.

4.2. Materials and Methods

4.2.1. Materials

Eight (8) indigenous flour samples and a reference (a commonly used commercial complementary porridge), (Table 7) were used in the study.

Table 7. *Complementary porridge flour samples used in the study*

Flour/Porridge	**Purchased from**	**Description**
Indigenous/local		
Maize	Local supermarket (Pretoria, RSA)	Super maize meal (commercially processed)
Sorghum	Local supermarket (Pretoria, RSA)	Super mabela flour (commercially processed)
Pearl Millet	Agricol (Pty) Ltd (Pretoria, RSA)	Commercially packed seeds
Teff	Pannar® Seed (Pty) Limited (Pretoria, RSA)	Commercial seeds, Rooiberg cultivar
Bambara groundnut	Mbare Produce market (Harare, Zimbabwe)	Seeds, cream cultivar
Cowpea	Agricol (Pty) Ltd (Pretoria, RSA)	Commercial seeds, Agrinawa cultivar
Cassava	Thai Farm International (Ogun, Nigeria)	High quality cassava (84,4% starch)
OFSP**	Exilite 499 cc (Tzaneen, Limpopo, RSA)	Dried with electric dryer (60 °C, 6-8 h)
A1- Reference *	Local supermarket (Pretoria, RSA)	Enzyme-hydrolysed cereal (Maize 62 %), add water

**Commercial reference (containing skim milk powder, 25 %) was purchased from local supermarkets in Pretoria, South Africa. The reference (25 % solids) was mixed at 50g powder to 150 ml warm water to prepare it for infants and young children 6-24 months old. **Orange-fleshed sweetpotato. Cooked porridges had a cooking loss of 5 %. Adapted from Michaelsen and Friis (1998); Amagloh et al. (2012); Abeshu et al. (2016)*

4.2.2. Methods

Bambara groundnut and cowpea seeds were first decorticated (61.0 and 70.5 % extraction rate respectively) using a Tangential Abrasive Dehulling Device (TADD, Venables Machine Works, Saskatoon, Canada) and milled to below 250 µm flour particle size with a laboratory mill (Laboratory mill 3100, Perten Instruments, Hägersten, Sweden). Pearl millet and teff grains were milled whole because of their very small size which is difficult to dehull. The surface mean diameter and volume for a pearl millet grain are 1.7 mm – 2.0 mm and 3.8 mm^3 – 5.8 mm^3 respectively (Jain and Bal, 1997), and teff is an even smaller grain. All flour samples used were passed through a 250 µm particle size sieve.

4.2.3. Analyses

4.2.3.1 Proximate analysis of complementary flour samples

Moisture analysis of flour samples was done according to method 925.09 (AOAC, 2000). The Dumas Method, AOAC 968.06 was used for protein content analysis using a nitrogen factor of 6.25 recommended for all types of infant formula (Koletzko et al., 2005). Fat content was measured according to method AOAC, 2003.05 using a Soxtec Fat Extractor (Raypa®, Barcelona, Spain) and petroleum ether solvent. For ash analysis, method AOAC 942.05, (AOAC, 2012) was used. Total carbohydrate (%) was calculated by the difference from 100 %. Determinations were done in triplicate for each flour type, using a fresh flour sample with each replication.

4.2.3.2 Energy content of complementary flour samples

Energy values were calculated from the protein, fat and carbohydrate contents using the Atwater's conversion factors according to Bazaz et al. (2016):

$$Energy\ content\ (kJ\ per\ 100g) = 4.18[(4 \times carbohydrate\ \%) + (4 \times protein\ \%) + (9 \times fat\ \%)] \qquad \textit{Equation 1}$$

The value of 4.18 is the conversion factor between kcal and kJ, the SI units (kJ), where 1 kcal is equivalent to 4.18 kJ. (Fulgoni et al., 2009).

4.2.3.3 Flow properties and apparent viscosity of complementary porridge samples

A rotational rheometer (Physica MCR 101, Anton Paar, Ostfildern, Germany) with temperature control and data acquisition software (Rheoplus version 3.0x, Anton Paar, Ostfildern, Germany) was used to measure the viscosity of porridge samples at different shear rates with a vane spindle (ST22-4V-40, SN 20447, Anton Paar, Ostfildern, Germany). The reference commercial complementary porridge was prepared according to the manufacturer's instructions (Table 1) and a 22 g sample transferred to a rheometer cup. The vane spindle was set to measuring position, the sample was covered with a layer of paraffin oil to minimize moisture loss by evaporation and equilibrated to 40 °C for 10 minutes. The test started in controlled shear rate (CSR) mode from 0.001 - 1000 s^{-1} and back, to measure the apparent viscosity (mPa.s). The shear rate range was chosen to cater for changes in oral shear capacity with increasing infant age. Each experiment was done in triplicate, using a fresh sample prepared from a different infant porridge pack each time.

Indigenous complementary flour samples (maize, sorghum, pearl millet, teff, bambara, cowpea, cassava and OFSP) were first pasted using a paddle spindle (SN 14282, Anton Paar, Ostfildern, Germany). Flour suspensions (2% to 16% (w/v), and up to 24% for OFSP) were prepared in 22 mL of deionised water in a rheometer cup, mounted on a rheometer and covered before pasting began to reduce moisture loss during pasting. Each suspension was equilibrated at 50 °C for 1 min then heated to 91 ^{o}C at a uniform rate of 5 ^{o}C min^{-1} with constant stirring at 160 rpm. The heated slurry was held at 91 ^{o}C for 7 min, cooled to 50 ^{o}C at a rate of 5 ^{o}C min^{-1} and then held at this temperature for 2 min. Immediately after pasting, the paddle spindle was carefully replaced with a vane spindle (ST22-4V-40, SN 20447, Anton Paar, Ostfildern, Germany) and flow properties were recorded. Dynamic viscosity was carried out over a shear rate range of 0.001 _ 1000 s^{-1}, and values taken at 0.001- (zero-shear), 1, 10 and 50 s^{-1} were used for estimating the in-mouth viscosity of complementary porridge for 6 - 8, 9 - 11 and 12 - 24 months old infants and young children respectively. There is presently no consensus on the shear rates most representative of the mastication and swallowing processes, although 50 s^{-1} has been used (Newman et al., 2016, Sukkar et al., 2018). To this effect, Steele et al. (2015) recommended that until new research findings emerge, the apparent viscosities (for dysphagia clinical fluids- which may have similar flow properties to infant foods) be reported across a range of shear rates (1, 10, 30, 50, and 100/s) for reasonable comparison. Low shear rates are particularly more relevant because the oral motor deficits in compromised groups (infants, elderly and dysphagia) may affect abilities to generate the shear forces and physiological behaviours typical of healthy swallowing.

4.2.4. Energy and protein content of the complementary porridge samples

The energy (kJ/100g) and protein (g/100g) content of indigenous porridge samples were calculated from proximate data based on the dilution ratios determined through flow property analysis. The solids content (%) for which the porridge has a viscosity value of 3 Pa.s (recommended viscosity limit for complementary porridges given to children below 3 years) (Treche, 1999, Thaoge et al., 2003) was used in the calculations. Atwater's conversion factors were used to calculate the energy content of porridge samples as described under section 2.3.2. For a commercial reference complementary porridge, the nutritional information declared on the product package was used in the calculations.

4.2.5. Daily energy and protein intakes from complementary porridge samples

The daily nutrient intake (energy and protein) from complementary porridge were calculated from the energy and protein content as below:

$$Daily\ nutrient\ intake\ = \frac{Nutrient}{1g\ porrige} \times functional\ gastric\ capacity \times meal\ frequency \qquad \textit{Equation 2}$$

based on some assumptions of 3 meals/day and functional gastric capacities of 249 g/meal, 285 g/meal and 345 g/meal for infants and young children of ages 6 - 8, 9 - 11 and 12 - 24 months respectively (Michaelsen and Friis, 1998, Dewey and Brown, 2003).

4.2.6. Statistical analysis

All experiments and analyses were conducted in triplicate from distinct complementary porridge sample units or packets, and data reported as mean values with standard deviations. One-way analysis of variance (ANOVA) at $p \leq 0.05$ was performed to compare the differences in mean values of samples, using Xlstat software (version 2017.5) (Addinsoft, 2019). Fisher's LSD test was used to detect significant differences among samples. Curve fitting in Xlstat® was also used to model viscosity changes from the porridge solids content (%). The suitability of the model fittings was assessed based on the higher correlation coefficient (R^2) and low percent root mean square error (*rmse* %) values and levels of significance for the models. Rheological data of both indigenous and commercial porridge samples were fitted to the power-law model and the Cross rheology models, in order to predict the flow properties of the complementary porridges. The equations of the models are as follows in sequence:

the power-law model: $$\eta = k\gamma^{n-1} \qquad \textit{Equation 3}$$

the Cross rheology model: $$\mu = \frac{\mu 0 + \mu\infty \,.\, \alpha\gamma^{n}}{1 + \alpha\gamma^{n}} \qquad \textit{Equation 4}$$

or the simplified Cross rheology model: $$\mu = \mu\infty + \frac{\mu 0}{\alpha}\gamma^{-n} \qquad \textit{Equation 5}$$

where η or μ represent the effective viscosity of the fluid food as a function of shear rate, γ is the shear rate, μ_0 is the zero-shear viscosity when the shear rate is close to zero, $\mu\infty$ is the viscosity when the shear rate is infinite, n is the flow behavior index, and k or α is the consistency index with dimensions of s^n (Jun and Yee-Chung, 2016).

4.3. Results and discussion

4.3.1. Proximate and energy content of indigenous/locally available flour samples

Table 8 shows the proximate composition of some indigenous/locally available flour samples often used to prepare complementary porridge for feeding young children in some low-income African households. Maize and pearl millet flours were the highest ($p < 0.05$) in energy content, followed by sorghum, teff and cassava, then legumes (cowpea and Bambara groundnut) and lastly OFSP. Fat content % of pearl millet was significantly higher than maize, sorghum, teff, cassava, cowpea followed by Bambara groundnut while OFSP had the lowest fat %. The legumes cowpea and Bambara had the highest protein content, while OFSP and cassava were lowest on dry basis.

Table 8. *Proximate and energy density of common African indigenous and locally available flours used in complementary porridge preparation for infant and young child feeding.*

Flour type	**Moisture (%, as is)**	**Ash (% db)**	**Protein (% db)**	**Fat (% db)**	**Carbohydrate* (% db)**	**Energy (kJ/100 g)**
Maize**	$12.7^{a}\pm1.0$	$0.7^{f}\pm0.2$	$7.4^{e}\pm0.1$	$1.9^{b}\pm0,6$	$89.9^{b}\pm0.4$	1701.2^{b}
Sorghum	$14.0^{a}\pm0.0$	$1.1^{e}\pm0.1$	$6.5^{f}\pm0.2$	$1.9^{b}\pm0.8$	$90.4^{b}\pm0.8$	1695.5^{b}
Pearl Millet	$9.2^{c}\pm0.3$	$1.5^{d}\pm0.2$	$13.1^{c}\pm0.2$	$6.0^{a}\pm0.8$	$79.4^{e}\pm0.6$	1774.0^{a}
Teff	$7.1^{e}\pm0.3$	$2.1^{c}\pm0.2$	$11.4^{d}\pm0.2$	$2.6^{b}\pm0.7$	$83.9^{d}\pm0.6$	1694.2^{b}
Cowpea	$9.1^{c}\pm0.3$	$3.6^{b}\pm0.0$	$27.9^{a}\pm0.1$	$2.8^{b}\pm0.2$	$65.7^{g}\pm0.2$	1672.0^{c}
Bambara groundnut	$8.1^{d}\pm0.3$	$3.5^{b}\pm0.0$	$21.5^{b}\pm0.2$	$2.1^{b}\pm0.2$	$72.9^{f}\pm0.2$	1657.3^{c}
OFSP	$8.0^{d}\pm0.0$	$4.3^{a}\pm0.2$	$5.6^{g}\pm0.1$	$0.5^{c}\pm0.0$	$89.7^{b}\pm0.1$	1612.6^{d}
Cassava	$10.9^{b}\pm0.0$	$0.6^{f}\pm0.0$	$1.18^{h}\pm0.0$	$2.0^{b}\pm0.2$	$96.3^{a}\pm0.2$	1705.9^{b}
Reference#	2.5	3.00	15.0	9.5	70.0	1774.0

**Calculated by difference. Values in the same column with different superscripts show that the means ± standard deviations (3 replicates) are different at $p \leq 0.05$. #A reputable commercial porridge sample (Table 1).*

Prior to cooking, all flour samples generally were closer and comparable to the commercial complementary reference energy content (1772 kJ/100g). However, it is the amount of a specific nutrient in a cooked porridge of acceptable viscosity,- that determines its efficacy in meeting the nutrient requirements of infants and young children (Dewey and Brown, 2003). Nutrient density is dependent on the total solids content in a porridge, but the physicochemical properties of the flour also influence porridge viscosity.

The significantly higher ($p < 0.05$) energy content of pearl millet compared to other flour types may be attributed to its elevated lipid content (Table 2) because of the inclusion of the germ, which is about 17.4% of the kernel (Nambiar et al., 2011). The energy content results for pearl millet flour agree with literature reported findings of 1516 kJ/100g (NIN, 2003) and 1660 – 1747 kJ/100g (Sade, 2009). In earlier studies, Kikafunda et al. (1997) and Nuss and Tanumihardjo (2010) reported similar energy content results (1543 kJ and 1526 kJ respectively) for maize flour. The absence of a germ component in OFSP and cassava, and in legumes due to dehulling probably explains the lower energy content of these flours. The energy content of the commercial reference porridge was much higher due to its processing history involving the enzymatic hydrolysis of macromolecular carbohydrates. Hydrolysis reduces the viscosity of complementary porridges and permits more solids addition to the porridge leading to a higher energy density (Michaelsen and Friis, 1998).

As expected for legumes, cowpea and Bambara had the highest protein content ($p \leq 0.05$) in agreement with other studies (Olalekan and Bosede, 2010, Balail, 2014) (Table 2). The protein content of maize was within the range of 7 – 10 g/100 g reported by Nuss and Tanumihardjo (2010). Previous studies reported on the protein content of various African indigenous and locally available complementary flour samples: pearl millet 13.6 – 14 % (Saleh et al., 2013, Rathore et al., 2016); sorghum 8.3 %, OFSP 2.7 – 5.8 % (Alam et al., 2016a) and cassava 1.1 % (Rodríguez-Sandoval et al., 2008). The protein content of teff and pearl millet was similar to those of Gebremariam et al. (2014) reported as 11 % and 11.5 %, respectively. For adequate protein intake, infants and young children of ages 6 – 8, 9 – 11 and 12 – 24 months require at least 9.1, 9.6 and 10.9 g total protein intake per day, respectively, and a porridge of acceptable viscosity must provide about 5.2, 6.7 and 9.1 g total protein per day for children aged 6 – 8, 9 – 11 and 12 – 24 months respectively to support healthy growth (Dewey and Brown, 2003). Unless complemented with a legume complementary porridge prepared from cereals, roots and tubers are unlikely to provide adequate protein and energy to infants and young children because the porridge become too viscous at very low solids content. This makes the porridges difficulty to consume and swallow for infants due to their limited oromotor capacity (Cichero, 2017).

4.3.2. Effect of shear rate on the apparent viscosity of indigenous/local porridge samples at different solids content

Figures. 15 (2 % solids), 16 (4 and 6 % solids), 17 (8 and 10 % solids) and 18 (16 % solids) shows the effect of shear rate on the apparent viscosity of the complementary porridge samples. The information given on the nutritional panel for a commercial reference states that it was manufactured by a process involving enzymatic carbohydrate hydrolysis. Initially and at very low shear rate, the apparent viscosity values for all samples seems to be constant (zero-shear viscosity). The zero-shear viscosity was more prominent at higher solid concentration (6 % - 16 %).

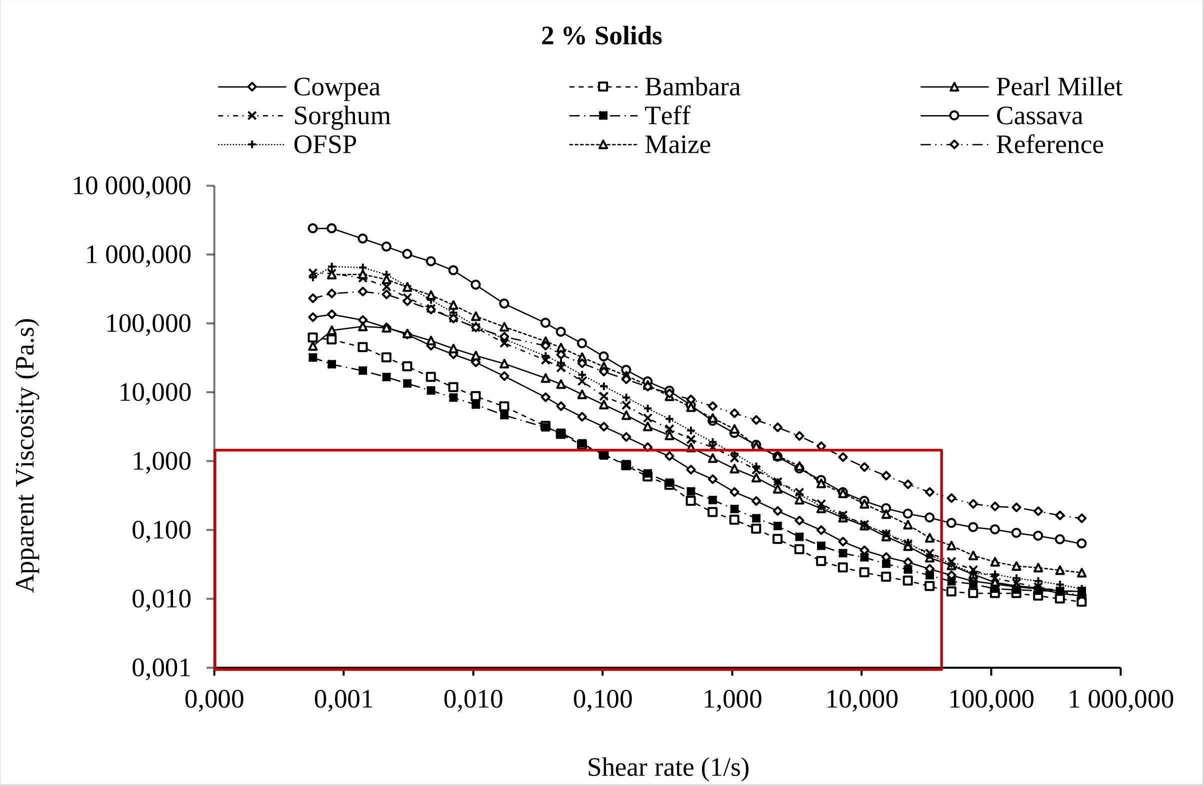
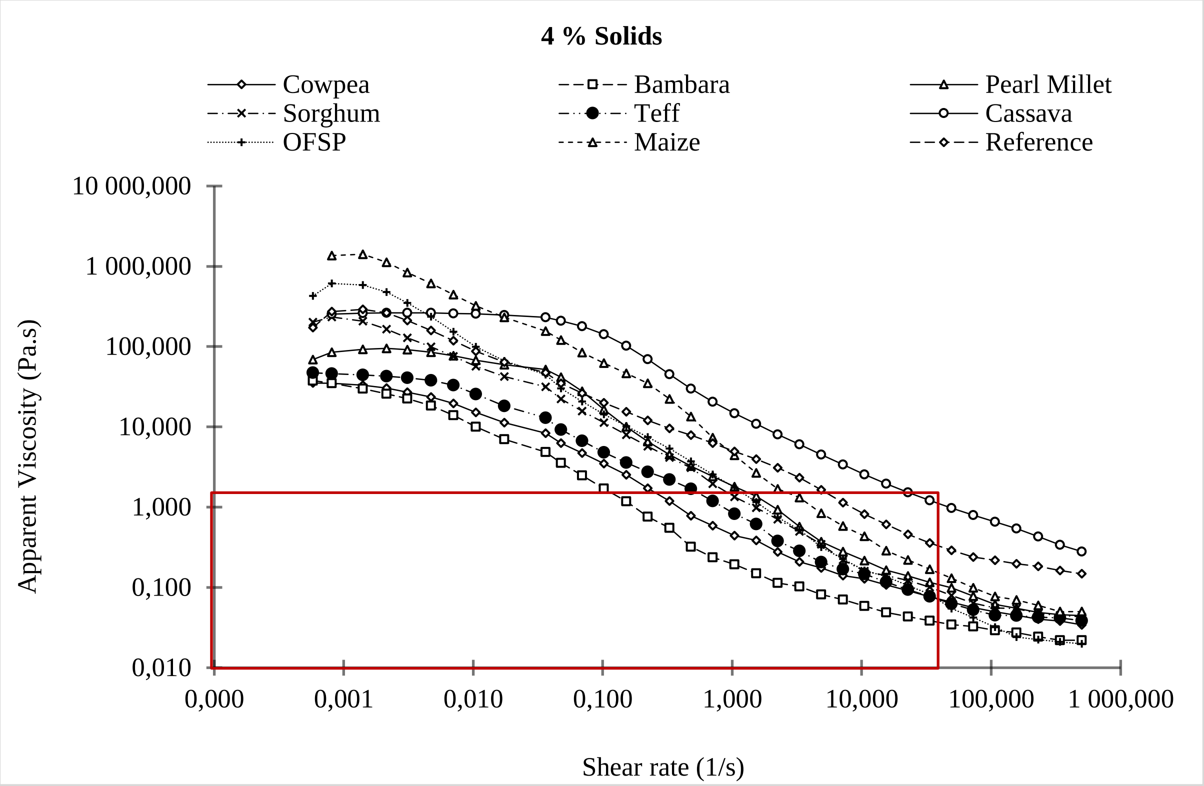


Figure 15. *Viscosity profiles of some African indigenous/ local complementary porridge samples at 2 % solids content. The red box shows a region of optimal viscosity bounded by the recommended viscosity limit of 3 Pa.s (Nout and Ngoddy, 1997a, Rombo et al., 2001, Thaoge et al., 2003) and a shear rate of 50 s*$^{-1}$.



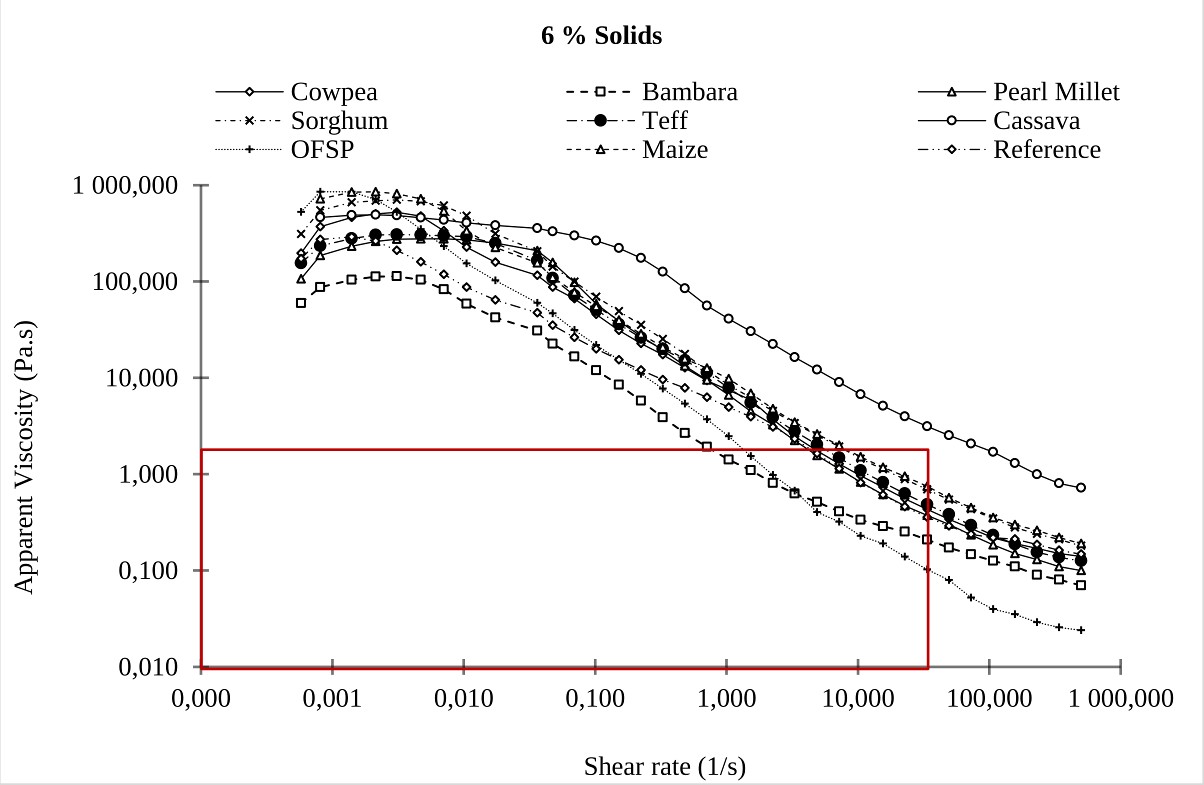
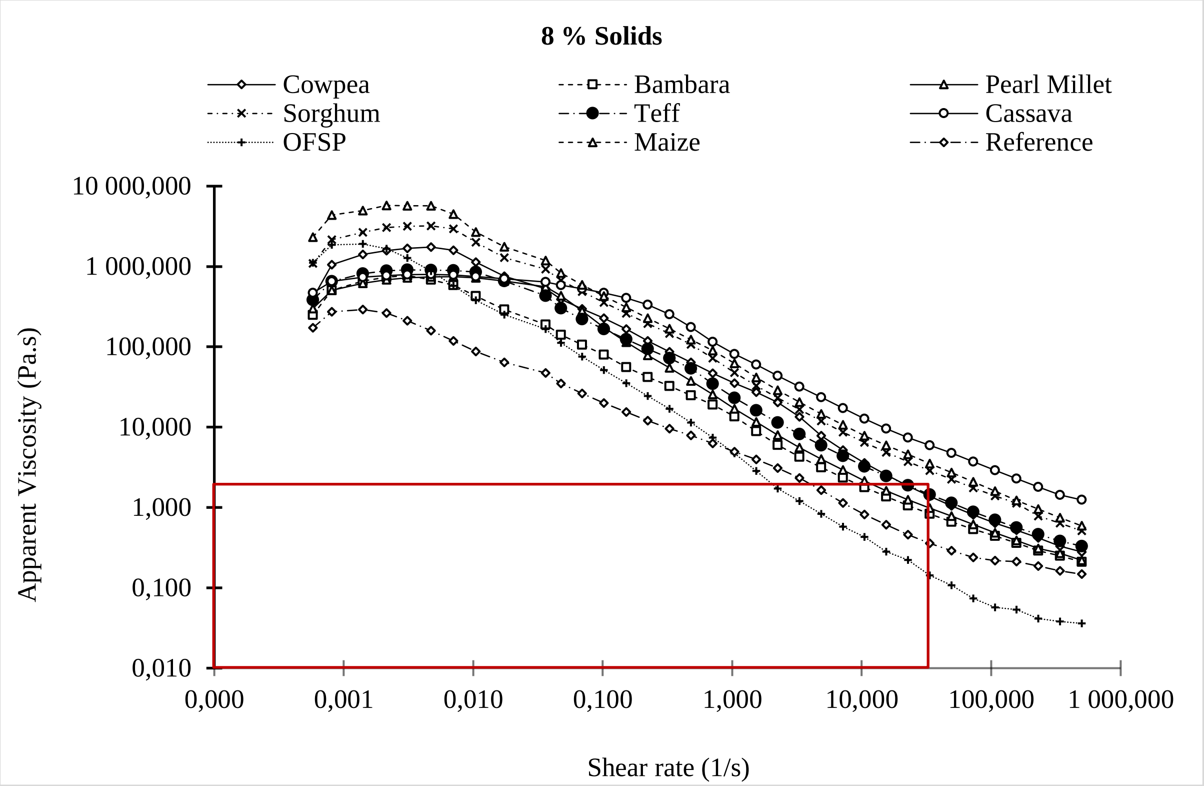


Figure 16. *Viscosity profiles of some African indigenous/ local complementary porridge samples at 4 and 6 % solids content respectively. The recommended viscosity limit: 3 Pa.s (Continued from Figure 15).*



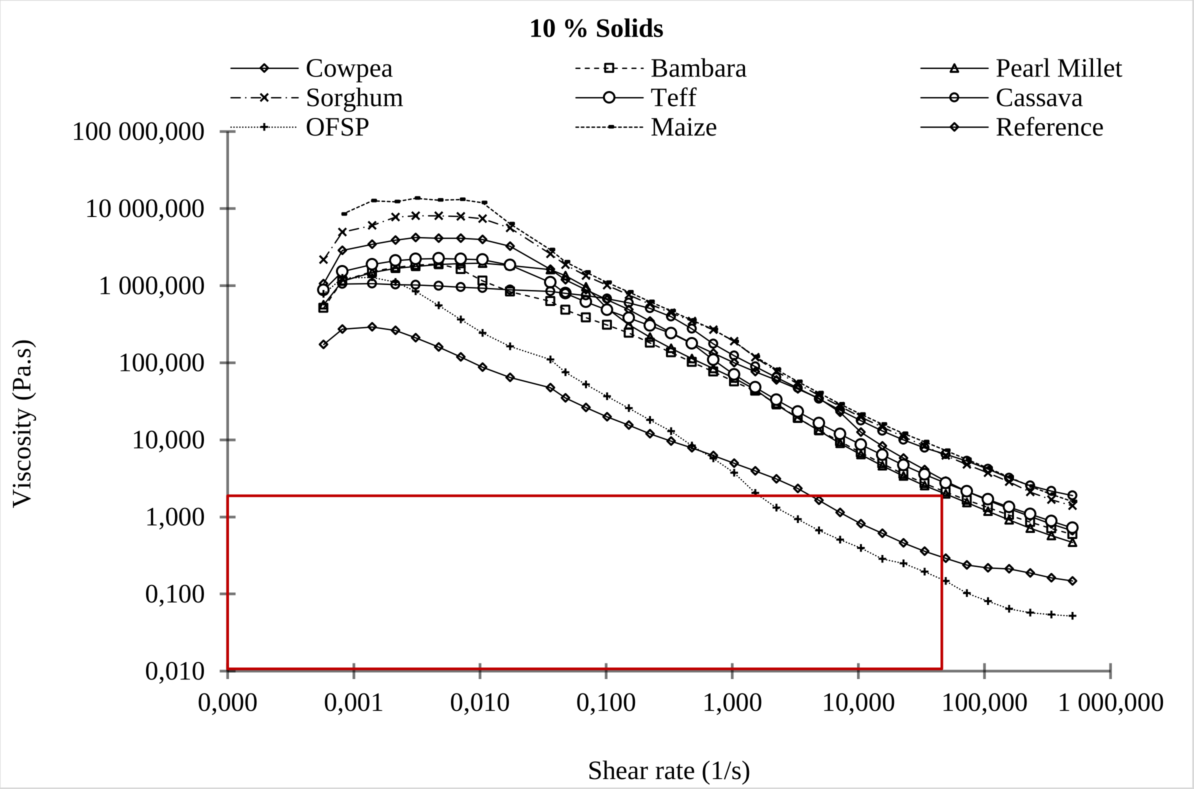


Figure 17. *Viscosity profiles of some African indigenous/ local complementary porridge samples at 8 and 10 % solids content respectively. The recommended viscosity limit: 3 Pa.s (Continued from Figure 15).*

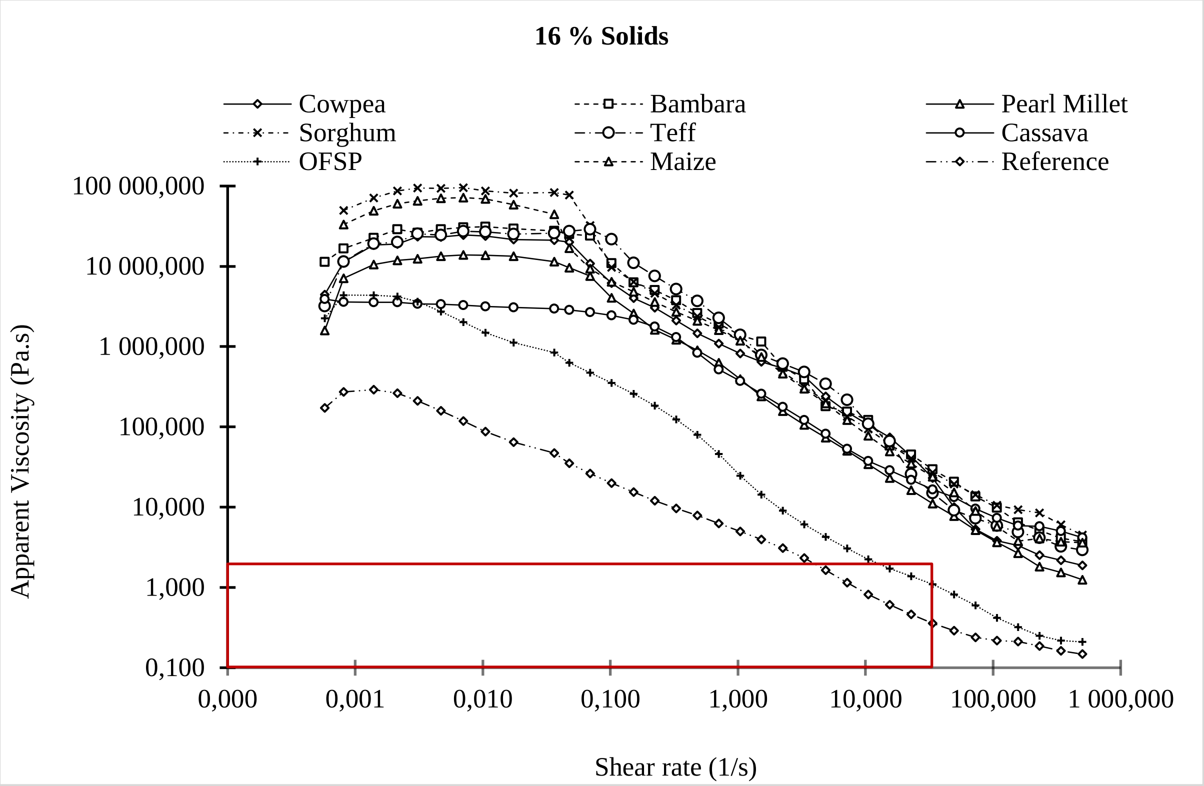


Figure 18. *Viscosity profiles of some African indigenous/ local complementary porridge samples at 16 % solids content. The recommended viscosity limit: 3 Pa.s (Nout and Ngoddy, 1997a, Rombo et al., 2001, Thaoge et al., 2003) (Continued from Figure 15).*

Maize, cassava and sorghum porridges had the highest zero-shear viscosity values at all solids content values ($p \leq 0.05$), while OFSP and the commercial reference porridge had the lowest values. The recommended viscosity limit is 3 Pa.s (Mosha and Svanberg, 1983, Nout and Ngoddy, 1997b, Rombo et al., 2001, Trèche, 2001, Thaoge et al., 2003). OFSP and the reference commercial porridge achieved this limit, within the shear rate range of 1/s – 100/s assumed as applicable for oral processing (Steele et al., 2015, Newman et al., 2016, Sukkar et al., 2018). These two showed much lower apparent viscosity profiles compared to the rest.

Beyond the zero-shear viscosity zone, increasing the shear rate led to a uniform decrease in the apparent viscosity of the porridge samples (the Newtonian, shear-thinning region) (Figures 15 - 18). Viscosity is the tendency of fluids to resist deformation and flow when subjected to an applied force (Tiest, 2015). The flow properties of starch-containing foods depends predominantly on starch hydrodynamic changes during preparation (Delcour and Hoseney, 2010, Guo et al., 2017). Starch is a glucose polymer of amylose and amylopectin. Amylose is essentially a linear macromolecule made up of mainly α-(1,4)-linked D-glucopyranosyl units, with a low degree of branching of less than 1% linkages (Delcour et al., 2010). Uncooked starch forms a temporary suspension in water which eventually settles to the bottom (Wernersson, 2016). However, during cooking, starch loses its molecular structural organization due to melting of crystallites during a process of gelatinisation , accompanied by simultaneous changes such as water absorption, granular swelling and amylose solubilisation to produce a viscous paste (Guggisberg, 2004). Pasting increase the apparent viscosity of complementary porridges due to granular water absorption, swelling and leaching of amylose into the surrounding media (Wernersson, 2016).

The higher zero-shear viscosity values for maize, sorghum and cassava porridges are consistent with the higher starch: sugars ratio in these porridge samples compared to OFSP and the reference sample. Johnson et al. (2010) reported starch: sugar proportions in cassava (75 %: 6 %), sweet potato (70 %: 11 %) while for sorghum, Adeyeye (2016) found the value of 70 %: 1 %. In a previous study, Amagloh et al. (2013b) observed much lower apparent viscosity values for sweet potato-based complementary porridge formulations relative to maize-based and suggested that a higher sugar to starch ratio in OFSP-based complementary food must have caused the viscosity differences. The long chain starch macromolecules have greater participation in molecular entanglement as opposed to simple sugars which are predominant in OFSP and the commercial reference. The simple sugars do not contribute to high viscosity due to their non-involvement in molecular entanglement. Sugars also make swollen granules less sensitive to mechanical disruption (Mason, 2009). Polymers with larger molecules display effective entanglements between individual molecular chains in the low-shear range (zero-shear viscosity), the higher the molar mass, the higher the zero-shear viscosity plateau (Mezger, 2014).

The zero-shear viscosity range is due to the superposition of two concurrent processes of molecular disentanglement and elastic recoil. When a low shear load is applied, some amylose macromolecules partially disentangle and align with the shear direction thus decreasing viscosity. At the same time, some macro-molecules already shear-oriented and disentangled are relinking and re-entangling continuously (elastic recoil), thus reverting to high viscosity (Gina, 2016). The high zero-shear viscosity values, even at low solids (10%) for porridge samples prepared from the major cereals (maize and sorghum) and cassava is problematic considering that ease of swallowing demands the food bolus to be readily deformable and flowable (Chen and Lolivret, 2011). For easier consumption and safe swallowing, complementary porridge must have lower zero-shear viscosity to compensate for the limited oral processing abilities in infants and young children (Schwartz et al., 2018). Hydrophilic solutes such as sucrose and glucose compete for water, and can delay and inhibit starch swelling, decrease the rate of thickening and the enthalpy of gelatinization (Mason, 2009).

In the shear-thinning range (Figures. 15 - 18), maize, sorghum and cassava exhibited the least shear thinning behaviour, with OFSP and the reference sample being more shear-thinning. All porridge samples showed viscoelastic and pseudoplastic behaviour. According to Mezger (2014), shear-thinning occurs because at increasingly higher shear rates more and more polymer chain interactions within the porridge are being broken down because the shear load is now greater than the inter-molecular recoil (spring behaviour). Consequently, the number of molecular chain disentanglements exceeds that of re-entanglements leading to a decrease in apparent viscosity (Van Hecke et al., 2012).

The main inter-molecular forces operational in flowing dispersions are ionic, hydrodynamic, Brownian motion and elastic colloidal forces (Genovese et al., 2007). These are progressively broken down with increasing shear force. The typical shear rate range for chewing and swallowing has variously been reported as 10/s – 100/s (Brookefield, 2017), and in some cases 5/s – 1000/s (Sukkar et al., 2018, la Fuente et al., 2019).

Table 9 shows the power law model parameter values for 8 indigenous/local complementary porridge samples (10 % solids) and the commercial complementary porridge reference (25 %).

Table 9. *Power law model parameters for some African indigenous complementary porridge samples (10 % solids, analysed at 40 °C) used in this study.*

Complementary Porridge Name	**K* (Pa.sn)**	**n****	**R^2**
Maize (decorticated)	$173.2^{a} \pm 3.5$	$0.2^{d} \pm 0.0$	0.95
Sorghum (decorticated)	$134.7^{b} \pm 1.2$	$0.3^{a} \pm 0.0$	0.80
Teff	$57.5^{e} \pm 0.4$	$0.3^{a} \pm 0.0$	0.77
Pearl Millet	$7.1^{g} \pm 0.1$	$0.3^{bc} \pm 0.0$	0.80
Cowpea (decorticated)	$84,61^{d} \pm 17.0$	$0.3^{c} \pm 0.0$	0.71
Bambara (decorticated)	$43.11^{f} \pm 6.8$	$0.2^{d} \pm 0.1$	0.96
Cassava	$105.9^{c} \pm 2.9$	$0.3^{ab} \pm 0.0$	0.88
OFSP	$3.5^{g} \pm 0.6$	$0.1^{e} \pm 0.0$	0.14
Commercial reference	$4.7^{g} \pm 0.6$	$0.3^{ab} \pm 0.0$	0.99

K is the consistency coefficient; n** is the flow behaviour index. R^2 is a power-law regression coefficient which estimates the degree of fit of the model to the shear-thinning behaviour. Values in the same column with different superscripts are different ($p \leq 0.05$). Replicates (3 in each case) analyses at shear rates of 0.01 to 1000 s^{-1}.*

Consistent with figures. 15 (2 % solids), 16 (4 and 6 % solids), 17 (8 and 10 % solids) and 18 (16 % solids), all porridge samples differed significantly ($p \leq 0.05$) in terms of the flow behaviour index ($n < 1$), with OFSP having the lowest value. The results agree with Alvarez and Canet (2013) who also observed shear-thinning behaviour in some vegetable-based infant purees. The commercial reference porridge had a good power law model fit confirmed by the R^2 value of 0.99, while indigenous porridge samples showed lower R^2 values (0.71 – 0.96) depending on the botanical source of the flour used. One of the obvious limitations of the power-law model however, is that it fails to describe the low-shear rate region (Rao, 2007b), and at high shear rates it tends to give too low apparent viscosity values in comparison with empirical data (Whitty and Wain, 2018). These weaknesses are resolved when the Cross model (Cross, 1965) is applied, which states that at extreme shear rates (i.e. at very low or very high), thixotropic fluids assume a Newtonian viscosity (Modigell et al., 2018). Table 10 shows results of the Cross model fitted to the rheological data.

Table 10. *Cross model parameters prediction for the flow behaviour index, zero-shear viscosity and infinite viscosity values of some African indigenous porridge samples at 40 °C.*

Complementary - porridge name	**Solids (%)**	**Flow behaviour-index (n)**	**Infinite viscosity (Pa.s)**	**Zero-shear - viscosity (Pa.s)**
Maize	6.0	0.6	0.3	303.4
	10.0	0.8	4.8	4789.4
Sorghum	6.0	0.6	0.2	210.3
	10.0	0.8	5.0	5038.0
Teff	6.0	0.7	0.2	222.8
	10.0	0.7	1.8	1761.0
Pearl millet	6.0	0.7	0.2	218.2
	10.0	0.8	1.7	1668.0
Cassava	6.0	0.7	0.9	882.2
	10.0	0.7	3.2	3156.3
OFSP	6.0	0.8	0.1	87.5
	10.0	0.7	0.2	156.0
Bambara	6.0	0.5	0.0	48.6
	10.0	0.8	1.5	1491.0
Cowpea	6.0	0.7	0.3	305.0
	10.0	0.9	0.7	691.0
Commercial reference	25.0	0.6	0.2	182.3

Although the n-values for the Cross model were higher compared to those for the power-law model, the values confirmed the shear-thinning behaviour for all complementary porridges. Shear-thinning fluids are characterized by a value of $n < 1$ (range of 0.3 - 0.7) for many polymer melts and solutions (Chhabra, 2010). Maize, sorghum and cassava porridges across all solids content levels had the highest Cross model zero-shear viscosity estimates consistent with Figure 16 (A – F), indicating a good prediction of the low shear viscosity of the porridges. The Cross model is an empirical model designed to fit a straight line portion between the two Newtonian plateaus (zero shear and infinite shear viscosities) of thixotropic fluids (Whitty and Wain, 2018), in order to predict shear-thinning behaviour and recover the zero-shear viscosity and infinite viscosity values (Chhabra, 2010). Low-shear viscosity for in-mouth food oral processing is becoming increasingly more relevant, especially in consideration of infants and young child feeding. Using an adult sensory evaluation panel, Conti-Silva et al. (2018) found that the apparent viscosity of some gelatin samples measured at shear rate of 10 s^{-1} highly correlated positively with the samples' oral viscosity and body (sensory texture attributes evaluated by oral perception), although a strong and positive correlation was also found between body and apparent viscosity at higher shear rates (50 and 100 s^{-1}).

4.3.3 Effect of solids content on the apparent viscosity profiles of indigenous/local porridge samples at different shear rates

The effect of increasing the solids content of indigenous complementary porridges at different shear rates, on the apparent viscosity of porridges is represented in Figures. 19 (shear rate 0.01 and 0.1 s^{-1}), Figure. 20 (shear rate 1 and 10 s^{-1}) and Figure. 21 (shear rate 50 s^{-1}).

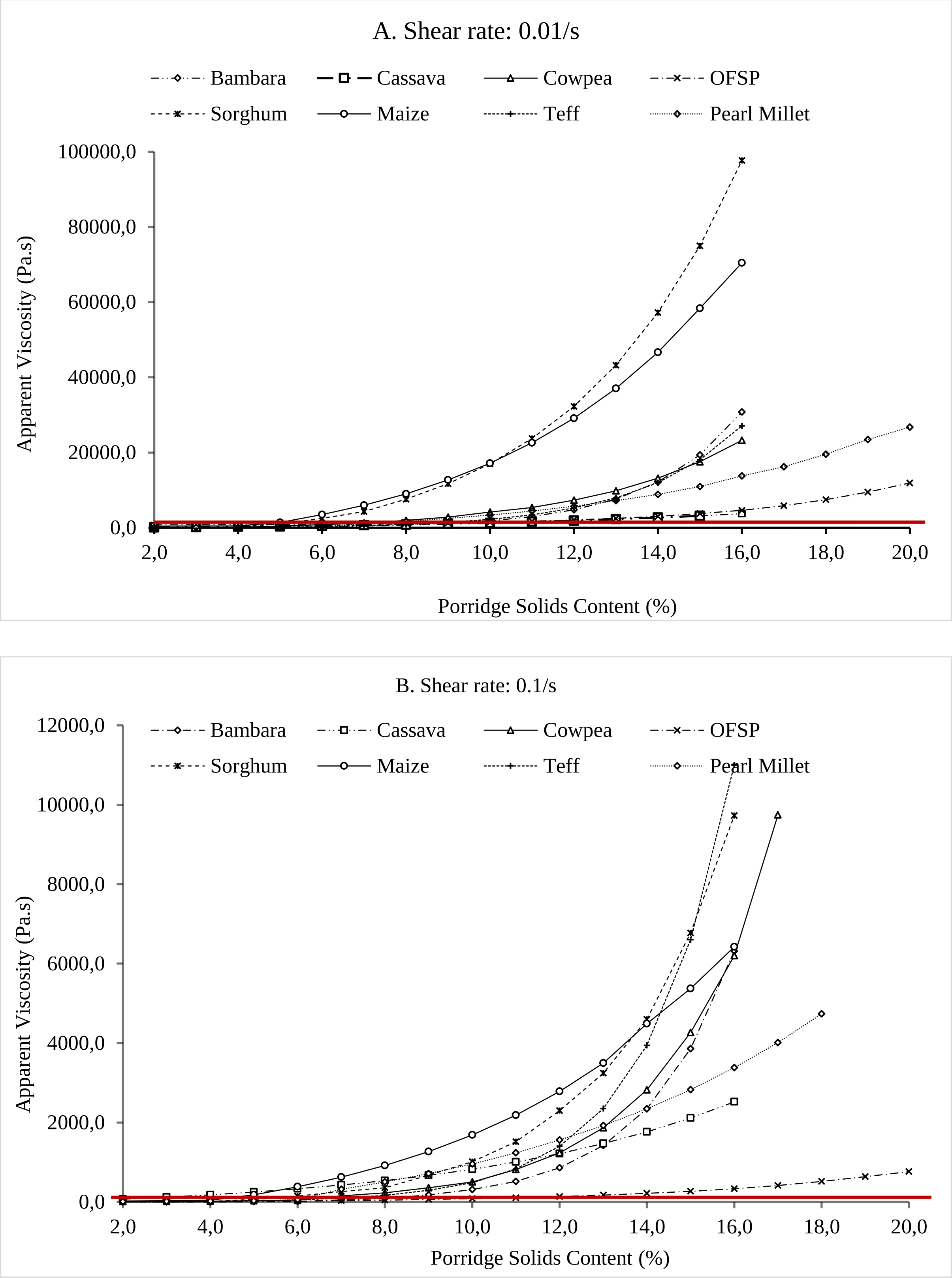


Figure 19. *Effects of solids content and shear rate (0.01 and 0.1/s) on the apparent viscosity of African indigenous and local complementary porridge samples analysed at a temperature of 40 °C. The critical viscosity limit of ≤ 3 Pa.s (Mosha and Svanberg, 1983, Mosha and Vicent, 2005, Mouquet et al., 2006) is shown with a red line.*

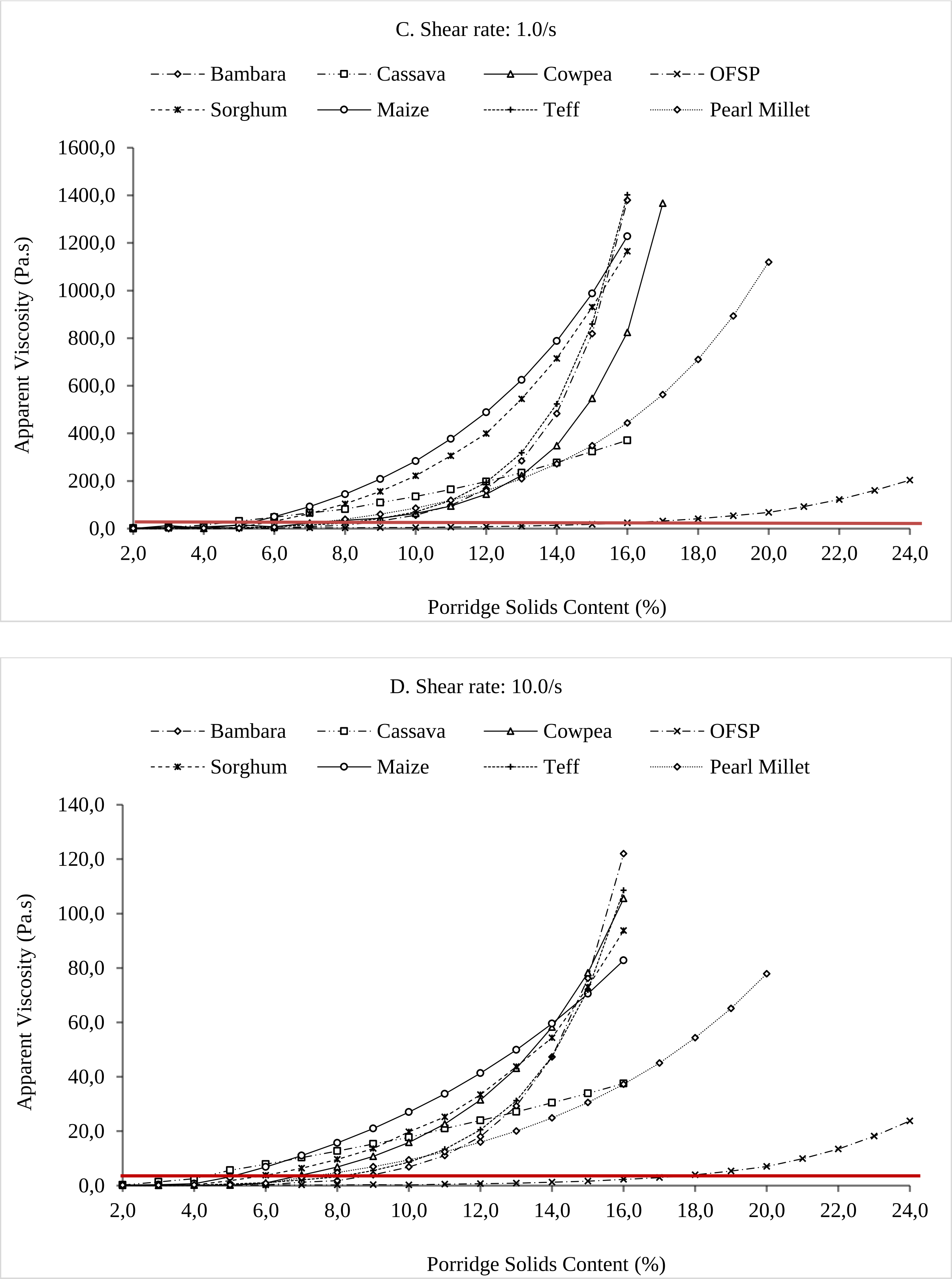


Figure 20. *Effects of solids content and shear rate (1.0 and 10.0 /s) on the apparent viscosity of African indigenous and local complementary porridge samples analysed at a temperature of 40 ℃ (Continued).*

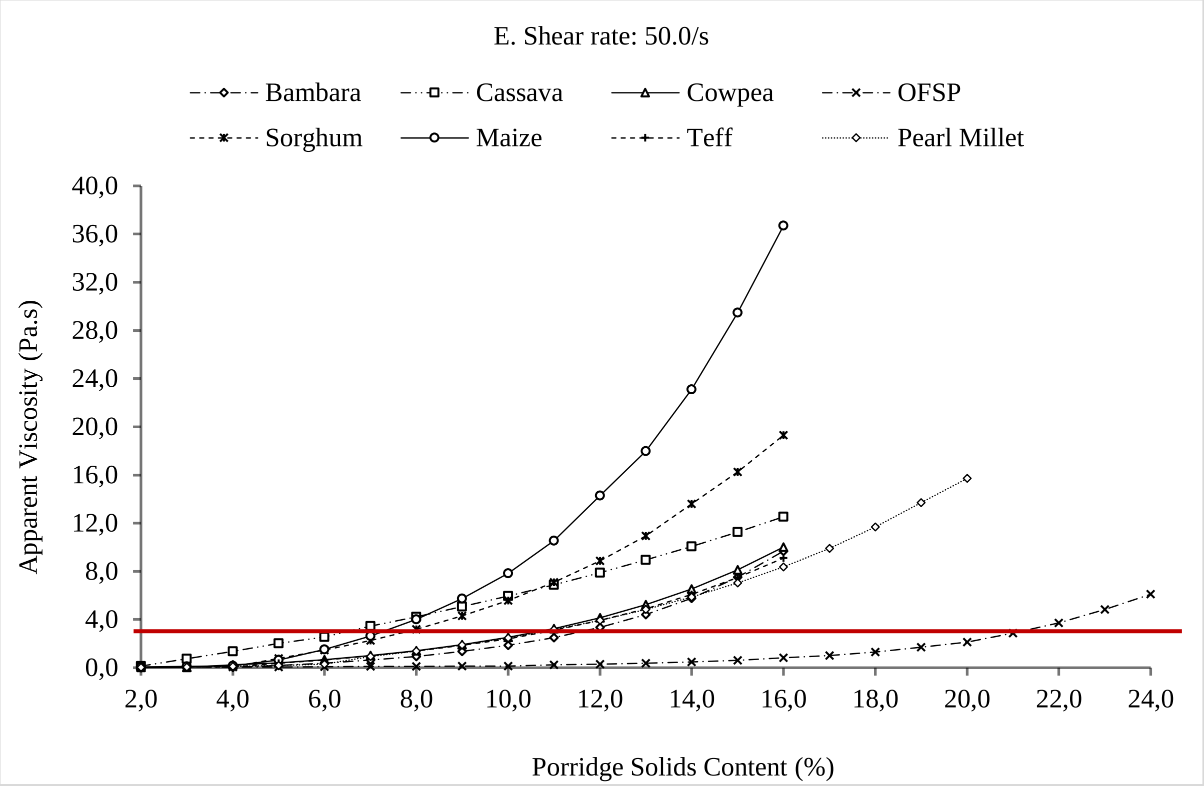


Figure 21. *A – E. Effects of solids content and a shear rate of 50.0/s on the apparent viscosity of African indigenous and local complementary porridge samples analysed at a temperature of 40 °C (Continued).*

Irrespective of shear rate, an increase in solids content led to an exponential increase in the viscosity of the porridge. Experimental data were fitted to an exponential first order model:

$\eta = a^{bX}$ Equation 4

where **η** is the apparent viscosity (mPa.s), **a** is empirical constant (mPa.s), **b** is constant (%$^{-1}$) and **X** is solid content (%) (Table 4).

The constant of the equation '**a**' relates the apparent viscosity exponentially with concentration (X) (Manjunatha and Raju, 2013). According to Dak et al. (2008), the effect of solids content on apparent viscosity is generally described by an exponential type relationship.

The rate of exponential viscosity increase was porridge type dependent, such that for maize, sorghum and cassava porridges the increase was much more rapid with an increase in solids, while OFSP had the slowest viscosity increment. This was probably attributable to a general increase in amylose content of non-OFSP porridges at higher solids content. Higher amylose content increases entanglements between chains, since the highly branched amylopectin do not form effective entanglements (Babu et al., 2015). Likewise, the lower rate of increase in apparent viscosity of OFSP may be explained by its higher levels of sugars, which do not form entanglements. With the exception of OFSP (20.8 % solids), indigenous porridges exceeded the critical viscosity limit (3 Pa.s) at very low solids content (≈ 10 %) even at shear rate above 50/s - a value conventionally taken to represent the oral shear rate (Sukkar et al., 2018) in healthy adults. These differences in the rate of change of viscosity could be related to the variations in starch type and source, and in the amylose : amylopectin ratio which varies between the crops (Bahaji et al., 2014). The concentration, granule size, and distribution, extent of swelling, hardness of starch granule particles, as well as the state of entanglement, all affect the viscoelasticity of starch-containing food systems (Hsu et al., 2000).

Results were in agreement with Taga and Nono (2017), who found that gruels prepared from starchy African indigenous flours had viscosity profiles that increases very rapidly as a function of their dry matter concentration. In another study, Adebowale and Sanni (2013) found that at 10% tapioca solid concentration, the paste produced was very thick and very close to a ‘stiff paste’ usually consumed by adults. When the concentration of particles of a dispersion system is increased, molecular chains get in contact with each other, increasing effective interactions to form coils and entanglements which increases molecular friction and flow resistance (Mezger, 2014). The viscosity of the porridge samples therefore increases with solids content. In previous similar studies on soups (Wernersson, 2016) and fruit and vegetable purees (Krokida et al., 2001), an increase in solids content has been shown to cause a concomitant increase in soup apparent viscosity.

Table 11 shows the effect of shear rate on the solids content of a porridge having a viscosity considered acceptable for baby feeding (3 Pa.s), and nutrient intake from such porridges.

Table 11. *Effect of shear rate on the solids content of African indigenous/local complementary porridge samples, and energy and protein intake estimates in children per day, analysed at apparent viscosity of 3 Pa.s and a temperature of 40 °C.*

	Shear rate	**Model Parameters$^{\#}$**			**Solids**	**Energy**	**Protein**	**Energy intake (kJ/day)**			**Protein intake (g/day)**		
									Months			**Months**	
Porridge type	**(/s)**	**a (Pa.s)**	**b (%-1)**	**rmse (%)**	**(%)**	**(kJ/100g)**	**(g/100g)**	**6 - 8**	**9 - 11**	**12 - 24**	**6 - 8**	**9 - 11**	**12 - 24**
Maize	0.1	143.3 ± 175.0	0.2 ± 0.0	461.7	< 2.0	< 29.0	< 0.2	< 216.6	< 247.8	< 299.9	< 1.2	< 1.4	< 1.7
	1.0	0.6 ± 0.4	0.6 ±0. 1	6.6	2.1	29.0	0.2	216.5	247.8	299.9	1.2	1.4	1.7
	10.0	0.1 ± 0.1	0.5 ± 0.1	0.7	6.2	85.6	0.5	639.1	731.5	885.5	3.5	4.0	4.9
	50.0	0.01± 0.0	0.5 ± 0.1	0.2	8.1	111.8	0.6	835.0	955.7	1156.9	4.6	5.3	6.4
Sorghum	0.1	30.6 ±3.7	0.4 ± 0.0	75.0	< 4.5	< 76.3	< 0.3	< 569.9	< 652.3	< 789.7	< 2.2	< 2.5	< 3.0
	1.0	0.2 ± 0.1	0.7 ± 0.0	2.2	4.5	76.3	0.3	569.9	652.3	789.7	2.2	2.5	3.0
	10.0	0.1 ± 0.0	0.6 ± 0.0	0.4	6.6	111.9	0.4	835.9	956.8	1158.2	3.2	3.7	4.4
	50.0	0.0 ± 0.0	0.5 ± 0.0	0.1	8.4	140.0	0.6	1045.8	1197.0	1449.0	4.1	4.7	5.7
Pearl Millet	0.1	10.0 ± 3.6	0.1 0.0	455.8	< 4.5	< 79.8	< 0.6	< 596.3	< 682.5	<826.2	< 4.4	< 5.0	< 6.1
	1.0	3.2 ± 1.4	0.3 ± 0.0	7.5	4.5	79.8	0.6	596.3	682.5	826.2	4.4	5.0	6.1
	10.0	0.5 ± 0.2	0.3 ± 0.0	0.6	8.5	150.8	1.1	1126.4	1289.3	1560.7	8.3	9.5	11.5
	50.0	0.3 ± 0.1	0.2 ± 0.0	0.2	11.1	200.00	1.5	1494.0	1710.0	2070.0	11.2	12.8	15.5
Teff	0.1	2.8 ± 0.1	0.5 ± 0.0	4.7	< 4.6	< 77.9	< 0.5	< 582.2	< 666.3	< 806.6	< 3.9	< 4.5	< 5.4
	1.0	0.5 ± 0.0	0.5 ± 0.0	1.1	4.6	77.9	0.5	582.2	666.3	806.6	3.9	4.5	5.4
	10.0	0.1 ± 0.0	0.4 ± 0.0	0.2	7.8	132.1	0.9	987.1	1129.9	1367.7	6.6	7.6	9.2
	50.0	0.6 ± 0.3	0.2 ± 0.0	0.3	10.3	170.0	1.2	1269.9	1453.5	1759.5	9.0	10.3	12.4
Cowpea	0.1	8.7 ± 1.1	0.4 ± 0.0	76.8	< 4.7	< 78.6	1.3	587.0	671.9	813.3	9.8	11.2	13.6
	1.0	3.5 ± 0.9	0.3 ± 0.0	7.2	4.7	78.6	< 1.3	< 587.0	< 671.9	< 813.3	< 9.8	< 11.2	< 13.6
	10.0	0.4 ± 0.1	0.4 ± 0.0	1.2	7.8	130.4	2.2	974.2	1115.1	1349.8	16.3	18.6	22.5
	50.0	0.5 ± 0.3	0.2 ± 0.0	0.4	10.1	170.0	2.8	1269.9	1453.5	1759.5	21.1	24.1	29.2
Bambara	0.1	2.2 ± 0.4	0.5 ± 0.0	16.9	< 6.3	< 103.6	< 1.3	< 773.8	< 885.6	< 1072.1	< 10.0	< 11.5	13.9
	1.0	0.3 ± 0.1	0.5 ± 0.0	3.0	6.3	103.6	1.3	773.8	885.6	1072.1	10.0	11.5	< 13.9
	10.0	0.1 ± 0.0	0.5 ± 0.0	0.4	8.5	140.8	1.8	1052.3	1204.4	1458.0	13.7	15.6	18.9
	50.0	0.2 ± 0.1	0.3 ± 0.0	0.3	10.7	180.0	2.3	1344.6	1539.0	1863.0	17.2	19.7	23.8

Table 11. *Effect of shear rate on the solids content of African indigenous/local complementary porridge samples, and energy and protein intake estimates in children per day, analysed at apparent viscosity of 3 Pa.s and a temperature of 40 °C, "Continued".*

	Shear rate	Model Parameters[#]			Solids	Energy	Protein	Energy intake (kJ/day)			Protein intake (g/day)		
								Months			Months		
Porridge type	**(/s)**	**a (Pa.s)**	**b (%-1)**	**rmse (%)**	**(%)**	**(kJ/100g)**	**(g/100g)**	**6 - 8**	**9 - 11**	**12 - 24**	**6 - 8**	**9 - 11**	**12 - 24**
OFSP	0.1	13.8 ± 8.2	0.2 ± 0.0	30.8	< 6.7	< 108.0	< 0.4	< 807.1	< 923.8	1118.3	< 2.8	< 3.2	< 3.9
	1.0	0.3 ± 0.0	0.3 ± 0.0	0.6	6.7	108.0	0.4	807.1	923.8	1118.3	2.8	3.2	3.9
	10.0	0.02 ± 0.0	0.3 ± 0.0	0.1	16.7	269.3	0.9	2011.7	2302.6	2787.3	7.0	8.0	9.7
	50.0	0.01 ± 0.0	0.3 ± 0.0	0.0	20.8	340.0	1.2	2539.8	2907.0	3519.0	9.0	10.3	12.4
Cassava	0.1	204.6 ± 113.7	0.2 ± 0.0	118.6	< 2.2	< 36.7	0.0	< 274.0	< 313.6	< 379.6	< 0.2	< 0.2	< 0.3
	1.0	34.6 ± 18.2	0.2 ± 0.0	4.4	2.2	36.7	0.0	274.0	313.6	379.6	0.2	0.2	0.3
	10.0	11.3 ± 8.6	0.1 ± 0.1	0.8	4.2	71.6	0.0	535.2	612.6	741.6	0.4	0.4	0.5
	50.0	4.6 ± 4.0	0.1 ± 0.1	0.3	6.4	110.0	0.1	821.7	940.5	1138.5	0.7	0.9	1.0
Reference#	10.0 & 50.0	Na	na	na	25.0	444.0	3.125	2661.0	2661.0	2661.0	18.9	18.9	18.9
RNI** for Low BME*** infants:			na	na	na	335.0		2310.0	2933.0	4301.0	5.2	6.7	9.1
RNI** for Average BME*** infants:			na	na	na	335.0		1490.0	2004.0	3230.0	2.0	3.1	5.0

[#] *A First order exponential type equation [$\eta = aExp(bX)$], where η is the predicted apparent viscosity, a and b are empirical constants, and X is the solids content (%). Xlstat exponential growth function: asymptotic regression ($Y = pr1*Exp(pr2*X1)+ pr3$) was selected for model fitting by least squares method ($p \leq 0,05$). rmse is the root mean square error. **Recommended nutrient intake, ***Breast milk energy intake. #A commercial baby cereal. na: not applicable and not analysed. Each value is a mean of 3 replicates. Nutrient intake estimates were calculated using solids (%) for porridge of 3 Pa.s at 40 °C, making assumptions of 3 meals/day and functional gastric capacities of 249g, 285g and 345g/meal for infants and young children aged 6-8, 9-11 and 12-24 months respectively (Brown et al., 1998, Dewey and Brown, 2003).*

.

All porridge samples had low root-mean-square error (*rmse)* values (< 1) at shear rates values of 10 s^{-1} and 50 s^{-1}, significant F-test p-values and high R^2 values (> 0.99), indicating a strong exponential model fit between predicted and observed/measured data under these conditions. Results were consistent with Bhattacharya and Bhattacharya (1994), who showed that the consistency index (a measure of viscosity) of cooked maize suspensions (2 – 10 % solids) followed an exponential relationship with concentration. In other studies, Adebowale and Sanni (2013), Manjunatha and Raju (2013), Kumar et al. (2015), and Taga and Nono (2017) also found that exponential regression best modelled the apparent viscosity of diverse fluid foods based on solids content, with R^2 values (0.991 - 0.999).

The values for *'a'* and *'b'* for all porridge samples decreased significantly ($p \leq 0.05$) with an increase in shear rate, especially for *"a"*, indicating that at lower shear rates, the viscosity of porridge samples increases rapidly when concentration increases. This could be due to changes in the vibrational kinetic energy of the molecules and inter-molecular spacing. The magnitude of *"a"* at a low shear rate (0.001/s) was very high for cassava (1228.19) and maize (143). According to Adebowale and Sanni (2013), *"a"* is an indication of the sensitivity of the cooked porridge suspension to changes in solid content. The decrease in the size of "a" with increasing shear rate mean that porridge viscosity at low shear may be more sensitive to solids content increase, especially beyond a critical solid content where the biopolymers are high enough to get in contact and form entanglements (Mezger, 2014). Because the developmental differences in oral physiology may impact on infants and young children's abilities to orally process thick and sticky indigenous complementary porridges, the knowledge regarding the porridge viscosity dependence on in-vivo shear rate and solids content has important implications for feeding infants, considering that a change from munching pattern to a more efficient rotary chewing occurs at about 12 months of age (Rudolph and Link, 2002, Cichero, 2016). Reduced dentition in infants compromises masticatory efficiency and the tongue's capability in positioning food, and this reduces the effectiveness of food oral break down (Fontijn-Tekamp et al., 2004, Ketel et al., 2019).

Viscosity modelling of indigenous complementary porridge samples at multiple shear rates is important for understanding their rheological behaviour to appreciate their functional qualities (Rao, 2014). Food formulation scientists and product developers can use this information to make quantitative predictions about optimal infant porridge solids content, given the target apparent viscosity and shear rate estimates. The apparent viscosity of non-Newtonian fluids is a function of strain rate, hence a single measurement of viscosity gives a rather poor indication of rheology (Mueller et al., 2009). Moreover, reliance on a single shear rate may not be practical since the oral physiology and shear capacity of infants evolve with growth (Nicosia, 2013).

4.3.4. Daily protein and energy intake estimates

Table 11 shows the daily energy and protein intake estimates from indigenous/local complementary porridge samples when consumed by infants and young children. Intake assumptions were made at various shear rates. The recommended energy intakes from complementary foods for children receiving a low-breast milk energy intake (Low BME) at 6 – 8 months, 9 – 11 months and 12 – 24 months are 2318 kJ/day (552 kcal/day), 2944 kJ (701 kcal/day) and 4318 kJ (1028 kcal/day), respectively. In terms of protein intake, they should receive 5.2 g/day, 6.7 g/day and 9.1 g/day at 6 – 8 months, 9 – 11 months and 12 – 24 months of age, respectively (Dewey and Brown, 2003).

For children getting an average breast milk energy intake (Average BME), complementary foods must provide 1495 kJ/day (356 kcal/day), 2011.8 kJ/day (479 kcal/day) and 3242.4 kJ/day (772 kcal/day) at 6 – 8 months, 9 – 11 months and 12 – 24 months of age, respectively. The protein intakes from complementary foods must be 2.0 g/day, 3.1 g/day and 5.0 g/day, respectively.

For all porridge samples the solids content, energy and protein intakes increased with an increase in shear rate from 0.001/s to 50/s at constant porridge viscosity of 3 Pa.s. At the recommended meal frequency of 3 - 4 meals/day, OFSP porridge has the potential to provide adequate energy intake for all age-groups (6 - 24 months) to children getting average BME intake, and for the 6 – 8 months low BME intake group. The inherently low viscosity of OFSP complementary porridge is related to its low starch: sugar ratio (Amagloh et al., 2013b). This rheological property of OFSP flour makes it an ideal candidate as an ingredient in the formulation of low-viscosity baby porridges. Jemberu et al. (2016) also reported a reduction in viscosity values of maize-based porridges with an increase in OFSP flour in the formulation. A low apparent viscosity flour will be good for inclusion in preparing calorie-dense foods having high solids concentration (Onweluzo and Nwabugwu, 2009b, Deepa and Hebbar, 2017). The porridges were inadequate in energy provision for the low and average BME intake children at all age-groups. Legumes were better energy providers for infants (6 – 8 months) receiving average BME intake, when their in-mouth shear rate is assumed to be 50 s^{-1}.

The total energy intake and protein intake from a complementary porridge depend on its solids content at the acceptable viscosity for infant feeding, as well as functional gastric capacity and oral processing ability and/or efficiency (Dewey, 2013). The assumed functional gastric capacity of infants and young children is normally expressed in grams per body mass (e.g., 30 g/kg body mass), from determinations of how much food is consumed per meal (initial mass - final mass) for many infants and calculating the mean value. Although volume (ml/kg body mass) is also used, it is less preferable because as the infant food becomes more solid it becomes convenient to work with mass than volume. A complementary porridge with at least 1.0 kcal/g (4.2 kJ/g) can provide adequate energy intakes to children experiencing low to average BME intake across the 3 age-groups (6 - 8, 9 -11, 12 - 24 months) if consumed at 3 meals per day (Dewey and Brown, 2003). At 0,8 kcal/g (3,36 kJ/g), the porridge can meet the energy needs of 6 - 11 months old children (1495 kJ/day – 2944 kJ/day) at 3 meals/day, and at 12 - 24 months 3242 kJ/day – 4318 kJ/day) with 4 meals/day. However, maize, sorghum and cassava porridges tended to approach the critical viscosity limit (3 Pa.s) at very low solids content (6.4 % - 8.4 %) compared to that of the reference (25 %), becoming highly viscous as the solids content is raised. Thaoge et al. (2003) reported similarly low energy densities (0.84 – 1.68 kJ/g) in porridge prepared with starchy cereal flours at 5 - 10% dry matter. Baby porridges should have a semi-liquid consistency of about 1 – 3 Pa.s for easy infant consumption (Nout, 1993).

The consistency and energy density of complementary porridge are important in meeting the energy and nutrient requirements of young children (Usman et al., 2016). At the solids content (%) matching a viscosity of 3 Pa.s, indigenous/local complementary porridge samples were unable to meet the daily energy needs (RNI) of the low to average BME intake categories across all 3 age-groups. To raise the energy density and protein value of indigenous/local complementary foods, several researchers have suggested increasing the solids content (Tizazu et al., 2010, de Carvalho et al., 2013, Amagloh et al., 2013b). The present results showed that increasing the solids content resulted in a significant ($p < 0.05$) first-order exponential increase in the apparent viscosity at all shear rate levels (0.001 – 50/s). An increase in solids content reduces the degree of hydration of solute molecules and inter-molecular spacing (Manjunatha and Raju, 2013), and this increases viscosity.

A highly viscous complementary porridge is not acceptable for children (Oyarekua, 2011, Bazaz et al., 2016), because the in-mouth oral shear rates of infants are much lower (Nicosia, 2013). Complementary porridges must allow a high solids content to increase their nutrient density without significantly changing their semi-liquid consistency (Alain et al., 2007). Therefore, it is critical to optimize the apparent viscosity of indigenous/local complementary porridges to match the oromotor readiness of infants and young children for improved the nutritional security. Laguna and Chen (2016) have argued that there is a lack of technical guidance in matching the rheological properties of foods with individuals' oral motor capabilities. The ease of swallowing a food bolus is highly linked to its rheological quality (Gallegos et al., 2017).

4.4 Concluding remarks

The viscosity values of most indigenous/local African complementary porridges are not well matched to the oral developmental readiness of infants and young children. Commonly used porridges tend to be highly viscous (high viscosity values) at low solids content, when evaluated under shear rates estimates for infant oral processing (0.001/s - 50/s). Consequently, they do not meet the recommended daily energy and protein intakes for infants and young children between 6 – 24 months of age.

At any constant shear rate, the apparent viscosity of the porridge samples increases exponentially making the porridges too thick at low solids (%). However, the ability of OFSP porridge to allow for incorporation of high solids while maintaining low viscosity makes it more suitable in the preparation of complementary porridge with higher nutrient density. High porridge viscosity limits protein and energy intake in infants and young children, especially those receiving low to average BME intake. This perpetuates protein-energy malnutrition.

The study provides policy makers with a framework and an evidence base to influence child nutrition in an African context. There is need to promote inclusion of OFSP in energy dense complementary porridge preparations and to improve the flow properties and oral viscosity of indigenous/local complementary porridges for better energy and protein intakes among African infants and young children. Further work involving bio-tribology is recommended to establish more precise shear rates applicable for in-mouth oral processing in infants and young children, and to understand the rheological properties of a food bolus immediately before swallowing which may affect nutrient intake. This is important in designing more effective novel foods to meet the needs of people with differing oral abilities.

5.0. Dynamic Oral Texture Properties of Selected Indigenous Complementary Porridges used in African Communities

5.1 Introduction

Food oral processing (OP), the manipulation and break down of food inside the mouth up to the moment of swallowing (Chen, 2009, Stieger and van de Velde, 2013), plays a key and important role in sensory perception, consumer acceptance, and food intake (Aguayo-Mendoza et al., 2019). It is a dynamic process; however, the scientific explanations regarding the sensory quality of baby food is lacking (Seidel et al., 2015), particularly the effects of interactions between complementary porridge (CP)'s texture properties and the oral physiology of infants. Oral texture perception remains poorly understood, despite it being a key driver of food acceptance or rejection (Breen et al., 2019). Most infants in Africa are nourished on low-cost CPs prepared from starchy plant materials (cereals, roots, tubers, and legumes) (WHO/UNICEF, 2003, Faber et al., 2016). Such porridges are often thick even at low (about 8–10%) solids content (Ratnayake and Jackson, 2006, Li et al., 2008, Amagloh et al., 2013a). In infants and young children, physiological capacity (chewing, salivation, and digestion) and sensory and oral motor skills are important determinants of food choice (Schwartz et al., 2018). Food texture is a perception arise from the interactions of the food physical structure with mechanoreceptors in the oral cavity (Breen et al., 2019). Inappropriate porridge viscosity may compromise nutrient intake and lead to child malnutrition, a major public health problem especially in low- to middle-income countries (Akombi et al., 2017).

Children of different ages have different OP abilities to successfully chew and swallow foods of different physical forms (Dewey and Brown, 2003). The process of bolus formation is under the coordinated action of mastication (reduction of food in particles), salivation (lubrication of particles), and tongue movements (agglomeration of particles with saliva and swallowing) (Chen, 2009) and depends, thus, mainly on the development of the infant masticatory apparatus. For ingestion and break down of solid foods, children need to acquire specific feeding skills, which require more effort than the oral manipulation of liquid milk (Demonteil et al., 2019b). The acceptance of food with a given texture, (in this context defined as the infant's ability to swallow the food (Schwartz et al., 2018)), strongly depends on the acquisition of feeding skills, which can develop differently in children of the same age (Nicklaus et al., 2015b). At 12 months, munching/chewing behavior is well-established and continues to develop and optimize by 2–3 years (Le Révérend et al., 2014). However, the age of chewing maturation (i.e., transition of up and down movements of the jaw to rotary movements) remains not so clear and is estimated to be later than 3 years old (Demonteil et al., 2019b). Good quality CPs must have low viscosity, high nutrient density, appropriate texture, and a consistency that allows for easy consumption by infants and young children (WHO, 2003, Balasubramanian et al., 2014). At the beginning of complementary feeding (4–6 months), infants prefer soft and smooth textures as it requires limited oral manipulation before being swallowed (Schwartz et al., 2018). Commercial infant porridges are considered to have the optimal quality, but they are too expensive for many poor families (Brown et al., 2016).

Bolus flow and ease of swallowing depend on the rheology of the bolus and the oral physiological conditions of the consumer (Saitoh et al., 2007, Alsanei and Chen, 2014). Infants have limited dentition, weak masticatory muscles, and reduced tongue or pharyngeal muscle strength (Steele et al., 2015). For safe and comfortable consumption, the porridge consistency should be matched with the child's oromotor readiness (Black et al., 2017). At present, there is a paucity of research on the relationship between the in-mouth perceived texture of indigenous CPs and the sensorimotor development (oromotor readiness) of infants (6–12 months) and young children (13–24 months). Yet, infants and toddlers present a challenge to sensory and consumer researchers because of their inability to communicate verbally, limited cognitive abilities, and very low attention span (Plemmons and Resurreccion, 1998, Guinard, 2000). Sensory testing with infants and young children, therefore, often employ indirect approaches. Descriptive sensory profiling has been used to evaluate the sensory quality of baby foods (purees) (Seidel et al., 2015).

For preference evaluation, parents' liking is important in deciding if a given CP would be suitable for their infants (Haro-Vicente et al., 2017). The primary caretaker (typically the mother) interprets the behavior of the child during food tasting and rates acceptance on a hedonic scale (Kevin, 1995, Madrelle et al., 2017, Schwartz et al., 2018). The adult also tastes and rate the samples after the child, providing a control and confirmation of the acceptability of the samples (Guinard, 2000). In most studies, mothers are often asked to report on the presence/absence of positive and negative behaviors and on infant's liking during feeding. Alternative testing approaches employed include parents completing an Infant Behavior

Questionnaire and rating of videotapes of infants' facial reactions to foods rated (Longfier et al., 2016).

Data from rheological studies (not included in this paper) have shown that indigenous porridge samples at very low solids content (Maize 8.1%, Sorghum 8.4%, Cassava 6.4%, Bambara groundnut 10.7%, and Cowpea 10.1%) exceeded the recommended CP viscosity limit (3 Pa·s at 40 °C and shear rate of 50 s^{-1}, (Rombo et al., 2001, Thaoge et al., 2003)) for infants and children below 3 years of age. When starch is heated in water, it swells, gelatinizes, and pastes to form a thick gruel (Ratnayake and Jackson, 2006, Li et al., 2008, Amagloh et al., 2013a). Infants and young children have difficulty to consume and swallow a viscous porridge due to their limited oromotor capacity (Cichero, 2017). The thickness or viscosity of shear-thinning foods is perceived by mechanoreceptors in the mouth, and oral thickness perception depends on the in-mouth shear stress applied and the resultant shear rate (Cook et al., 2005). At the critical solids concentration (C*), the gelatinized, amorphous random starch polymer coils come in contact with one another, eventually overlapping at the entanglement concentration (c_e) (Wool, 1993). Polymers with larger molecules display effective molecular entanglements (Mezger, 2014, Gina, 2016) and are generally perceived as more viscous and thick. High viscosity in CP elicits high lingual swallowing pressure (Vickers et al., 2015). Thicker and harder foods are eaten at a slower rate, often requiring smaller bite sizes and more chewing time in the mouth before swallowing compared to softer foods (Boesveldt et al., 2018). The formation of a bolus that can be safely swallowed is a complex oral process (Schwartz et al., 2018), and infants and young children have the limited oral capacity to perform this process.

The aim of this study was to characterize the texture of selected indigenous CPs typically used for feeding infants and young children aged 6–24 months in African communities during OP (therefore dynamic), in order to make recommendations for optimizing their oral texture to improve nutrient intake. A trained sensory panel consisting of adults was used because infants are not capable of carrying out evaluation instructions and tasks expected in descriptive sensory evaluation. To understand the temporal in-mouth textural nuances, the design applied two different OP methods: a novel procedure (the Up-Down mouth movements- munching) that mimics how infants with limited OP abilities process food and a control method (chewing with lateral mouth movements), representing normal adult OP.

5.2. Materials and Methods

5.2.1. Samples and Sample Preparation

Table 12 shows the descriptions of indigenous and commercial CP samples used in the study.

Table 12. *Description of complementary porridges (CPs) evaluated for oral texture by the trained TCATA sensory panel.*

Porridge Indigenous/Local	**Flour (g)**	**Water (g)**	**Solids (%) #**	**Description and Source**
Maize	40	960	4	Super maize meal (commercially processed) from the local supermarket (Pretoria, RSA)
	80	920.0	8	
	100	900	10	
Sorghum	40	960	4	Super mabela flour (commercially processed) from local supermarket (Pretoria, RSA)
	80	920	8	
	100	900	10	
Bambara	100	900	10	Dry Seeds, cream cultivar, Mbare Produce market (Harare, Zimbabwe)
Cowpea	100	900	10	Commercial seeds, Agrinawa cultivar Agricol (Pty) Ltd. (Pretoria, RSA)
Cassava	40	960	4	High-quality cassava (84.4% starch), Thai Farm International (Ogun, Nigeria)
	60	940	6	
	100	900	10	
OFSP (Orange-fleshed sweet potato)	100	900	10	Dried with electric dryer (60 °C, 6–8 h), Exilite 499 cc (Tzaneen, Limpopo, RSA)
	160	840	16	
Commercial Porridges (Code)	**Age (Months)**	**Flour g: Liquid mL**	**Solids (%)**	**Description/Manufacturers' Instructions Guide ****
A1-Reference	6 to 24	50:150	25.0	Enzyme-hydrolyzed cereal (maize 62%), add water
A2	6 to 24	50:150	25.0	Enzyme-hydrolyzed cereal (rice 63%), add water
A3	6 to 24	50:150	25.0	Enzyme-hydrolyzed cereal (wheat 61%), add water
C2	6 to 24	50:140	26.3	Oat flakes 32%, add water
F1	6 to 8	45:150	23.1	Enzyme-hydrolyzed cereal (wheat 51%), add water
	9 to 12	67:200	25.1	
	13 to 36	80:250	24.2	
F2	6 to 8	35:150	18.9	Enzyme-hydrolyzed cereal (rice 51%), add water
	9 to 12	60:200	23.1	
	13 to 36	75:250	23.1	

Table 12. *Description of complementary porridges (CPs) evaluated for oral texture by the trained TCATA sensory panel, "Continued".*

Porridge Indigenous/Local	**Flour (g)**	**Water (g)**	**Solids (%) #**	**Description and Source**
F3	9 to 12	67:200	25.1	Enzyme-hydrolyzed cereal (wheat, rice, corn, rye, barley 54%), add water
	13 to 36	80:250	24.2	
F4	9 to 12	67:200	25.1	Enzyme-hydrolyzed cereal (wheat, rice, corn, rye, barley 43%), add water
	13 to 36	80:250	24.2	
B1	6 to 24	50:160	35.1	Enzyme-hydrolyzed cereal (maize), add water
B2	6 to 24	50:160	35.1	Enzyme-hydrolyzed cereal (wheat), add water
C1	6 to 24	20:170	24.8	Whole oat flour 70%, banana flakes 30%, add milk
D	6 to 36	20:140	26.3	Maize flour minimum 86%, add milk
E1	6 to 12	25:200	26.7	Maize meal flour, 3 min cook with milk *** Cooking loss of 5%
	13 to 36	35:280	25.8	
E2	6 to 12	25:125	30.0	Sorghum flour (minimum 89%), add milk
	13 to 36	35:190	29.1	
G	13 to 36	20:80	32.8	Wheat flour, maize flour, soy flour, add milk

* NAN Optipro milk (Formula 2 for 6–12 and Formula 3 for 13–24 months, respectively) was prepared as per manufacturer (mixing 32 g milk powder with 200 mL pre-boiled luke-warm water) to give a 16% solids content milk. The "add-water" commercial samples contain whole or skim milk (23–40%). #determined from rheological experiments, such that the flour % in water gives the recommended cooked porridge viscosity ≤ 3 Pa·s (at 40 °C and shear rate of 50 s^{-1}). **Information given on the product pack. ***Native maize meal flour with unhydrolyzed or non-depolymerized starch molecules.

To make flour, Bambara groundnut (*Vigna subterranean* (L.) Verdc) and Cowpea *(Vigna unguiculata*) grains were first decorticated using a Tangential Abrasive Dehulling Device (TADD, Venables Machine Works, Saskatoon, Canada) and milled to < 250 μm particle size flour (Laboratory mill 3100, Perten Instruments, Hägersten, Sweden). All indigenous CP samples were prepared as described by (Ndagire et al., 2015) with adaptations. A specific amount of flour was measured into an aluminum pot following Table 12, and 250 mL of cold water was added while stirring to form a uniform slurry. The flour quantities for each treatment represent the solids % determined from rheological experiments, that give the recommended porridge viscosity limit of 3 Pa·s (at 40 °C and shear rate of 50 s^{-1}). The pot was placed over a hot plate, and the remaining quantity of boiling water was slowly added to the slurry while continuously stirring. Once the mixture began to boil, the timer was started, and the porridge was cooked for 7 min with continuous stirring. Porridge samples were transferred to appropriately labelled containers placed over a water-bath maintained at 55 °C until serving. Commercial porridges were prepared, according to the manufacturers' instructions, by mixing with water or milk depending on the product. The processing techniques for commercial porridges allow them to remain thin at a much higher solids content (%) compared to indigenous porridges.

5.2.2. Sensory Analysis

The sensory analysis of the porridges was conducted in individual booths under white light and standardized conditions at the University of Pretoria Sensory Evaluation Laboratory. The use of human subjects in the study was approved by the Faculty of Natural and Agricultural Sciences Ethics Review Committee at the University of Pretoria (EC 180000086). Each participant signed a consent form prior to taking part in the study.

Ten assessors (3 males and 7 females, aged 22–27 years) were selected and trained on the Temporal Check-All-That-Apply (TCATA) evaluation method in three sessions of 2 h each, according to the guidelines of the International Organization for Standardization (ISO) standard 8586:2012 (International Organization for Standardization, 2012). Prior to training, panelists were screened for interest, availability, general health status, and product discrimination abilities. With TCATA, panelists taste the samples and select all the sensory attributes they perceived at each moment of the evaluation (Castura et al., 2016). They are allowed to check several attributes, which enables them to describe sensory characteristics that are simultaneously perceived (Ares et al., 2017). During training, the assessors familiarized themselves with the oral texture of the CPs, discussed, and agreed on 14 attributes (Table 13). The panel was also trained on the evaluation protocol and use of the data acquisition software, Compusense Cloud version 7.8.2 (Compusense Inc., Guelph, ON, Canada).

TCATA has often been used with a large number of consumers in evaluating different products (Esmerino et al., 2017, Jaeger et al., 2018). However, coupled with training, fewer panelists (10–15) have also previously been used for the temporal profiling of products based on 8–10 attributes (Castura et al., 2016, Baker et al., 2016). The current study used 10 panelists well trained in carrying out the TCATA task and a list of 14 attributes (Table 13).

Temporal methods are more cognitively demanding and usually rely on shorter lists (Varela and Ares, 2014, Reyes et al., 2017).

Table 13. *Definitions of the in-mouth texture attributes used during the evaluation of complementary porridges (CPs) by a trained Temporal Check-All-That-Apply (TCATA) sensory panel (n = 10).*

No.	**TCATA Attribute**	**Definition**
1	Soft	Selected when little force is required to orally process and move around the mouth.
2	Smooth	Selected when the sample is perceived as smooth when squeezed between the palate and tongue (Nguyen et al., 2017).
3	Creamy	Selected when the sample is perceived as creamy, with a silky smooth sensation in the mouth (Nguyen et al., 2017).
4	Grainy	Selected when grainy particles are perceived in the mouth.
5	Too thick/Semi-solid	Viscosity perception of cooked maize meal pastes 15–20% solids in water. Similar to mashed potato (Australia and Speech Pathology Association of Australia Limited, 2007).
6	Thick	Viscosity perception of cooked maize meal paste (10–15% solids in water). Selected when the sample is perceived as thick (viscous) as opposed to thin like a fluid (Nguyen et al., 2017).
7	Thin	Selected when the sample is perceived as thin and fluid-like as opposed to thick (viscous).
8	Chewy	Selected when the sample requires a substantial number of chews before it is ready to swallow (Lazo et al., 2016).
9	Sticky	Selected when the sample sticks to the teeth and palate (Nguyen et al., 2017).
10	Watery	Selected when the sample was perceived as thin and watery (Australia and Speech Pathology Association of Australia Limited, 2007).
11	Easy to swallow	Selected when the sample requires little effort (exertion/force) to swallow (Chambers IV et al., 2017).
12	Difficult to swallow	Selected when the sample requires a lot of effort (exertion/force) to swallow.
13	Slimy	Selected when the sample is perceived as slimy and slippery, a mildly sticky perception on the palate/tongue.
14	Pasty	Selected when the sample has the consistency of a (starch) paste, semi-solid with some stickiness.

The terms "watery" and "too thick" were used to anchor the two extremes of the sensory space for porridge viscosity informed by panel feedback.

Thirty-two CPs listed in Table 12 were evaluated in duplicate, using two different OP methods, over 7 days with a maximum of ten CPs per day. The CPs were first evaluated using the Up-Down method that mimics feeding in infants and young children with limited OP ability. Assessors moved their mouths only up and down, avoiding sideways movements and ensuring limited tongue movement. Babies initially use immature feeding skills characterized by the up and down movements of the jaws, eventually transitioning to mature feeding skills defined by rotary jaw movements, which facilitate efficient chewing (Demonteil et al., 2019b, Black et al., 2017). In the second method (experienced adult chewing called Normal), panelists orally processed the food in a normal adult way involving the lateral mouth and tongue movements, applying oral shear and chewing where necessary. The Up-Down method was always used first before the Normal method during the evaluation sessions because the former required more conscious procedural effort due to its artificial nature compared to normal adult oral processing.

All attributes were presented in a three-column format on the computer screen. The order position of attributes on the TCATA list was randomized across assessors, but the list order remained consistent for a given assessor across all samples (Meyners and Castura, 2016). Porridge samples (± 20 g) were presented to assessors monadically at 40 °C in glass ramekins covered with aluminum foil following a random balanced order. Due the necessity to minimize the time-dependent viscosity changes in the samples, panelists received the sample to be evaluated by the normal method immediately after evaluating that same sample by the up-down method. The evaluation instructions requested the panelists to select all terms on the TCATA list (Table 13) that described the sensations experienced at a given time of evaluation (measurements per second). Concurrently, they had to deselect the terms that were no longer relevant to describe the sensation of a given sample at that moment during the evaluation. To begin the evaluation, assessors took a spoonful (± 5 g) of porridge into their mouth, clicked ‘‘start” on the computer screen (t = 0 s), and proceeded according to the instructions. After 20 s, they were prompted to swallow the sample and continued to note the sensations until the end of the evaluation. The evaluation duration (30 s) was established through an iterative process with assessors consuming some fluid foods falling within similar sensory spectra to common complementary porridges during training. It was an estimate of the time required for assessors to orally process a spoonful of porridge from intake to swallow while eating like a baby (munching). A 1 min break was enforced between samples for assessors to rinse their palate with deionized water.

5.2.3. Data Analysis

Attribute citations proportions were calculated using a procedure described by (McMahon et al., 2017), as the percentage of assessors selected an attribute ('1') at any given moment (every 1 s) during the evaluation period. TCATA curves were plotted from the full evaluation data using statistical software R (R Core Team, 2018), package tempR (version 0.9.9.15.) (Castura, 2018), and the lines smoothed by the cubic smoothing spline function to reduce noise in the data. For each attribute, reference lines per treatment at every 1 s during the evaluation period were calculated, according to (Meyners and Castura, 2018), as the average across all other CPs, excluding the one that this average is contrasted with. Principal Component Analysis (PCA) — a multivariate data analysis method for visualization of correlations between multiple quantitative observations and variables (XLStat, 2018), was used to produce PCA product trajectories (biplot) based on a complete 30s data set. Only the first two principal components (PCs) accounting for the greatest percentage of inertia (total variation) in the data were used. Visualizing observations in a 2- or 3-dimensional space permits identification of uniform or atypical groups of observations. PCA can be considered as a projection method, which projects observations from a p-dimensional space with p variables to a k-dimensional space (where $k < p$) so as to conserve the maximum amount of information from the initial dimensions (XLStat, 2018).

For the average citation proportions, TCATA data were divided into 3 equal time slices of 10 s each (Initial: 1–10 s; Middle: 11–20 s; End: 21–30 s), and the mean values were obtained for each attribute at each time slice, as the attribute was selected at the proportion of the 10 s evaluation time. For example, if an assessor selected chewy for a duration of 8 s and creamy for a duration of 2 s, then the citation proportions for chewy would be 8/10 = 0.8, and for creamy would be 2/10 = 0.2. Data were analyzed using a mixed effects ANOVA model:

$$\text{AUC} = \text{Porridge Sample} + \text{OP Method} + \text{Porridge Sample x OP Method} + \text{Assessor}, \quad (1)$$

where AUC refers to the area under the citation proportion by time (s) curve (average citations proportions) for each attribute in each treatment. The Sample, Method, and their two-way interaction were the fixed factors, whereas Assessors was a random effect. Multiple comparisons were done using Fischer's Least Significant Difference (LSD) test to detect which sample pairs were significantly different. XLStat software (version 2019.1.2) (Addinsoft, Long Island, New York, USA) (Addinsoft, 2019) was used for the analysis. Citation proportions (range: 0 to 1) correspond to the AUC in Time Intensity studies [48].

In order to test if the porridge samples differed significantly with respect to presence or absence of the 14 specific oral texture attributes, the data, pooled over OP methods and replications, were submitted to Cochran's Test, as described by (Baker et al., 2016). Cochran's Q is used for testing $k = 2$ or more matched sets, where a binary response (e.g., 0 or 1) is recorded from each category within each subject. Cochran's Q tests the null hypothesis that the proportion of "successes" is the same in all groups versus the alternative that the proportion is different in at least one of the groups. For pairwise differences between each treatment within a time-segment, Marascuilo's Test was used (Marascuilo and McSweeney, 1977). The Cochran's Q test followed by Marascuilo's test was done in XLSTAT software (version 2019.1.2) (Addinsoft,Long Island, New York, USA) (Addinsoft, 2019).

5.3. Results

5.3.1. Dynamic Oral Texture: TCATA Product Profiles

Figure 22 – 24 shows TCATA curves for the three most common types of African CP (Maize, Sorghum, and Cassava, all 10% solids). When evaluated by the Normal OP method (Figure 17A, C, E), these porridges were perceived ($p < 0.05$) as much thicker or too thick, more sticky, and less creamy during the initial (1–10 s) and middle (11–20 s) phases in comparison with the mean (dotted lines) of all other samples. Maize porridge was thicker and with much higher citation proportions for a much longer period in the Up-Down method than in the Normal OP method ($p < 0.05$) (Figure 22). The panel also perceived Cassava porridge as thick, too thick, sticky, slimy, and not creamy by both OP methods (Figure 24). In the Up-Down method, however, the Cassava porridge attributes were more prevalent and more persistent, being further described as significantly not thin (between 10 and 15 s) and less easy to swallow compared to the rest of the samples.

The Cochran's Q test was carried out on the TCATA data collected during the 30 s evaluation period for the indigenous CPs and a commercial reference. The frequency of perception (citation proportion) for attributes used differed in time ($p \leq 0.05$) as a function of Samples

(Table 14). The 6th, 16th, and 26th s time moments were taken to represent three phases of OP during the evaluation. Initially and mid-way during OP, assessors described Maize and Sorghum porridges (8–10 % solids) and Cassava 10 % as thick, and even too thick, relative to the other CPs ($p \leq 0.05$). Cassava CPs (6 and 10 % solids) were also characterized as significantly ($p < 0.05$) sticky and pasty and together with Bambara groundnut and Cowpea (all perceived as slimy $p \leq 0.05$) when compared with the other porridges. CP attribute differences declined as OP progressed, meaning that the CPs became more similar towards the end of OP. During swallowing, more panelists perceived Cassava 10 % as thick, sticky, pasty, and slimy compared to the other porridges ($p \leq 0.05$). The slimy texture was more frequently perceived in all legume porridges (Bambara groundnut and Cowpea) but not in the cereal and orange-fleshed sweet potato (OFSP) based porridges.

When applying a 2-way mixed model ANOVA to evaluate the effect of Sample and OP method (Table 15), similar results were noted. Maize and Sorghum (8 – 10 % solids) and Cassava (10 % solids) were characterized by the panel as significantly thick or too thick, sticky, slimy, and pasty compared to the rest of the samples, in all three time-slices (only results for initial and end time-slices are shown in Table 15). The Up-Down OP method gave significantly higher thick and too thick citation proportions compared to the Normal OP method for Maize (8 – 10 % solids), Sorghum (8 – 10 % solids), and Cassava (10 % solids) porridges. As in Cochran’s Q test, slimy texture during swallowing was more perceived in cassava and leguminous CPs, with Cassava 10% described as not easy to swallow by a higher proportion of panellists.

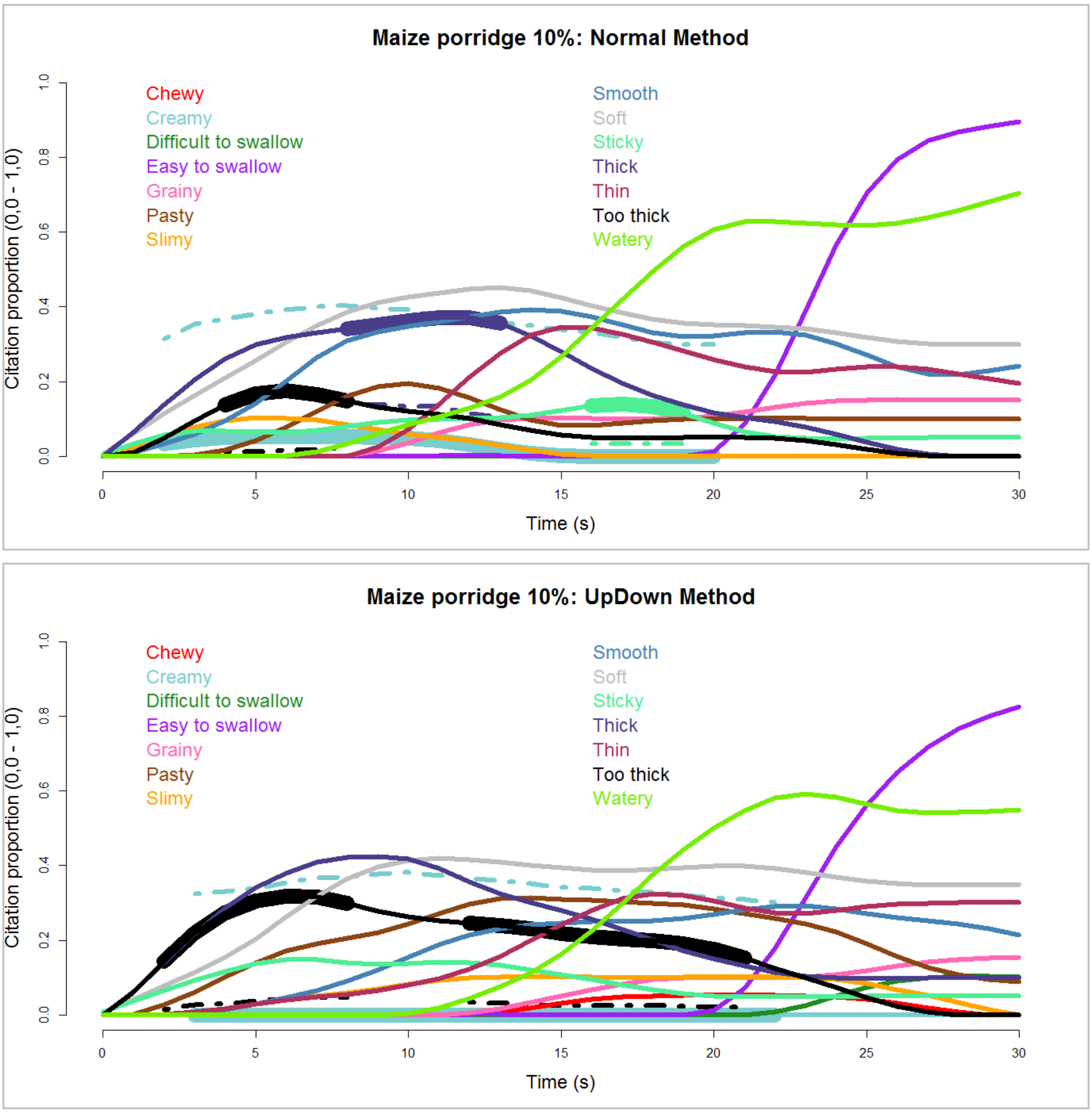


Figure 22. *Temporal Check-All-That-Apply (TCATA) texture attribute curves for maize, complimentary porridges (CPs) (10%) solids evaluated by the Normal and the Up-Down OP method. Attribute reference lines (represented as dotted lines in the figures) are shown only during periods of significant differences (p ≤ 0.05) in citation proportion for that porridge compared to the mean of all other CPs. Significant reference line segments are contrasted with highlighted thicker sections of attribute curves for convenient visualization.*

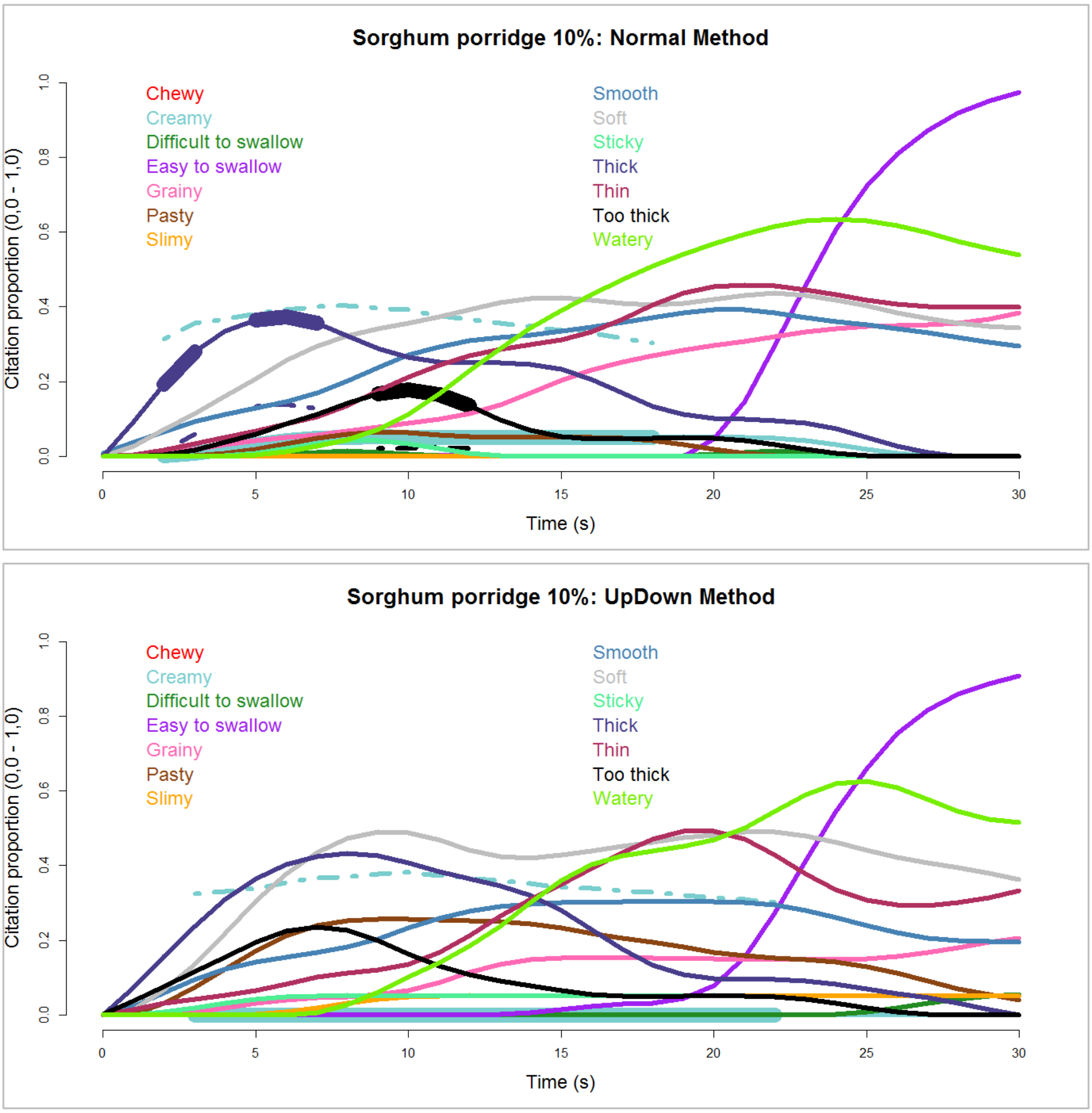


Figure 23. *Temporal Check-All-That-Apply (TCATA) texture attribute curves for sorghum, complimentary porridges (CPs) (10%) solids evaluated by the Normal and the Up-Down OP method. Attribute reference lines (represented as dotted lines in the figures) are shown only during periods of significant differences (p ≤ 0.05) in citation proportion for that porridge compared to the mean of all other CPs. Significant reference line segments are contrasted with highlighted thicker sections of attribute curves for convenient visualization.*

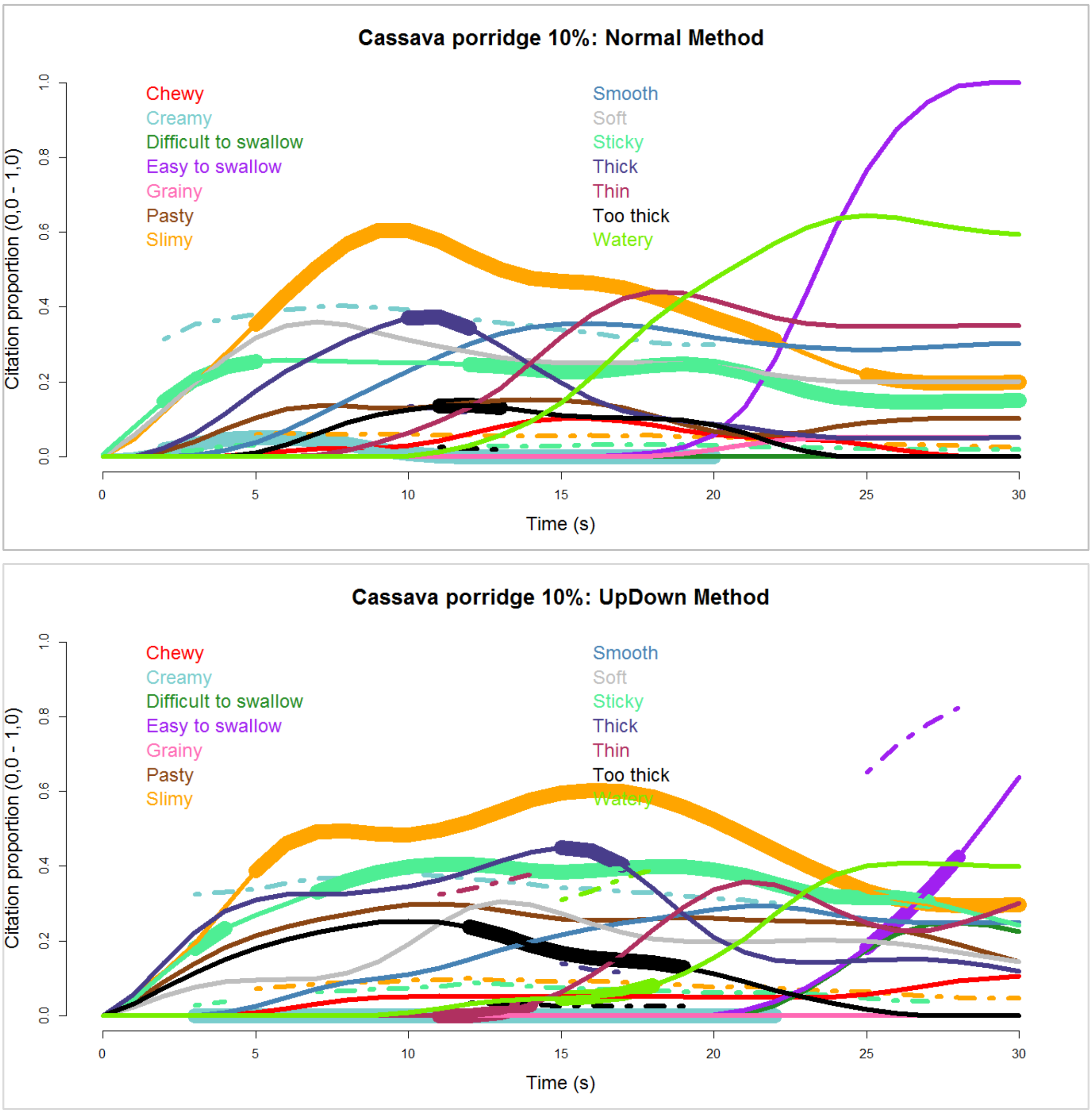


Figure 24. *Temporal Check-All-That-Apply (TCATA) texture attribute curves for Cassava, complimentary porridges (CPs) (10%) solids evaluated by the Normal and the Up-Down OP method. Attribute reference lines (represented as dotted lines in the figures) are shown only during periods of significant differences (p ≤ 0.05) in citation proportion for that porridge compared to the mean of all other CPs. Significant reference line segments are contrasted with highlighted thicker sections of attribute curves for convenient visualization.*

Table 14. The effect of porridge type on the citation proportions for some oral texture attributes at three different moments during evaluation by a trained TCATA sensory panel (n = 10). Data analysis: Cochran Q test and Marascuillo's pairwise comparison test.

Porridge Type	**Beginning (6 s)**					**Middle (16 s)**					**End (26 s)**			
	Thick	**Sticky**	**Too thick**	**Pasty**	**Slimy**	**Thick**	**Sticky**	**Too thick**	**Pasty**	**Slimy**	**Thick**	**Sticky**	**Pasty**	**Slimy**
Bambara 10%	0.05 ^{a}	0.03 ^{ab}	0.00 ^{a}	0.03^{ab}	0.25 ^{b}	0.00 ^{a}	0.00 ^{a}	0.00 ^{a}	0.05 ^{ab}	0.20 ^{b}	0.00 ^{a}	0.00 ^{a}	0.03 ^{ab}	0.15 ^{b}
Cowpea 10%	0.08 ^{a}	0.13 ^{cd}	0.00 ^{a}	0.05 ^{abc}	0.35 ^{bc}	0.05 ^{ab}	0.08 ^{ab}	0.03 ^{a}	0.08 ^{abc}	0.20 ^{b}	0.03 ^{ab}	0.05 ^{a}	0.05 ^{ab}	0.13 ^{b}
Cassava 4%	0.00 ^{a}	0.10 ^{bcd}	0.00 ^{a}	0.03 ^{ab}	0.40 ^{bc}	0.00 ^{a}	0.05 ^{ab}	0.00 ^{a}	0.00 ^{a}	0.25 ^{bc}	0.00 ^{a}	0.05 ^{a}	0.00 ^{a}	0.13 ^{b}
Cassava 6%	0.08 ^{a}	0.18 ^{de}	0.00 ^{a}	0.15 ^{cd}	0.43 ^{c}	0.05 ^{ab}	0.05 ^{ab}	0.00 ^{a}	0.05 ^{ab}	0.38 ^{c}	0.00 ^{a}	0.05 ^{a}	0.03 ^{ab}	0.18 ^{bc}
Cassava 10%	0.30 ^{b}	0.25 ^{e}	0.10 ^{b}	0.20 ^{d}	0.50 ^{c}	0.33 ^{f}	0.30 ^{c}	0.13 ^{b}	0.20 ^{c}	0.55 ^{d}	0.10 ^{c}	0.25 ^{b}	0.18 ^{cd}	0.25 ^{c}
Maize 4%	0.00 ^{a}	0.03 ^{ab}	0.00 ^{a}	0.00 ^{a}	0.05 ^{a}	0.00 ^{a}	000 ^{a}	0.00 ^{a}	0.00 ^{a}	003 ^{a}	0.00 ^{a}	0.00 ^{a}	0.00 ^{a}	0.00 ^{a}
Maize 8%	0.40 ^{b}	0.05 ^{abc}	0.05 ^{ab}	0.03 ^{ab}	0.08 ^{a}	0.15 ^{cd}	0.03 ^{a}	0.05 ^{a}	0.05 ^{ab}	0.00 ^{a}	0.03 ^{ab}	0.00 ^{a}	0.03 ^{ab}	0.00 ^{a}
Maize 10%	0.33 ^{b}	0.10 ^{bcd}	0.25 ^{d}	0.13 ^{bcd}	0.08 ^{a}	0.23 ^{de}	0.13 ^{b}	0.13 ^{b}	0.20 ^{c}	0.05 ^{a}	0.05 ^{b}	0.05 ^{a}	0.13 ^{bcd}	0.03 ^{a}
Sorghum 4%	0.05 ^{a}	0.00 ^{a}	0.00 ^{a}	0.00 ^{a}	0.05 ^{a}	0.00 ^{a}	0.00 ^{a}	0.00 ^{a}	005 ^{ab}	0.05 ^{a}	0.00 ^{a}	0.00 ^{a}	0.03 ^{ab}	0.00 ^{a}
Sorghum 8%	0.30 ^{b}	0.03 ^{ab}	0.05 ^{ab}	0.00 ^{a}	0.03 ^{a}	0.10 ^{bc}	0.08 ^{ab}	005 ^{a}	0.08 ^{abc}	0.03 ^{a}	0.05 ^{b}	0.03 ^{a}	0.08 ^{abc}	0.03 ^{a}
Sorghum 10%	0.40 ^{b}	0.03 ^{ab}	0.18 ^{c}	0.15 ^{cd}	0.00 ^{a}	0.25 ^{ef}	0.03 ^{a}	0.05 ^{a}	0.13 ^{abc}	0.03 ^{a}	0.03 ^{ab}	0.00 ^{a}	0.05 ^{ab}	0.03 ^{a}
OFSP 10%	0.00 ^{a}	0.00 ^{a}	0.00 ^{a}	0.08 ^{abc}	0.00 ^{a}	0.00 ^{a}	0.00 ^{a}	0.00 ^{a}	0.10 ^{abc}	0.03 ^{a}	0.03 ^{ab}	0.00 ^{a}	0.10 ^{abcd}	0.03 ^{a}
OFSP 16%	0.10 ^{a}	0.03 ^{ab}	0.00 ^{a}	0.05 ^{abc}	0.03 ^{a}	0.00 ^{a}	0.08 ^{ab}	0.00 ^{a}	0.15 ^{bc}	0.03 ^{a}	0.00 ^{a}	0.05 ^{a}	0.20 ^{d}	0.03 ^{a}
A1 *	0.00 ^{a}	0.00 ^{a}	0.00 ^{a}	0.03 ^{ab}	0.03 ^{a}	0.00 ^{a}	0.03 ^{a}	0.00 ^{a}	0.10 ^{abc}	0.05 ^{a}	0.00 ^{a}	0.00 ^{a}	0.10 ^{abcd}	0.03 ^{a}

^{abcdef} *Citation proportions with different letters within a column represent significant differences among treatments at p ≤ 0.05 as analyzed using Marascuillo's test. Responses were pooled across replicates, and oral processing method (40 TCATA runs × 14 samples) was used to determine the citation proportion values. A1 * is a commercial reference porridge.*

Table 15. *Effect of complimentary porridge (CP) type and oral processing (OP) method on citation proportions for texture attributes during the initial (1–10 s) and ending (21–30 s) phases of evaluation by the trained TCATA panel (n = 10). Main effects ANOVA followed by Fisher's Least Significant Difference (LSD) test for pairwise comparisons.*

Porridge-Sample	**Oral-Method**	**Initial: 1–10 s**					**End: 21–30 s**				
		Thick	**Too thick**	**Sticky**	**Slimy**	**Pasty**	**Thick**	**Too Thick**	**Slimy**	**Pasty**	**Swallow (+)**
Maize 4%	Normal	0.00^{a}	0.00^{a}	0.02^{ab}	0.04^{a}	0.00^{a}	0.00^{a}	0.00^{a}	0.00^{a}	0.00^{a}	$0.64^{bcdefghij}$
	Up-Down	0.00^{a}	0.00^{a}	0.01^{a}	0.06^{abc}	0.00^{a}	0.00^{a}	0.00^{a}	0.01^{a}	0.00^{a}	0.77^{ij}
Maize 8%	Normal	0.23^{def}	0.03^{ab}	0.05^{abc}	0.02^{a}	0.00^{a}	0.05^{abc}	0.01^{ab}	0.00^{a}	0.00^{a}	0.76^{hij}
	Up-Down	0.37^{g}	0.03^{ab}	0.07^{abcd}	0.05^{ab}	0.05^{abc}	0.01^{bc}	0.03^{ab}	0.00^{a}	0.05^{abc}	$0.59^{bcdefgh}$
Maize 10%	Normal	0.26^{defg}	0.11^{cd}	0.07^{abcd}	0.07^{abc}	0.08^{abcd}	0.04^{abc}	0.02^{ab}	0.00^{a}	0.10^{abcd}	$0.62^{bcdefghi}$
	Up-Down	0.31^{efg}	0.20^{e}	0.10^{bcd}	0.00^{a}	0.13^{bcde}	0.01^{cd}	0.00^{a}	0.10^{abcd}	0.18^{cde}	0.53^{bcde}
Sorghum 4%	Normal	0.01^{a}	0.00^{a}	0.00^{a}	0.02^{a}	0.01^{a}	0.00^{a}	0.00^{a}	0.02^{ab}	0.05^{abc}	$0.65^{cdefghij}$
	Up-Down	0.02^{a}	0.00^{a}	0.00^{a}	0.04^{a}	0.01^{a}	0.00^{a}	0.00^{a}	0.01^{a}	0.00^{a}	$0.63^{bcdefghij}$
Sorghum 8%	Normal	0.20^{cde}	0.04^{abc}	0.04^{abc}	0.00^{a}	0.02^{a}	0.00^{a}	0.01^{a}	0.00^{a}	0.07^{abc}	0.56^{bcdefg}
	Up-Down	0.36^{g}	0.04^{abc}	0.04^{abc}	0.04^{a}	0.05^{ab}	0.09^{bcd}	0.03^{ab}	0.05^{abcd}	0.05^{abc}	$0.59^{bcdefgh}$
Sorghum 10%	Normal	0.28^{defg}	0.08^{bc}	0.02^{ab}	0.00^{a}	0.03^{a}	0.04^{abc}	0.01^{a}	0.00^{a}	0.00^{a}	$0.67^{defghij}$
	Up-Down	0.32^{fg}	0.17^{de}	0.03^{abc}	0.01^{a}	0.16^{de}	0.06^{abc}	0.02^{ab}	0.05^{abcd}	0.11^{abcd}	$0.63^{bcdefghij}$
Bambara 10%	Normal	0.02^{a}	0.00^{a}	0.01^{a}	0.18^{cd}	0.00^{a}	0.00^{a}	0.00^{a}	0.15^{bcde}	0.00^{a}	0.75_{hij}
	Up-Down	0.03^{a}	0.00^{a}	0.01^{a}	0.18^{cd}	0.05^{ab}	0.00^{a}	0.00^{a}	0.15^{bcde}	0.05^{abc}	0.76^{hij}
Cowpea 10%	Normal	0.07^{ab}	0.00^{a}	0.09^{abcd}	0.24^{de}	0.01^{a}	0.00^{a}	0.00^{a}	0.11^{abcde}	0.05^{abc}	0.70^{efghij}
	Up-Down	0.05^{a}	0.00^{a}	0.09^{abcd}	0.28^{def}	0.06^{abc}	0.07^{abcd}	0.00^{a}	0.16^{cde}	0.08^{abc}	0.52^{bcd}
Cassava 4%	Normal	0.00^{a}	0.00^{a}	0.08^{abcd}	0.28^{def}	0.02^{a}	0.00^{a}	0.00^{a}	0.13^{abcde}	0.00^{a}	0.73^{ghij}
	Up-Down	0.00^{a}	0.00^{a}	0.08^{abcd}	0.35^{ef}	0.05^{ab}	0.00^{a}	0.00^{a}	0.18^{de}	0.00^{a}	0.55^{bcdef}

Table 15. *Effect of complimentary porridge (CP) type and oral processing (OP) method on citation proportions for texture attributes during the initial (1–10 s) and ending (21–30 s) phases of evaluation by the trained TCATA panel (n = 10). Main effects ANOVA followed by Fisher's Least Significant Difference (LSD) test for pairwise comparisons, "Continued".*

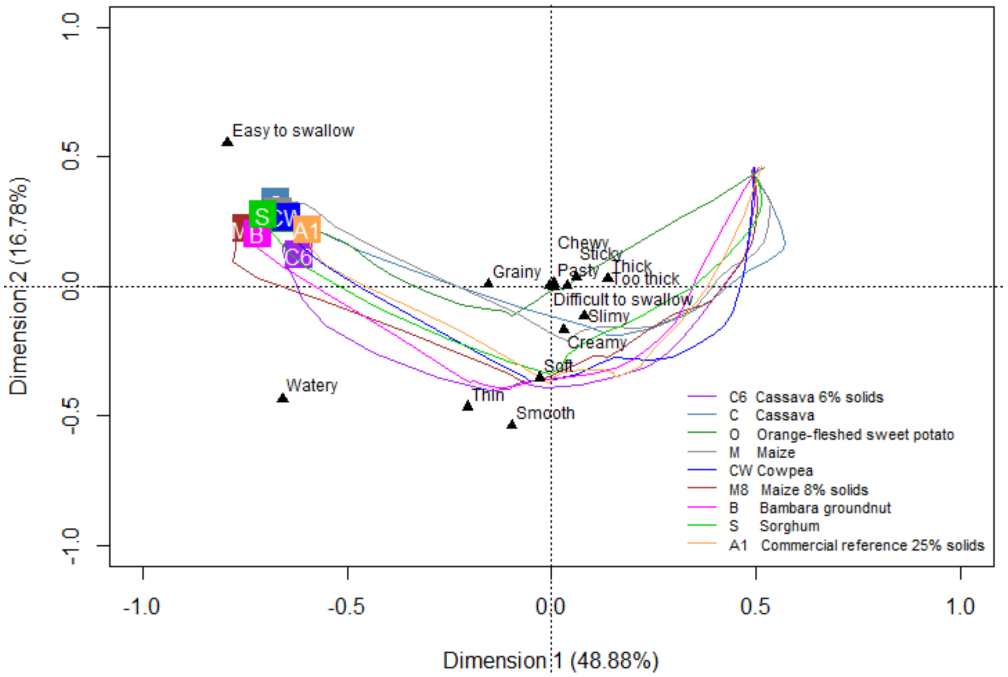
Porridge-Sample	**Oral-Method**	**Initial: 1–10 s**					**End: 21–30 s**				
		Thick	**Too thick**	**Sticky**	**Slimy**	**Pasty**	**Thick**	**Too Thick**	**Slimy**	**Pasty**	**Swallow (+)**
Cassava 6 %	Normal	0.05^{a}	0.00^{a}	0.12^{cde}	0.33^{ef}	0.07^{abcd}	0.00^{a}	0.00^{a}	0.19^{de}	0.00^{a}	$0.67^{cdefhij}$
	Up-Down	0.06^{a}	0.00^{a}	0.16^{def}	0.39^{f}	0.14^{cde}	0.01^{ab}	0.00^{a}	0.24^{de}	0.08^{abc}	$0.60^{bcdefhi}$
Cassava 10%	Normal	0.19^{bcd}	0.04^{abc}	0.22^{ef}	0.38^{f}	0.08^{abcd}	0.05^{abc}	0.01^{a}	0.24^{ef}	0.09^{abc}	0.70^{efghij}
	Up-Down	0.27^{defg}	0.17^{de}	0.26^{f}	0.35^{ef}	0.20^{e}	0.15^{d}	0.03^{ab}	0.35^{f}	0.22^{de}	0.26^{a}
OFSP 10%	Normal	0.00^{a}	0.00^{a}	0.00^{a}	0.00^{a}	0.06^{abc}	0.00^{a}	0.00^{a}	0.03^{abc}	0.13^{bcde}	0.56^{bcdefg}
	Up-Down	0.00^{a}	0.00^{a}	0.00^{a}	0.00^{a}	0.08^{abcd}	0.05^{abc}	0.00^{a}	0.00^{a}	0.05^{abc}	$0.65^{cdefghij}$
OFSP 16%	Normal	0.03^{a}	0.00^{a}	0.02^{ab}	0.00^{a}	0.03^{a}	0.00^{a}	0.00^{a}	0.00^{a}	0.13^{abcd}	0.47^{b}
	Up-Down	0.10^{abc}	0.00^{a}	0.05^{abc}	0.03^{a}	0.08^{abcd}	0.00^{a}	0.00^{a}	0.05^{abcd}	0.25^{e}	0.50^{bc}
A1	Normal	0.00^{a}	0.00^{a}	0.00^{a}	0.02^{a}	0.01^{a}	0.00^{a}	0.05^{b}	0.00^{a}	0.05^{abc}	0.68^{defghi}
	Up-Down	0.00^{a}	0.00^{a}	0.00^{a}	0.04^{a}	0.05^{abc}	0.00^{a}	0.00^{a}	0.05^{abcd}	0.15^{cde}	0.72^{fghi}
A2	Normal	0.08^{abc}	0.00^{a}	0.00^{a}	0.00^{a}	0.00^{a}	0.00^{a}	0.00^{a}	0.04^{abc}	0.05^{abc}	$0.62^{bcdefghi}$
	Up-Down	0.06^{a}	0.00^{a}	0.00^{a}	0.00^{a}	0.04^{ab}	0.05^{abc}	0.00^{a}	0.01^{a}	0.11^{abcd}	0.53^{bcde}
A3	Normal	0.00^{a}	0.00^{a}	0.00^{a}	0.00^{a}	0.01^{a}	0.00^{a}	0.00^{a}	0.00^{a}	0.00^{a}	0.80^{j}
	Up-Down	0.01^{a}	0.00^{a}	0.00^{a}	0.00^{a}	0.04^{ab}	0.00^{a}	0.00^{a}	0.00^{a}	0.02^{ab}	$0.65^{cdefghi}$

For the same column, mean values with different superscripts are significantly different ($p \leq 0.05$). Values are average citations over a 10 s oral processing period. A1 is a commercial reference. A2 and A3 are selected commercial porridge samples. Swallow (+) refers to easy to swallow.

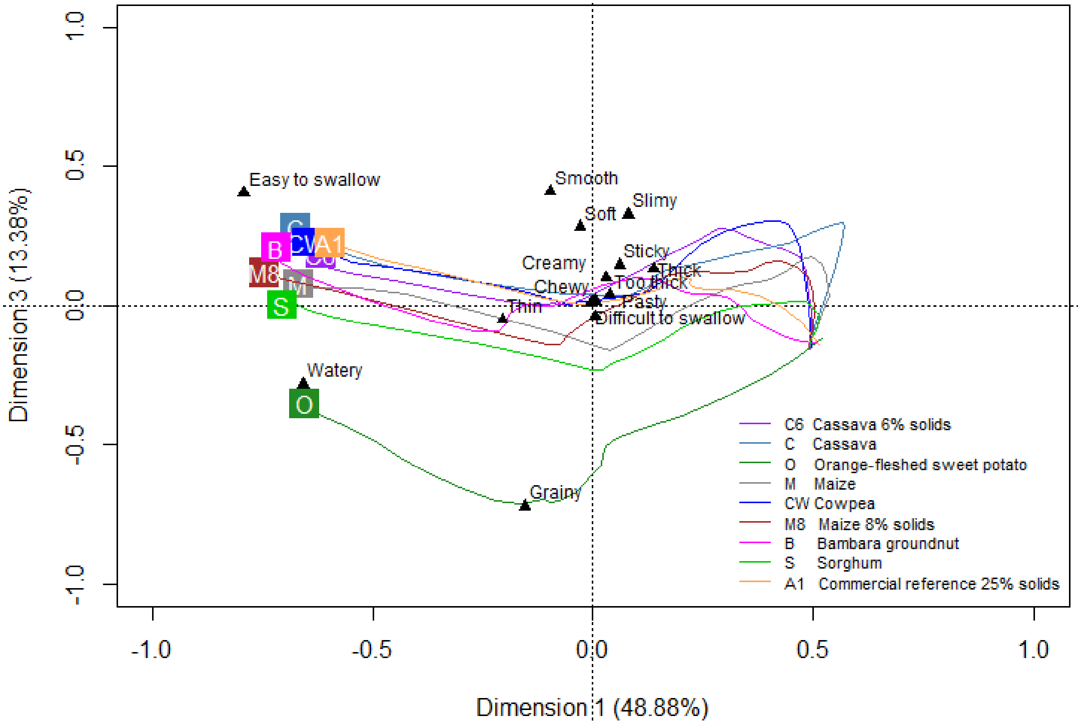
5.3.2. Dynamic Oral Processing Trajectories for Selected Indigenous/Local CPs and a Commercial Porridge Reference

The correlation between the CPs and attribute changes over the 30 s OP duration (both Normal and Up-Down methods) was explored graphically via PCA product trajectory biplots on three dimensions (D1 to D3) (Figure 25).

A. Normal OP method: D1D2



B. Normal OP method: D1D3



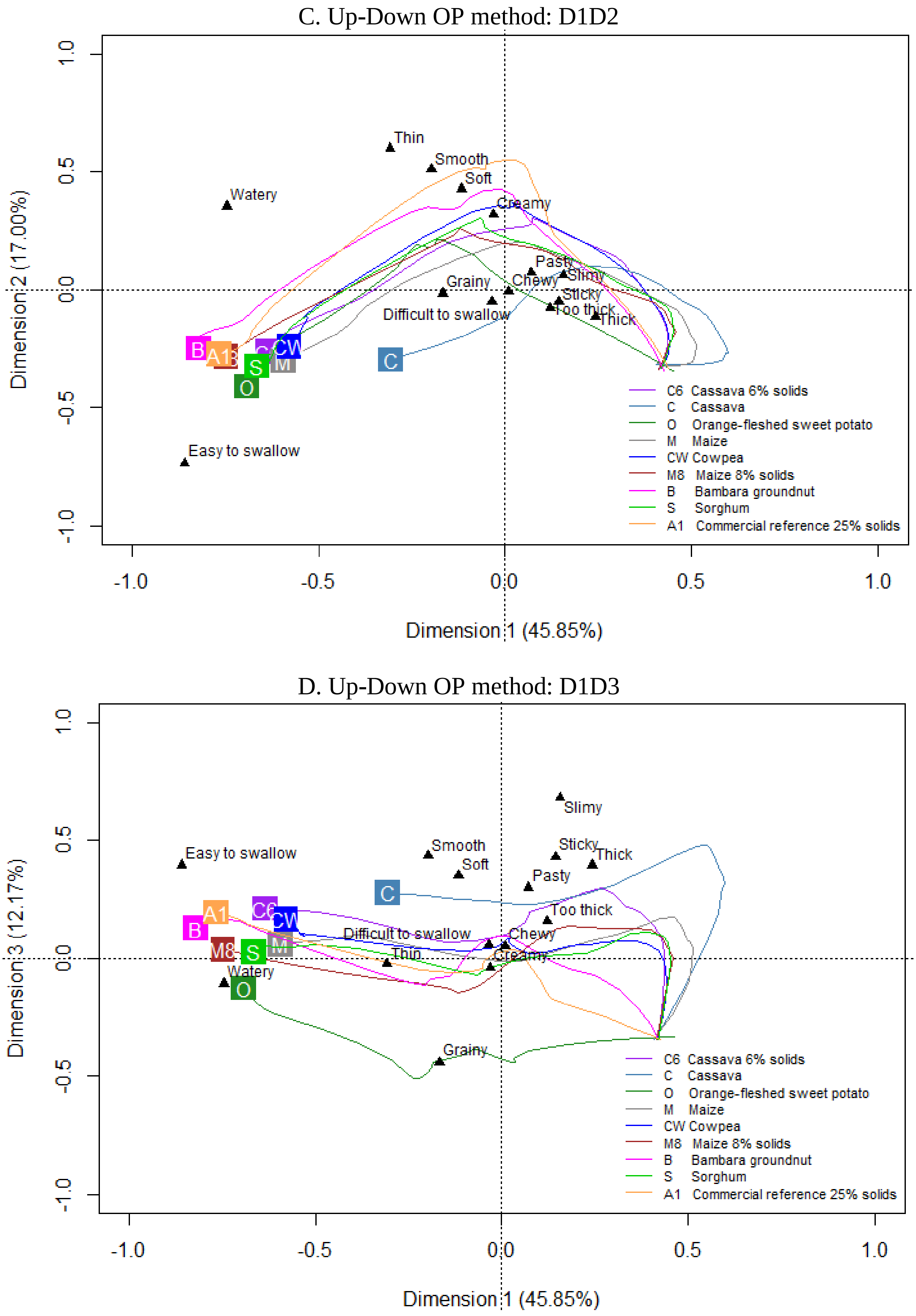


Figure 25. *Smoothed Principal Component Analysis (PCA) product trajectory biplots show the evolution of attributes during oral processing for nine complimentary porridges (CPs) at 10% solids unless otherwise specified.*

The first three dimensions (D1 to D3) in the normal OP method explained 79% of the total inertia, while for the Up-Down OP method, these explained 75% of the model information. For both methods, during the evaluation, D1 (Figure 25A, C) explains early the CP differences due to attributes thick, slimy, sticky (and too thick in Up-Down method) in contrast to differences in watery and easy to swallow perceived towards the end of OP. Soft, grainy, smooth, and thin became relevant differentiation attributes midway in the evaluation. In both methods, D2 is associated with CP differences described as smooth, thin, watery, and creamy (Figure 25A, C). It is, however, clear that the distribution of CPs is different in D2 for the two OP methods. This implies that the CPs are perceived differently when processed by Up-Down or Normal methods. With the Up-Down method (Figure 2C), the commercial porridge (A1) is clearly distinguished from the other CPs and, particularly, Cassava (C). With Normal OP (Figure 18A), the commercial porridge was not distinguished in D2 from most of the indigenous CPs, while OFSP (O), Cassava (C), and Maize porridges were more closely grouped.

However, while all CPs were watery and easy to swallow at the end of OP in the Normal method, there was more variation with regards to these attributes amongst CPs in the Up-Down method (Figure 25C). Cassava was the least watery and least easy to swallow. Differences in the perception of the CPs as a function of the two OP methods are also explained in the D3 axes of the respective maps (Figure 25C, D). With the Normal method (Figure 25B), D3 separates CPs that are easy to swallow, smooth, soft, and slimy at the top from those that are grainy and to a lesser extent watery at the bottom of the plot (notably OFSP, O). With the Up-Down method (Figure 25D), slimy at the top is the main distinguishing attribute, particularly, contrasting the texture of solids to the grainy and watery character of OFSP (O) at the bottom of the plot.

5.4. Discussion

The early detection of viscosity-related attributes (too thick, thick, sticky, slimy, pasty) during OP of CPs was consistent with the generally known evolution of sensory perception during OP of semi-solid foods, as reported by (Devezeaux de Lavergne et al., 2017). The attributes thick, too thick, sticky, pasty and slimy, and less easy to swallow characterized the most common indigenous African CPs (Maize, Cassava, and Sorghum, 6 – 10 % solids) early in OP. Similarly, tracking the changes in the oral texture of soft and semi-solid foods (Scholten, 2017b) found that bulk-related attributes, such as thickness, dominate the initial phase (low shear). As food oral processing progresses, thixotropy (the time-dependent change in the viscosity) is observed along with shear thinning and physical food breakdown by masitication and saliva interactions.

The characterization of Cassava, Maize, and Sorghum CPs (all 10 % solids) as sticky, thick, too thick, slimy, and pasty, especially when eaten using the Up-Down method, has important implications for infant feeding. Children generally dislike sticky and slimy textures because of their lack of control over these texture attributes in the mouth (Szczesniak, 2002). A study (Assad-Bustillos et al., 2019) on the temporal texture quality of two soft cereal products of different composition (sponge-cake and brioche) for the elderly found that oral eating quality was negatively correlated with perceived stickiness and pastiness, but positively correlated with perceived easiness to eat, easy to chew, and easy to swallow the food bolus. The authors reported that sticky and pasty attributes were perceived and characterized as unpleasant (Assad-Bustillos et al., 2019). According to (Aboubacar et al., 1999), stickiness in the mouth and cohesiveness are the most important textural attributes to control in thin porridge.

The developmental differences in oral physiology may impact the infants and young children's ability to orally process thick and sticky indigenous CPs. The age of a child impacts chewing and mastication abilities (Fucile, 1998). However, (Demonteil et al., 2019b) observed that starting from 6 months onwards, acceptance of sticky textures was increasing with increasing infant age most likely due to familiarity. Eating skills develop gradually from sucking to munching and then chewing (a more complex rotary pattern) (Nicklaus et al., 2015b). The capacity to transform food into a safely swallow-able bolus influences food acceptability and nutrient intake, yet it is severely limited in infants and young children (Schwartz et al., 2018). For easy swallowing, the food bolus should be readily deformable and flowable (Chen and Lolivret, 2011). The eruption of front teeth typically between 6 and 8 months and the distal ones from 12 – 24 months of age improves the ability to break down more challenging foods only later in infancy (Cichero, 2016). The change from the munching pattern to a more adapted, rotary chewing pattern occurs after at least 12 months of age (Cichero, 2016, Rudolph and Link, 2002). This is because, in infants, milk and liquid foods are delivered directly to the posterior of the oral cavity during sucking and suckling- the optimal spot for swallow reflex initiation (Cichero, 2016). However, for handling solids, the infant must accept the food into the front of the mouth, masticate it, and then actively (with energy expenditure) use the tongue to transport the bolus to the posterior of the oral cavity for the swallow reflex to be triggered (Morris et al., 2001). Mastication of more deformable structures requires different chewing movements in bolus preparation (Koç et al., 2014), which are not present early in infancy.

Cassava and Maize porridge (at 10 % solids) were described as the least easy to swallow and still thick (21–30 s) in the Up-Down OP method; observations which were absent when these porridges were consumed in the Normal OP method. Although the oral physiology of infants is quite different from that of adults (Kohyama et al., 2003), in a study involving young adults (mean age 26.5 years) with a high number of functional dental units, and some elders (mean age 67.2 years) with varying numbers of opposing post-canine teeth pairs (i.e., functional units) it was found that the same amount of work is needed to transform food from its initial form to an easy to swallow bolus regardless of age. The lingual propulsive force in adults is thought to be the main driving force for bolus flow (Gilbert et al., 2007), making OP much easier in adults than in infants. Reduced dentition as is the case in infants compromises masticatory efficiency, as well as the tongue's capability in positioning food, and this reduces the efficiency of oral food break down (Fontijn-Tekamp et al., 2004, Ketel et al., 2019). It is acknowledged that young children and adults differ in oral processing, and the adults' usage of different oral processing apparatus, saliva secretion, etc. cannot fully explain the texture perception and eating behavior of small children.

Cassava porridges (6 – 10 % solids) were described as smooth during the initial OP phase and easy to swallow in the normal OP method, but thick, sticky, and less easy to swallow with the Up-Down OP method. The capacity of the Up-Down OP method to detect sensory differences at relatively high viscosity levels confirmed a proposition (He et al., 2016) that low shear viscosity is more relevant in differentiating thickness perception in fluid foods. The Up-Down method employed low shear viscosity, making handling and break down of thick and sticky porridges more problematic, while shear was higher with the Normal OP method, enabling greater intraoral food-mixing ability. In a research study on the dynamic texture break down of some soft foods (caramel), (Cakir et al., 2012) noted that an increase in stickiness only led to an increase in the total amount of muscle used but to a slower masticatory process, which had a larger opening and closing strokes. In infants, the more advanced motor skills for handling semisolid foods only appear between 9 – 12 months, followed by molars at 12 – 18 months (Campoy et al., 2018). As clinically noted, when children do not have the required OP abilities to break down foods, they often hold them in the mouth to soften with saliva and/or attempt to swallow the pieces whole, which increases the risk of choking (Cichero, 2016, Morris et al., 2001, Gisel, 1991). The α-amylase and the lingual lipase enzymes in saliva are thought to digest starch and lipids, causing a decrease in the perceived thickness of fluids (De Wijk et al., 2006).

However, in this study saliva may not have influenced differences in texture across OP methods, since the panel was constant.

Maize porridge (10 % solids) in the Up-Down method was pasty midway during OP, while soft and easy to swallow by the Normal OP method at 8% solids. The apparent more pleasant oral texture perception in the Normal OP method may be explained by the greater efficiency of use of dentition and other developed oral structures, such as the tongue. Teeth action improves oro-tactile sensitivity and assists in cutting and grinding of more textured foods (Delaney and Arvedson, 2008). The tongue has a fundamental role in bolus containment and propulsion (Marconati et al., 2019). Fluid food thickness affects the chewing rate and muscular work (van der Bilt and Abbink, 2017). A thick food bolus is difficult to deform and flow, as swallowing muscles may have to work much harder and much longer to generate enough oral pressure/stress to transform the bolus into appropriate flow-ability for swallowing (Chen and Lolivret, 2011). The clear shift in oral texture from thick, sticky, and too thick to thin and watery in the Normal OP method compared to the Up-Down method was probably due to a high shear rate in the Normal OP method because of a fully developed oral physiology. In a study on infant formulas, (Prakash et al., 2014) reported a similar decrease in viscosity with increasing shear load (non-Newtonian shear thinning behavior). The oral shear rates in infants are extremely low due to the absence of lateral jaw movements. When a bolus is easily deformable and flowable, it can be swallowed comfortably with a minimal oral effort. A limitation of the study is that the panel always applied the Up-Down method first followed by the Normal OP method, which could potentially affect results through order effects.

The relative increase in the initial perceptions of thick, too thick, sticky and pastiness of CPs with increasing solids content show a progression towards a more solid food state, which would be more challenging for infants to orally process. In infants whose OP is limited, this may lead to increased difficulty in food oral break down and oral manipulation. Food structure determines, to a large extent, how fast the food falls apart in the mouth, which influences the total chewing time and number of chews (Scholten, 2017a). The impact of food composition on texture perception originate from differences in microstructural and physical-chemical properties (Devezeaux de Lavergne et al., 2017). The bulk volume of indigenous porridges results from gelatinized starch (Nout and Ngoddy, 1997a). Consumer perception of the texture of porridge is influenced by processing technique and solids concentration (Muoki, 2013a). For commercial CPs, processing steps, such as hydrolysis, dextrinization, and pre-gelatinization, contribute to pleasant oral sensory texture by breaking down complex and long chains of food biopolymers into short-chain molecules, lowering thickness and stickiness of porridges (Prakash et al., 2014, Nasirpour et al., 2006). Foods are processed differently in the mouth, depending on their physical-chemical and mechanical properties (Scholten, 2017a). High bolus viscosity increases submental electromyographic (EMG) activity, indicating the use of additional muscular force during swallowing as viscosity increases (Smith et al., 1997). (Laguna and Chen, 2016) reported that compromised OP capabilities (e.g., during transporting food to the mouth, opening and closing the mouth, and swallowing) is closely associated with a high level of eating difficulty, low energy intake, and malnutrition.

Food composition and structure influence mastication (number of chews) and salivation (Witt and Stokes, 2015). (Shama, 1973b), studying the sensory properties of a variety of foods showed that the stress applied during consumption depends on the viscosity of the food. Low viscosity foods were observed to be associated with minimum stress and increasing rate of deformation, while for high viscosity foods, the deformation rate was maintained as the stress was increased (Scholten, 2017a).

The effect of the OP method, porridge type, and the temporal nature of OP (i.e., the evolution of oral texture attributes over time) on the in-mouth texture perceptions of CP samples was demonstrated. Food texture perception is a highly dynamic process that depends on the constant manipulations and transformations of foods in the oral cavity (Devezeaux de Lavergne et al., 2017). In both OP methods, the initial texture of Maize, Cassava, and Sorghum CP (10 %) was described as thick and/or too thick, sticky, slimy, progressing to soft, smooth, watery, then easy to swallow towards the end of OP. This is partly due to the shear-thinning behavior of the CPs. At very low shear rates (zero-shear viscosity η0), polymer suspensions are entangled many times, showing visco-elastic behavior arising from the balance between molecular disengagements and elastic recoil when an initial shear force is applied (Mezger, 2014). Each polymer chain assumes a spherical shape, entangled many times with neighboring macromolecules, leading to a higher viscosity at rest (Gina, 2016), often perceived as initial thickness and stickiness. When a shear load is applied during chewing, food molecules disentangle to a certain extent and gets aligned in the shear direction, and agglomerates disintegrate releasing bound liquid to flow again (Mezger, 2014). Together with the possible dilution effect of saliva, these events reduce porridge viscosity as OP progresses, which is perceived as a thin and watery consistency towards swallowing.

According to Hayakawa et al. (2013), the attribute “soft” when used to describe a food during OP implies pleasantness, and “easy to swallow” denotes a pleasant feeling as the bolus pass through the throat. “Viscous (thick)” and “sticky” imply unpleasantness of a material that adheres to or entangles on the eating utensils or teeth and is difficult to remove. OP was more complete in the Normal method as all samples achieved a watery and easy to swallow state, while in the Up-Down method, the samples achieved varying degrees of OP at the 30 s end-point, with Cassava (10 % solids) the least easy to swallow. This correlated strongly with its perceived stickiness, pastiness, and sliminess prior to swallowing.

The reference porridge (A1) was characterized as creamy, smooth, and soft towards the end of OP. The feeling of creaminess is associated with the lubrication properties of the oil droplets between the tongue and the palate (Scholten, 2017a). Smoothness is a complex tactile sensation implying the absence of graininess (Cai et al., 2017). From an oral motor development perspective, optimal complementary foods should be well suited to infants’ chewing and swallowing abilities in order to provide a pleasant early feeding experience. Yet that seems to not be the case with common indigenous and locally available CPs. An immediate effect of eating difficulty is reduced food intake, increasing the risk of malnutrition (McLaren and Dickerson, 2000, Tamine et al., 2010).

5.5. Conclusions

This study applied a trained adult sensory panel to gain insights into the temporal oral texture characteristics of indigenous porridges for infants and young children. The oral texture sensory perceptions of porridge samples were different depending on the OP method used. Indigenous CPs were thick, sticky, pasty, and slimy even at very low solids content, making the porridges potentially difficult to process, unpleasant, and not easy to swallow. The Up-Down OP method that mimics the restricted oral processing abilities of infants and young children leads to more enhanced perceptions of the thick, too thick, sticky, slimy, pasty, and difficulty to swallow attributes. This could ultimately limit food and nutrient intake perpetuating protein and energy malnutrition in infants that rely on these food types. OFSP porridge had a satisfactory oral texture at its highest solids content, comparable to a commercial reference (A1). Parents and caregivers are advised to consider the use of OFSP flour in composite with a legume (e.g., Cowpea or Bambara) for the preparation of CPs with relatively high solids content, suitable oral texture, and nutritive quality. Simple traditional approaches for reducing the viscosity of indigenous CPs at home (e.g., malting, fermentation, souring) need consideration by primary caregivers. This study provides scientific insight for baby foods manufacturers on the OP characteristics of complementary foods for infants and young children in African communities. Smart tech innovations for processing indigenous flours that give CP an optimal oral texture and solids content are required. Moreover, further research is needed to explore the dynamic sensory interplay between bolus properties of the foods and the oro-tactile phenomena (tongue coordination, mastication, and lubrication) in infants and young children, which, at present, is not well understood.

6.0. Nutrient density and oral processing properties of common commercial complementary porridge samples in Africa: effect on energy and protein intakes among children aged 6 – 24 months.

6.1. Introduction

Good nutrition in the first 1000 days of life is essential for the health and development of children, with implications throughout life (Black et al., 2017). Breastfeeding is the gold standard recommended for infant feeding up to 2 years and beyond (WHO/UNICEF, 2003). However, from about six months onwards, breastmilk alone can no longer provide adequate energy and nutrients that babies need at this age, and new foods (complementary foods) must be included in infants' diet following regulated norms (Alvarez et al., 2008) .

In addition to homemade complementary foods- the first-choice recommendation by WHO/UNICEF (2003) to supplement breastmilk-, commercially available complementary foods (CACFs) constitute an increasingly significant proportion of baby foods consumed by young children in developing countries (Aryeetey and Tay, 2015). CACFs are usually made from cereals or starchy raw materials to which different sources of proteins and lipids, mainly legumes, but also dried fish or milk powder, micronutrient premix, and other ingredients are added to improve the nutritional value and taste (Dimaria et al., 2018). These products are purchased in an instantized form requiring minimal cooking if any, or heating before consumption (Maslin and Venter, 2017). Common examples of CACFs include infant cereals made from rice, oat, barley, wheat, mixed-grain infant cereals, and some infant cereal and fruit combinations (Ng et al., 2012).

Good quality complementary food must have a high nutrient density (energy, protein and micronutrients), low viscosity and appropriate texture with a consistency that allows easy consumption (WHO, 2003, Balasubramanian et al., 2014, Bazaz et al., 2016). However, very few studies directly show whether commercial infant foods are really beneficial or unfavourable to infant health compared to homemade (Maslin and Venter, 2017). Extensive rheological studies have been carried out on cereal flour and starch paste, but rheological data on CACFs are limited since the majority of cereal-based baby foods are available in the dehydrated form (Ahmed, 2007). In addition, food product development in the complementary food sector needs technological data related to baby foods to drive continuous quality improvement, yet such data is not readily available. Most research on product development is kept secret by individual food processors or patented (Ahmed, 2007). Many governments and WHO member states require guidance on steering baby food manufacturers to improve the quality of their products and provide accurate information on packets to avoid misleading consumers or undermining public health recommendations (World Health Organization, 2019b).

It has generally been reported that marketed baby foods are semi-solid in nature to make them easy for children to handle and eat (Ahmed and Ramaswamy, 2007, Alvarez and Canet, 2013). In spite of this, systematic studies on the rheology, texture and ingredient interactions in commercial baby foods commonly used in different communities are limited (Ahmed, 2007, Alvarez and Canet, 2013). This fact becomes especially important because consumption of baby foods is directed at a population that cannot express their opinion (Alonso et al., 1995), thus impeding the acceptance or rejection of the products on the part of the baby consumers (Alvarez and Canet, 2013). According to Nicklaus et al. (2015b), little information is available on the texture of commercial baby foods as a function of age.

A recent European study on commercial foods for infants and young children found that foods of inappropriate nutritional quality were being marketed for infants and young children, although the study did not explore texture aspects (World Health Organization, 2019a). The in-mouth texture of complementary foods must be matched to the oromotor readiness and overall developmental milestones of infants and young children (Black et al., 2017). When prepared according to the label directions for use, processed cereal-based foods should have a texture appropriate for the spoon-feeding of infants or young children of the age for which the product is intended (Codex Alimentarius, 1981, World Health Organization, 2019a).

The viscosity and mouthfeel perception of complementary foods is an important property that influences not only the quantity of food a child can consume, but also the energy intake (Mosha and Svanberg, 1983, Bazaz et al., 2016). Hence, Nutrient Profiling - the science of classifying or ranking foods according to their nutritional composition- is critical to the prevention of disease and promotion of health (World Health Organization, 2019b). In infants and young children, the physiological capacity, sensory quality and oral motor skills are significant determinants of food choice (Schwartz et al., 2018). Therefore, more research is needed to substantiate data on CACFs for better handling, processing, use and quality control (Ahmed, 2007). The flow properties of commercial baby foods are very important with respect to the eating quality of the product (Ahmed and Ramaswamy, 2007, Alvarez and Canet, 2013).

Infants and young children are more likely to accept soft textures which they can easily manipulate initially using only an up-and-down motion, their tongues and jaws are much weaker and they cannot chew or orally process any solid or textured foods (Le Révérend et al., 2014, Sampallo-Pedroza et al., 2014). Poorly adapted textures may contribute to child malnutrition- an endemic public health problem in Africa. Typically, desirable porridge viscosity is one that allows ease of consumption while maintaining adequate solid content (Kikafunda et al., 1997).

This phase of the research explored the nutrient (protein – energy) content, flow properties (viscosity), and dynamic oral texture quality of some commercial complementary porridges commonly used in African communities, to establish how these factors influence the CACFs' capacity to meet the recommended nutrient intakes (protein and energy) for infants and young children aged 6 - 8; 9 - 11 and 12 - 24 months. Such information may help to guide the design and processing of developmentally appropriate foods for infants and young children, and to inform science-based policy formulation to improve child nutrition.

6.2. Materials and Methods

6.2.1. Materials

Fifteen (15) commercially available complementary foods with recipes for usage according to different age-groups as shown in Table 16, were used in the study.

Table 16. *Descriptions of selected commercially available complementary foods (CACFs) commonly used in African communities.*

Commercial complementary porridge*[x]	Age (Months)	Dilution rate powder (g): liquid (ml	Solids (%)	Description / Manufacturer's guide
A1- Reference	6 to 24	50:150	25.0	Enzyme-hydrolysed cereal (Maize 62 %)/ add water
A2	6 to 24	50:150	25.0	Enzyme-hydrolysed cereal (Rice 63 %), add water
A3	6 to 24	50:150	25.0	Enzyme-hydrolysed cereal (Wheat 61 %), add water
C2	6 to 24	50:140	26.3	Oat flakes 32%, add water
F1	6 to 8	45:150	23.1	Enzyme-hydrolysed cereal (Wheat 51 %), add water
	9 to 12	67:200	25.1	
	13 to 36	80:250	24.2	

Table 16. *Descriptions of selected commercially available complementary foods (CACFs) commonly used in African communities, "Continued".*

Commercial complementary porridge*^{x}	**Age (Months)**	**Dilution rate powder (g): liquid (ml**	**Solids (%)**	**Description / Manufacturer's guide**
F2	6 to 8	35:150	18.9	Enzyme-hydrolysed cereal (Rice 51 %), add water
	9 to 12	60:200	23.1	
	13 to 36	75:250	23.1	
F3	9 to 12	67:200	25.1	Enzyme-hydrolysed cereal (Wheat, rice, corn, - rye, barley 54 %), add water
	13 to 36	80:250	24.2	
F4	9 to 12	67:200	25.1	Enzyme-hydrolysed cereal (Wheat, rice, corn, - rye, barley 43 %), add water
	13 to 36	80:250	24.2	
B1	6 to 24	50:160	35.1	Enzyme-hydrolysed cereal (Maize), add milk
B2	6 to 24	50:160	35.1	Enzyme-hydrolysed cereal (Wheat), add milk
C1	6 to 24	20:170	24.8	Whole Oat flour 70 %, Banana flakes 30 %, add milk.
D	6 to 36	20:140	26.3	Maize flour minimum 86 %, add milk
E1**	6 to 12	25:200	26.7	Maize meal flour, 3 min cook with milk
	13 - 36	35:280	25.8	
E2	6 to 12	25:125	30.0	Sorghum flour (Minimum 89%), add milk
	13 to 36	35:190	29.1	
G	13 to 36	20:80	32.8	Wheat flour, Maize flour, Soya flour, add milk

**All samples were analysed within best before dates. NAN Optipro milk (Formula 2 and Formula 3 for 6 -12 and 13 - 24 months respectively) were prepared as per manufacturer by mixing 32 g milk powder with 200 ml pre-boiled luke-warm water, to give a 16 % solids content milk. All commercial complementary porridge samples were purchased from local supermarkets in Pretoria, South Africa. **Cooking loss of 5 %. The "add-water" commercial porridge samples contain whole or skimmed milk powder within a range of 23 % - 40 %. ^{x}Code names were used in place of the actual commercial complementary porridge names.*

6.2.2. Methods and Analyses

6.2.3. Nutrient composition- Protein and energy density

Nutrient composition was conducted based on declared nutrients contents on the product labels. The dry cereal-based baby foods were sampled from different retail shops in the low- and high-income areas in the city of Pretoria. For reconstituted, ready-to-eat or cooked products, the nutrient density was calculated based on the solid content in the meal as consumed.

6.2.4. Flow properties and apparent viscosity of complementary porridge samples

A rotational rheometer (Physica MCR 101, Anton Paar, Ostfildern, Germany) with temperature control and data acquisition software (Rheoplus version 3.0x, Anton Paar, Ostfildern, Germany) was used to measure the viscosity of porridge samples at different shear rates with a vane spindle. Commercial complementary porridge samples were prepared according to the manufacturer instructions (Table 16) and a 22 g sample transferred to a rheometer cup. The spindle was set to measuring position, sample covered with a layer of paraffin oil to minimize moisture loss by evaporation and equilibrated to 40 °C for 10 minutes. The test started in controlled shear rate (CSR) mode from 0.001 - 1000 s^{-1} and back, to measure the apparent viscosity (mPa.s). The shear rate range was chosen to cater for changes in oral shear capacity with increasing infant age. Each experiment was done in triplicate, using a fresh sample prepared from a different infant porridge pack each time. Shear rates of 0.001, 1.0, 10.0 and 50.0 s^{-1} were used for estimating the in-mouth viscosity of complementary porridge for 6 - 8, 9 - 11 and 12 - 24 months old infants and young children respectively.

6.2.5. Energy and protein content of the complementary porridge samples

The viscosity of the complementary porridge samples prepared according to the manufacturer was measured at four shear rates levels (0.001 s^{-1}; 1.0 s^{-1}; 10.0 s^{-1}; 50.0 s^{-1}). The energy (kJ/100g) and protein (g/100g) content of commercial porridge samples as consumed on the nutritional information panel, was used in calculating the energy content of the porridges when diluted with milk or water as directed by the manufacturers.

6.2.6. Daily energy and protein intakes from commercial complementary porridges

The daily nutrient intake (energy and protein) from commercial complementary porridge were calculated from the energy and protein content as below:

$$Daily\ nutrient\ intake\ = \frac{Nutrient}{1g\ porrige} \times functional\ gastric\ capacity \times meal\ frequency \qquad \textit{Equation 6}$$

based on some assumptions of 3 meals/day and functional gastric capacities of 249g/meal, 285g/meal and 345g/meal for infants and young children of ages 6 - 8, 9 - 11 and 12 - 24 months respectively (Michaelsen and Friis, 1998, Dewey and Brown, 2003).

6.2.7. Sensory Analysis

Sensory analysis of the CACFs was conducted by a trained panel in individualized booths under standardized conditions at the University of Pretoria Sensory Evaluation Laboratory. The use of human subjects in the study was approved by the Faculty of Natural and Agricultural Sciences Ethics Review Committee at the University of Pretoria (EC 180000086). Panellists were screened for interest, availability, general health status, and product discrimination abilities. Each participant signed a consent form prior to taking part in the study.

Ten assessors (aged 22 – 27 years) were selected and trained on the Temporal Check-All-That-Apply (TCATA) evaluation method in three sessions of 2 h each, according to the International Organization for Standardization (ISO) standard 8586:2012 for the training of sensory assessors (International Organization for Standardization, 2012). During training, the assessors familiarized themselves with the oral texture of the CPs, discussed, and agreed on 14 TCATA attributes, whose definitions are described in chapter 5. With TCATA, panellists evaluate each sample and select all the sensory attributes that best describe their perception at each moment of the evaluation (Castura et al., 2016). The panel was also trained on the evaluation protocol and use of the data acquisition software, Compusense Cloud version 7.8.2 (Compusense Inc., Guelph, ON, Canada). The CACFs were first evaluated using the Up-Down method that mimics feeding in infants and young children with limited OP ability. Assessors moved their mouths only up and down, avoiding sideways movements and ensuring limited tongue movement. Babies initially use immature feeding skills characterized by the up and down movements of the jaws, eventually transitioning to mature feeding skills defined by rotary jaw movements, which facilitate efficient chewing (Demonteil et al., 2019b, Black et al., 2017). In the second method (involving experienced adult chewing actions, called the Normal method), panellists orally processed the food in a normal adult way involving the lateral mouth and tongue movements, applying oral shear and chewing where necessary. The Up-Down method was always used first before the Normal method during the evaluation sessions because the former required more conscious procedural effort due to its artificial nature compared to normal adult oral processing.

6.2.8. Statistical analysis

All experiments and analyses were conducted in triplicate using a fresh complementary porridge pack each time, and data reported as mean values with standard deviations. Statistical analysis was carried out as described in Chapter 4, section 7. Principal component analysis was carried out, with “add-milk” and “add-water” as supplementary variables, while the rest of the variables were active. Univariate analysis of CACFs was done to profile the energy and protein densities of the products. Rheological data of both indigenous and commercial porridge samples were fitted to the power-law model and the Cross rheology models as described in section 4.2.6, in order to predict the flow properties of the complementary porridges.

6.3. Results and Discussion

6.3.1 Nutrient profiling- Energy and protein density

The energy and protein density distributions for CACFs are shown in Figures 26 and 27(a-b).

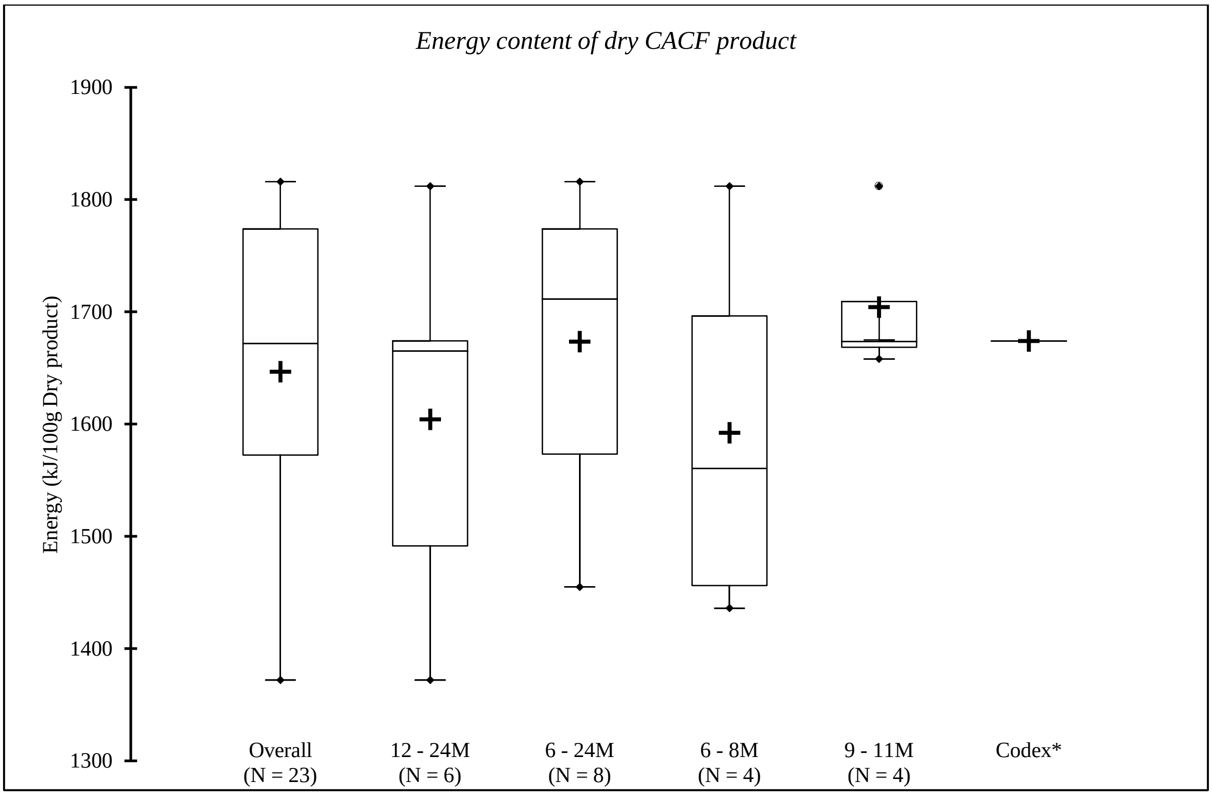
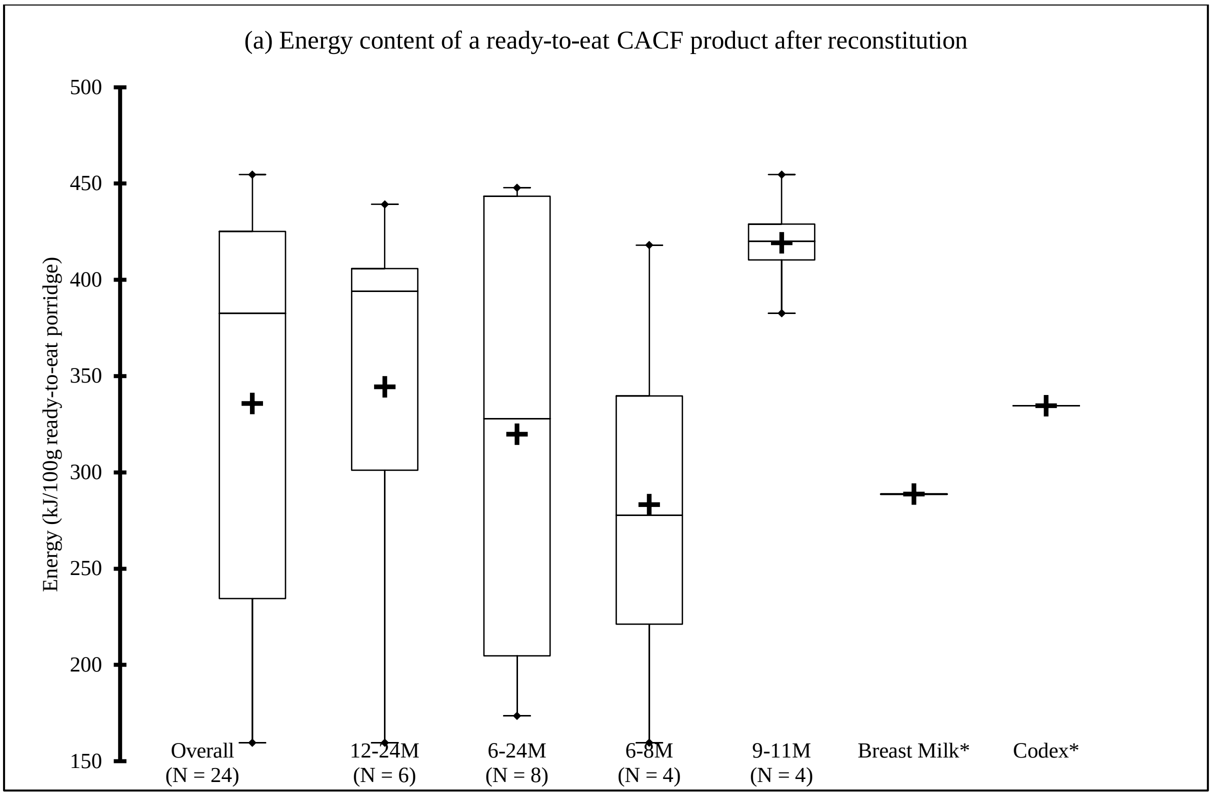
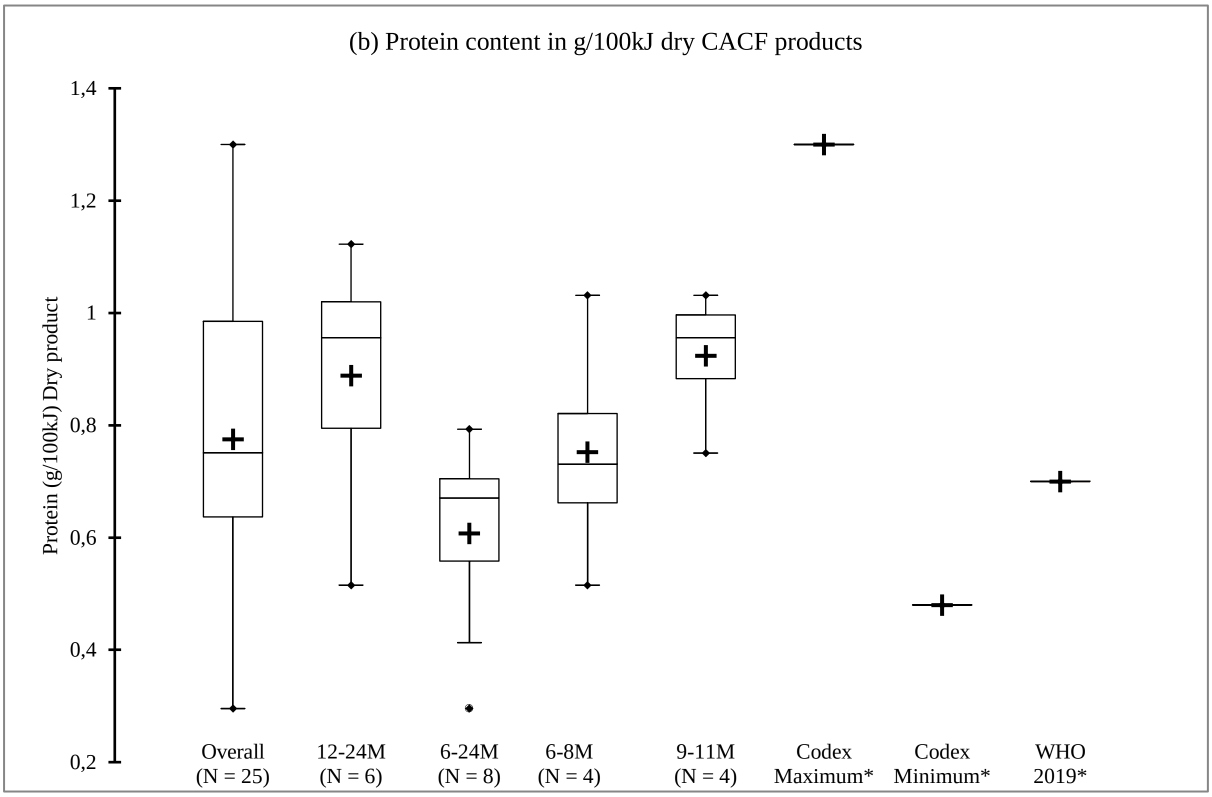


Figure 26. *The energy density boxplots for some CACFs (dry product) marketed in Africa versus a Codex Alimentarius standard for baby food, analysed by age group in months (M).*



(a) Energy content of a ready-to-eat CACF product after reconstitution



(b) Protein content in g/100kJ dry CACF products

Figure 27. *The nutrient density boxplots for some CACFs marketed in Africa versus breast milk, a Codex Alimentarius standard for baby food, and WHO 2019 study. 27(a): energy density ready-to-eat product, 27(b) Protein density dry product. *Infants foods should have an energy density (on a ready-to-eat basis) of 288.7 kJ/100g (69 kcal/100g) provided by breast milk, or 334.6 kJ/100g (80.0 kcal/100g) (World Health Organization, 2019a). *The protein content shall not be less than 0.48 g/100 kJ (2 g/100 kcal), and shall not exceed 1.3 g/100 kJ (5.5 g/100 kcal) (Codex Alimentarius, 1981).*

The energy density of dry products (Figure 26) ranged from 1372.0 kJ/100g for a product in the 12 – 24 months age group, to 1816.0 kJ/100g for products in all age groups. Overall mean energy density for the products across age-groups and in particular, products for the 6 – 8 and 12 – 24 months age group was below the Codex standard of 1674 kJ/100g dry product. In the ready-to-eat form (Figure 27a), all products had energy densities at least similar to breastmilk (288.7 kJ/100g). However, breastmilk is known to be inadequate from 6 months onwards and therefore may not represent a good standard comparator for energy content of CACFs. When compared with a Codex reference standard for energy content of dry products (334.6 kJ/100g), CACFs for 6 – 8 months and 6 – 12 months age-groups were below the recommended level. In terms of protein density, all products analysed met the minimum (0.48 g/100 kJ) and maximum (1.3 g/100 kJ). However using a minimum protein content of 0.7 g/100 kJ as used in a European study by the World Health Organization (2019a), about 8 recipes within the 6 – 24 months age group were inadequate in protein content. The product labels had some preparation information for the age-groups 6 – 8; 9 – 11; 12 – 24 months; and in some cases, 6 – 12; 6 – 24 and 13 – 36 months.

These results suggest a lack of compliance with published standards and international recommendations for nutrient content of complementary foods, which could lead to malnutrition for children subsisting on such foods for a prolonged period. The energy density of cereal-based CACFs should not be less than 3.3 kJ/g (0.8 kcal/g), and added protein content shall not be less than 0.48 g/100 kJ (2 g/100 kcal) (Codex Alimentarius, 1981, World Health Organization, 2019b). Soft–wet spoonable foods for infants should generally have a minimum energy density (on a ready-to-eat basis) of 252 kJ/100 g (60 kcal/100 g), or at least 288.6 kJ/100 g (69 kcal/100 g) considered to be provided by breast milk- to provide adequate nutrition for infants and young children between 6 and 12 months (Codex Alimentarius, 1981, World Health Organization, 2019a, World Health Organization, 2019b). For dry products, Codex recommends that the energy density should be at least 400 kcal per 100 g on a dry weight basis (World Health Organization, 2019a).

The current findings support previous studies in many regions of the world including African countries (Benin, Burkina Faso, Ghana, and Senegal, Tanzania) (Treche, 1999, Muhimbula and Issa-Zacharia, 2010, Dimaria et al., 2018), Saudi Arabia in Western Asia (Al-Othman et al., 1997), the UK (García et al., 2013) and Europe (World Health Organization, 2019a) where some CACFs were found to be nutritionally inadequate. In a separate investigation, Lockyer (2016) observed that some commercial infant foods which were soft and ‘spoonable’ had a lower nutrient density than home-made foods, and supplied no more energy than breast and formula milk. Similarly, Masters et al. (2017) also reported a wide variation in nutrient densities, and frequent inconsistency between the products' actual composition and the information printed on labels of some commercial complementary foods for sale in low-and middle-income countries. Low energy density is problematic because infants' and young children's small stomachs mean that they can consume only relatively small amounts at mealtimes (World Health Organization, 2019a). In the absence of enough energy the body uses protein to meet the energy needs, thus creating a protein deficiency amongst infants.

Regarding matching the CACFs serving size (the manufacturer's recommended amount of food in grams, to be consumed per meal) and preparation instructions to infants' age, it was worrying that 8 out of the 22 products evaluated had the same serving size and instructions for preparation spanning the needs of infants from 6 – 24 months. It is important that baby food preparation instructions are adapted to the narrow developmental stages of infants and young children (Black et al., 2017). As recommended by Brown et al. (1998), recommendations on complementary feeding must focus on fairly narrow age ranges for results to be meaningful in light of the continuous progression of young children's physiological development and increasing nutritional needs.

6.3.2. Viscosity of commercial complementary porridge samples

The viscosity profiles of some commercial complementary porridge samples used in feeding infants and young children of age-groups 6 – 8, 9 – 11 and 12 – 24 months in many African communities are presented in Figures 28 and 29(a - b).

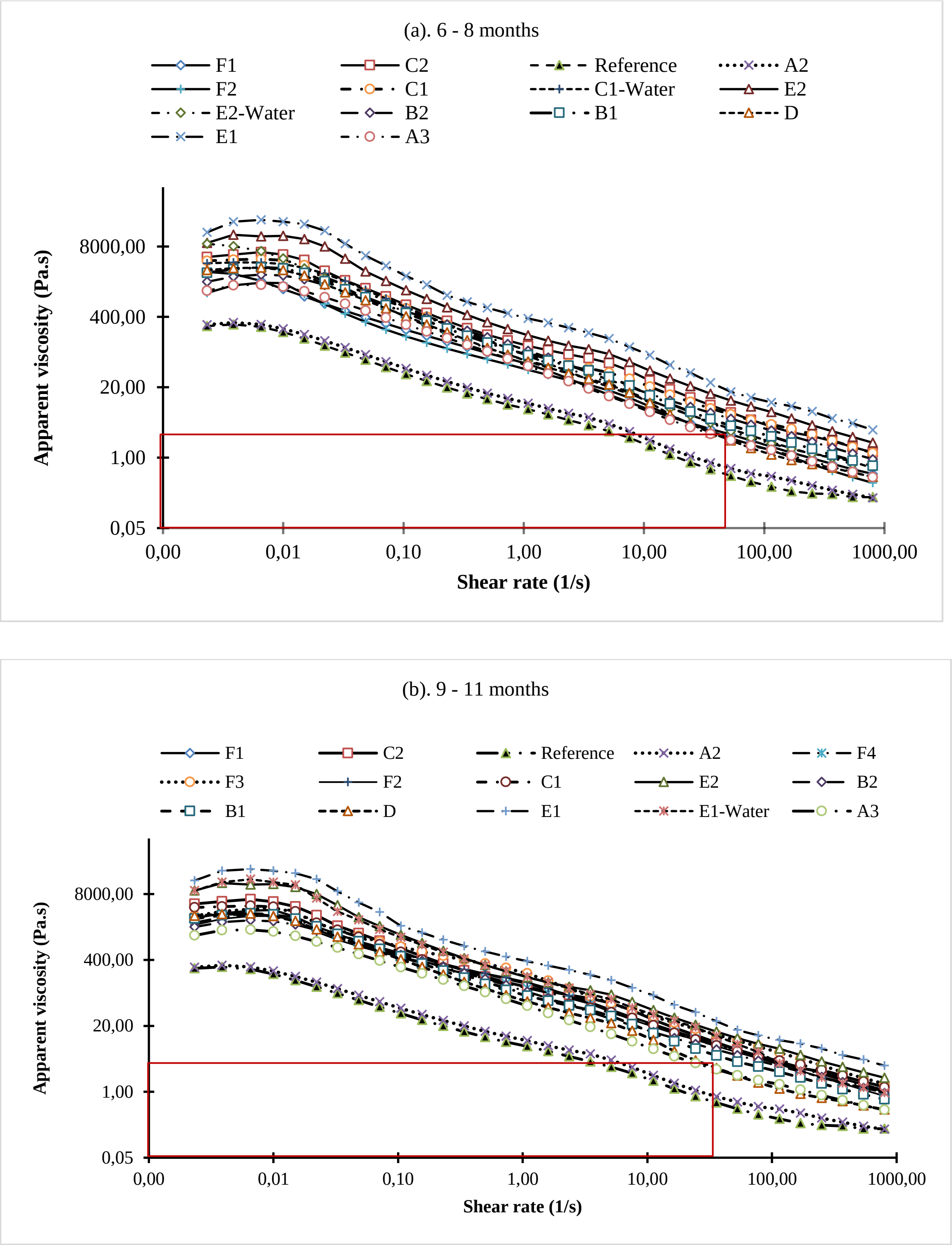


Figure 28. *Viscosity profiles of some CACFs commonly used to feed infants in African communities at the age of 6 – 8 months (a) and 9 – 11 months (b). Samples were prepared according to the manufacturer's guide. Recommended viscosity limit: 3 Pa.s (Nout, 1993, Thaoge et al., 2003).*

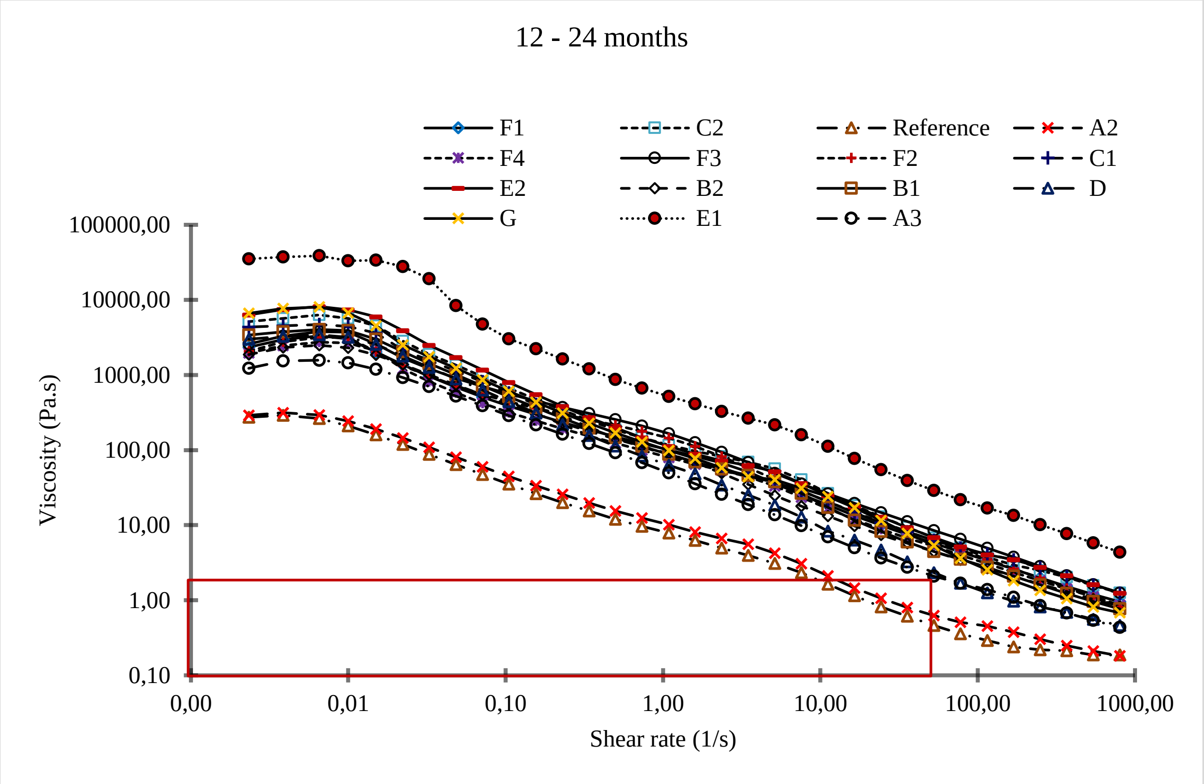


Figure 29. *Viscosity profiles of some CACFs commonly used to feed infants in African communities at the age of 12 – 24 months. Samples were prepared according to the manufacturer's guide. Recommended viscosity limit: 3 Pa.s (Nout, 1993, Thaoge et al., 2003).*

The viscosity profiles for all samples showed a zero-shear viscosity region (viscosity at low shear rates), and a shear-thinning viscosity (Newtonian) region with increasing shear force. With the exception of A1 (reference) and A2, most commercial porridges had high viscosity profiles not meeting the critical viscosity limits (3 Pa.s) generally considered to be acceptable for infants food oral processing (Thaoge et al., 2003). Porridge E1 (prepared by a 3 minutes cook of native corn/maize meal in milk) and E2 (prepared by instant mixing of sorghum flour with milk) had the highest viscosity profiles across all age-groups. The samples A1 (reference), A2 and A3 (the enzyme-hydrolyzed add water formulations) had the lowest viscosity profiles, meeting the critical viscosity limit (3 Pa.s) at low shear rates (10/s) - even at higher solids content (25 %). Table 17 shows results of fitting the power-law and Cross models to the rheological data for the CACFs.

Table 17. *Predicting the steady shear flow properties from rheological data using the power-law and Cross model, for some selected commercial complementary porridge samples commonly used in African communities.*

Complementary -	**Infant Age**	**Water-**	**Solids**	**Power law model***			**Cross model****		
porridge name	**(Months)**	**or milk**	**(%)**	**K**	**n**	**R^2**	**n**	**η_∞ (Pa.s)**	**η_0 (Pa.s)**
A1 reference	6 - 24	water	25.0	4.7	0.31	0.99	0.6	0.07	71.8
A2	6 - 24	water	25.0	6.2	0.33	0.99	0.6	0.04	36.3
A3	6 - 24	water	25.0	24.2	0.31	0.85	0.7	0.8	797.6
C1	6 - 24	water	26.3	62.9	0.29	0.97	0.7	0.7	666.0
F1	6 - 8	water	23.1	47.7	0.28	0.99	0.7	1.0	1042.2
	9 - 12	water	25.1	69.9	0.29	0.99	0.7	0.6	603.5
	13 - 24	water	24.0	55.3	0.31	0.98	0.7	0.3	250.9
F2	6 - 8	water	18.9	24.2	0.30	0.97	0.8	0.6	623.5
	9 - 12	water	23.1	62.9	0.29	0.95	0.8	1.4	1420.5
	13 - 24	water	23.1	65.3	0.30	0.95	0.8	0.7	691.0
F3	9 - 12	water	25.1	99.3	0.31	0.98	0.7	2.2	2249.2
	13 - 24	water	24.2	80.6	0.32	0.98	0.7	0.8	844.5
F4	9 - 12	water	25.1	62.4	0.31	0.99	0.7	0.4	363.9
	13 - 24	water	24.2	47.6	0.33	0.98	0.7	0.7	744.6
B1	6 - 24	milk	27.4	49.0	0.24	0.98	0.8	1.0	1022.0
B2	6 - 24	milk	27.4	40.3	0.31	0.96	0.7	1.2	1198.9
C2	6 - 24	milk	24.8	77.5	0.26	0.96	0.7	2.3	2293.1
D	6 - 36	milk	25.3	30.8	0.25	0.78	0.8	0,50	526.9
E1	6 - 12	milk	25.3	184.9	0.34	0.87	0.7	3.2	3217.5
	13 - 36	milk	25.3	294.2	0.36	0.88	0.7	7.5	7516.9
E2	6 - 12	milk	30.0	130.7	0.25	0.96	0.7	2.9	2855.9
	13 - 36	milk	29.1	79.5	0.27	0.93	0.7	1.4	1416.4
G	13 - 36	milk	32.8	54.8	0.28	0.87	0.8	2.5	2519.7

K is the consistency coefficient; n** is the flow behaviour index; η_0 and η_∞ are the zero-shear and infinite viscosity estimates respectively; R^2 is a power-law regression coefficient which estimates the degree of fit of the model to shear-thinning behaviour. Samples were analysed at 40 °C and shear rates of 0.001 to 1000 s-1. ^{x}Code names for commercial complementary porridges.*

The zero-shear viscosity estimate (Cross model) and K-values (power-law model) were generally higher for non-hydrolyzed CACFs (E1), lower when hydrolyzed (A1, A2, A3) and higher with milk added (B1, B2, C2, E2). There is need to fully describe the rheological characteristics of TMFs, to aid understanding of how food is perceived temporally during eating (Munialo et al., 2019). However, the power law model has some limitations, which includes its singularity at zero shear rate and its inability to capture high shear rate dependency (Gallagher et al., 2019). The Cross model was able to describe the high and low shear regions of the CACFs, due to its ability to cope with insufficient data for estimation of high shear rate viscosity (Whitty and Wain, 2018). The model has been used previously to characterize flow behaviour of polymer dispersions and other shear-thinning fluids (Rao, 2007a).

High viscosity in food systems is because the rheology of complex protein-starch systems depends on many factors (starch concentration, protein type, protein concentration and thermo-mechanical process) (Kumar et al., 2017). The high viscosity of some add-milk formulations (e.g. E1 high in unhydrolyzed starch, B1, B2, D) could be due to the interactions of starch with milk proteins during cooking, as other researchers (Jamilah et al., 2009, Hudson, 2013, Lu et al., 2016) previously observed. When starch and milk protein are cooked together, the resulting viscosity may be greater than if cooked separately and mixed (Mason, 2009). Lelievre and Husbands (1989) found that blends of starch and caseinate concurrently cooked were synergistic in viscosity enhancement. According to Kumar et al. (2017), interactions in a starch-milk protein system during thermo-mechanical processes include penetration and adsorption of proteins on starch granules; protein aggregation; hydrogen bonding, and covalent and non-covalent bonding between starch molecules and proteins during cooking.

The n-values of all samples were below 1, which indicated all CACFs were shear-thinning. The flow behavior index for most polymer solutions has been shown to range between 0.3 – 0.7 ((Chhabra, 2010). The power-law R^2 values for all samples except D (0.78), E1 (0.87), E2 (0.88) and G (0.87) were above 0.90 showing a good fit of the commercial complementary porridge flow behavior to the power law model. Shear-thinning behavior can be related to the increased alignment of the constituent molecules as shear rate increases (Maskan and Göğüş, 2000). CACFs are complex multiphase systems made up of blends of whey, casein or soy protein, a fat source, carbohydrates, a vitamin-mineral mix, and other functional ingredients depending on the manufacturer (Nasirpour et al., 2006, Prakash et al., 2014). The most important ingredient affecting the porridge’s flow properties is starch at different degrees of depolymerization. Viscosity is directly proportional to the molar mass, because smaller molecules show no effective entanglements and typically display viscous flow behaviour (Mezger, 2014). The recommended carbohydrates for use in CACFs are lactose, maltose, sucrose, maltodextrins, glucose syrup or dried glucose syrup, enzyme-hydrolysed starch, pre-cooked or gelatinised starch (European Communities, 2000).

The relatively low viscosity of porridge samples A1 (reference), A2 and A3 were consistent with their compositions and processing histories (Table. 16). For lower molecular weight components the critical entanglement concentration is higher because effective entanglements are limited, therefore a much higher solids concentration can be tolerated in the porridge before viscosity start to rise (Mahmood et al., 2017). Starch hydrolysis and dextrinization lower the molecular size of CACFs ingredients, whereas pre-cooking and pre-gelatinisation reduces starch granule hydration and swelling. Where agglomerated particles exist in the porridge, at rest the particles are linked together by weak forces. However, when the hydrodynamic forces during shear as in oral processing are sufficiently high, the inter-particle linkages are broken down resulting in structural unit size reduction, lowering the resistance to flow (Van Hecke et al., 2012, Alvarez and Canet, 2013). In other studies, high viscosity in infant foods containing meat and fish as protein sources has been linked to protein gel formation, produced by molecular interactions between protein molecules via hydrogen bonding, ionic bonding, disulphide bonding and hydrophobic association (Alvarez and Canet, 2013).

The higher viscosity profiles of porridge samples B1, B2, D, and E2 may be attributed to the nature of ingredients used, their hydration properties and dispersions types the CACFs produce upon reconstitution (Prakash et al., 2014). Rheological properties have been shown to depend on the protein and carbohydrate content, as well as the degree of protein hydrations which cause pseudo-gel structure formations foods (Ahmed and Ramaswamy, 2006, Ahmed and Ramaswamy, 2007). In a related study, protein gelation influenced by molecular interactions (hydrogen bonding, ionic bonding, disulphide bonding and hydrophobic association) between protein molecules increased the viscosity in infant foods (Alvarez and Canet, 2013).

6.3.3. Daily energy and protein intake estimates from commercial complementary porridges for 6 – 24 months old children.

The daily energy and protein intakes and viscosity values at different shear rates for some common commercial complementary porridge samples consumed in Africa are presented in Table 3. At low shear rates (0,001/s – 1/s), all porridge samples except the reference and A2 at 1 s^{-1}, had high viscosity values (> 3 Pa.s) not matching the oral processing capacity of infants. At 10 s^{-1} only a reference porridge and A2 were below 3 Pa.s. Even at higher shear rate (50 s^{-1}), most (12/23) commercial porridge samples were above the critical viscosity limit, suggesting that infants may find the porridge samples too viscous to orally process and swallow. At the porridge solids content specified by the manufacturers, samples D and G met the recommended viscosity limit but were inadequate in providing the recommended protein and energy intakes for all 3 age-groups (Table 18).

Table 18. *Viscosity values, protein and energy intakes from selected commercial complementary porridge samples analysed at different shear rates and 40 °C.*

Commercial	**Recipe**	**Solids**	**Viscosity (Pa.s) at different shear rates**				**Energy**	**Protein**
Porridge ^{x}	**(Months)**	**(%)**	**0.001/s - 0.01/s ^{y}**	**1/s**	**10/s**	**50/s**	**(kJ/day)**	**(g/day)**
A2	6 - 24	25.0	303.2	6.6	1.1	**0.5**	2658	23
A3	6 - 24	25.0	1443.3	26.3	3.7	**1.4**	2658	23
B1	6 - 24	35.1	3906.7	55.8	8.2	**2.7**	2607	16
B2	6 - 24	35.1	2363.3	49.2	7.4	**2.5**	2574	19
C1	6 - 24	24.8	4558.9	53.8	10.8	4.1	2160	22
C2	6 - 24	26.3	4456.7	65.6	10.6	**3.1**	2703	22
D	6 - 36	26.3	3290.0	37.2	4.7	**1.1**	2049	11
E1	6 - 12	26.7	25350.0	248.5	39.6	10.6	2757	18
	13 - 36	25.8	35166.7	327.3	54.6	16.9	3861	25
E2	6 - 12	30.0	12696.7	117.7	21.0	7.0	2139	15
	13 - 36	29.1	7660.0	71.8	12.8	4.0	3120	22
F1	6 - 8	23.1	2568.9	53.8	7.7	**2.7**	3045	23
	9 - 12	25.1	3653.3	81.0	11.7	4.0	3045	23
	13 - 24	24.2	3102.2	67.2	9.9	**3.4**	4350	33
F2	6 - 8	18.9	1645.6	27.2	4.3	**1.4**	2364	24
	9 - 12	23.1	2824.4	78.0	10.6	**3.4**	2364	24
	13 - 24	23.1	3028.3	81.9	11.0	3.5	1244	38
F3	9 - 12	25.1	3974.4	109.0	17.4	6.0	3366	33
	13 - 24	24.2	3597.8	94.0	14.7	5.0	4020	40
F4	9 - 12	25.1	3031.1	71.4	11.2	3.8	3360	31
	13 - 24	24.2	2618.9	53.6	8.8	3.1	4014	37
G	13 - 36	32.8	7487.5	58.2	11.5	**2.5**	1494	14
Reference (A1)	***6 - 24***	***25.0***	***254.6***	***5.0***	***0.8***	***0.3***	***2658***	***23***
RNI* for Low BME infants:**		6 - 8 M$^{\#}$	≤ 3 Pa.s	≤ 3 Pa.s	≤ 3 Pa.s	≤ 3 Pa.s	**2318**	**5.2**
		9 - 11 M$^{\#}$	≤ 3 Pa.s	≤ 3 Pa.s	≤ 3 Pa.s	≤ 3 Pa.s	**2944**	**6.7**
		12 - 24 M$^{\#}$	≤ 3 Pa.s	≤ 3 Pa.s	≤ 3 Pa.s	≤ 3 Pa.s	**4318**	**9.1**
RNI for Average BME infants:		6 - 8 M$^{\#}$	≤ 3 Pa.s	≤ 3 Pa.s	≤ 3 Pa.s	≤ 3 Pa.s	**1495**	**2.0**
		9 - 11 M$^{\#}$	≤ 3 Pa.s	≤ 3 Pa.s	≤ 3 Pa.s	≤ 3 Pa.s	**2012**	**3.1**
		12 - 24 M$^{\#}$	≤ 3 Pa.s	≤ 3 Pa.s	≤ 3 Pa.s	≤ 3 Pa.s	**3242**	**5.0**
RNI for High BME infants:		6 - 8 M$^{\#}$	≤ 3 Pa.s	≤ 3 Pa.s	≤ 3 Pa.s	≤ 3 Pa.s	**672**	**1.1**
		9 - 11 M$^{\#}$	≤ 3 Pa.s	≤ 3 Pa.s	≤ 3 Pa.s	≤ 3 Pa.s	**1079**	**1.7**
		12 - 24 M$^{\#}$	≤ 3 Pa.s	≤ 3 Pa.s	≤ 3 Pa.s	≤ 3 Pa.s	**2167**	**3.6**

**Recommended nutrient intake. Each viscosity value represents a mean of three replicates. The energy and protein values declared on product package were used to calculate the daily intake estimates assuming 3 meals/day. **BME refers to the breast milk energy intake. Children are classified into low, average and high BME intake groups based on energy quantities acquired from mothers' milk (Dewey and Brown, 2003).* ^{x} *Codes represent the actual names of CACFs used in the study.* ^{y}*Zero-shear viscosity values.*

Even though samples A1 (reference), A2 A3, B1, B2, and F2 had acceptable viscosity values, they were not suitable for meeting the energy and protein requirements for the 9 - 24 months age-group. Porridge F1 was adequate in energy and protein for the 6 - 11 months age groups.

Although in most cases, the CACFs' nutritional information panel claim that the food provides adequate daily nutrient intakes to infants and young children, some CAFS do not meet the minimum regulatory energy and protein requirements (Figure 19 and Table 18) and are therefore nutritionally inadequate. As shown in Table 17, at low shear rates up to 1/s, all porridges failed to meet the viscosity criterion (3 Pa.s). At shear rate of 10/s, only 2/23 of the porridges (8.7 %) had appropriate viscosity, while at 50/s only 12/23 (52.2 %) met the recommended viscosity level. In cases where the energy and protein content of the porridges were adequate, the viscosity was often high and not suitable for infant food oral processing and swallowing due to lower shear rates and absence of rotary chewing skills which begin to develop late around 10–12 months of age (Cichero, 2017). Hence in a previous study Faber et al. (2016) reported that some caregivers (about 66 %) do not serve CACFs as per manufacturer's recommendations due to the high viscosity, but rather dilute with water which lowers the porridge's nutrient density.

From an oral motor development perspective, optimal complementary foods should be well suited to infants' chewing and swallowing abilities for a pleasant early feeding experience (Black et al 2017). High viscosity porridge will be difficult to digest and swallow for children due to their limited oral motor abilities. Laguna and Chen (2016) have argued that there is a lack of technical guidance in matching the rheological properties of foods with individuals' oral-motor capabilities. The ease of swallowing a food bolus is highly linked to its rheological quality (Gallegos et al., 2017). In resource-poor African communities, inappropriate rheological properties of complementary foods may limit nutrient intake in infants and young children, eventually leading to child malnutrition. The daily energy needs of children increase from approximately 600 kcal (2520 kJ/100 g) at 6–8 months of age to 900 kcal (3780 kJ/100 g) by 12 – 23 months of age (World Health Organization, 2019a). Therefore, children require the correct amounts of food of appropriate texture for age for healthy growth and development.

6.3.4. Global overview of the CACFs properties (rheological, sensory and nutritive)

Figures. 30, 31 and 32 shows Principal component analysis (PCA) maps obtained using data for the overall characterization of commercial complementary porridges examined in the study.

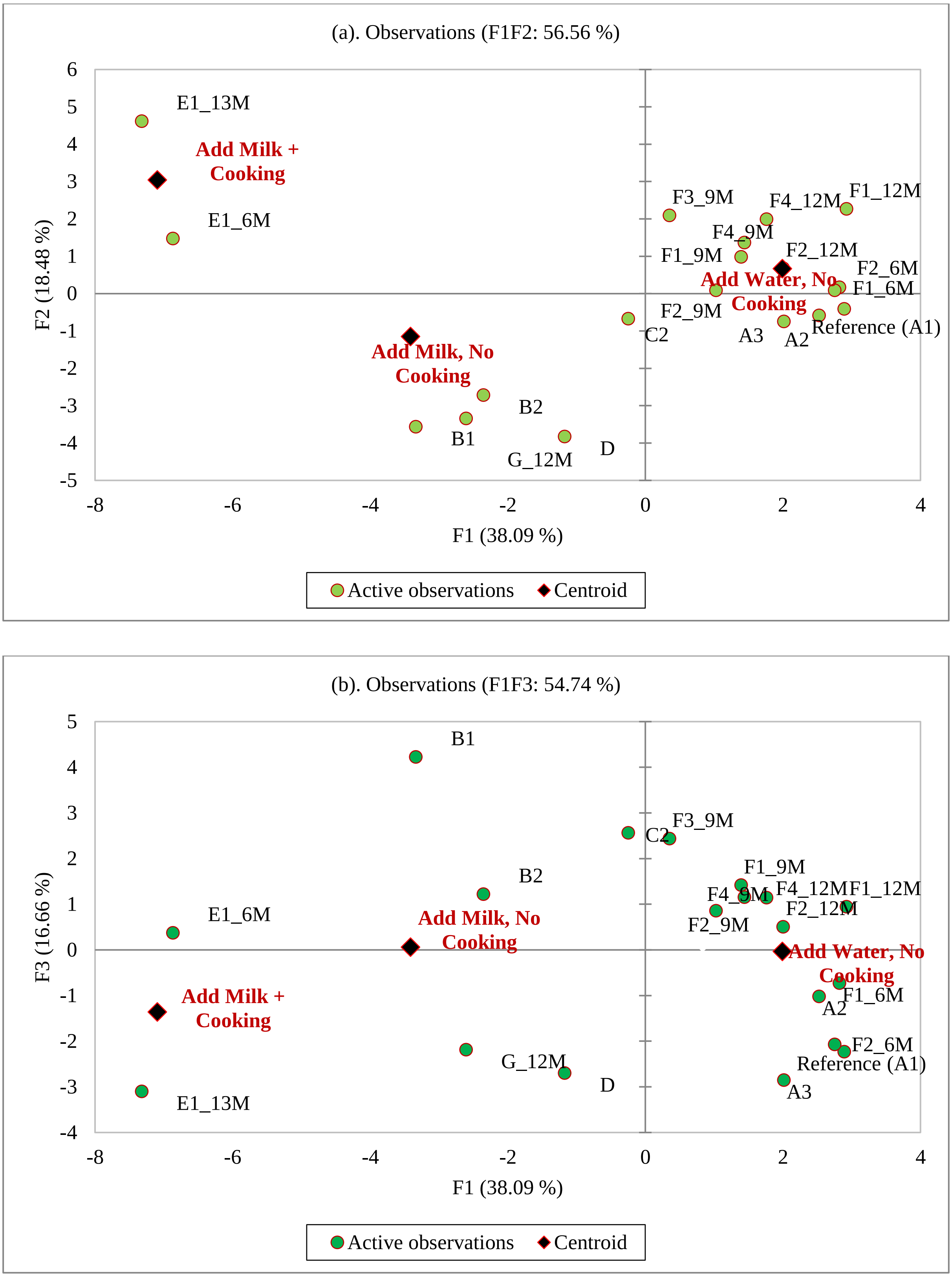
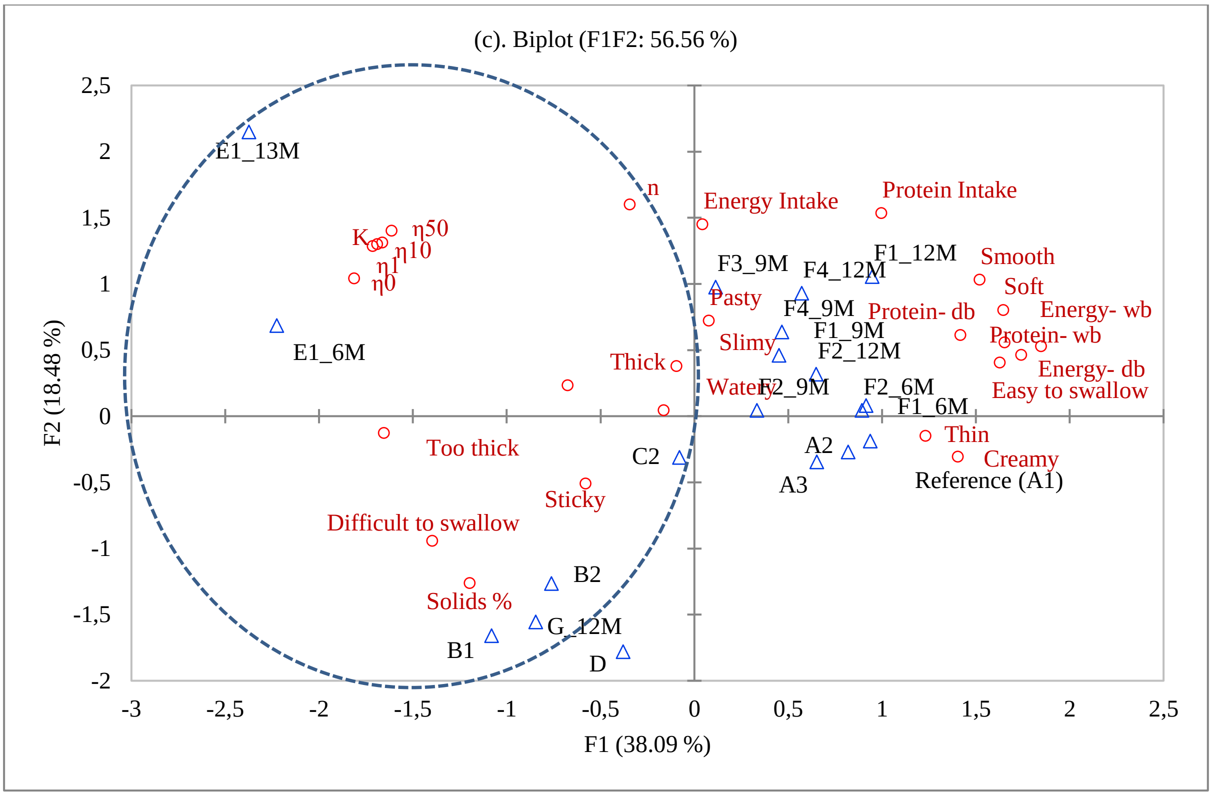


Figure 30. *PCA maps for the observations/ CACFs, showing the overall relationships among samples based on sensory, rheological, nutrient composition and intake data. The "add-milk" and "add-water" qualitative descriptors represent the supplementary variables.*



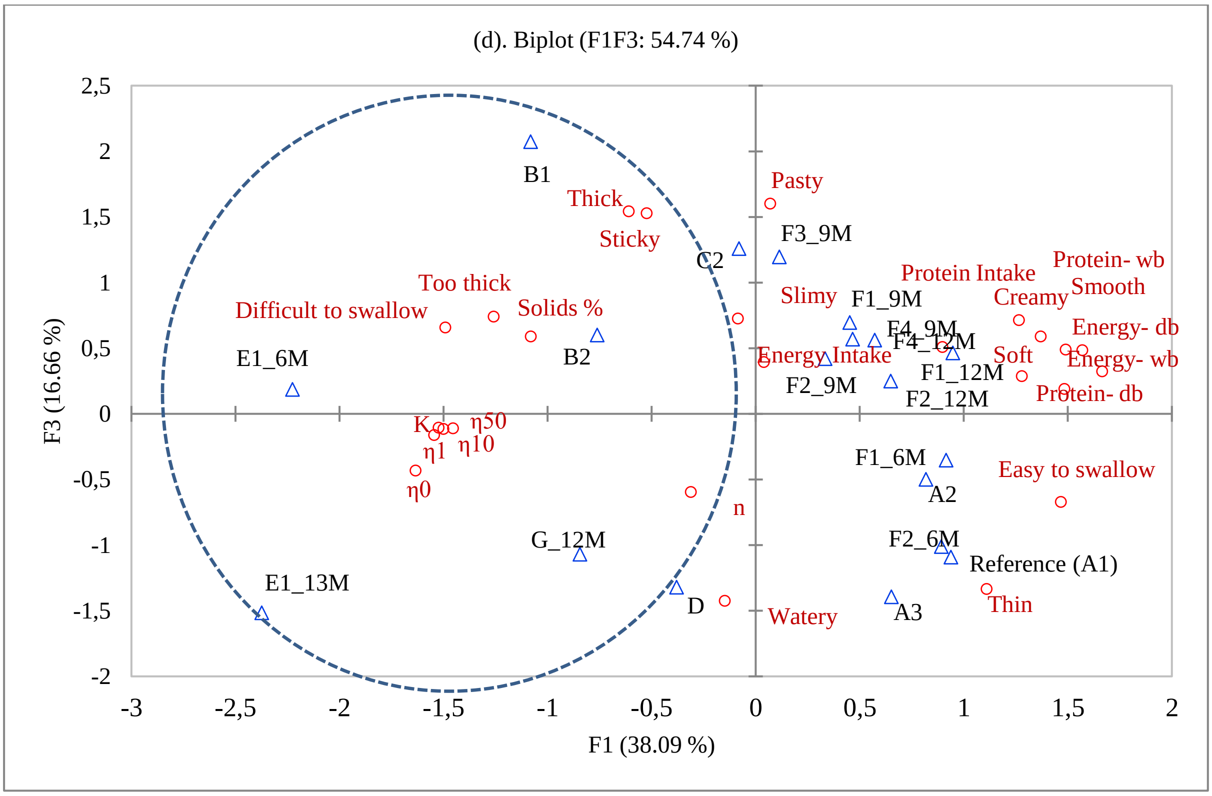
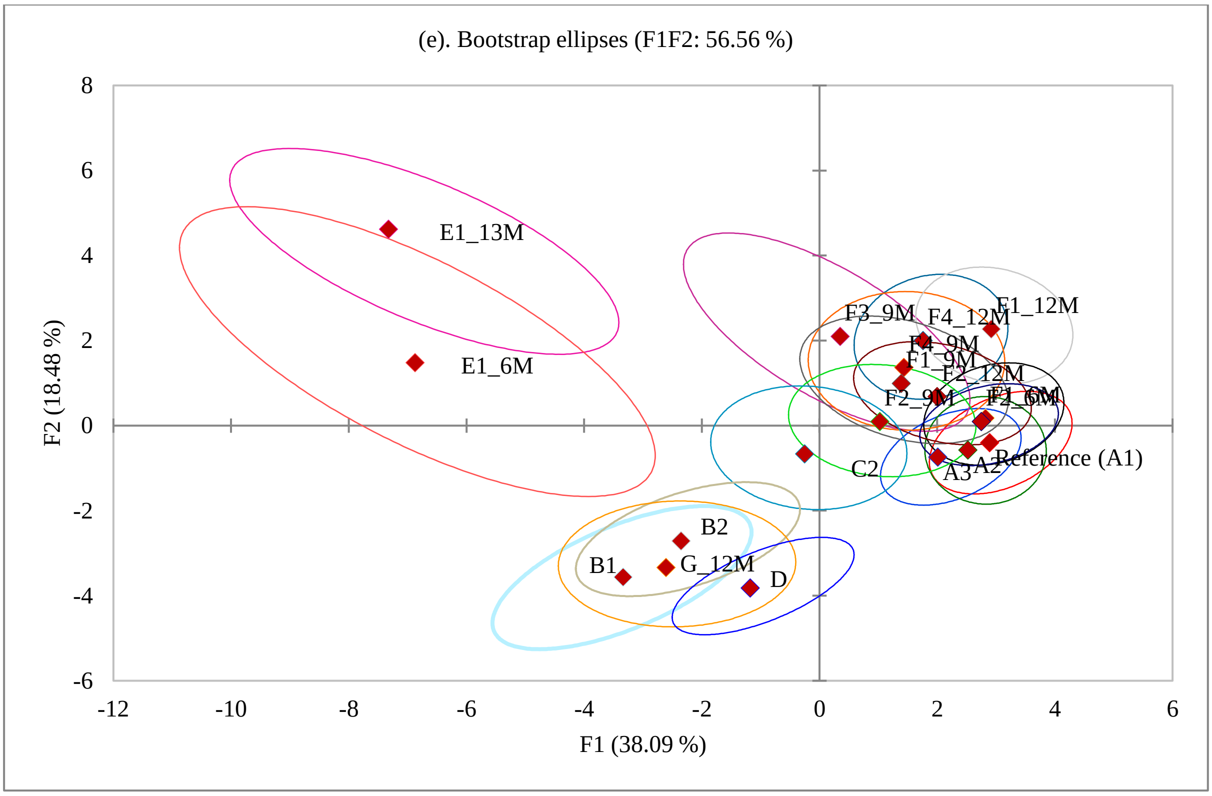


Figure 31. *PCA biplots for the overall relationships among CACF samples based on sensory, rheological, nutrient composition and intake data. Small red circles are the active variables, while the small blue triangles are the active observations (CACF samples).*



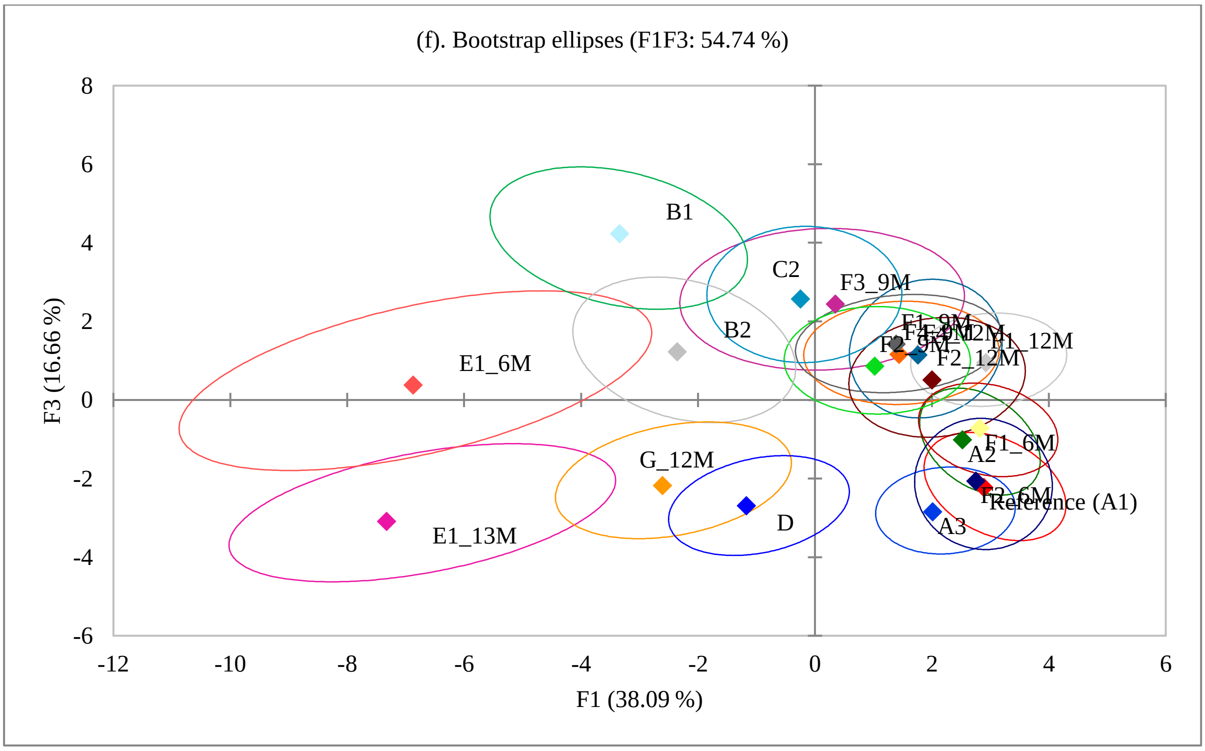


Figure 32. *PCA bootstrap confidence ellipses for CACF samples, constructed from the overall sample variables interactions among the sensory, rheological, nutrient composition and intake data.*

The first three PCA factors explain about 73 % of the total information (inertia) contained in the PCA model, with F1 (38 %) separating the samples clearly into "add-milk" and "add-water groupings" (Figure. 30). The centroids of each group are shown as bold, solid diamonds, while the samples are shown as solid round dots. Bootstrap ellipses (Figure. 32) provides further consolidation for these two groupings. The "add-milk" porridges were associated with high consistency coefficients (K), high viscosity at all shear rates, being too thick and difficult to swallow (Figure. 31). Porridge sample E1- prepared by a 3 min cook of unprocessed maize flour in milk, differed the most from the add-water samples which included a commercial reference sample.

The "add-water" samples were positively correlated with low apparent viscosity, high energy and protein densities and intakes, being soft, thin and easy to swallow (Figure. 31). This was probably due to incorporation of enzyme-hydrolysis ingredients and the absence of a cooking step- both of which reduce the occurrence of starch-protein interactions in the porridge which are thought to enhance viscosity. The absence of gelatinization process in the add-water types of CACF may also be a probable factor for their low viscosity profiles. Overall, the commercial complementary porridges showed a wide variation in their suitability for infant feeding in terms of their flow properties, sensory texture and nutritive properties.

Texture affects liking or rejection of many foods for clinically relevant populations (Breen et al., 2019). As such, a food formulation is expected to be suited to a child's oromotor readiness, for it to promote a pleasant eating experience (Black et al., 2017, Lorieau et al., 2018). Food is judged difficult to eat when the bolus is difficult to form (Laguna et al., 2017). The products described as too thick, sticky and difficult to swallow in this study may present feeding challenges to infants, ultimately affecting daily nutrient intakes leading to undernutrition. A child's oromotor readiness refers to its ability to efficiently and safely chew and swallow a given texture (Black et al., 2017). During swallowing, the tongue generates the primary propulsive forces that transport the food bolus through the oral cavity toward the pharynx (Steele et al., 2019). Higher forces and tongue pressure amplitudes for flow initiation- are generated for extremely thick foods compared with thin liquids (Steele et al., 2010, Steele et al., 2019).

The current results agree with a study by Nicklaus et al. (2015b) who reported large variations in oral texture quality versus changes in infant age, between brands and recipes of baby foods on the French market. When prepared according to the label directions for use, processed cereal-based foods should have a texture and consistency appropriate for the age of young children for which they are intended (World Health Organization, 2019a). Presently, there are no regulations regarding the texture of baby food products, and textural inconsistencies are likely to persist for some time into the future (Nicklaus et al., 2015b).

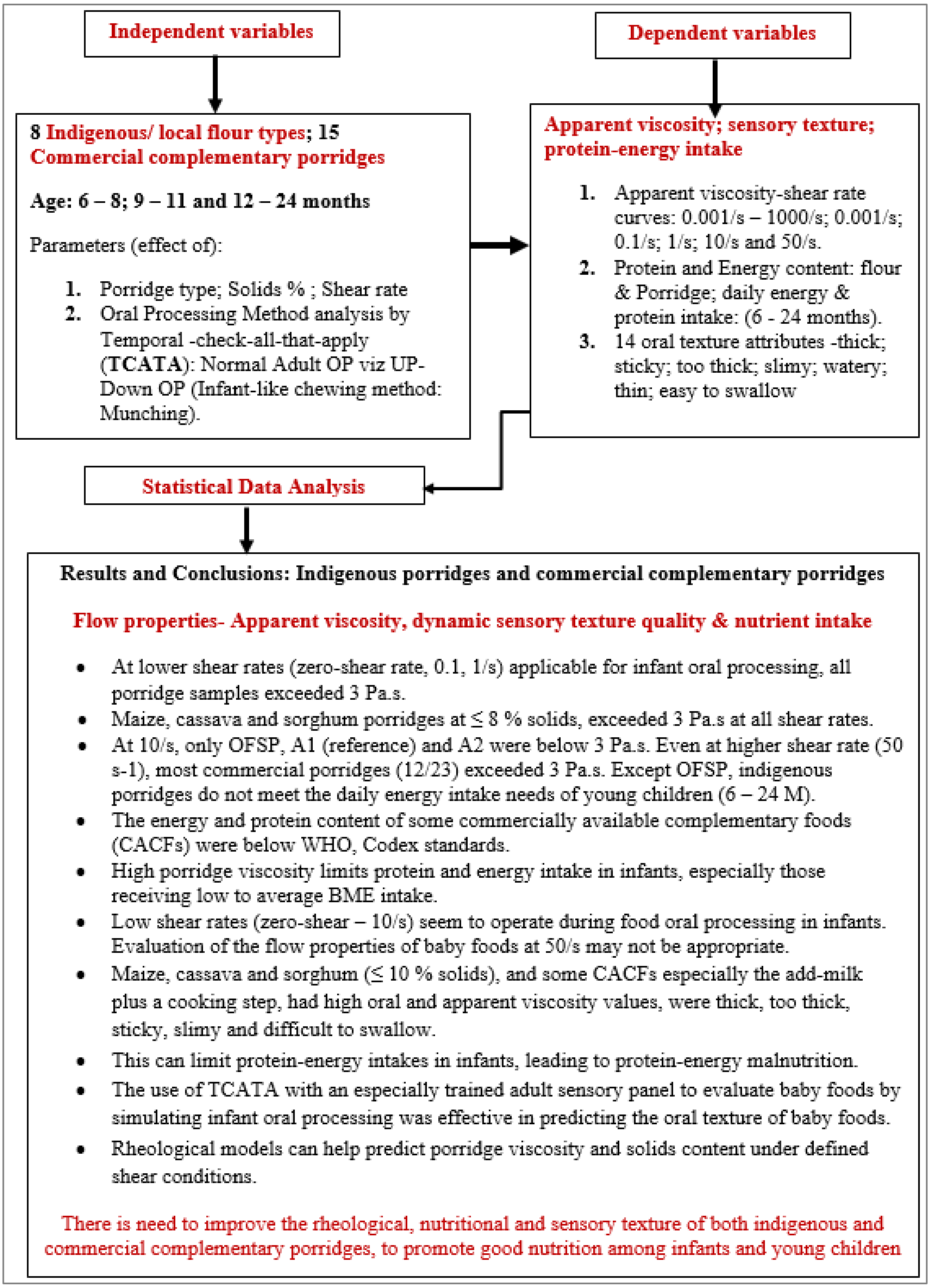
6.4. Conclusion

This study examined the generally held assumptions that all commercially produced complementary foods are balanced and optimized in rheological, sensory and nutritional quality. Some commercially available complementary foods (CACFs) do not meet WHO, Codex or other international standards for energy and protein content and other nutrient quality parameters. As a result, such products fail to support public health dietary recommendations for healthy growth and development of infants and young children. The viscosity values of most commercial complementary porridges at shear rates estimates for infant oral processing (0,001/s – 50 s^{-1}) are high, exceeding the recommended limit for baby porridge. This makes most common commercial porridges not able to meet recommended daily energy and protein intakes for infants and young children between 6 – 24 months of age. High porridge viscosity limits protein and energy intake in infants and young children, especially those receiving low to average BME intake and this perpetuates protein-energy malnutrition.

There is a need for improving the flow properties, oral viscosity and texture of commercial complementary porridges for better energy and protein intakes among African infants and young children. Further work is recommended to establish more precise shear rates applicable for in-mouth oral processing in infants and young children. This is important in designing more effective novel foods to meet the needs not only of infants and young children, but also for people with differing oral abilities. There is also a need to improve nutritional quality and labelling of the food products for infants and young children. Manufacturers and retailers should comply with the International Code and the WHO Guidance, including for composition, nutrition, health or development claims or statements. It is also important to define upper age limits appropriate for some products which are labelled as 6 – 24 or 36 months, to encourage a timely transition to family foods and adapting textures to the developmental readiness of children.

7.0. General Discussion

This section is an overall post-study critical review aimed at identifying possible weaknesses in the research, with a view to progressively improve the practice and outputs of science in this specific discipline. It interrogates the nature of the study design, experimental methodologies employed, their limitations, the potential biases and any other issues which may have had an impact on the accuracy, reliability and validity of the results and conclusions arrived at. The section also highlights the gaps in knowledge which this study may have either not addressed or has laid bare- which becomes the raw material for future research to advance science and to solve problems for humanity. The section begins with an outline scheme of the overall research and its findings (Figure. 33), followed by a critique of various elements related to the whole study design starting with methodological considerations (7.1).



Independent variables

8 Indigenous/ local flour types; 15 Commercial complementary porridges

Age: 6 – 8; 9 – 11 and 12 – 24 months

Parameters (effect of):

1. Porridge type; Solids % ; Shear rate
2. Oral Processing Method analysis by Temporal -check-all-that-apply (**TCATA**): Normal Adult OP viz UP-Down OP (Infant-like chewing method: Munching).

Dependent variables

Apparent viscosity; sensory texture; protein-energy intake

1. Apparent viscosity-shear rate curves: 0.001/s – 1000/s; 0.001/s; 0.1/s; 1/s; 10/s and 50/s.
2. Protein and Energy content: flour & Porridge; daily energy & protein intake: (6 - 24 months).
3. 14 oral texture attributes -thick; sticky; too thick; slimy; watery; thin; easy to swallow

Statistical Data Analysis

Results and Conclusions: Indigenous porridges and commercial complementary porridges

Flow properties- Apparent viscosity, dynamic sensory texture quality & nutrient intake

- At lower shear rates (zero-shear rate, 0.1, 1/s) applicable for infant oral processing, all porridge samples exceeded 3 Pa.s.
- Maize, cassava and sorghum porridges at ≤ 8 % solids, exceeded 3 Pa.s at all shear rates.
- At 10/s, only OFSP, A1 (reference) and A2 were below 3 Pa.s. Even at higher shear rate (50 s-1), most commercial porridges (12/23) exceeded 3 Pa.s. Except OFSP, indigenous porridges do not meet the daily energy intake needs of young children (6 – 24 M).
- The energy and protein content of some commercially available complementary foods (CACFs) were below WHO, Codex standards.
- High porridge viscosity limits protein and energy intake in infants, especially those receiving low to average BME intake.
- Low shear rates (zero-shear – 10/s) seem to operate during food oral processing in infants. Evaluation of the flow properties of baby foods at 50/s may not be appropriate.
- Maize, cassava and sorghum (≤ 10 % solids), and some CACFs especially the add-milk plus a cooking step, had high oral and apparent viscosity values, were thick, too thick, sticky, slimy and difficult to swallow.
- This can limit protein-energy intakes in infants, leading to protein-energy malnutrition.
- The use of TCATA with an especially trained adult sensory panel to evaluate baby foods by simulating infant oral processing was effective in predicting the oral texture of baby foods.
- Rheological models can help predict porridge viscosity and solids content under defined shear conditions.

There is need to improve the rheological, nutritional and sensory texture of both indigenous and commercial complementary porridges, to promote good nutrition among infants and young children

Figure 33. *Summary: The nutritive, rheological and sensory quality of selected indigenous and locally available commercial complementary porridges used for 6 – 24 months infants and young children in African communities.*

7.1. Methodological considerations

In the TCATA sensory evaluation phase of the study, panellists were asked to take a spoonful (about 5 ml) of the porridge sample into the mouth and proceed with the evaluation according to instructions given. This approach may introduce potential rheological bias during spooning or handling the sample if panellists take non-uniform porridge amount in the spoon or handle the samples differently from the recommended procedure. To control for this potential bias in an earlier related work (Steele et al., 2014b), the experimenter would fully load a 5-ml teaspoon and hand the spoon to the participant for evaluation, as opposed to panellists spooning the sample individually. While this could have been possible, it would have made the evaluation procedure much more burdensome and complex.

Another concern relates to the time- and temperature dependent nature of complementary porridges, which was a critical challenge during the sensory evaluation. Even with the use of water baths and trained assistants, maintaining the samples at a standardized temperature (40 °C) during the entire evaluation was not completely guaranteed, because assessors may inherently evaluate porridges at different rates. Additionally, because the viscosity of complementary porridges increases over time with a decrease in shear and temperature, panellists evaluated the same samples by the normal method immediately after an evaluation by the up-down method, the two separated by a 60s time delay. While this was only necessitated by the instability of the porridge samples (high propensity to thicken over time and with decrease in temperature), this procedure is likely to have introduced some analytical biases to the study. It is herein recommended that where stable samples are involved in a study, the samples as well as the methods must be randomized over separate sessions.

7.2. The use of model porridge systems

For this research, simplistic porridge model systems composed of only flour and water were studied, while it is possible that the actual porridge recipes as traditionally consumed by infants and young children in different homes may have other ingredients added. Compiling real traditional recipes from communities and replicating the preparation processes in the laboratory, or alternatively using immersion observational techniques (where the researcher immerses self in the community participating in the research) to study the infant diets within the different home situations (fieldwork) would have been very expensive in terms of time, cost and practical feasibility. This approach would also have required collaboration with other stakeholders and training of clinical field workers and data collectors, including further training in mixed methods research techniques. As a result of the foregoing, the current results on flow properties, dynamic sensory quality and nutrient densities may vary from scenarios where actual complex recipes as consumed in the communities were considered.

If exploratory, multivariate and mixed methods approaches had been used, it is possible that the results would have been more robust given the inclusion and interactions of multiple factors in the design. Ideally for study results to have high ecological validity, complementary porridges need to be studied within the community and at the actual point of use. Complementary porridges consumed by infants and young children in the home environment are complex in composition, involving diverse ingredients and preparation methods such as fermentation and souring (Gabaza et al., 2018). All these aspects may potentially modify the apparent viscosity, sensory and nutritional quality of baby porridges.

7.3. Physiological differences between infants and adults

The involvement of infants and young children in research work is often complicated due to legal issues, ethical concerns, and the limited cognitive and physical capabilities of infants to carry out evaluation tasks. Therefore, an adult panel standardized by training to enhance uniformity and consistency during the evaluation was rather used. However, physiological and experiential differences exist between adults and infants- in oral processing skills like food bolus manipulation and chewing behaviour, potentially introducing bias. For example, while the average volume of an adult mouth is 30 – 40 ml (Yagi et al., 2006), in young children different mouthful volumes have been suggested e.g. 0.2 ml (Selley, 1990), and 5 ml for children the aged 1.25 and 3.5 years (Jones, 1961). From a distinct calculation for children aged 3.3 years, Ratnapalan et al. (2003) reported a mean mouthful volume value of 9 ml. According to Jones (1961), the mean swallow volume estimate for adult men is 21 ml and for women is 14 ml. Minimum studies have been conducted on quantification of mouthful volumes in infants and young children, and further research in this area is required (Cichero and Murdoch, 2006). The size of a mouthful of food is inconsistent until the individual's appropriate amount is learned over time with growth (Yagi et al., 2006). Additionally, adaptations for food oral processing rely on variations in the number of chewing cycles, muscle strength and the volume of emitted saliva (Peyron et al., 2017)- which differ between infants and adults. Therefore, even with training, the results from an adult panel might potentially vary from those when infants or young children were to be used.

Regarding efficiency and experience in food oral processing and chewing, adults are generally more experienced chewers and efficient at oral processing, while infants and young children are inefficient, immature chewers. According to Burbidge and Le Révérend (2016), when provided with information (stimuli), the brain uses past experiences and heuristics to make decisions from the enormous amount of data available to it. Such past experiences will naturally be more significant in adults compared to young children. This fact is further reinforced by (Bourne, 2002), stating that the perception produced by food while present in the mouth is affected by prior experience, expectations, sensory impressions before eating and the interplay of olfactory, mechanical and trigeminal sensations in the oral cavity. The current results may not have been free from this potential bias considering that an adult panel was used.

7.4. The challenge of panel calibration for texture evaluation

Another issue that was difficult to handle in the study is the complex nature of an exercise in calibrating the TCATA sensory panel for texture perception of complementary porridges. This is because the perception of texture is inherently a dynamical process, with no obvious equilibrium state of adsorption of an agonist (e.g., a tastant or aroma molecule) to a particular receptor, and the texture stimuli are therefore intrinsically dependent on the exact modes of deformation and the deformation history of the tested material itself (Burbidge and Le Révérend, 2016). Rheological instruments are calibrated to reproducible units but the standardization of the human mouth is more difficult or rather impossible because of tremendous variations between individuals (Stanley and Taylor, 1998). For oral mechano-reception, the substance to be sensed is moved and manipulated inside the mouth to come in contact with the sensing regions/organs (tongue, palate, cheeks, teeth etc), this oral manipulation is likely to vary in different people (Wagner et al., 2017). As a result, two individuals (or even the same individual on subsequent occasions) may perceive a completely different mechanical stress field for an identical sample- making successful calibration very difficult. Hence, a distinction has to be clearly made between the food structure (an implicit property of the material), and the food texture (an individual's interpretation of a particular consumption event of a sample) of food (Burbidge and Le Révérend, 2016).

7.5. The shear rates representative of oral processing in infants and young children- an area of wide contestation

There is still much debate about the magnitude and distribution of shear rates and shear stress levels in the oral cavity, as well as the effect of non-rheological parameters on the perception of sensory texture (Malone et al., 2003). This too, although not necessarily a limitation - may mean that our results may not validate some of the available literature due to different protocols used. It has also been suggested that the transient shear rate in mouth can reach values as high as 10^5 s/1 (Nicosia and Robbins, 2001), and therefore although such shear rates are highly unlikely in infants and young children, it may be necessary to consider high shear viscosity in relation to the in-mouth behaviour of foods. It is also known that elongation of the bolus occurs while swallowing and therefore in addition to shear, it is probable that extensional deformation properties (i.e., bolus cohesiveness, surface tension) of fluid foods are also relevant to swallowing and should be evaluated (Hadde et al., 2019). The basis is that foods are initially compressed between the tongue and the palate akin to a squeezing flow between two parallel plates (He et al., 2016). Then, on separation, biaxial extensional flow develops as if the plates were lubricated (Chatraei et al., 1981). Yet, the relationship between extensional flow behaviour and sensory mouthfeel perception has barely been investigated. The present study however focussed on low shear rheology, assumed to be more relevant for food oral processing in infants. The existence of many different protocols for fluid food viscosity evaluation in the literature indicates that the mechanisms for perception of texture in the mouth remain relatively poorly comprehended (Skedung et al., 2013).

According to Kohyama (2015), rhythmical chewing in human beings occurs at 1 – 2 Hz and the tongue movements for tasting are somewhat below 1 Hz. Other workers (He et al., 2016) have measured complex viscosity at a frequency of 100 rad/s for some fluid foods, and found high correlations with mouthfeel perceptions. Thickness perception was better predicted from a model including both low and high shear viscosity, while stickiness and mouth-coating perceptions had better predictions from models including both low shear and extensional rheology (He et al., 2016). Recently, there has been a growing view that the low and high shear, (along with inclusion of extensional rheology) may provide better insights into the flow behaviours of complementary porridges. The reasons includes findings by Nicosia (2013) for example, that a single shear rate for oropharyngeal swallowing is too simplistic and instead, bolus viscosity and physical properties, degree of lubrication, pressure applied by the oropharyngeal musculature, and the resulting geometric changes of the oropharynx may have a strong effect on shear rate. Shear rates are dynamic during FOP, with low shear rates in the oral cavity and much higher shear rates during the pharyngeal phase of swallowing (Gallegos et al., 2012). Additionally, there is increasing confirmation of the relevance of both shear and extensional deformations in FOP (Chen and Lolivret, 2011).

7.6. Confounding factors- the nuisance variables

Additional factors in and outside the mouth may also have potentially influenced the perceived rheology of complementary porridges. The structure of the bolus and its rheology can be influenced by many other physiological, psychological and chemical factors (Nishinari et al., 2019). Nuisance variables, such as panellist individual differences in mouth geometry, the amount and rate of saliva secreted, and variable tongue behaviours when evaluating the samples, may affect the accuracy of results. It is well known that chemical senses affect swallowing behaviour (Loret, 2015), but interactions between the rheological properties and chemical senses are still not well understood.

Furthermore, the presence of non-rheological cues such as shine, visual appearance and lumpiness can give panellists textural cues, contributing to a biased judgement of texture. Non rheological cues have been shown to influence the perception of texture and mouthfeel (Malone et al., 2003), and such cues may have had a role in the current research. Controlling or eliminating confounding factors such as taste and aroma is always hard (Engmann and Burbidge, 2013), and in most cases a combination of taste, sound and touch contributes the perception of the texture (Kim and Lee, 2016). However, the use of red or other masking light is recommended in future similar studies to mask and standardize the appearance factors- where they are not the focus of the study.

7.7. Oral texture perception itself is not well understood

Although the study was able to discriminate complementary porridges based on their rheology, oral-sensory texture and nutritional properties, the absence of complete scientific understanding on the oro-tactile mechanisms for texture perception in human beings militated against our capacity to deeply appreciate the in-mouth mechanical behaviours of the porridges at consumption. Food texture is a perception, arising from the interaction of food with mechanoreceptors in the oral cavity; it depends not only on the physical structure of the stimulus, but also on the neural impulses carried by multiple afferent nerves (Kandel et al., 2000, Breen et al., 2019). Therefore, individual differences in neurological behaviours of the panellists can potentially affect results.

The tongue plays a key role in both sensory and motor aspects of food oral processing-preparing, forming, manipulating and transporting the bolus (Steele et al., 2014a), yet presently, the biophysiological mechanics for texture sensation is not fully understood. According to Smith et al. (1997), the location and nature of sensory receptors for fluid foods viscosity perception have not been well mapped out, nor is the degree of changes in viscosity (JNDs and Weber fractions) required to initiate these physiological changes known. In the absence of complete knowledge on mechano-sensation in the mouth, we can only understand the textural perception of complementary porridges in part, and not in full. It is also of interest to understand the sensory function of the tongue in tasks that require its motor behaviour, such as to explore, squeeze or move a bolus in order to ascertain the flow properties, and also in detecting differences in the flow characteristics during swallowing (Steele et al., 2014a).

7.8. Enabling complementary techniques

A lack of relevant modern technologies to augment the rheological and sensory methods had the potential also, to restrict the capacity of the research. In the presence of complementary techniques such as video-fluoroscopy, the study could potentially have generated more insights particularly into the dynamic physiological events happening in-mouth and in the throat, as well as the neurological activities going on in the brain during food oral processing. There are many different instruments available for studying specific aspects of food oral-processing behaviours and swallowing physiology. Examples include imaging technologies (Functional Magnetic Resonance Imaging -fMRI, 3-D imaging, ultrasound), electromyography (EMG), and manometry as techniques for revealing information about eating and swallowing function and behaviours (Steele, 2015).

7.9. A critique of the overall study findings

Forces, deformation, and particle properties of complementary porridges must be explored, in order to obtain a more complete picture of oral food texture. This indeed is a difficult undertaking, given that foods are complex composites of biopolymers in a heterogeneous matrix. Rheological data on the porridge samples showed that the viscosity of most common African indigenous/local complementary porridges (maize, cassava and sorghum) was high at low solids content, and some commercial porridge samples also had elevated viscosity values. Although the power-law model fit to the rheological data revealed a shear-thinning behaviour in all complementary porridges, the model is only valid within a limited range of shear rates beyond which its predictive power fails. According to Gallagher et al. (2019), the power-law model is unable to determine the asymptotic viscosity values at near zero shear rate and high (infinite) shear rates. As a result, determinations resulting from power-law extrapolation to extremely high and low shear rates may provide incorrect results (Picchi et al., 2017, Modigell et al., 2018). In complementary porridges processing or preparation by caregivers, this can affect flow predictions especially the zero-shear viscosity.

To rectify the potential problems arising from the limitations of the power-law model, the Cross model was also fitted to the data to determine the zero-shear viscosity of the porridge samples. The Cross model can more accurately predict the η_0 and $\eta\infty$ in the limits of $\gamma \to 0$ (very low) and $\gamma \to \infty$ (very high) shear rates respectively (Cross, 1965, Modigell et al., 2018). The zero-shear viscosity is an important parameter particularly in infant foods, where oral shear rates are thought to be very low. In an earlier study by Ross et al. (2019), the apparent viscosities of some fluid foods at lower shear rates (10 s^{-1} compared to 50 and 100 s^{-1}) were also found to strongly correlate positively with perceived oral texture in individuals with impaired food oral processing abilities, showing that low shear rates seem to be associated with a limited oral processing capacity.

Despite the high capabilities of instrumental rheological measurements coupled with improved viscosity modelling from the Cross model, it is known that foods encounter different forces in the mouth from those in an engineering (or even laboratory) environment (Tunick, 2011). In addition to this, the mechanisms of oral processing that may result in the temporal changes in texture perception of foods may vary with physiological development of the oral system (Munialo et al., 2019). It was therefore apparent from the study that simple instrumental viscosity measurements alone cannot be used directly to assess the consistency of the porridge samples, in part due to the different ways that food is handled in the mouth. Consequently, the TCATA sensory evaluation method was used so as to understand the in-mouth tactile responses of human subjects to the complementary porridges.

The inferences from the sensory evaluation method newly developed in this study (the Up-Down method, which simulates infant food oral processing) confirmed further that most indigenous complementary porridges, and some commercial porridges are not well matched to the oral developmental readiness of infants. In terms of dynamic oral texture, indigenous CPs were thick, sticky, pasty, and slimy even at very low solids content, making the porridges potentially difficult to process, unpleasant to eat, and not easy to swallow. If this can happen in infants and young children, it could ultimately limit food and nutrient intake, perpetuating protein and energy malnutrition in infants that rely on these porridge types. The Up-Down OP method that mimics the restricted oral processing abilities of infants and young children leads to more enhanced perceptions of the thick, too thick, sticky, slimy, pasty, and difficulty to swallow attributes. It is fair however, to indicate that although the ease/difficulty of swallowing is used as a sensory descriptor in food oral texture profiling, its relationship to objective measures of bolus flow or physiology remain unclear (Munialo et al., 2019).

Taken together (rheological and sensory studies) it can be generalized that the specification of a single shear viscosity is insufficient to capture the rheological response associated with the in-mouth texture of complementary foods. This is because of the dynamic nature of food oral process as well as the individual differences among infants, in addition to their restricted oral physiology as a function of their age. Food oral processing is a complex, individualised dynamic phenomenon involving mechano- and chemoreceptors, salivary mixing, temperature changes and friction (Martínez et al., 2019). In infants and young children particularly, this research proposes that low shear rates tending towards the zero-shear viscosity region, are more representative of the in-mouth handling and processing of food.

8.0. Conclusions, Recommendations and Future Research

8.1. Conclusions

The rheological and sensory properties of most common African indigenous/local complementary porridges (especially maize, sorghum and cassava) limit their capacity to meet the recommended daily energy and protein intakes for infants and young children. Some commercial complementary foods on the market too, had inappropriate sensory, rheological and nutritional quality, which puts infants and young children at high risk of malnutrition. The recipes of some commercial complementary porridge samples spanned wider age-ranges (e.g., 6 – 24 months), and are therefore not tailored to the specific developmental stages of young children's growth (6 – 8; 9 – 11; 12 – 24 months). Viscosity modelling of complementary porridges at lower but multiple shear rates helps to understand their rheological behaviour, and to make quantitative predictions about optimal porridge solids content to promote good nutrition.

The temporal oral texture characteristics of indigenous porridges and commercially available complementary porridge samples for infants and young children were significantly different, and dependent on the OP method used. Importantly, this study showed that the Up-Down oral processing method that mimics the restricted oral processing abilities of infants and young children, along with rheological measurements at multiple, lower shear rates (0.01, 0.1, 1, 10 and 50) especially the low-shear (zero-shear rate), and the predictive power of the Cross model- may be used for characterizing oral viscosity and in-mouth texture of complementary porridges. There were high PCA correlations between instrumental viscosity at the cited shear rates (zero-shear – 50 s^{-1}) and the oral texture perception of complementary porridge samples. Although it is often difficult to collect some viscosity data for the very low- and very high shear rates ranges for pseudoplastic fluids such as complementary porridges, the application of the Cross model to predict the zero-shear viscosity is highly imperative. The measurement of non-Newtonian characteristics can be applied to engineer the structure of complementary foods in order to impart the desired rheological properties. The study provides scientific insight for baby foods manufacturers on the OP characteristics of complementary foods for infants and young children in African communities. The insights could potentially help manufacturers in improving the overall quality of baby foods.

8.2. Recommendations

A multidisciplinary approach including tribology, extensional (elongational) rheology, oral physiology, neuroscience, psychology among other disciplines, will be required to gain a better understanding of the relationships between complementary porridge microstructure, its physicochemical properties and its perceived sensory properties. Extensional viscosity is the resistance of a fluid to extension (Vlachopoulos and Strutt, 2003). A shear deformation refers to fluid deformation under the application of a stress in parallel to the surface, whereas an extensional deformation occurs when a stress is applied perpendicularly to the surface of the deformation (Lv et al., 2017).

Oral processing (mastication and swallowing) has been shown to involve both shear and extensional deformation components (Chen and Lolivret, 2011), with many fluid foods potentially displaying significant differences in their responses to shear and extensional forces. Extensional flow may cause much higher deformations in colloidal systems in comparison with shear deformation (Yuan et al., 2018). Furthermore, Lv et al. (2017) found that although the perception of both shear and extensional viscosity follow a power law relationship, humans has a greater discriminatory capacity in perceiving extensional viscosity, yet this is largely understudied (Yuan et al., 2018). Therefore, information on the extensional viscosity of complementary foods is critical for practical oral texture sensory predictions (Lv et al., 2017).

Although OFSP is rich in calories and provitamin A, it falls short of protein when compared to maize (9.4%), rice (7.1%) and sorghum (11.6%) (Neela and Fanta, 2019). It is also lacking in fats (< 1 %) (Alam et al., 2016b) and certain important minerals (calcium, magnesium, sodium), but provides more bioavailable zinc (≈ 5.22 - 6.22mg/100g) albeit in very small quantities (Eke-Ejiofor and Onyeso, 2019), along with moderate to good concentrations of phosphorus, potassium and iron (Neela and Fanta, 2019). Consumption of optimum concentration of minerals is recommended for balanced, healthy metabolism (Soetan et al., 2010). So, to combat Protein Energy Malnutrition (PEM) as well as micronutrient malnutrition, it is very important to add the protein-rich pulses and animal foods in the diets of communities where increased OFSP adoption is considered (Neumann et al., 2002).

Parents, caregivers and manufacturers of infant complementary porridges are therefore advised to consider the use of OFSP- legume (e.g., Cowpea or Bambara) composite flours - modified to incorporate higher solids at low viscosity, for preparing CPs with potentially improved energy and protein density. Such CPs will need further profiling for oral texture suitability and overall nutritive quality. Simple traditional approaches for reducing the viscosity of indigenous CPs in the home in rural and low-income areas, where access to commercial porridges may be limited, (e.g., malting, fermentation, souring) need consideration by primary caregivers. In this regard, the village health workers or local healthcare practitioners may have an important role in assisting households to adopt these simple recommendations. These strategies can be reinforced through empowering communities with simple and easy to use knowledge on how to achieve a complementary porridge of suitable viscosity/consistence and with optimal nutrient density for health child growth and development.

Research in consumer behaviour is required to understand how these low-cost technologies could be applied at scales within the appropriate policy framework to reduce PEM. In addition to this, innovative methods for processing indigenous flours are required to give CPs optimal oral textures at much higher solids content for improved infant nutrient intake. With respect to CACFs, careful assessment of the viscosity level at the point of use is recommended to ensure an appropriate porridge viscosity (consistency) and a pleasant consumption experience which supports high nutrient intake. Where feasible, the viscosity and oral texture specifications of CACFs must be defined and listed on the product label for users to be able to predict the oral processing behaviours of the porridge under specified conditions.

Further research is also recommended to explore the dynamic sensory interplay between bolus properties of baby foods and the oro-tactile phenomena (tongue coordination, mastication, and lubrication) in infants and young children, which, at present, is not well understood. This should also entail conducting practical assessment of infants and young children’s abilities to consume food of different consistencies (viscosity), and the time required for the consumption, in light of the different age groups and levels of neurological development. As previously recommended by Brown et al. (1998), child feeding studies may require to be conducted in many locations and focussing on much broader environmental factors as available foods, including socioeconomic characteristics, food preparation methods, exposure to infectious agents and cultural beliefs influencing child feeding- in order to increase the ecological validity of the results.

Due to the continuous progression of young children’s physiological development and nutritional needs, complementary feeding research must be focussed on fairly narrow age ranges for results to be meaningful. These narrow age-ranges must also be reflected on the product panel labels. Shear rates of 0 $s^{-1} \leq 1$ s^{-1} for 6 -12 month, and ≤ 50 s^{-1} for 12 – 24 months may be more practical and relevant for infant feeding. The zero-shear viscosity is particularly recommended for foods specified for infants at 6 – 8 months because at this stage, FOP is dominated by the vertical, up-and-down chewing behaviour (Himmlova et al., 2007), which represents a near zero-shear rate. FOP skills develop gradually from sucking to munching and then chewing (a more complex rotary pattern) (Nicklaus et al., 2015b), representing the evolution of oral shear with age from very low shear (η_0) to much elevated shear rates. As revealed by this study, although the apparent viscosity values from relatively higher shear rates (10 s^{-1} and 50 s^{-1}) were relevant for oral texture perception, the viscosity at zero-shear and 1 s^{-1} were highly correlated positively to the attributes thick, too thick, sticky and difficult to swallow especially in the Up-Down OP method (Figure. 31). The zero-shear viscosity η_0 (the limiting viscosity at very low shear rates) is therefore an important parameter in the study of shear-thinning fluids (Manrique et al., 2016) such as complementary porridge.

For infants and young children, oral shear rates increase with age, and during FOP of complementary foods, a large drop in viscosity from the zero-shear viscosity is observed when a critical shear rate or shear stress is achieved, signifying the beginning of the shear thinning region (Malvern Instruments Limited, 2016). Since infants have reduced tongue or pharyngeal muscle strength, limited dentition, and weak masticatory muscles (Steele et al., 2015), they are highly unlikely to be able to generate these critical shear stresses and shear rates for initiating shear-thinning. This is because when a very low stress is applied to a shear-thinning fluid, the Brownian forces are not overcome by the shear and the food macromolecules remain intact and folded in a network arrangement, which then shows a high zero-shear viscosity (η_0) resulting from particle/molecular interactions (Larson, 1999). Chhabra and Shankar (2017) have reported that chewing and swallowing occur at shear rates of 10 - l00 s^{-1} for all foods, suggesting that infants' oral shear rates are much lower since initially they are unable to chew. Hence the apparent viscosity of infant foods for 6 – 8 months must be characterized at zero-shear to ≤ 1 s^{-1}. Much higher shear rates (10 – 50 s^{-1}) may be considered with increasing age as children acquire rotary chewing abilities (Himmlova et al., 2007), and their tongues gain the capacity to transport and manipulate food efficiently beyond the midline and around the mouth (Fucile et al., 1998). The movement of the tongue (which is highly restricted in at 6 – 8 months) contributes to FOP by exerting a shearing force on the food between the tongue and hard palate during processing (Yamada et al., 2015).

Lastly, more studies are required to gain insights into the physical drivers of texture and mouthfeel perceptions in infant foods, to assist food manufacturers in designing foods with enhanced nutritional profiles and acceptable sensory appeal (textures) for young children. Studies into the economics of the OFSP value chain relative to more common staples (maize, sorghum, cassava etc) are also encouraged to inform strategies to increase its adoption and utilization in African communities. Overall, this study potentially provides scientific evidence to policymakers, assisting them with a framework for influencing child nutrition in Africa.

8.3. Future research

It is herein suggested that future studies should consider the use of size exclusion HPLC for biopolymer analysis (e.g., starch composition- amylose and amylopectin), to generate important scientific data to objectively explain the rheology-sensory-nutrient density interactions in the porridge systems prepared from different botanical sources. Such future instrumental analysis would assist to substantiate sensory observations such as the slimy texture more frequently perceived in all legume porridges (Bambara groundnut and Cowpea) and cassava, but not in the cereal and orange-fleshed sweet potato (OFSP) based porridges.

Research in future should intensify efforts to modify the functional properties of common African indigenous complementary food flours to improve their flow properties in baby porridges. This may entail research on processing technologies that are low-cost, less energy-intensive, environmentally sustainable, easy to use and adaptable especially to low-income rural and poor urban communities. Further work involving bio-tribology and the sensory science of food oral processing, in addition to rheology is recommended to establish more precise shear rates applicable for in-mouth oral processing in infants and young children. This is important in designing more effective, nutritionally optimal foods for infants and other people with restricted oral processing abilities. Given that the physiological mechanism behind the high sensitivity of the tongue in detecting small changes in stresses applied to its tissue remains un-confirmed, additional research is required to understand how the topological features of the tongue assist in texture perception of foods. More studies on the texture-rheology of complementary porridges are needed to validate whether models comprising shear and extensional rheological parameters will be more beneficial in predicting the in-mouth viscosity of complementary porridges.

Appendix A. Study deliverables and outcomes

The outcomes and deliverables from this research are as listed below:

Papers published in peer reviewed journals

1. MAKAME, J., CRONJE, T., EMMAMBUX, N. M. & DE KOCK, H. 2019. Dynamic Oral Texture Properties of Selected Indigenous Complementary Porridges Used in African Communities. *Foods*, 8, 221.

Oral Papers presented at international conferences

2. MAKAME, J., CRONJE, T., DE KOCK, H.L & EMMAMBUX, M.N. Dynamic oral texture properties of African indigenous complementary porridge samples: is there a link with child protein-energy malnutrition? *SAAFoST 23rd biennial international congress and exhibition, 1 – 4 September 2019, Birchwood Hotel and Conference Centre, Johannesburg, South Africa*.
3. MAKAME, J., EMMAMBUX, M.N & DE KOCK, H.L. Does the temporal in-mouth texture of African indigenous/locally available complementary porridge samples match the oromotor readiness of infants and young children? *13th Pangborn Sensory Science Symposium, 28 July - 1 August 2019, Edinburgh, UK.*
4. MAKAME, J., EMMAMBUX, M.N & DE KOCK, H.L. A nutrition-secure childhood for 6-24 months old infants and young children in South Africa: does the viscosity of sorghum and other complementary porridge samples limit nutrient intake? *The 1st international global sorghum conference, 9 - 12 April 2018, Cape Town, South Africa.*
5. MAKAME, J., DE KOCK, H.L & EMMAMBUX, M.N. Flow properties of commercial and indigenous/local complementary foods in South Africa. *SAAFoST conference, 3 - 6 September 2017, Cape Town South Africa.*

Posters presented at international conferences

6. MAKAME, J., DE KOCK, H.L & EMMAMBUX, M.N. Viscosity, protein and energy content of common commercial and indigenous complementary porridge samples in

South Africa. *The 5th international conference on food oral processing, 1 – 4 July 2018, Nottingham, UK.*

7. MAKAME, J., DE KOCK, H.L & EMMAMBUX, M.N. Viscosity, protein and energy content of common commercial and indigenous complementary porridge samples in South Africa. *The 3rd international conference on global food security, 3 - 6 December 2017, Cape Town, South Africa.*

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