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# Nutrient density and oral processing properties of common commercial complementary porridge samples used in southern Africa: Effect on energy and protein intakes among children aged 6–24 months

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## Abstract

Child malnutrition is an endemic public health problem in Africa. Infants are supposed to receive complementary foods from about 6 months onwards, as breastmilk alone no longer provide adequate nutrients. Commercially available complementary foods (CACFs) form an important part of baby foods in developing countries. However, systematic evidence on whether they really meet optimal quality specifications for infant feeding is limited. Some CACFs commonly used in Southern Africa and other parts of the world were investigated to establish if they meet optimal quality standards for protein and energy content, viscosity, and oral texture. For the energy content, most CACFs for 6–24-month-old children both in the *dry* and *ready-to-eat* forms (range: 372.0–1816.0 kJ/100 g), were below Codex Alimentarius guidelines. The protein density of all CACFs (0.48–1.3 g/100 kJ) conformed with Codex Alimentarius requirements, but some (33%) were below the minimum World Health Organization (World Health Organization. Regional Office for Europe (2019a). *Commercial foods for infants and young children in the WHO European region*) target of 0.7 g/100 kJ. Most CACFs had high viscosity values even at high shear rate of 50 $s^{-1}$, and were too thick or thick, sticky, grainy, and slimy, which may limit nutrient intake in infants, potentially causing child malnutrition. There is a need to improve the oral viscosity and sensory texture of CACFs for better nutrient intake by infants.

KEYWORDS
baby foods, malnutrition, oral texture, oromotor readiness, viscosity

## 1 | INTRODUCTION

Good nutrition in the first 1,000 days of life is essential for the health and development of children, with implications throughout life. Breastfeeding is the gold standard for infant nutrition up to at least 2 years (Black, Makrides, & Ong, 2017; WHO/UNICEF, 2003). However, from about 6 months onwards, breastmilk alone can no longer provide adequate nutrients, and new foods (complementary foods) must be included in infants' diets following regulated norms (Alvarez, Cancela, Delgado-Bastidas, & Maceiras, 2008). Although homemade

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complementary foods are the first-choice recommendation to supplement breastmilk (WHO/UNICEF, 2003), commercially available complementary foods (CACFs) constitute a significant proportion of baby foods consumed in developing countries (Aryeetey & Tay, 2015). CACFs are usually made from starchy raw materials, added proteins and lipids (both from legumes, dried fish, milk powder), micronutrient premixes, and other ingredients to improve nutritional value and taste (Dimaria et al., 2018). These products are often purchased in instantized forms requiring minimal cooking, if any, before consumption. Examples include infant cereals made from rice, oat, barley, wheat, mixed-grains, and some cereal-fruit combinations (Ng, Dibley, & Agho, 2012).

Good quality complementary food must have a high nutrient density (energy, protein and micronutrients), appropriate texture with low viscosity, semi-solid consistency that allows easy handling and consumption by children (Ahmed & Ramaswamy, 2007; Alvarez & Canet, 2013; Balasubramanian, Kaur, & Singh, 2014; Bazaz, Baba, & Masoodi, 2016; World Health Organization, 2003). Although commercially available infant complementary foods serve as a convenient option for parents and caregivers, their appropriateness for different ages has been called into question (Tan, Lim, McCrickerd, & Forde, 2022). Very few studies directly show whether commercial infant foods really meet recommendations to promote infant health (Maslin & Venter, 2017), and systematic investigations on their rheological, textural and ingredient interactions are also limited (Ahmed, 2007; Alvarez & Canet, 2013).

Extensive studies have been conducted on homemade complementary porridges, but there is scant rheological data on CACFs, which are mainly available in dehydrated forms (Ahmed, 2007). Equally, while there is considerable literature on static sensory measures for the texture of various complementary porridges, the dynamic oral sensory texture spectra for CACFs remains to be well investigated. As Nicklaus, Demonteil, and Tournier (2015) argues, little information is available on the oral processing properties of commercial baby foods as a function of age. Such information is important because CACFs are directed at consumers who cannot express their opinion regarding product acceptance or rejection. Complementary food product development needs technological data to drive continuous quality improvements, yet such is not readily available, in part because most research is kept confidential by food processors or protected by patents (Ahmed, 2007). Many governments and WHO member states require guidance to regulate baby food manufacturers to improve quality and provide accurate information on the product packaging, to avoid misleading consumers or undermining public health recommendations (World Health Organization. Regional Office for Europe, 2019b).

In Europe, some CACFs were shown to be of inappropriate nutritional quality, but information on their oral texture and its potential effects on nutrient intake was not available (World Health Organization. Regional Office for Europe, 2019a). The in-mouth texture of complementary foods must be matched to the oromotor readiness and developmental milestones of infants and young children. When prepared according to label directions for use, CACFs should have a texture appropriate for the spoon-feeding of infants or young children of the target age (Codex Alimentarius, 1981; World Health Organization. Regional Office for Europe, 2019a).

The viscosity and mouthfeel of complementary foods influences not only the quantity of food a child can consume, but also nutrient intake (Bazaz et al., 2016; Mosha & Svanberg, 1983), which if not optimal, may lead to malnutrition. In infants and young children, oral physiological capacity, motor skills, and sensory quality are significant determinants of food choice (Schwartz, Vandenberghe-Descamps, Sulmont-Rossé, Tournier, & Feron, 2018). Therefore, more research is needed to characterize CACFs for better handling, processing, use and quality control (Ahmed, 2007). The flow properties of commercial baby foods affect their eating quality (Ahmed & Ramaswamy, 2007; Alvarez & Canet, 2013). During early transition to solid foods, infants are more likely to accept soft textures which they can easily manipulate using only an up-and-down motion (munching) (Le Révérend, Edelson, & Loret, 2014; Sampallo-Pedroza, Cardona-López, & Ramírez-Gómez, 2014). Maladapted textures may lead to child malnutrition if infants are unable to comfortably consume and digest such foods because of limited oral processing abilities. Typically, desirable porridge viscosity is one that allows ease of consumption while maintaining adequate solids content for optimal nutrient density- and this is often a challenging triad to balance.

This research explored the protein and energy content/density, flow properties (viscosity), and dynamic oral texture quality of some CACFs commonly used in Southern Africa, to establish if they meet recommended nutrient intakes for infants and young children aged 6–8, 9–11, and 12–24 months. Such information may help to guide the design, processing, and preparation of developmentally appropriate foods for infants and young children, and to inform science-based policy formulation to improve child nutrition.

## 2 | MATERIALS AND METHODS

### 2.1 | Materials

Fifteen CACFs for infants of different age-groups (Table 1) were used in the study, with some having specific recipes for different child age-groups to give a total of 25 recipes. The CACFs were purchased from shops around Pretoria, South Africa. Products with 8 month or more *Best Before* dates were acquired so that all analyses were conducted on unexpired products.

### 2.2 | Methods and analyses

#### 2.2.1 | 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 CACF porridge apparent viscosity at different shear rates with a vane spindle, following a method described by Makame, De

**TABLE 1** Description of commercially available complementary foods (CACFs) used in the study.

| Commercial complementary porridge[a,c] | Age (months) | Dilution rate powder (g): liquid (ml) | Solids (%) | Description/manufacturer's guide |
|---|---|---|---|---|
| A1-reference | 6–24 | 50:150 | 25.0 | Enzyme-hydrolyzed cereal (maize 62%)/add water |
| A2 | 6–24 | 50:150 | 25.0 | Enzyme-hydrolyzed cereal (rice 63%), add water |
| A3 | 6–24 | 50:150 | 25.0 | Enzyme-hydrolyzed cereal (wheat 61%), add water |
| C2 | 6–24 | 50:140 | 26.3 | Oat flakes 32%, add water |
| F1 | 6–8 | 45:150 | 23.1 | Enzyme-hydrolyzed cereal (wheat 51%), add water |
| | 9–12 | 67:200 | 25.1 | |
| | 13–36 | 80:250 | 24.2 | |
| F2 | 6–8 | 35:150 | 18.9 | Enzyme-hydrolyzed cereal (rice 51%), add water |
| | 9–12 | 60:200 | 23.1 | |
| | 13–36 | 75:250 | 23.1 | |
| F3 | 9–12 | 67:200 | 25.1 | Enzyme-hydrolyzed cereal (wheat, rice, corn, rye, barley 54%), add water |
| | 13–36 | 80:250 | 24.2 | |
| F4 | 9–12 | 67:200 | 25.1 | Enzyme-hydrolyzed cereal (wheat, rice, corn, rye, barley 43%), add water |
| | 13–36 | 80:250 | 24.2 | |
| B1 | 6–24 | 50:160 | 35.1 | Enzyme-hydrolyzed cereal (maize), add milk |
| B2 | 6–24 | 50:160 | 35.1 | Enzyme-hydrolyzed cereal (wheat), add milk |
| C1 | 6–24 | 20:170 | 24.8 | Whole oat flour 70%, banana flakes 30%, add milk. |
| D | 6–36 | 20:140 | 26.3 | Maize flour minimum 86%, add milk |
| E1[b] | 6–12 | 25:200 | 26.7 | Maize meal flour, 3 min cook with milk |
| | 13–36 | 35:280 | 25.8 | |
| E2 | 6–12 | 25:125 | 30.0 | Sorghum flour (minimum 89%), add milk |
| | 13–36 | 35:190 | 29.1 | |
| G | 13–36 | 20:80 | 32.8 | Wheat flour, maize flour, soya flour, add milk |

[a] All samples were analyzed within best before dates. NAN Optipro milk (Formula 2 for 6–12 and Formula 3 for 13–24 months) 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 supermarkets in Pretoria, South Africa.
[b] Cooking loss of 5%. The 'add-water' commercial porridge samples contain whole or skimmed milk powder within a range of 23–40%.
[c] Code names were used in place of the actual commercial complementary porridge names.

Kock, and Emmambux (2020). CACFs were prepared according to the manufacturers' instructions (Table 1) and a 22 g sample was transferred to a rheometer cup. The shear rate range was chosen to cater for estimates of changes in oral shear capacity with increasing infant age. Each CACF porridge was evaluated in triplicate, using a freshly prepared sample. Shear rates of zero, 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 respectively.

### 2.2.2 | Energy, and protein density of the complementary porridge samples

Nutrient density was determined based on the declared nutrients contents of dry products as specified on the product labels according to the manufacturers' preparation instructions. For the reconstituted, ready-to-eat or cooked products, the nutrient density was calculated from the solid content per 100 g of ready-to-eat porridge.

### 2.2.3 | Daily energy and protein intakes from commercial complementary porridges

The daily energy and protein intake from the CACFs were calculated as follows:

$$\text{Daily nutrient intake} = \frac{\text{Nutrient}}{1\,\text{g porridge}} \times \text{functional gastric capacity} \times \text{meal frequency} \quad (1)$$

based on 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 6–8, 9–11, and 12–24 months, respectively (Dewey & Brown, 2003).

### 2.2.4 | Sensory analysis of the dynamic oral texture properties

The in-mouth textural properties of CACFs were evaluated by a trained sensory panel of 10 adult assessors (3 males and 7 females, aged 22–27 years), following procedures described in Makame, Cronje, Emmambux, and De Kock (2019). The Temporal Check-All-That-Apply (TCATA) method was used for the sensory evaluation, with data collection in Compusense Cloud version 7.8.2 (Compusense Inc., Guelph, ON, Canada). The texture attributes used for the evaluation of the CACFs are described in Table S1. Ethical clearance was approved by the University of Pretoria Faculty of Natural and Agricultural Sciences Ethics Review Committee (EC 180000086). All persons gave their informed consent prior to their inclusion in the study.

### 2.2.5 | Statistical analysis

All analyses were conducted in triplicate using fresh CACF samples each time, and data reported as mean values with standard deviations. Rheological data were fitted to the power-law and Cross models to predict the flow properties of the complementary porridges.

Power-law model:

$$\eta = k\dot{\gamma}^{n-1} \tag{2}$$

Cross rheology model:

$$\eta = \frac{\eta_0 + \eta_\infty \cdot \alpha\dot{\gamma}}{1 + k\dot{\gamma}^n} \tag{3}$$

or simplified Cross rheology model:

$$\eta = \eta_\infty + \frac{\eta_0}{k}\dot{\gamma}^{-n}, \tag{4}$$

where $\eta$ represents the fluid food's effective viscosity as a function of shear rate, $\gamma$. In the power-law model, $n$ is the flow behavior index; and $k$ is the consistency index at specific shear rate, $s^{-1}$ (Jun & Yee-Chung, 2016). In the Cross model, $\eta_0$ is the zero-shear viscosity (Pa.s), $\eta_\infty$ is the infinite shear viscosity (Pa.s), $k$ is the characteristic (Cross) time constant (s) or $1/k$ is the onset shear rate for shear thinning behavior, and $n$ is the (Cross) rate constant with $n \to 0$ for Newtonian liquid and $n \to 1$ for increasingly shear thinning behavior (Gamonpilas, Kongjaroen, & Methacanon, 2023). The Cross model fitting was done using a Solver Add-in in MS EXCEL software, following a procedure described in literature (Kongjaroen et al., 2022; Morrison, 2005; Roberts, Barnes, & Mackie, 2001). The optimization process is based on minimizing the normalized root mean square error between the measured/experimental and predicted viscosity for all shear rate data point (Kongjaroen et al., 2022). Sensory, rheological and nutrient density data were analyzed by principal component analysis (PCA), and the temporal oral texture sensory data processed via TCATA data analysis function in XLSTAT software (version 2022.3.1). The distribution of energy and protein density of the CACFs were visualized through boxplots.

## 3 | RESULTS AND DISCUSSION

### 3.1 | Nutrient profiling—energy and protein density

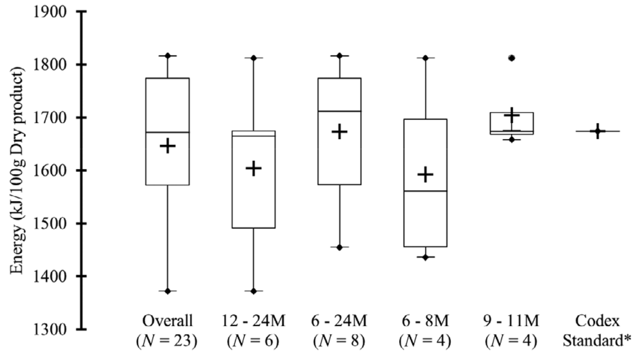
The energy and protein density distributions for CACFs in the dry and reconstituted (ready-to-eat) forms are shown in Figure 1a–c.

The overall mean energy density (range: 1,372.0–1,816.0 kJ/100 g) of CACFs for 6–8 and 12–24 months age groups (Figure 1a) were below the recommended Codex Alimentarius Standard value (at least 1,674 kJ/100 g; ≈400 kcal/100 g on a dry weight basis) for processed cereal-based foods for infants and children (Codex Alimentarius, 1981; World Health Organization. Regional Office for Europe, 2019a). Although the nutritional information on dry weight basis is important, it is the solids content in a reconstituted, ready-to-eat porridge of suitable oral processing quality that determines the CACF's ultimate nutritive value. Hence, the nutrient amount potentially available to infants and young children from porridge depend on the viscosity of reconstituted porridge and infants' oromotor readiness. In the reconstituted, ready-to-eat products (Figure 1b), the energy contribution of CACFs for 6–8 months and 6–24 months age-groups were below the recommended level of 334.6 kJ/100 g (80 kcal/100 g) (Codex Alimentarius, 1981).

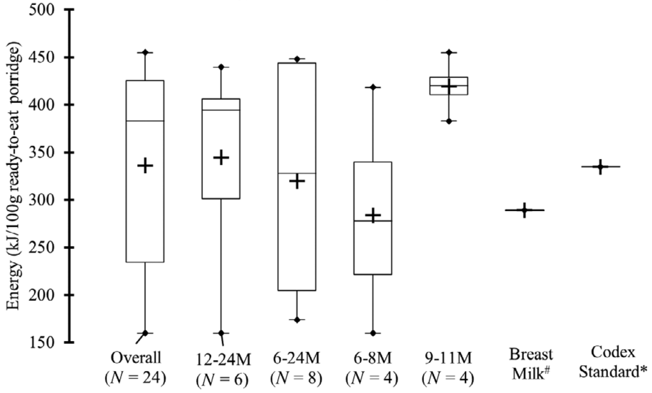
In terms of protein density (Figure 1c), all products analyzed met the recommended minimum content requirement of 0.48 g/100 kJ (2 g/100 kcal) (Codex Alimentarius, 1981). However, using a protein content specification of 0.7 g/100 kJ applied in a European study by the World Health Organization. Regional Office for Europe (2019a), about eight formulations for the 6–24 months age group were inadequate in protein. It is recommended to evaluate the protein quality of foods for human consumption using the Protein Digestibility Corrected Amino Acid Score (PDCAAS) (FAO, 2013), but the amino acid scores of the CACFs evaluated were not declared on the product packs. Infants require essential amino acids such as lysine and phenyalanine from complementary foods for healthy growth and development (Pencharz & Ball, 2004).

The current findings support previous studies in Africa (Benin, Burkina Faso, Ghana, and Senegal, Tanzania) (Dimaria et al., 2018; Muhimbula & Issa-Zacharia, 2010; Treche, 1999), Western Asia (Saudi Arabia) (Al-Othman, Khan, & Al-Kanhal, 1997), the UK (García, Raza, Parrett, & Wright, 2013) and Europe (World Health Organization. Regional Office for Europe, 2019a) where some CACFs were found to be nutritionally inadequate. Additionally, Masters, Nene, and Bell (2017) also reported wide variations in nutrient densities, and frequent inconsistencies between products' actual composition and information printed on labels of some CACFs marketed in low-and middle-income countries. Regarding matching CACFs to infants age (a proxy for infants' oromotor readiness), about 36% had the same manufacturer's recommended serving size and preparation instructions across all age-groups (6–8, 9–11, and 12–24 months). It may be helpful to adapt CACFs textures to the narrow developmental stages of infants and young children, to effectively meet their increasing nutritional needs and oral processing abilities.

(a) *Energy content of dry CACF products*



(b) Energy content of ready-to-eat CACFs



(c) Protein content of dry CACFs

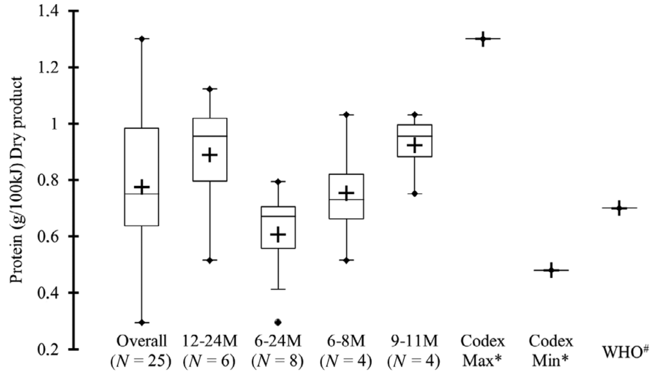


**FIGURE 1** (a) Energy density of dry CACF products, (b) energy density of ready-to-eat CACF products, and (c) protein density of dry CACF products; all compared against the Codex Alimentarius standard for baby foods, WHO 2019 recommendation, and breast milk (for energy density). The analysis was done per age group in months (M). For each CACF group, the mean value where applicable is shown with a '+', the line inside the box represents the median, and the top and bottom of the box are the first (25%) and third quartiles (75%), respectively, with vertical lines (whiskers) showing the minimum and maximum values excluding outliers (shown as stand-alone dots above or below the whiskers. #Infants foods should have an energy density (on a ready-to-eat basis) of at least 334.6 kJ/100 g (80.0 kcal/100 g), which exceeds the energy provided by breast milk (288.7 kJ/100 g, ≈69 kcal/100 g) (World Health Organization. Regional Office for Europe, 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).

## 3.2 | Viscosity of commercial complementary porridge samples

Infants and young children require foods of appropriate viscosity and textures which they can easily chew and swallow due to their less developed oral processing capacity, but which also offers some challenging and diverse textural experiences to encourage them to learn healthy feeding habits (Black et al., 2017). Figures 2a–c shows the viscosity profiles of the CACFs explored in this study.

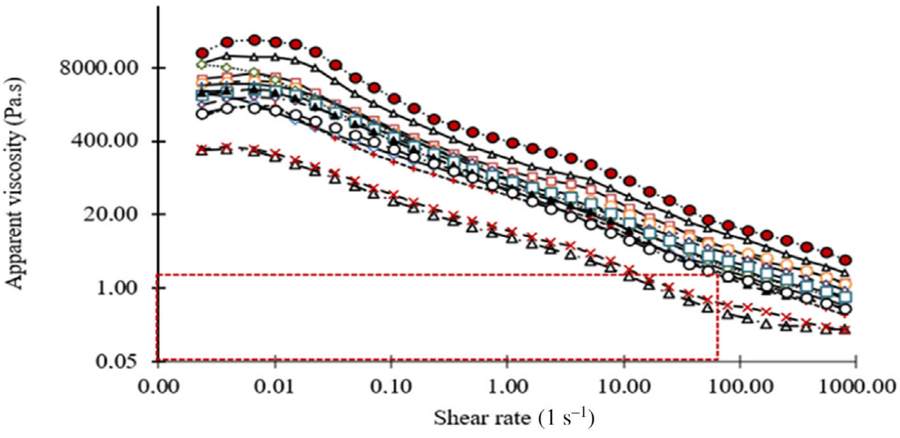
The viscosity profiles (Figure 2a–c) showed a zero-shear viscosity region (viscosity at low shear rates), and a shear-thinning viscosity region with increasing shear rate. With the exception of A1 (reference) and A2 across the three age-groups, most commercial porridges had high non-Newtonian viscosity exceeding the critical viscosity limits of 3 Pa.s at the shear rate of 50 $s^{-1}$ generally considered as acceptable for infants porridge (Thaoge et al., 2003). Porridge E1 (prepared by a 3-min cooking 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 reference A1, A2, and A3 (the enzyme-hydrolyzed add water formulations) had the lowest viscosity values, meeting the critical viscosity limit (3 Pa.s) at low shear rates (10 $s^{-1}$)—even at higher solids content of 25%.

According to model predictions (Table 2), the zero-shear viscosity estimate, and *K*-values were generally higher for non-hydrolyzed CACFs (E1), lower when hydrolyzed (A1, A2, A3) and were higher when milk was added (B1, B2, C2, E2).

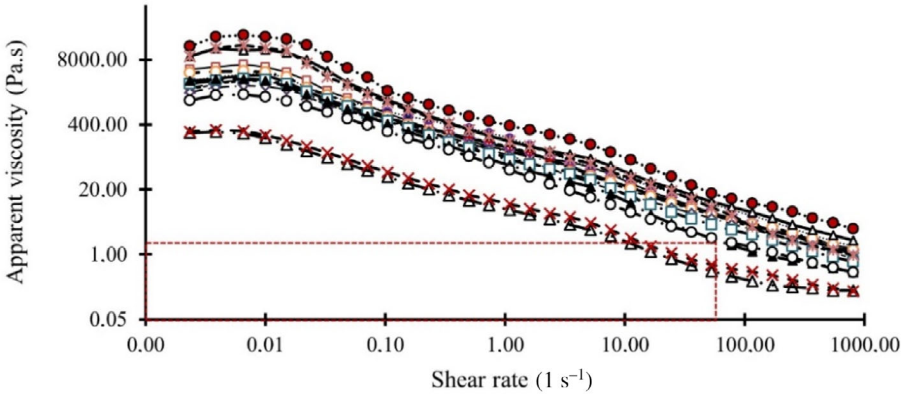
There was consistency and good agreement between the predicted $\eta_0$ values from the Cross-model (Table 2), and the zero-shear plateau values from the graphs across all porridge samples (shown in Table 3: 0.001–0.01 $s^{-1}$). The elevated viscosity of some add-milk formulations (e.g., E1 high in unhydrolyzed starch, B1, B2, D) could be due to the colloidal dispersions types produced upon reconstitution, and to interactions of starch molecules with milk proteins (α-casein, β-casein, and whey proteins—β-lactoglobulins and α-lactalbumins) during thermal processing (Hudson, 2013; Jamilah et al., 2009; Kumar, Brennan, Mason, Zheng, & Brennan, 2017). Previous studies (Lelievre & Husbands, 1989) found synergistic viscosity enhancement in cooked starch-caseinates blends. The starch–protein interactions in food systems normally involve hydrogen bonds, electrostatic interactions and van der Waals forces (Yang, Zhong, Goff, & Li, 2019). High viscosity in protein-starch food systems depends on the starch and protein types, concentrations, degree of molecular entanglements, and potential pseudo-gel food structure formations (Kumar et al., 2017). Intermolecular bonding among the CACFs ingredient components during cooking may produce stronger networks with higher resistance to shear force. Caseinates have been shown to increase the viscosity of starch paste through formation of large aggregates by self-assembly, which arises from molecular conformational changes due to hydrophilic and hydrophobic end groups (Kumar et al., 2017).

The viscosity of common food systems is also dependent on the intrinsic biopolymer characteristics such as molecular mass,

(a) 6 - 8 months



(b) 9 - 11 months



(c) 12 - 24 months

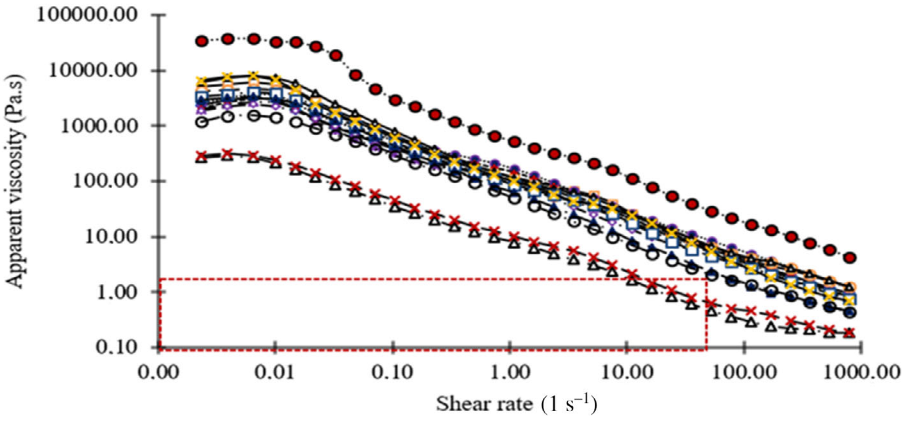


**FIGURE 2** (a) 6–8 months; (b) 9–11 months; (c) 12–24 months. Viscosity profiles of some CACFs commonly used to feed infants and young children at the age groups. Samples were prepared according to the manufacturer's guide. The red box shows the region of acceptable viscosity, defined by a recommended viscosity limit of 3 Pa.s (Nout, 1993; Thaoge et al., 2003) at the assumed oral shear rate of 50 s$^{-1}$. Refer to Table 1 for detailed descriptions of the coded CACFs. Legend key: Reference —·△·—; A2 - -✕- - -; A3 —·○·—; B1 —·□·—; B2 —·◆·—; C1 -·-○-·-; C1-water ——+——; C2 ——□——; D —·▲·—; E1 ·····●·····; E1-water ---✳---; E2 ——△——; E2-water ·····◇·····; F1 ——◇——; F2 ----+----; F3 ·····◆·····; F4 —·✳·—; G ——✕——.

hydrodynamic volume (the volume fraction a coiled polymer takes up in solution), molecular size, shape, surface charge, deformability, esterification degree in polysaccharides, and amino acids content, in addition to pH, temperature, ionic strength, and solvent, which affect protein folding (Masuelli, Sansone, & Aplicada, 2012). In a study by Alvarez and Canet (2013), high viscosity in meat powder-containing infant porridges was attributed to protein gel formation via molecular interactions (hydrogen bonding, ionic bonding, disulphide bonding and hydrophobic association). In the at-rest state for ready-to-eat CACFs, the porridge matrix particles commonly exist in agglomerated state, linked up by weak forces. When the shear forces during oral processing are sufficiently high, the inter-particle linkages are broken down resulting in structural unit size reduction, and this lowers viscosity.

All CACFs showed shear-thinning, pseudoplastic behavior ($n < 1$, Table. 2). The flow behavior index for most polymer solutions has been shown to range between 0.3 and 0.7 (Picchi, Poesio, Ullmann, & Brauner, 2017). Based on this, the Cross model showed better predictions of non-Newtonian fluids behavior, compared to the power law

**TABLE 2** Predicting the steady shear flow properties from rheological data using the power-law and Cross model, for selected commercial complementary porridge samples.

| | | | | Power law model[a] | | | Cross model[b] | | |
|---|---|---|---|---|---|---|---|---|---|
| Complementary porridge code[c] | Infant age (months) | Water or milk | Solids (%) | $K$ | $n$ | $R^2$ | $n$ | $\eta_\infty$ (Pa.s) | $\eta_0$ (Pa.s) |
| A1-reference | 6–24 | Water | 25.0 | 4.7 | 0.31 | 0.99 | 0.6 | 0.001 | 358.7 |
| A2 | 6–24 | Water | 25.0 | 6.2 | 0.33 | 0.99 | 0.6 | 0.001 | 371.4 |
| A3 | 6–24 | Water | 25.0 | 24.2 | 0.31 | 0.85 | 0.3 | 0.001 | 1,690.5 |
| C1 | 6–24 | Water | 26.3 | 62.9 | 0.29 | 0.97 | 0.7 | 0.001 | 5,728.8 |
| F1 | 6–8 | Water | 23.1 | 47.7 | 0.28 | 0.99 | 0.7 | 0.001 | 4,159.0 |
| | 9–12 | Water | 25.1 | 69.9 | 0.29 | 0.99 | 0.7 | 0.001 | 3,985.8 |
| | 13–24 | Water | 24.0 | 55.3 | 0.31 | 0.98 | 0.7 | 0.001 | 3,532.0 |
| F2 | 6–8 | Water | 18.9 | 24.2 | 0.30 | 0.97 | 0.8 | 0.001 | 45,620.3 |
| | 9–12 | Water | 23.1 | 62.9 | 0.29 | 0.95 | 0.8 | 0.001 | 3,035.7 |
| | 13–24 | Water | 23.1 | 65.3 | 0.30 | 0.95 | 0.8 | 0.001 | 3,231.0 |
| F3 | 9–12 | Water | 25.1 | 99.3 | 0.31 | 0.98 | 0.7 | 0.001 | 4,290.6 |
| | 13–24 | Water | 24.2 | 80.6 | 0.32 | 0.98 | 0.7 | 0.001 | 3,894.6 |
| F4 | 9–12 | Water | 25.1 | 62.4 | 0.31 | 0.99 | 0.7 | 0.001 | 3,303.2 |
| | 13–24 | Water | 24.2 | 47.6 | 0.33 | 0.98 | 0.7 | 0.001 | 2,955.7 |
| B1 | 6–24 | Milk | 27.4 | 49.0 | 0.24 | 0.98 | 0.8 | 0.001 | 3,620.0 |
| B2 | 6–24 | Milk | 27.4 | 40.3 | 0.31 | 0.96 | 0.7 | 0.001 | 2,493.5 |
| C2 | 6–24 | Milk | 24.8 | 77.5 | 0.26 | 0.96 | 0.7 | 0.001 | 7,110.6 |
| D | 6–36 | Milk | 25.3 | 30.8 | 0.25 | 0.78 | 0.8 | 0.001 | 3,506.0 |
| E1 | 6–12 | Milk | 25.3 | 184.9 | 0.34 | 0.87 | 0.7 | 0.001 | 25,565.7 |
| | 13–36 | Milk | 25.3 | 294.2 | 0.36 | 0.88 | 0.7 | 0.001 | 45,620.3 |
| E2 | 6–12 | Milk | 30.0 | 130.7 | 0.25 | 0.96 | 0.7 | 0.001 | 14,472.5 |
| | 13–36 | Milk | 29.1 | 79.5 | 0.27 | 0.93 | 0.7 | 0.001 | 9,073.1 |
| G | 13–36 | Milk | 32.8 | 54.8 | 0.28 | 0.87 | 0.8 | 0.001 | 9,811.5 |

*Note*: Samples were analyzed at 40°C and shear rates of 0.001–1,000 $s^{-1}$.

[a] $K$ is the consistency coefficient; $R^2$ is a power-law regression coefficient which estimates the degree of fit of the model to shear-thinning behavior.

[b] $n$ is the flow behavior index; $\eta_0$ and $\eta_\infty$ are the zero-shear and infinite viscosity estimates respectively. All $\eta_\infty$ values were taken as positive irrespective of sign.

[c] Codes for commercial complementary porridges.

model, although the CACFs would be expected to show different rheological behavior compared to pure polymer solutions. Shear-thinning behavior is due to increased alignment of the constituent molecules as shear rate increases (Maskan & 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, Scher, & Desobry, 2006; Prakash, Ma, & Bhandari, 2014). Viscosity is directly proportional to molar mass, with low molecular weight biopolymer solutions showing no effective entanglements and displaying low viscosity (Mezger, 2014).

The use of hydrolytic enzymes is often used in industry to yield porridges of both acceptable flow behavior (viscosity) and improved energy and nutrient density. Bennett et al. (1999) reported that amylase liquefaction of high energy density, high viscosity (HD-HV) porridges resulted in increased energy consumption by young children. Enzymatic hydrolysis and dextrinization of starch lowers its molecular size, improving its ease of flow and deformation when prepared as a complementary porridge. Drum-drying (Trèche, 2002) and extrusion cooking (Muoki, 2013) are also applied to reduce the viscosity of CACFs and increase nutrient density. Mukwevho and Emmambux (2022) also illustrated the viscosity lowering effect of exposing Bambara flour paste to infrared + microwave heat treatments, which was explained by the unavailability of starch to form a viscous paste due to a surrounding protein matrix that forms around the starch granules. Methods such as roasting, fermentation, and germinating cereal and legume grains prior to processing into flours (Ademulegun & Koleosho, 2012; Ejigui, Savoie, Marin, & Desrosiers, 2007; Syeunda, Anyango, & Faraj, 2019), could be adopted as alternative viscosity-lowering options by the food industry. These processing technologies cause desirable changes in texture with preservation of nutrients and flavors (Kaavya et al., 2022).

Although lactose, maltose, sucrose, maltodextrins, glucose syrup or dried glucose syrup, (along with enzyme-hydrolyzed starch, precooked, or pre-gelatinized starch) are recommended in CACFs (Nasirpour et al., 2006), it is important to note that added free sugars, being a cause for public health concern, should not be more than 10% of total energy intake (World Health Organization. Regional Office for Europe, 2019a). No added sugars were listed on labels, however, most CACFs had declared total sugar content values between 20% and 40%. This was consistent with Marais, Christofides, Erzse, and Hofman (2019) who reported that about 78.7% of CACFs in their study had a high total sugar content, promoting sweet-taste preferences and eventually, diet related non-communicable diseases (NCDs). According to the Standard for Processed Cereal-Based Foods for Infants and Children, Codex Alimentarius Standard 74 (Codex Alimentarius, 1981), sucrose, fructose, glucose, glucose syrup or honey added to the 'add-milk' products shall not exceed 1.8 g/100 kJ (7.5 g/100 kcal), and for fructose, 0.9 g/100 kJ (3.75 g/100 kcal). For the 'add-water' products, the limit shall be 1.2 g/100 kJ (5 g/100 kcal) and 0.6 g/100 kJ (2.5 g/100 kcal) for fructose.

### 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 the CACFs are presented in Table 3. At zero shear rates, all CACFs except A1-reference and A2 at 1 $s^{-1}$, had high viscosity values (>3 Pa.s) for infant oral processing. At 10 $s^{-1}$ only a reference porridge and A2 were below 3 Pa.s. At the porridge solids content specified by 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 3).

Even though samples A1, A2, A3, B1, B2, and F2 had acceptable viscosity, they did not meet the energy and protein requirements for the 9–24 months age-group.

Although in most cases, the CACFs' nutritional information panels claim to provide adequate daily nutrient intakes to infants and young children, some CACFs do not meet the minimum regulatory requirements for energy and protein especially when reconstituted and consumed at 3 meals/day. At zero shear rates, all porridges failed to meet the viscosity criterion (3 Pa.s) (Table 2). At a shear rate of 10 $s^{-1}$, only 2/23 of the porridges (8.7%) had appropriate viscosity, while at 50 $s^{-1}$ 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 potentially not suitable for infant feeding due to lower operational shear rates and absence of rotary chewing skills which begin to develop late (around 10–12 months) in infants (Cichero, 2017). Previously, Faber, Laubscher, and Berti (2016) reported that some caregivers (about 66%) do not serve CACFs as per manufacturer's recommendations due to high viscosity, but rather dilute with water, a practice which lowers the porridge's nutrient density.

While it is generally believed that optimal complementary foods should be well suited to infants' chewing and swallowing abilities for a pleasant early feeding experience, emerging research (for example, Black et al., 2017; Nicklaus et al., 2015) is showing the importance of introducing diverse and reasonably challenging textures to infants at appropriate stages of oral development. This helps infants to learn to accept different textures later in life. A child's oromotor readiness refers to its ability to efficiently and safely chew and swallow a given texture. Hence, caution should always be exercised, and this nutrition transition should be well managed, as very high viscosity porridge is difficult to orally breakdown and swallow for children due to their limited oral motor abilities. The ease of swallowing a food bolus is highly linked to its rheological quality (Gallegos, Brito-de la Fuente, Clavé, Costa, & Assegehegn, 2017). Yet, there is a lack of technical guidance in matching the rheological properties of foods with individuals' oral-motor capabilities. The inappropriate rheological properties of CACFs may limit nutrient intake in infants, eventually leading to child malnutrition. The daily energy needs of children increase from approximately 600 kcal (2,520 kJ/100 g) at 6–8 months of age to 900 kcal (3,780 kJ/100 g) by 12–23 months of age (Dewey & Brown, 2003). Therefore, children require the correct amounts of food of appropriate texture for age, for healthy growth and development. Low energy density CACFs are undesirable because infants' and young children's small stomachs limit food consumption to only relatively small amounts at mealtimes (World Health Organization. Regional Office for Europe, 2019a), thus potentially leading to protein–energy malnutrition.

### 3.4 | Linking the rheological, sensory, and nutritive properties of the CACFs

Instrumental viscosity measurements alone may not fully describe the consistency and oral textural perceptions of porridges, in part due to the differences in mechanisms by which food is physiologically handled in-mouth. Figure 3a(i)–h(ii) shows 16 TCATA product curves (dynamic sensory texture spectra) obtained from sensory evaluation by using two oral processing (OP) methods. Additional graphs for the rest of the samples are provided in Appendix S1X1a(i)–k(ii).

Across all products and method, the texture attributes creamy, smooth, and soft were common, being perceived early on during food oral processing and retaining high citation proportions throughout. B2_6–24 M (Figure 3c[ii]) was evaluated as significantly creamier than the rest early in oral processing, while E1_13–24 M (Figure 3g[i–ii]) and G_12–24 M (Figure 3h[i–ii]) were perceived as significantly less creamy during the same initial oral processing phase by both the normal and up-down methods. However, B1, B2, E1, D, and G had high citation proportions for thick, too thick, sticky, grainy, less smooth, and slightly chewy compared to the other porridges, in some case low citation proportions for easy to swallow (Figure 3b,c,e–h[both i–ii]). These sensory characteristics were more pronounced in the up-down method and contrasted with the texture profile of A1 which was generally thin, watery, and easy to swallow. The texture profiles were dependent on the product composition and preparation method as directed on the label information panel for the ready to eat form.

**TABLE 3** The viscosity values analyzed at 40°C, and predicted nutrient intakes (protein and energy, based on assumed shear rate of 50 $s^{-1}$ and viscosity cut-off of 3 Pa.s) from CACFs, in comparison to the recommended age-appropriate protein and energy intakes.

| Commercial porridge[c] | Recipe (months) | Solids (%) | Viscosity (Pa.s) at different shear rates | | | | Energy (kJ/day) | Protein (g/day) |
|---|---|---|---|---|---|---|---|---|
| | | | 0.001–0.01 $s^{-1}$ [d] | 1 $s^{-1}$ | 10 $s^{-1}$ | 50 $s^{-1}$ | | |
| A2 | 6–24 | 25.0 | 303.2 | 6.6 | 1.1 | **0.5** | 2,658 | 23 |
| A3 | 6–24 | 25.0 | 1,443.3 | 26.3 | 3.7 | **1.4** | 2,658 | 23 |
| B1 | 6–24 | 35.1 | 3,906.7 | 55.8 | 8.2 | **2.7** | 2,607 | 16 |
| B2 | 6–24 | 35.1 | 2,363.3 | 49.2 | 7.4 | **2.5** | 2,574 | 19 |
| C1 | 6–24 | 24.8 | 4,558.9 | 53.8 | 10.8 | 4.1 | 2,160 | 22 |
| C2 | 6–24 | 26.3 | 4,456.7 | 65.6 | 10.6 | **3.1** | 2,703 | 22 |
| D | 6–36 | 26.3 | 3,290.0 | 37.2 | 4.7 | **1.1** | 2,049 | 11 |
| E1 | 6–12 | 26.7 | 25,350.0 | 248.5 | 39.6 | 10.6 | 2,757 | 18 |
| | 13–36 | 25.8 | 35,166.7 | 327.3 | 54.6 | 16.9 | 3,861 | 25 |
| E2 | 6–12 | 30.0 | 12,696.7 | 117.7 | 21.0 | 7.0 | 2,139 | 15 |
| | 13–36 | 29.1 | 7,660.0 | 71.8 | 12.8 | 4.0 | 3,120 | 22 |
| F1 | 6–8 | 23.1 | 2,568.9 | 53.8 | 7.7 | **2.7** | 3,045 | 23 |
| | 9–12 | 25.1 | 3,653.3 | 81.0 | 11.7 | 4.0 | 3,045 | 23 |
| | 13–24 | 24.2 | 3,102.2 | 67.2 | 9.9 | **3.4** | 4,350 | 33 |
| F2 | 6–8 | 18.9 | 1,645.6 | 27.2 | 4.3 | **1.4** | 2,364 | 24 |
| | 9–12 | 23.1 | 2,824.4 | 78.0 | 10.6 | **3.4** | 2,364 | 24 |
| | 13–24 | 23.1 | 3,028.3 | 81.9 | 11.0 | 3.5 | 1,244 | 38 |
| F3 | 9–12 | 25.1 | 3,974.4 | 109.0 | 17.4 | 6.0 | 3,366 | 33 |
| | 13–24 | 24.2 | 3,597.8 | 94.0 | 14.7 | 5.0 | 4,020 | 40 |
| F4 | 9–12 | 25.1 | 3,031.1 | 71.4 | 11.2 | 3.8 | 3,360 | 31 |
| | 13–24 | 24.2 | 2,618.9 | 53.6 | 8.8 | 3.1 | 4,014 | 37 |
| G | 13–36 | 32.8 | 7,487.5 | 58.2 | 11.5 | **2.5** | 1,494 | 14 |
| Reference (A1) | 6–24 | 25.0 | 254.6 | 5.0 | 0.8 | 0.3 | 2,658 | 23 |
| RNI[a] for low BME[b] infants | | 6–8 month | ≤3 Pa.s | ≤3 Pa.s | ≤3 Pa.s | ≤3 Pa.s | 2,318 | 5.2 |
| | | 9–11 month | ≤3 Pa.s | ≤3 Pa.s | ≤3 Pa.s | ≤3 Pa.s | 2,944 | 6.7 |
| | | 12–24 month | ≤ 3 Pa.s | ≤ 3 Pa.s | ≤ 3 Pa.s | ≤3 Pa.s | 4,318 | 9.1 |
| RNI for average BME infants | | 6–8 month | ≤3 Pa.s | ≤3 Pa.s | ≤3 Pa.s | ≤3 Pa.s | 1,495 | 2.0 |
| | | 9–11 month | ≤3 Pa.s | ≤3 Pa.s | ≤3 Pa.s | ≤3 Pa.s | 2,012 | 3.1 |
| | | 12–24 month | ≤3 Pa.s | ≤3 Pa.s | ≤3 Pa.s | ≤3 Pa.s | 3,242 | 5.0 |
| RNI for high BME infants | | 6–8 month | ≤3 Pa.s | ≤3 Pa.s | ≤3 Pa.s | ≤3 Pa.s | 672 | 1.1 |
| | | 9–11 month | ≤3 Pa.s | ≤3 Pa.s | ≤3 Pa.s | ≤3 Pa.s | 1,079 | 1.7 |
| | | 12–24 month | ≤3 Pa.s | ≤3 Pa.s | ≤3 Pa.s | ≤3 Pa.s | 2,167 | 3.6 |

*Note*: The viscosity values for the CACF porridge samples that may have acceptable viscosity of about 3Pa.s at 50 $s^{-1}$ are shown in bold.

[a] Recommended nutrient intake based on (Dewey & Brown, 2003). 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.

[b] 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 & Brown, 2003).

[c] Codes represent the actual names of CACFs used in the study.

[d] Zero-shear viscosity values based on the first/lower plateau of the viscosity-shear rate curves.

Figures 4a,b and 5a,b show visually the relationships among rheological (viscosity), and oral texture, and nutritional content data of the CACFs. The results indicate that if the rheological properties and sensory texture are not optimized, nutrient intake in infants and young children may be reduced.

In Figure 5a,b, the first three PCA factors explain 73% of the variation among samples, with F1 (38%) separating samples into 'add-milk' and 'add-water groupings'. The 'add-milk' CACFs were associated with high consistency coefficients and higher viscosity at all shear rates, being too thick and difficult to swallow. However, 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 (rheology) or physiology is unclear (Munialo, Kontogiorgos, Euston, & Nyambayo, 2019). E1- a minimally processed

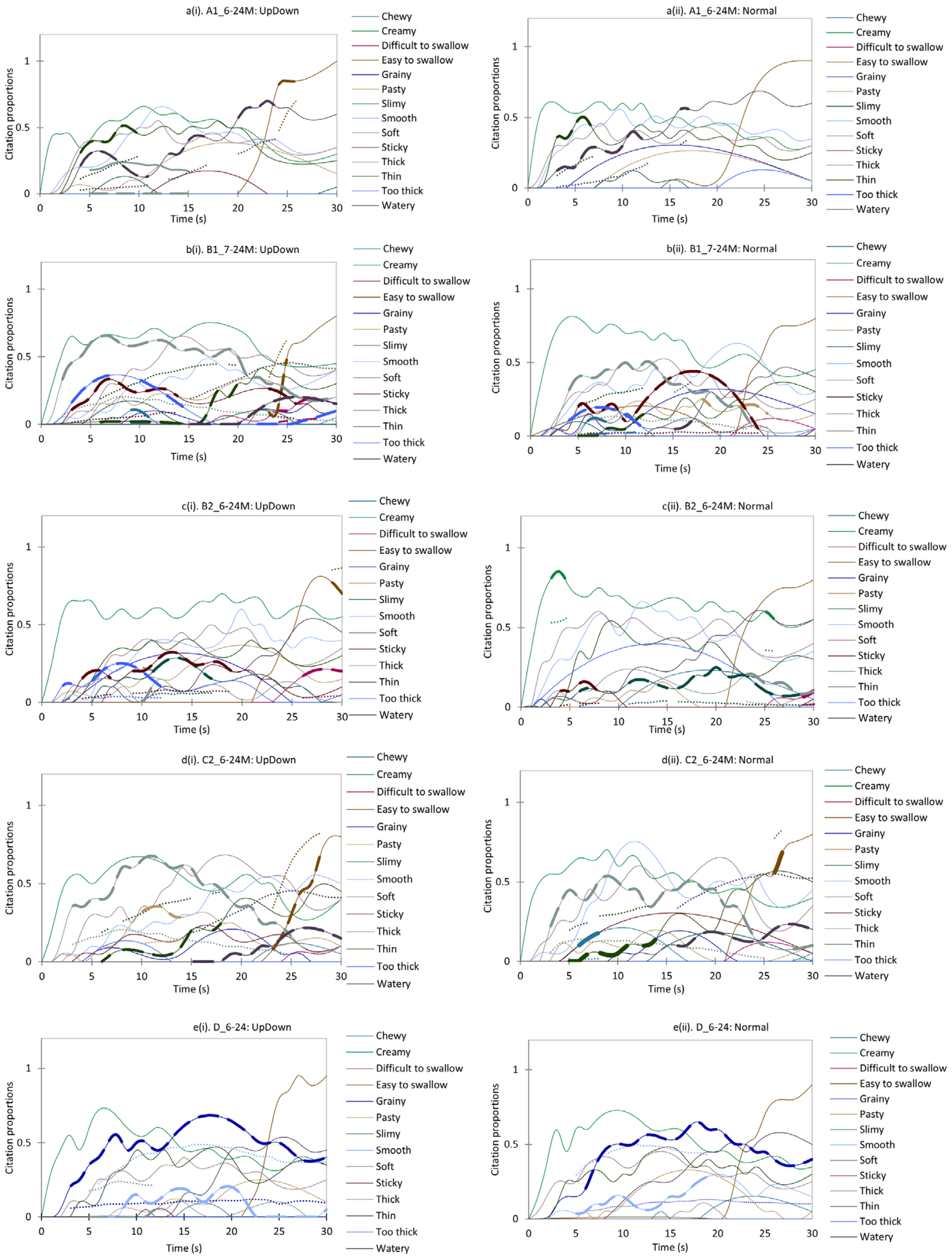


**FIGURE 3** a(i)–h(ii). Temporal check-all-that-apply (TCATA) texture attribute curves for eight selected commercially available complementary foods (CACFs, porridge form). Attribute reference lines (represented as dotted lines in the figures) are shown only during periods of significant differences ($p \leq .05$) in citation proportion for a specific CACF sample compared to the mean of all others. Significant reference line segments are contrasted with highlighted thicker sections of attribute curves for convenient visualization. The 'letter_number' at the beginning of a product name is the code for a specific CACF, while the 'number and a letter' after the name shows the infant age group for which the recipe was specified on the product packaging. Samples were evaluated by the Normal (healthy, normal adult chewing) and the up-down (munching, as with babies learning to chew) OP method respectively. Nineteen CACFs were investigated and 11 which are not shown here were provided in Appendix S1.

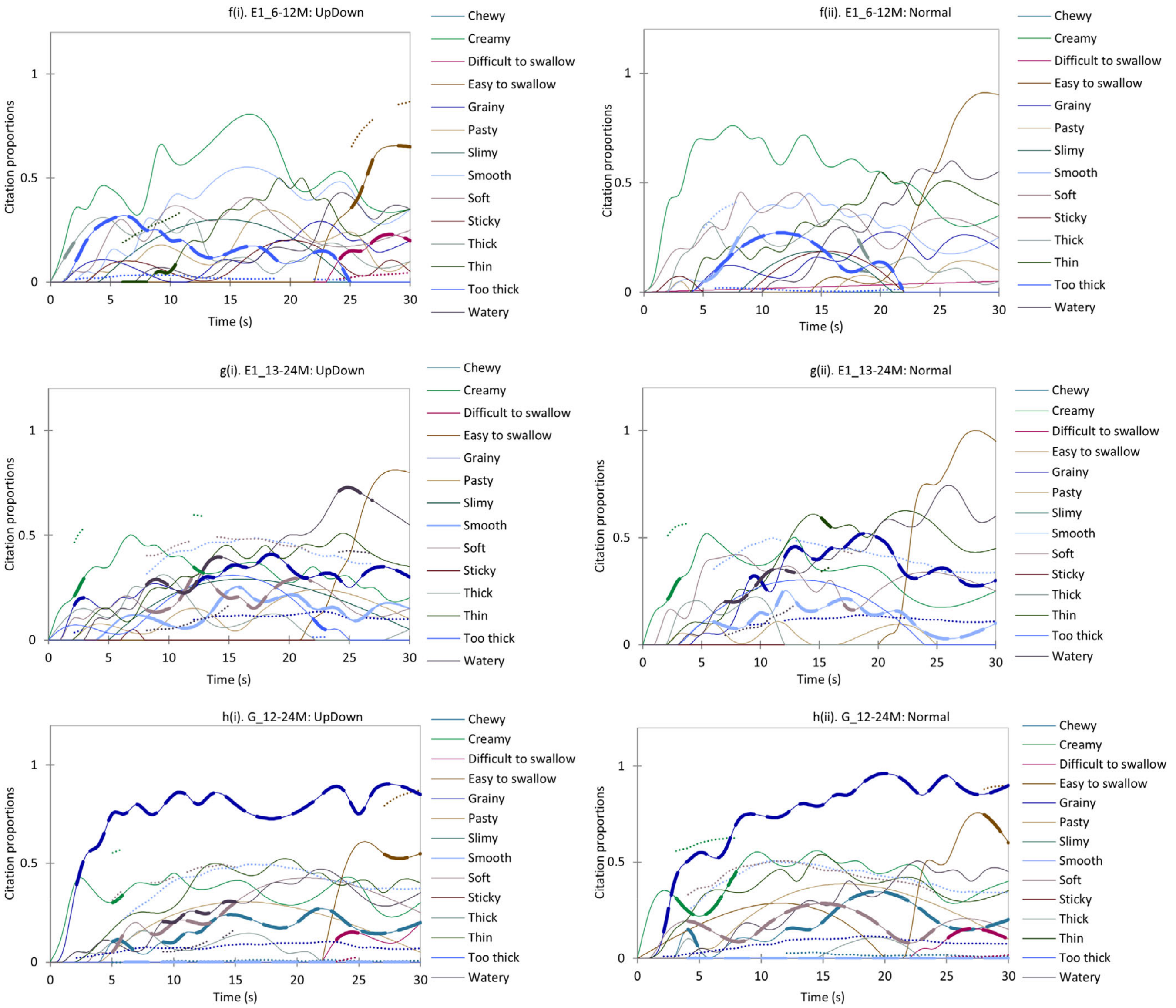


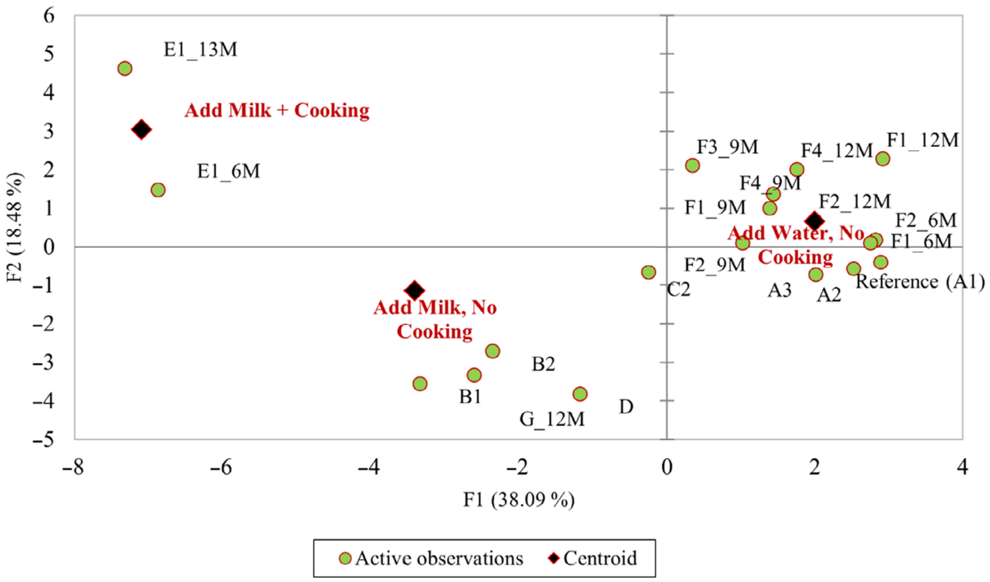
**FIGURE 3** (Continued)

maize flour requiring a 3 min cook in milk, differed the most from the add-water samples, being characterized as difficult to swallow, too thick, and with high viscosity (Figure 5a,b).

The 'add-water' CACFs (which already had a protein source included) were positively correlated with low apparent viscosity, high energy and protein densities and intakes, being soft, thin, and easy to swallow (Figure 5b). This was probably due to incorporation of enzyme-hydrolyzed ingredients and the absence of a cooking step—both of which reduces starch–protein interactions in the porridge, as such interactions enhance viscosity. Overall, the CACFs showed a wide variation in their suitability for infant feeding based on their flow properties, sensory texture, and nutritive properties.

Texture affects liking or rejection of many foods for clinically relevant populations such as infants where lower oral shear rates apply. In another relevant study investigating the effect of dispersing media (water, apple juice, and low-fat milk) on the shear and extensional rheology of thickeners used for dysphagia management, Kongjaroen et al. (2022) found that the zero-shear viscosity was significantly affected by the dispersing media, whereas there was no marked effect on high shear viscosity, especially at shear rate 50 $s^{-1}$ traditionally assumed for oral processing. These results highlight the importance of the zero-shear viscosity as a critically relevant parameter especially in infant foods, where oral shear rates are thought to be very low (Manrique et al., 2016). For infants and young children, oral shear rates increase with age, and during food oral processing, 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. Infants have limited tongue or pharyngeal muscle strength, less developed dentition, and weak masticatory muscles to be able to generate the critical shear stress and shear rates for initiating shear-thinning. When very low stress is applied to a shear-thinning fluid, the Brownian forces are not overcome by the shear and

(a) Observations (F1F2: 56.56 %)



(b) Observations (F1F3: 54.74 %)

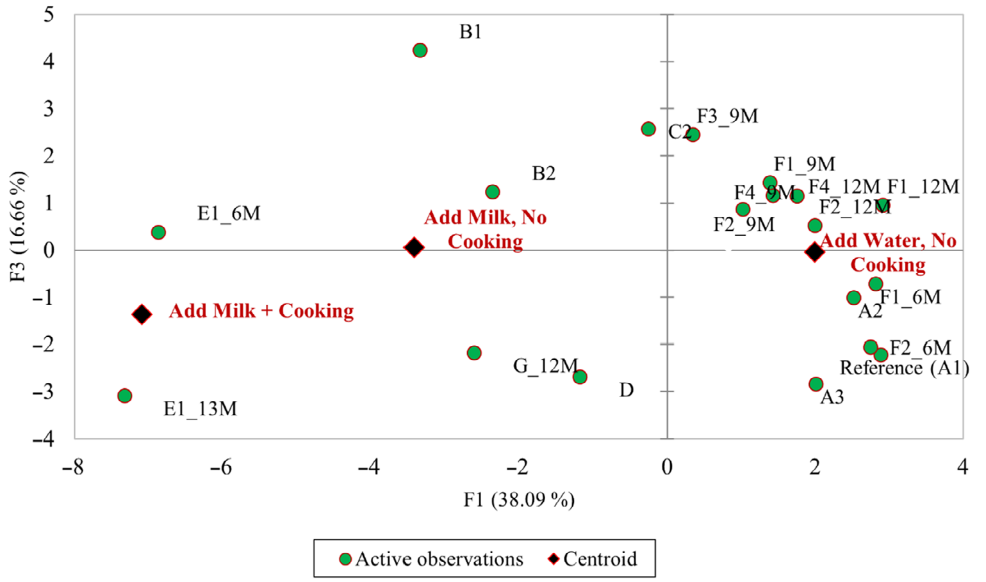


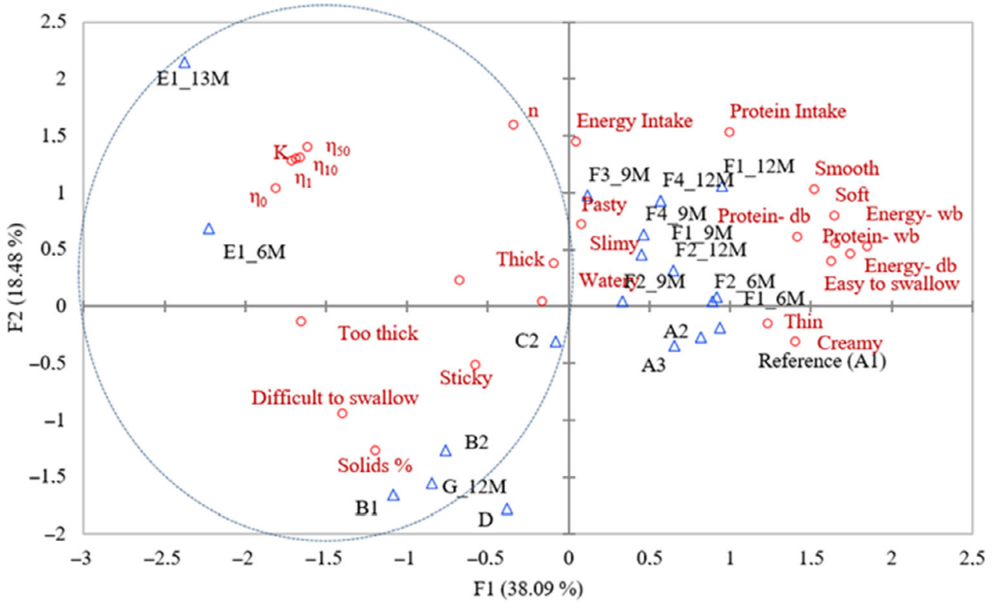
**FIGURE 4** (a) F1 and F2; (b) F1 and F3. PCA maps for the CACFs, showing the overall relationships among samples based on sensory, rheological, nutrient composition and intake data. CACFs are code-named, with the first letter representing the brand/manufacturer, a number to differentiate between CACFs from same manufacturer, and lastly the letter M preceded by a number to represent the target age for the porridge. The centroids of each group are shown as bold, solid diamonds, while the CACFs are shown as solid round dots. The 'add-milk' and 'add-water' qualitative descriptors represent the supplementary variable. The 'add-water' had a protein source already included in the formulation. Refer to Table 1 for detailed descriptions of the coded CACFs.

the food macromolecules remain folded in a network arrangement (elastic recoil), which then shows a high zero-shear viscosity ($\eta_0$) (Larson, 1999). Hence, there is need to consider characterizing the apparent viscosity of infant foods for 6–8 months at zero-shear to ≤1 $s^{-1}$. For this purpose, the Cross model which can more accurately predict the zero shear ($\eta_0$) and infinite shear ($\eta_\infty$) viscosities in the limits of $\gamma \rightarrow 0$ (very low) and $\gamma \rightarrow \infty$ (very high) shear rates respectively (Modigell, Pola, & Tocci, 2018), was used. Much higher shear rates (10–50 $s^{-1}$) may be considered with increasing age as children acquire rotary chewing abilities (Himmlova, Goldmann, Ihde, & Konvickova, 2007). Infant foods must be suited to children's oromotor readiness for a pleasant eating experience.

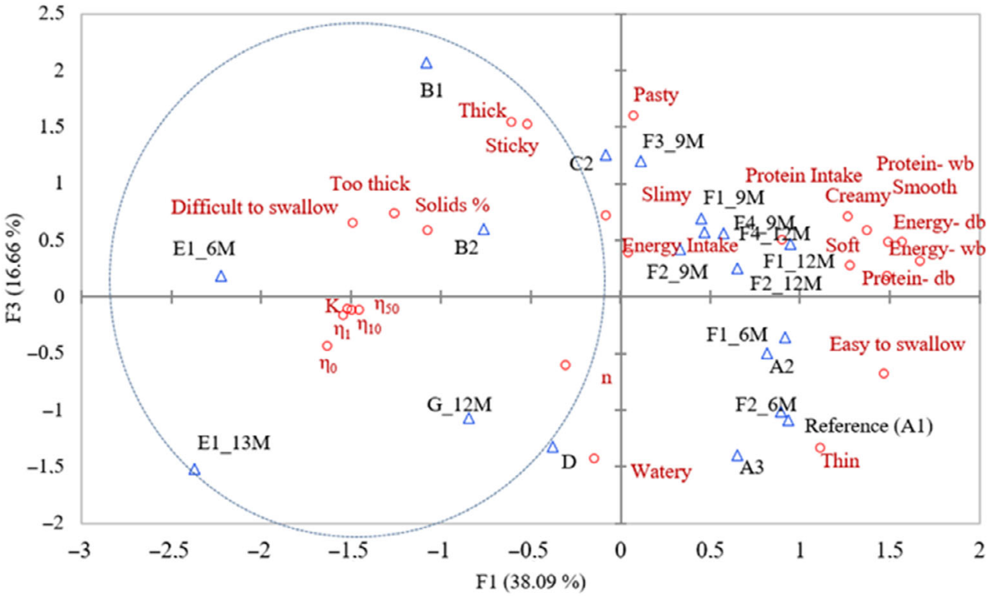
Food is judged as difficult to eat when the bolus is difficult to form (Laguna, Farrell, Bryant, Morina, & Sarkar, 2017). Too thick, sticky, and difficult to swallow CACFs may present feeding challenges to infants, reducing daily nutrient intakes, and contributing to undernutrition. The tongue movement (which is highly restricted at 6–8 months) contributes to food oral processing by exerting shear force on the food, aided by the hard palate during oral processing (Yamada, Kanazawa, Komagamine, & Minakuchi, 2015). In an earlier study by Ross, Tyler, Borgognone, and Eriksen (2019), the apparent viscosities of some fluid foods at lower shear rates (10 $s^{-1}$ compared to 50 $s^{-1}$ and 100 $s^{-1}$) showed strong and positive correlations with perceived oral texture in individuals with impaired food oral processing abilities, indicating that low shear rates seem to be associated with a limited oral processing capacity. During swallowing, the tongue generates higher propulsive forces and tongue pressure amplitudes to initiate flow in extremely thick foods compared with thin liquids (Steele, Bailey, & Molfenter, 2010).

**FIGURE 5** (a) F1 and F2 and (b) F1 and F3. PCA biplots for the 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). Refer to Table 1 for detailed descriptions of the coded CACFs.

(a) Biplot (F1F2: 56.56 %)



(b) Biplot (F1F3: 54.74 %)



Our results agree with those reported by Nicklaus et al. (2015), showing large variations in oral texture across infant age groups for CACFs on the French market. When prepared according to the label directions for use, commercial complementary foods should have a texture and consistency appropriate for the targeted age (World Health Organization. Regional Office for Europe, 2019a). Presently, there are no clear-cut regulations regarding CACFs texture, and inconsistencies may compromise public health objectives for child nutrition. As also suggested by Tan et al. (2022), there is need for closer alignment between CACFs' sensory texture properties and their recommended specific age and stage of infant development communicated through front-of-pack labels.

It is vital however to consider some important limitations to the study. Firstly, the magnitude and distribution of shear rates and shear stress levels in the oral cavity of infants, as well as the effects of non-rheological parameters on oral texture perception were not considered as they remain not known. Additionally, we acknowledge the limitation of using declared protein and energy contents rather than analyzing the porridges, as what is declared on the product pack may turn out to vary from what is analyzed. There is also increasing confirmation of the relevance of both shear and extensional deformations in food oral processing (Chen & Lolivret, 2011), with many fluid foods potentially displaying significant differences in their responses to shear and extensional forces. This study only focused on shear deformations, that is, fluid deformation under a stress applied parallel to the surface. Extensional deformation occurs when a stress is applied perpendicularly to the surface of the deformation (Lv, Chen, & Holmes, 2017), as in the up-down (munching) oral processing method. Extensional flow may cause much higher deformations in colloidal systems in comparison with shear deformation (Yuan, Ritzoulis, & Chen, 2018). Furthermore, Lv et al. (2017) have found that humans have a greater discriminatory capacity in perceiving extensional compared to shear viscosity, even though the mechanisms are not understudied (Yuan et al., 2018). Therefore, information on the extensional viscosity of complementary foods is critical for practical oral texture sensory predictions and require concurrent investigation in future studies.

Additional factors in and outside the mouth such as panelist individual differences in mouth geometry, the amount and rate of saliva secreted, and variable tongue behaviors when evaluating the samples, may also have influenced the perceived rheology of the CACFs. It is well known that chemical senses (olfaction, taste, and trigeminal) affect swallowing behavior (Loret, 2015), and since this aspect was not studied, the different CACFs would probably elicit varied chemical sensations, with unknown rheological interactions. Additionally, the mechanisms of mechano-sensation for foods viscosity have not been elucidated, nor is the degree of changes in viscosity (just noticeable differences [JNDs] and Weber fractions) required to initiate these physiological changes in perception (discrimination thresholds) known. This lack of complete scientific understanding of the oro-tactile mechanisms for infant texture perception limits understanding the texture of CACFs during consumption.

The specification of a single shear viscosity is insufficient to capture the dynamic rheological texture response associated with the in-mouth food process, of complementary foods, but also due to individual differences among infants and their restricted oral physiology as a function of their age. Food texture perception arises from the food's interactions with mechanoreceptors in the oral cavity, and the interpretations of neural impulses by the brain (Breen, Etter, Ziegler, & Hayes, 2019). Therefore, individual differences in neurological behaviors among panelists can potentially affect results. The study used an adult panel and not infants, due to the challenges of working with young children in research. The results would potentially vary if infants were to participate, given that the mechanisms of oral processing and food texture perception vary with physiological development of the oral system (Munialo et al., 2019). An additional limitation of this study is that we did not investigate the tribological properties of the CACFs. Soft tribology is increasingly becoming an important analytical tool in food science and food oral processing, for determining the lubricity and friction properties of thin food films acting as lubricants between the tongue and palate. This would help to understand the biophysical mechanisms behind perceived texture such as smoothness, creaminess, and grittiness.

## 4 | CONCLUSIONS AND REMARKS

Some CACFs do not meet international quality standards for energy and protein content, and therefore, fail to support public health dietary recommendations for healthy growth and development of infants and young children. The viscosity values of most CACFs at shear rate estimates for infant oral processing (zero-shear—50 $s^{-1}$) are high, exceeding recommended limits for baby porridge. Concurrently, information about the oral-texture profiles of CACFs is quite limited and requires more research. High porridge viscosity can limit protein and energy intake in infants and young children, especially those receiving low to average breast milk energy (BME) intake, and this perpetuates protein–energy malnutrition. Some CACFs are suboptimal in energy and protein content, not complying with published quality standards for nutrient content which could potentially lead to malnutrition in children.

There is a need for improving the flow properties, oral viscosity, and texture of CACFs for better energy and protein intakes among infants and young children. Careful assessment of the viscosity of CACFs at the point of use is recommended to ensure an appropriate porridge viscosity and a pleasant consumption experience which supports high nutrient intake. The viscosity and oral texture specifications of CACFs must be defined on the product label to inform users on the oral processing behaviors of the porridge under specified conditions. Further work is recommended to comprehend the precise shear rates applicable for in-mouth oral processing in infants and young children. Due to the continuous progression of young children's physiological development and nutritional needs, complementary foods research must be focussed on even narrower age ranges for results to be meaningful. This is important in designing more effective baby foods to meet the needs of infants and young children. These narrow age-ranges must also be reflected on the product panel labels. Shear rates from zero-shear ≤1 $s^{-1}$ for 6–12 month, and ≤ 50 $s^{-1}$ for 12–24 months may be more practical and relevant for infant feeding.

There is also a need to improve on manufacturers' preparation instructions and nutritional labeling of food products for infants and young children. Products should comply with the International Codex Alimentarius standards, relevant national government agencies and the WHO guidelines on composition, nutrition, or oral texture. It is also important for manufacturers to define appropriate upper age limits for some products which are labeled as 6–24 or 36 months, to encourage a timely transition to family foods and adapting textures to the developmental readiness of children.

### AUTHOR CONTRIBUTIONS

**James Makame:** Conceptualization; Funding acquisition; Resources; project administration; methodology; investigation; Data curation; formal analysis/Statistics; visualization; writing – original draft; writing – review & editing. **Henriette De Kock:** Conceptualization; Funding acquisition; Resources; methodology; Data curation; project administration; Supervision; writing – review & editing. **M. Naushad Emmambux:** Conceptualization; Funding acquisition; Resources; methodology; Data curation; project administration; Supervision; writing – review & editing.

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## DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

## ETHICAL STATEMENTS

Conflict of Interest: The authors have no conflict of interest to declare.

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## REFERENCES

Ademulegun, T., & Koleosho, A. (2012). Effects of processing method on the nutrients composition of maize/soya complementary food. *IOSR Journal of Pharmacy and Biological Sciences*, *4*(1), 39–43.

Ahmed, J. (2007). Rheological, thermal and dielectric properties of pureed baby foods. *Stewart Postharvest Review*, *5*, 2.

Ahmed, J., & Ramaswamy, H. S. (2007). Dynamic and steady shear rheology of fruit puree based baby foods. *Journal of Food Science and Technology*, *44*, 579–585.

Al-Othman, A. M., Khan, M. A., & Al-Kanhal, M. (1997). Nutritional evaluation of some commercial baby foods consumed in Saudi Arabia. *International Journal of Food Sciences and Nutrition*, *48*(4), 229–236.

Alvarez, E., Cancela, M. A., Delgado-Bastidas, N., & Maceiras, R. (2008). Rheological characterization of commercial baby fruit purees. *International Journal of Food Properties*, *11*(2), 321–329.

Alvarez, M. D., & Canet, W. (2013). Time-independent and time-dependent rheological characterization of vegetable-based infant purees. *Journal of Food Engineering*, *114*(4), 449–464.

Aryeetey, R. N. O., & Tay, M. (2015). Compliance audit of processed complementary foods in urban Ghana. *Frontiers in Public Health*, *3*, 243.

Balasubramanian, S., Kaur, J., & Singh, D. (2014). Optimization of weaning mix based on malted and extruded pearl millet and barley. *Journal of Food Science and Technology*, *51*(4), 682–690.

Bazaz, R., Baba, W. N., & Masoodi, F. (2016). Development and quality evaluation of hypo allergic complementary foods from rice incorporated with sprouted. *Cogent Food & Agriculture*, *2*(1), 1154714.

Bennett, V. A., Morales, E., González, J., Peerson, J. M., López de Romaña, G., & Brown, K. H. (1999). Effects of dietary viscosity and energy density on total daily energy consumption by young Peruvian children. *The American Journal of Clinical Nutrition*, *70*(2), 285–291.

Black, R. E., Makrides, M., & Ong, K. K. (2017). *Complementary feeding: Building the foundations for a healthy life: 87th Nestlé Nutrition Institute workshop, Singapore, May 2016*. Basel: Karger Medical and Scientific Publishers.

Breen, S. P., Etter, N. M., Ziegler, G. R., & Hayes, J. E. (2019). Oral somatosensory acuity is related to particle size perception in chocolate. *Scientific Reports*, *9*(1), 7437.

Chen, J., & Lolivret, L. (2011). The determining role of bolus rheology in triggering a swallowing. *Food Hydrocolloids*, *25*(3), 325–332.

Cichero, J. A. (2017). Unlocking opportunities in food design for infants, children, and the elderly: Understanding milestones in chewing and swallowing across the lifespan for new innovations. *Journal of Texture Studies*, *48*(4), 271–279.

Codex Alimentarius. (1981). *Standard for processed cereal-based foods for infants and children, Codex Stan, 74*. Rome: FAO.

Dewey, K. G., & Brown, K. H. (2003). Update on technical issues concerning complementary feeding of young children in developing countries and implications for intervention programs. *Food and Nutrition Bulletin*, *24*(1), 5–28.

Dimaria, S. A., Schwartz, H., Icard-Vernière, C., Picq, C., Zagre, N. M., & Mouquet-Rivier, C. (2018). Adequacy of some locally produced complementary foods marketed in Benin, Burkina Faso, Ghana, and Senegal. *Nutrients*, *10*(6), 785.

Ejigui, J., Savoie, L., Marin, J., & Desrosiers, T. (2007). Improvement of the nutritional quality of a traditional complementary porridge made of fermented yellow maize (Zea mays): Effect of maize–legume combinations and traditional processing methods. *Food and Nutrition Bulletin*, *28*(1), 23–34.

Faber, M., Laubscher, R., & Berti, C. (2016). Poor dietary diversity and low nutrient density of the complementary diet for 6-to 24-month-old children in urban and rural KwaZulu-Natal, South Africa. *Maternal & Child Nutrition*, *12*(3), 528–545.

FAO. (2013). Dietary protein quality evaluation in human nutrition. Report of an FAO Expert Consultation, FAO Food and Nutrition Paper 92. Italy, Rome.

Gallegos, C., Brito-de la Fuente, E., Clavé, P., Costa, A., & Assegehegn, G. (2017). Chapter eight – Nutritional aspects of dysphagia management. In F. Toldrá (Ed.), *Advances in food and nutrition research* (Vol. 81, pp. 271–318). Cambridge, MA: Academic Press. https://doi.org/10.1016/bs.afnr.2016.11.008

Gamonpilas, C., Kongjaroen, A., & Methacanon, P. (2023). The importance of shear and extensional rheology and tribology as the design tools for developing food thickeners for dysphagia management. *Food Hydrocolloids*, *140*, 108603.

García, A. L., Raza, S., Parrett, A., & Wright, C. M. (2013). Nutritional content of infant commercial weaning foods in the UK. *Archives of Disease in Childhood*, *98*(10), 793–797.

Himmlova, L., Goldmann, T., Ihde, S., & Konvickova, S. (2007). Time analysis of hard and soft bolus processing. *Biomedical Papers of the Medical Faculty of Palacky University in Olomouc*, *151*(2), 327–332.

Hudson, B. J. (2013). *Biochemistry of food proteins*. Berlin: Springer Science & Business Media.

Jamilah, B., Mohamed, A., Abbas, K., Rahman, R. A., Karim, R., & Hashim, D. (2009). Protein-starch interaction and their effect on thermal and rheological characteristics of a food system: A review. *Journal of Food, Agriculture and Environment*, *7*, 169–174.

Jun, X., & Yee-Chung, J. (2016). Parameter determination for the cross rheology equation and its application to modeling non-Newtonian flows using the WC-MPS method. *Engineering Applications of Computational Fluid Mechanics*, *10*(1), 111–129.

Kaavya, R., Pandiselvam, R., Gavahian, M., Tamanna, R., Jain, S., Dakshayani, R., … Arun Prasath, V. (2022). Cold plasma: A promising technology for improving the rheological characteristics of food. *Critical Reviews in Food Science and Nutrition*, 1–15.

Kongjaroen, A., Methacanon, P., Seetapan, N., Fuongfuchat, A., Gamonpilas, C., & Nishinari, K. (2022). Effects of dispersing media on the shear and extensional rheology of xanthan gum and guar gum-based thickeners used for dysphagia management. *Food Hydrocolloids*, *132*, 107857.

Kumar, L., Brennan, M. A., Mason, S. L., Zheng, H., & Brennan, C. S. (2017). Rheological, pasting and microstructural studies of dairy protein–starch interactions and their application in extrusion-based products: A review. *Starch-Stärke*, *69*(1–2), 1600273.

Laguna, L., Farrell, G., Bryant, M., Morina, A., & Sarkar, A. (2017). Relating rheology and tribology of commercial dairy colloids to sensory perception. *Food & Function*, *8*(2), 563–573.

Larson, R. G. (1999). *The structure and rheology of complex fluids* (p. 688). New York: Oxford University Press.

Le Révérend, B. J., Edelson, L. R., & Loret, C. (2014). Anatomical, functional, physiological and behavioural aspects of the development of mastication in early childhood. *British Journal of Nutrition*, *111*(3), 403–414.

Lelievre, J., & Husbands, J. (1989). Effects of sodium caseinate on the rheological properties of starch pastes. *Starch-Stärke*, *41*(6), 236–238.

Loret, C. (2015). Using sensory properties of food to trigger swallowing: A review. *Critical Reviews in Food Science and Nutrition*, *55*(1), 140–145.

Lv, Z., Chen, J., & Holmes, M. (2017). Human capability in the perception of extensional and shear viscosity. *Journal of Texture Studies*, *48*(5), 463–469.

Makame, J., Cronje, T., Emmambux, N. M., & De Kock, H. (2019). Dynamic oral texture properties of selected indigenous complementary porridges used in African communities. *Food*, *8*(6), 221.

Makame, J., De Kock, H., & Emmambux, N. M. (2020). Nutrient density of common African indigenous/local complementary porridge samples. *LWT*, *133*, 109978.

Manrique, Y. J., Sparkes, A. M., Cichero, J. A., Stokes, J. R., Nissen, L. M., & Steadman, K. J. (2016). Oral medication delivery in impaired swallowing: Thickening liquid medications for safe swallowing alters dissolution characteristics. *Drug Development and Industrial Pharmacy*, *42*(9), 1537–1544.

Marais, N., Christofides, N., Erzse, A., & Hofman, K. (2019). Evidence for high sugar content of baby foods in South Africa. *South African Medical Journal*, *109*(5), 328–332.

Maskan, M., & Göğüş, F. (2000). Effect of sugar on the rheological properties of sunflower oil–water emulsions. *Journal of Food Engineering*, *43*(3), 173–177.

Maslin, K., & Venter, C. (2017). Nutritional aspects of commercially prepared infant foods in developed countries: A narrative review. *Nutrition Research Reviews*, *30*(1), 138–148.

Masters, W. A., Nene, M. D., & Bell, W. (2017). Nutrient composition of premixed and packaged complementary foods for sale in low- and middle-income countries: Lack of standards threatens infant growth. *Maternal & Child Nutrition*, *13*(4), e12421.

Masuelli, M. A., Sansone, M. G., & Aplicada, D. (2012). Hydrodynamic properties of gelatin-studies from intrinsic viscosity measurements. In *Products and Applications of Biopolymers* (pp. 85–116). London: InTech.

Mezger, T. G. (2014). *The rheology handbook* (4th ed). Hanover: Vincentz Network. https://books.google.co.za/books?id=8xqZoAEACAAJ

Modigell, M., Pola, A., & Tocci, M. (2018). Rheological characterization of semi-solid metals: A review. *Metals*, *8*(4), 245.

Morrison, F. A. (2005). *Using the solver add-in in Microsoft Excel®*. Houghton, MI: Michigan Technological University.

Mosha, A. C., & Svanberg, U. (1983). Preparation of weaning foods with high nutrient density using flour of germinated cereals. *Food and Nutrition Bulletin*, *5*(2), 10–14.

Muhimbula, H. S., & Issa-Zacharia, A. (2010). Persistent child malnutrition in Tanzania: Risks associated with traditional complementary foods (a review). *African Journal of Food Science*, *4*(11), 679–692.

Mukwevho, P., & Emmambux, M. N. (2022). Effect of infrared and microwave treatments alone and in combination on the functional properties of resulting flours from bambara groundnut seeds. *LWT*, *153*, 112448.

Munialo, C. D., Kontogiorgos, V., Euston, S. R., & Nyambayo, I. (2019). Rheological, tribological and sensory attributes of texture-modified foods for dysphagia patients and the elderly: A review. *International Journal of Food Science & Technology*, *55*(5), 1862–1871.

Muoki, P. N. (2013). *Nutritional, rheological and sensory properties of extruded cassava-soy complementary porridges* [PhD Thesis, University of Pretoria, Pretoria, South Africa].

Nasirpour, A., Scher, J., & Desobry, S. (2006). Baby foods: Formulations and interactions (a review). *Critical Reviews in Food Science and Nutrition*, *46*(8), 665–681. https://doi.org/10.1080/10408390500511896

Ng, C. S., Dibley, M. J., & Agho, K. E. (2012). Complementary feeding indicators and determinants of poor feeding practices in Indonesia: A secondary analysis of 2007 demographic and health survey data. *Public Health Nutrition*, *15*(5), 827–839.

Nicklaus, S., Demonteil, L., & Tournier, C. (2015). Modifying the texture of foods for infants and young children. In J. Chen & A. Rosenthal (Eds.), *Modifying food texture* (pp. 187–222). Amsterdam: Woodhead Publishing. https://doi.org/10.1016/B978-1-78242-334-8.00008-0

Nout, M. (1993). Processed weaning foods for tropical climates. *International Journal of Food Sciences and Nutrition*, *43*(4), 213–221.

Pencharz, P. B., & Ball, R. O. (2004). Amino acid needs for early growth and development. *The Journal of Nutrition*, *134*(6), 1566S–1568S. https://doi.org/10.1093/jn/134.6.1566S

Picchi, D., Poesio, P., Ullmann, A., & Brauner, N. (2017). Characteristics of stratified flows of Newtonian/non-Newtonian shear-thinning fluids. *International Journal of Multiphase Flow*, *97*, 109–133.

Prakash, S., Ma, Q., & Bhandari, B. (2014). Rheological behaviour of selected commercially available baby formulas in simulated human digestive system. *Food Research International*, *64*, 889–895.

Roberts, G., Barnes, H., & Mackie, C. (2001). Using the Microsoft Excel 'Solver' tool to perform non-linear curve fitting, using a range of non-Newtonian flow curves as examples. *Applied Rheology*, *11*(5), 271–276.

Ross, A. I., Tyler, P., Borgognone, M. G., & Eriksen, B. M. (2019). Relationships between shear rheology and sensory attributes of hydrocolloid-thickened fluids designed to compensate for impairments in oral manipulation and swallowing. *Journal of Food Engineering*, *263*, 123–131.

Sampallo-Pedroza, R. M., Cardona-López, L. F., & Ramírez-Gómez, K. E. (2014). Description of oral-motor development from birth to six years of age. *Revista de la Facultad de Medicina*, *62*(4), 593–604.

Schwartz, C., Vandenberghe-Descamps, M., Sulmont-Rossé, C., Tournier, C., & Feron, G. (2018). Behavioral and physiological determinants of food choice and consumption at sensitive periods of the life span, a focus on infants and elderly. *Innovative Food Science & Emerging Technologies*, *46*, 91–106. https://doi.org/10.1016/j.ifset.2017.09.008

Steele, C. M., Bailey, G. L., & Molfenter, S. M. (2010). Tongue pressure modulation during swallowing: Water versus nectar-thick liquids. *Journal of Speech, Language, and Hearing Research*, *53*, 273–283.

Syeunda, C. O., Anyango, J. O., & Faraj, A. K. (2019). Effect of compositing precooked cowpea with improved malted finger millet on anti-nutrients content and sensory attributes of complementary porridge. *Food and Nutrition Sciences*, *10*(9), 1157–1178.

Tan, V. W. K., Lim, A. J., McCrickerd, K., & Forde, C. G. (2022). Sensory profiles and mothers' expectations and beliefs about age appropriate snacks for infants and toddlers in Singapore. *Food Quality and Preference*, *97*, 104474.

Thaoge, M., Adams, M., Sibara, M., Watson, T., Taylor, J., & Goyvaerts, E. (2003). Production of improved infant porridges from pearl millet using a lactic acid fermentation step and addition of sorghum malt to reduce viscosity of porridges with high protein, energy and solids (30%) content. *World Journal of Microbiology and Biotechnology*, *19*(3), 305–310.

Treche, S. (1999). Viscosity, energy density and osmolality of gruels for infants prepared from locally produced commercial flours in some developing countries. *International Journal of Food Sciences and Nutrition*, *50*(2), 117–125.

Trèche, S. (2002). Complementary foods in developing countries: Importance, required characteristics, constraints and potential strategies for improvement. In *Proceedings of the international colloqum promoting growth and development of under fives* (pp. 132–148). Antwerp: ITG Press.

World Health Organization. (2003). *Complementary feeding: Report of the global consultation, and summary of guiding principles for complementary feeding of the breastfed child*. Geneva: World Health Organization. Retrieved from https://apps.who.int/iris/handle/10665/42739

WHO/UNICEF. (2003). *Global strategy for infant and young child feeding*. Geneva: World Health Organization.

World Health Organization. Regional Office for Europe. (2019a). *Commercial foods for infants and young children in the WHO European Region: a* *study of the availability, composition and marketing of baby foods in four European countries*. UN City, Mamorvej, Copenhagen, Denmark: World Health Organization. Regional Office for Europe. Retrieved from https://apps.who.int/iris/handle/10665/346581

World Health Organization. Regional Office for Europe. (2019b). *Ending inappropriate promotion of commercially available complementary foods for infants and young children between 6 and 36 months in Europe: a discussion paper outlining the first steps in developing a nutrient profile model to drive changes to product composition and labelling and promotion practices in the WHO European Region*. UN City, Marmorvej, Copenhagen, Denmark: World Health Organization. Regional Office for Europe. Retrieved from https://apps.who.int/iris/handle/10665/346583

Yamada, A., Kanazawa, M., Komagamine, Y., & Minakuchi, S. (2015). Association between tongue and lip functions and masticatory performance in young dentate adults. *Journal of Oral Rehabilitation*, *42*(11), 833–839.

Yang, C., Zhong, F., Goff, H. D., & Li, Y. (2019). Study on starch-protein interactions and their effects on physicochemical and digestible properties of the blends. *Food Chemistry*, *280*, 51–58.

Yuan, B., Ritzoulis, C., & Chen, J. (2018). Extensional and shear rheology of okra polysaccharides in the presence of artificial saliva. *NPJ Science of Food*, *2*(1), 1–6.

## SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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