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Effect of pearl millet and cowpea pre-treatments on rheology, digestible starch, and molar mass distribution of soluble starch fragments in composite porridge

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ABSTRACT

This study investigated the rheological behaviour, digestible starch fractions, and molar mass distribution of solubilised starch fragments in composite porridges made from soaked, germinated, and fermented pearl millet and cowpea. All formulations exhibited shear-thinning behaviour at the consumption temperature of 40 °C and demonstrated viscoelastic characteristics, balancing between solid-like (elastic) and liquid-like (viscous) properties. Composite porridges containing germinated pearl millet exhibited the lowest apparent and final viscosities, as measured by both rheometer and Rapid Visco Analyser. All composite porridges were classified as rapidly digestible starch (RDS), with 60–62 % of DM hydrolysed within the first 20 min, and minimal change observed throughout the 240 min digestion period. RDS is a desirable attribute in composite porridges, as it provides a readily available source of dietary energy to support growth and promote weight gain. Formulations containing fermented pearl millet and fermented cowpea, either together or in combination with germinated pearl millet or cowpea (FMFP, FGMFP, and FMFGP), showed higher intrinsic viscosity and greater concentrations of degraded solubilised starch fragments than those made with soaked cowpea (FMSP, FGMSP and FMSGP). These molecular characteristics are consistent with the lower viscosities and the RDS observed across samples. The findings demonstrate that simple, low-cost pre-treatments influence the molecular characteristics of solubilised starch fraction and, consequently, the functional properties of composite porridges. These modifications may contribute to the development of nutrient-dense, culturally acceptable porridge for feeding undernourished children in Mozambique and other low-income countries facing similar challenges.

1. Introduction

Undernutrition in children can lead to long-term and often irreversible impairments in physical growth and cognitive development whilst increasing susceptibility to infection and mortality (Deng et al., 2024; Muller & Krawinkel, 2005). In countries such as Mozambique, children are often fed thick, starchy porridges that they struggle to consume in adequate amounts to meet their nutritional needs. Incorporating legumes and applying low-cost pre-treatments such as soaking, germination and fermentation can significantly reduce porridge viscosity and improve both nutrient and energy density, offering a promising solution for improving composite porridges for feeding undernourished children in low-income settings (Makame et al., 2020; Ogunniran et al., 2024; Walker, 1990).

Pearl millet and cowpea are climate-resilient, widely cultivated, and consumed crops in Mozambique. Both are recognised as nutrient-dense food crops across Africa and Asia (Abebe & Alemayehu, 2022; Punia et al., 2021; Satyavathi et al., 2021). Their functionality can be further enhanced through soaking, germination, and fermentation, which modify pasting behaviour, reduce antinutritional factors, and enhance nutrient digestibility (Gabaza et al., 2017; Gahlawat & Sehgal, 1994; Gaytán-Martínez et al., 2023). The nutritional composition of the individual pre-treated flours used in this study, including proximate composition, dietary fibre, and total starch, has been reported previously (Nurmomade et al., 2024), and the proximate composition of the formulations used in this study was calculated in earlier work

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(Nurmomade, 2025). In that study, twelve composite porridges were evaluated, and six formulations were identified as the most suitable for feeding malnourished children based on their low resistant starch, high digestible starch, reduced phytic acid content, and lower final viscosity. These composite porridges were selected for further investigation in the present study.

Composite porridges form a three-dimensional matrix where flour particles and swollen starch granules are embedded within a gel-like polysaccharide network. This structure influences swallowability, energy intake, and starch digestion, and depends on factors such as flour type, particle size, cooking time, and polysaccharide structure (Ojijo & Shimoni, 2004). Previous studies have reported nutritional and functional improvements in composite porridges (Adeyanju et al., 2025; Ogunniran et al., 2024; Oladiran & Emmambux, 2022). However, to our knowledge, no published study has investigated how seed pre-treatments alter the molar mass distribution of solubilised starch fragments extracted from cooked composite porridges, nor how these molecular changes relate to viscosity and digestible starch.

Size-exclusion chromatography (SEC) is a valuable technique for analysing the molar mass distribution of polymers, including starch fragments, providing insights into molecular size, heterogeneity, and chain architecture. Additionally, the Rapid Visco Analyser (RVA) mimics the cooking process and can monitor viscosity in real time, linking starch swelling, leaching, and gel formation. When combined with dynamic rheology and in vitro starch digestibility measurements, these techniques can help better understand how molecular characteristics influence porridge flow behaviour, gel structure, swallowability, and starch hydrolysis. Together, these approaches enable an assessment of the relationship between structure and function that governs porridge quality.

Therefore, this study investigates how pre-treatments such as soaking, germination, and fermentation of pearl millet and cowpea seeds affect the molecular characteristics of the solubilised starch fragments. We further characterised the flow and viscoelastic properties of composite porridges and quantify rapidly and slowly digestible starch. These findings will provide insights into how low-cost pre-treatments modulate molecular and functional properties relevant to the development of composite porridges suitable for feeding children in low-income settings such as Mozambique.

2. Materials and methods

2.1. Sample and pre-treatment preparation

Pearl millet (*Pennisetum glaucum* (L.) R. Br.) variety Changara and cowpea (*Vigna unguiculata* (L.) Walp) variety 10 were obtained from the Mozambican Agricultural Research Institute in Montepuez, Cabo Delgado. These varieties are commercially available and affordable in Mozambique, contributing to food and nutritional security. Both crop varieties were selected for their adaptability to local agro-climate conditions, tolerance to drought, and potential for high yields (Chiulele, 2010; INTSORMIL, 2012).

Sample preparation and the pre-treatments, soaking, germination, and fermentation, were prepared following the Mozambican tradition. Our previous study (Nurmomade et al., 2024) includes a detailed description of the preparation; a concise summary is given here. For soaking pre-treatment, seeds were steeped in tap water at room temperature (21 ± 2 °C) for 10 min and dried. For germination pre-treatment, seeds were soaked in tap water for 24 h, drained, and spread onto germination trays. Germination proceeded for 48 h at 30 ± 1 °C in an oven. For natural fermentation, the seeds were soaked in tap water and fermented with natural microbiota at 30 ± 1 °C for 72 h in an oven. After each pre-treatment, all samples were dried in an air oven at 40 °C for 24 h and milled using a laboratory cyclone sample mill fitted with a 0.5 mm sieve. The milled samples were stored in polyethylene plastic bags at a temperature of −21±2 °C until analysis.

2.2. Porridge formulation

In this study, six composite porridges made from fermented pearl millet were selected based on the results of our previous study (Nurmomade, 2025). These composite porridges were prepared with a mix of 60 % pearl millet and 40 % cowpea (see Table 1). The selection of this ratio and the experimental setup were based on earlier studies that effectively employed similar cereal-legume combinations to develop composite porridges (Almeida-Dominguez et al., 1993; Griffith et al., 1998; Oladiran & Emmambux, 2022).

2.3. Composite porridge preparation

The composite porridges were cooked using a Rapid Visco Analyser (RVA) (Newport Scientific, Australia) to mimic traditional cooking in Mozambique. A 3 g flour sample was dispersed in 23 mL of deionised water in an aluminium canister, giving a total solid content of 11.5 % in the composite porridge. The samples were heated from 50 °C to a maximum temperature of 95 °C, held for 2.5 min, and then cooled to 50 °C using the common Standard method (Std1). The pasting properties were recorded during cooking (pasting temperature, peak viscosity, peak time, breakdown, trough, setback, and final viscosity). Immediately after RVA, the porridges were kept at approximately 40 °C to perform dynamic rheological measurements.

2.4. Rheology

Rheological properties were obtained using a DHR-3 rheometer (TA Instruments, New Castle, DE, USA) equipped with a 40 mm parallel plate geometry. Peltier plate aluminium heating was used to maintain the desired sample temperature throughout the experiment. The freshly prepared samples were loaded onto the measurement plate of the rheometer, and a thin layer of low-viscosity paraffin oil was applied to the edges of the samples to prevent evaporation. The apparent viscosity was recorded at a shear rate range of 0.01 to 100 1/s by flow sweep measurements at 40 °C. Strain sweep experiments (0.1 to 100 % strain) were conducted at 1 Hz to determine the linear viscoelastic region for the porridge samples. For frequency sweep tests, strain was kept at 1.0 % to remain within the linear viscoelastic region, and angular frequency was raised from 1.0 to 100 rad/s. All experiments were conducted at a temperature of 40 °C.

2.5. Digestible starch

Composite porridges were cooked in a RVA (Newport Scientific, Australia). Composite flour mix (3 g) was added to 23 ml of water and run using the Std1 temperature program. Immediately after cooking, approximately 0.5 g of the samples was used to analyse in vitro starch hydrolysis.

Digestible starch was quantified using the assay kit K-DSTRS (Megazyme, Bray, Ireland). The method is based on the Englyst et al. (1992) method with some modifications. Starch digestion was carried out to quantify rapidly digestible starch (RDS), which comprises the amount of starch that breaks down within 20 min; slowly digestible starch (SDS), which breaks down within 120 min, and total digestible starch (TDS), which constitutes the amount of starch that breaks down within 240 min to reflect the rate of starch digestion. Digestion was performed at 37 °C for up to 4 h with continuous mixing, according to the assay kit protocol.

2.6. Molar mass distribution

Low concentration porridge was prepared using Rapid Visco Analyser (RVA) (Newport Scientific, Australia). Composite flour mix (1.00 g) was added to 25 ml of water and run using the Std1 temperature program. Immediately when the sample was ready, a positive displacement pipette was used to transfer 1 ml of the slurry into an Eppendorf tube

Table 1
Experimental design of composite porridges.

Formulations	Pearl millet				Cowpea			
Colour code	Treatments %				Treatments %			
FMFP	Fermented	60			Fermented	40		
FMSP	Fermented	60			Soaked	40		
FMFGP	Fermented	60			Fermented	35	Germinated	5
FMSGP	Fermented	60			Soaked	35	Germinated	5
FGMFP	Fermented	55	Germinated	5	Fermented	40		
FGMSP	Fermented	55	Germinated	5	Soaked	40		

that had already been prepared with 110 µl 1 M acetic acid. It was mixed and left at room temperature for 35 min. The tube was centrifuged for 10 min at 10 000 × *g* and supernatants were filtered through a 0.45 µm nylon filter. The molar mass distribution of solubilised starch fragments was measured by high-performance size exclusion chromatography (HPSEC). The HPSEC system consisted of three serially connected columns (OHpak SB-806 M HQ, OHpak SB-804 HQ, and OHpak SB-803 HQ, Shodex, Showa Denko KK, Miniato, Japan) which were kept at 50 °C and eluted with 0.1 M $NaNO_3$ at 0.5 ml/min. Chromatograms were detected by a multi-angle light scattering detector (Wyatt DAWN HELIOS II, Wyatt Technology, Santa Barbara, CA, USA), a viscometric detector (ViscoStar III, Wyatt Technology, Santa Barbara, CA, USA), and a refractive index detector (Shodex RI 501, Shodex, Showa Denko KK, Miniato, Japan). Molecular weights and intrinsic viscosity were calculated by Astra 8.2 software (Wyatt Technology, Santa Barbara, CA, USA) based on a dn/dc of 0.147.

2.7. Statistical analysis

All analyses were carried out in duplicates, except for the molar mass distribution, which was performed in triplicate. Multivariate statistical analysis was carried out using SIMCA 17 (Sartorius Stedim Data Analytics AB). Principal component analysis (PCA) was applied to visualise overall differences among the composite porridges and to explore relationships between variables. The PCA model was evaluated using SIMCA's internal cross-validation procedure, and only principal components that contributed meaningful explanatory power were retained for interpretation.

3. Results and discussion

3.1. Pasting

The pasting properties of composite porridges are illustrated in Fig. 1. The FMSP (fermented pearl millet and soaked cowpea) exhibited the highest viscosity, whilst the FGMFP (fermented and germinated pearl millet with fermented cowpea) exhibited the lowest. The addition of germinated pearl millet contributed to a decrease in the viscosity of the porridge. The lower viscosity in FGMFP and FGMSP (fermented and germinated pearl millet with fermented or soaked cowpea) may be attributed to the presence of enzymes in germinated pearl millet. In our previous study (Nurmomade et al., 2024), germination was shown to significantly affect pearl millet starch granule morphology, resulting in numerous holes and broken starch granules after germination, probably due to the activation of enzymes. The germination process is responsible for activating enzymatic activity in the seeds and thus the breaking down of complex carbohydrates into simpler forms (Griffith & Castell-Perez, 1998; Yang et al., 2021).

In Mozambique, traditional porridges are typically high in viscosity, and when diluted with water, they can experience reductions in their

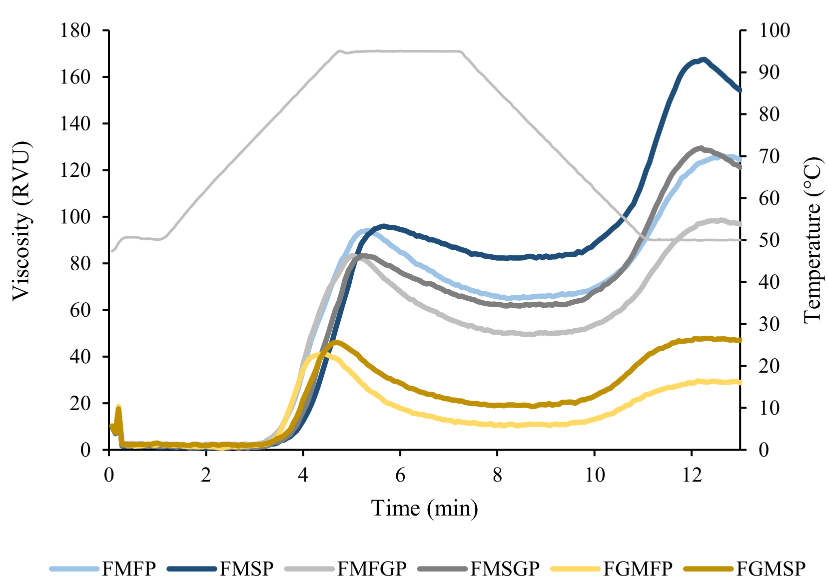

Fig. 1. Pasting properties of composite porridges (RVU = ~12 centipoises). For sample codes, see Table 1.

energy density. Thus, adding germinated flour to reduce the viscosity can be a useful strategy to increase energy density. This could be used to increase solids content and to achieve the appropriate viscosity in composite porridges for children.

3.2. Rheology

3.2.1. Flow properties

Fig. 2A illustrates the flow behaviour of the composite porridges, assessed at a total solids concentration of 11.5 % and a temperature of 40 °C. All formulations exhibited shear-thinning behaviour, characterised by a decrease in apparent viscosity with increasing shear rate. This behaviour is consistent with previous findings (Genç et al., 2002; Moriconi et al., 2023; Prakash et al., 2014; Tsai & Lai, 2021) and typical of starch-based food systems.

Among the samples, FGMFP recorded the lowest apparent viscosity of 2.3 Pa·s at a 10 s^{-1} shear rate followed by FGMSP with 3.7 Pa·s. Both porridges, which contain germinated pearl millet, consistently exhibited lower viscosity than the other formulations. This reduction is likely associated with endogenous enzyme activity, such as α-amylases, activated during germination. These enzymes hydrolyse starch, reducing its ability to form a highly viscous network during cooking (Kouakou et al., 2008; Traore et al., 2004). Our previous scanning electron microscopy (SEM) images confirmed this mechanism by showing starch granule breakdown and structural weakening in germinated flours (Nurmomade et al., 2024). This reduction in viscosity is beneficial in composite porridges because it allows higher solids content, increasing the energy and nutrient density whilst maintaining an acceptable consistency for consumption among children (Donnen et al., 1996; Makame et al., 2020; Thaoge et al., 2003; Trèche, 2001).

The ideal flow behaviour of porridge intended for consumption by children includes a moderate viscosity, shear-thinning and viscoelastic properties to ensure ease of swallowing (Cichero, 2017). Rheological characterisation of oral and swallowing conditions is commonly performed at shear rates of 1 to 100 s^{-1}, depending on the tongue movements and bolus deformation dynamics (Steele et al., 2015; Ross et al., 2019). Moreover, Steele et al. (2015) suggested that measuring apparent viscosity would provide a reasonable basis for comparison of flow behaviour at low shear rates to mimic a typical swallowing situation in a human's mouth when they are consuming liquid-like products.

Moriconi et al. (2023), suggested that shear rates between 6 and 10 s^{-1} was the most relevant for measuring foods intended for children aged

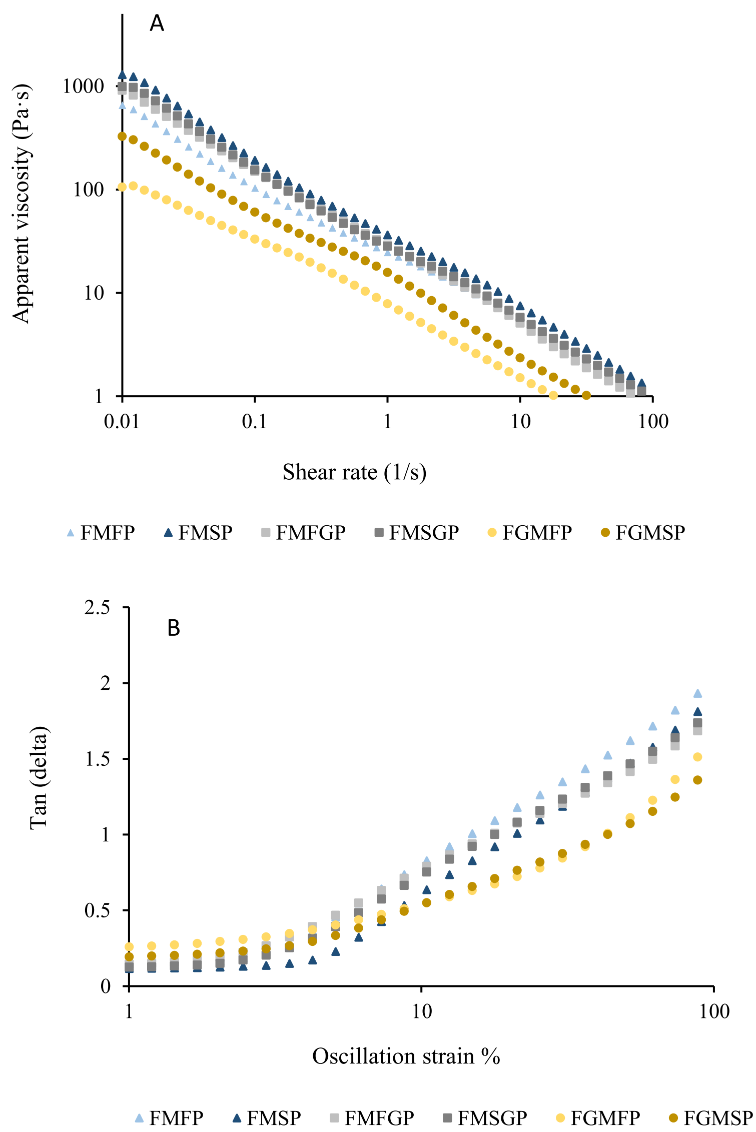

Fig. 2. (A) Apparent viscosity as a function of flow properties, (B) tan δ as a function of strain for composite porridges. For sample codes, see Table 1.

10–24 months, while Trèche (2001) assessed the viscosity of gruels for children at 83 s^{-1}. No standard guidance has been reported in the literature on the shear rate to use as a reference when investigating the apparent viscosity during the oral processing of food by children. In this study, a shear rate of 10 s^{-1} was selected as a reference condition for comparing apparent viscosity among composite porridges. This value is physiologically relevant because it falls within the lower boundary of the shear rate range commonly associated with oral-processing (~10–100 s^{-1}). Lower shear rates have been shown to correspond to the early oral manipulation stage and to sensory attributes related to cohesiveness and bolus formation (Isendahl, 2022; Makame et al., 2020; Ross et al., 2019). Furthermore, in the multivariate analysis conducted in this study (Fig. 5), apparent viscosity at a shear rate of 10 s^{-1} showed a clear and systematic relationship with the final viscosity values obtained from the RVA.

3.2.2. Strain sweep

The oscillation strain sweep of composite porridges is illustrated in Fig. 2B It represents the ratio of viscous to elastic behaviour in a viscoelastic material. At 2.5 % strain, all porridges exhibited tan δ below one, indicating that they were viscoelastic solid-like materials, balancing solid-like (elastic) and liquid-like (viscous) characteristics. FGMSP and FGMFP, both containing germinated pearl millet, had tan δ values around 0.3 at 2.5 % strain, suggesting more liquid-like behaviour compared to the other porridges. The linear viscoelastic region (LVR) occurred within approximately 2.5 % strain for all samples, indicating that the material behaves in a more elastic manner, like that of a solid. A structural breakdown of the material was observed at higher oscillation strains, and all porridge samples began to demonstrate fluid-like behaviour at higher strains.

The frequency sweep further characterises the viscoelastic properties of the developed composite porridges. The phase angle provides insights into the balance between elastic and viscous behaviour when the material is subjected to oscillatory stress, thereby serving as an indicator of its structure. A phase angle below 30° indicates more solid-like behaviour. Indeed, FMSP displayed the lowest phase angle and hence the firmest structure among all porridges. In contrast, FGMFP exhibited a higher phase angle throughout the frequency range, suggesting a softer, more deformable matrix likely reflecting the partial hydrolysis of starch during germination and fermentation, which weakens the gel network formation.

3.3. Digestible starch

The digestible starch profiles of the composite porridges are presented in Fig. 3. Approximately 60–62 % of DM was hydrolysed within the first 20 min, with minimal change observed throughout the 240 min digestion period. This indicates that all formulations were dominated by rapidly digested starch (RDS). The high proportion of RDS is likely related to the pre-treatments applied to the raw materials before porridge preparation.

Germination and fermentation processes are known to weaken and disrupt the protein-starch matrix, increasing starch swelling and enzymatic accessibility during digestion (Zhu et al., 2010). Similarly, our earlier work (Nurmomade et al., 2024) observed structural changes in germinated and fermented pearl millet and cowpea samples. Germinated samples exhibited numerous holes and broken starch granules, which became apparent after germination, likely due to amylase attack, whilst fermented samples displayed a loose matrix; these pre-treatments facilitate rapid starch hydrolysis. These effects were more pronounced in pearl millet than in cowpea, probably due to differences in starch–protein architecture.

Pre-treatments also reduce anti-nutritional factors and enhance starch digestibility. Starch digestibility is influenced by a combination of factors, including its physicochemical properties, plant seed microstructure and processing methods (Kingman & Englyst, 1994; Liu et al., 2006). Nurmomade (2025) reported that germination and fermentation lowered phytic acid levels in the same formulations and increased total digestible starch. Similar findings have been reported for pre-treated pearl millet (Eyzaguirre et al., 2006) and in fermented cereal-based baby foods (Rasane et al., 2014). Reduced phytic acid levels improve access to digestive enzymes and may contribute to the observed RDS values.

In this study, all composite porridges were classified as rapidly digestible starch (RDS), which is a beneficial attribute in foods intended for undernourished children. As noted by Weaver et al. (1995), malnourished children require foods that are easily digestible, low in viscosity, and rich in energy and nutrients to support growth. Recent evidence reinforces the nutritional relevance of consuming carbohydrate sources that provide readily available energy through processing in undernourished infants and toddlers (Cissé et al., 2025; Rodríguez et al., 2025).

3.4. Molar mass distribution

Fig. 4 presents the size exclusion chromatogram of the solubilised starch fraction extracted from the composite porridge. A confirmatory experiment with the addition of α-amylase verified that almost all polymer material in the size range shown originates from starch. Across all formulations, three distinct molecular weight populations were observed. The dashed vertical lines in Fig. 4 indicate the boundaries between these populations. The first fraction was observed with a

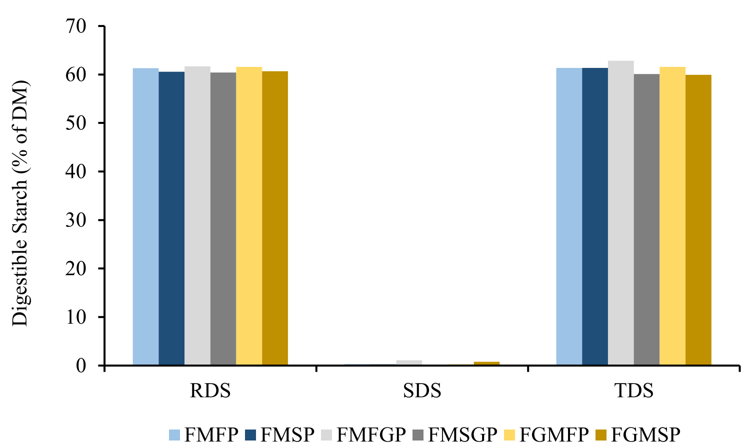

Fig. 3. Starch hydrolysis of composite porridges. For sample codes, see Table 1.

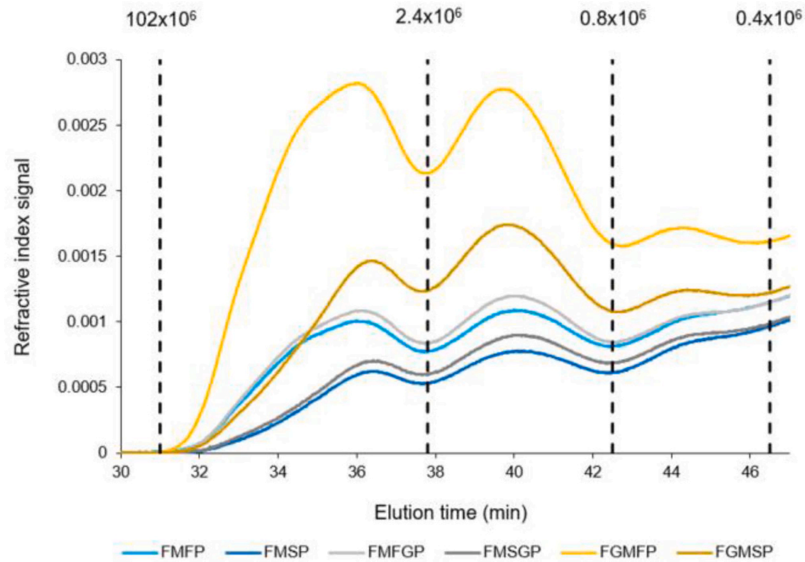

Fig. 4. Size exclusion chromatogram of the solubilised starch fraction in the composite porridge samples (molar mass in g/mol is given at four elution times). For sample codes, see Table 1.

molecular weight ranging between 2.4×10^6 and 102×10^6 g/mol. The second fraction had a molecular weight between 0.8×10^6 and 2.4×10^6 g/mol. Lastly, the third fraction eluted between 0.4×10^6 and 0.8×10^6 g/mol. The starch fractions followed an order of decreasing molecular weight from Peak 1 to Peak 3, and similarly, the polydispersity values (Mw/Mn) decreased. Quantitative parameters for all three peaks, including Mn-number average molar mass, Mw-weight average molar mass, Mw/Mn- polydispersity, $[\eta]n$- number average intrinsic viscosity, and $[\eta]$w- weight average intrinsic viscosity, are provided in the Supplementary Material (Annexure Table 1).

Polydispersity (Mw/Mn) is an important parameter for characterising the molecular weight distribution of starch; higher Mw/Mn values indicate a broader molecular weight distribution and greater polymer complexity. Formulations containing germinated pearl millet (FGMFP and FGMSP) exhibited higher polydispersity values in Peak 1 compared to other samples (Annexure, Table 1). This pattern suggests polymer fragmentation and heterogeneous polymer chain populations consistent with enzymatic starch degradation during germination. In contrast, FMFGP and FMSGP, which contained germinated cowpea, exhibited lower polydispersity values at Peak 1, indicative of less fragmentation and longer-chain molecules.

The chromatographic profiles show differences in molecular size distribution among formulations. FGMFP and FGMSP samples (yellow lines in Fig. 4), both containing germinated pearl millet, exhibited the highest concentration of solubilised starch fragments. FGMFP exhibited a broader first peak with a visible shoulder, suggesting a polydisperse population. In contrast, FGMSP displayed a sharp peak with no visible shoulder, indicating a narrow molecular weight distribution. These patterns suggest stronger starch hydrolysis activity in the samples. Although microstructural imaging was not performed in this study, previous SEM observations of germinated pearl millet samples (Nurmomade et al., 2024) demonstrated substantial starch granule breakdown. Similarly, Li et al. (2017) and Yang et al. (2021) showed that germination activates hydrolytic enzymes that breakdown complex carbohydrates into smaller and more soluble fragments.

In contrast, FMFGP and FMSGP (grey lines in Fig. 4), which contained germinated cowpea, displayed different behaviour. FMFGP exhibited a relatively narrow peak with a visible shoulder, reflecting partial heterogeneity. However, FMSGP exhibited a broad, flat peak with no shoulders, indicating more uniform molecular-weight fractions.

Interestingly, shoulders were consistently observed in porridges containing fermented pearl millet and cowpea, such as FMFGP, FGMFP, and FMFP. These shoulders likely represented a secondary population of large molecules. Similar behaviour has been reported for fermented millet and corn starch, where microbial and endogenous enzyme activity partially degraded starch polymers during fermentation (Bian et al., 2022; Yang et al., 2017).

Overall, these variations in the solubilised starch fraction among composite porridges demonstrate how different pre-treatments, such as soaking, germination, and fermentation, modulate the molecular characteristics of starch. The molecular differences observed, particularly the higher concentration of solubilised starch fragments in porridges containing germinated pearl millet, are consistent with the reduced viscosity of these porridges. Shortened polymer chains have a reduced capacity to form entangled networks during cooking, which lowers porridge viscosity. These same molecular fragments are more susceptible to enzymatic hydrolysis during digestion, contributing to the rapidly digestible starch observed in the composite porridges. Together, the molar mass profiles, rheological behaviour, and digestible starch findings reflect a shared mechanism in which germination and fermentation increase starch solubilisation and enzymatic accessibility.

3.5. PCA

Principal component analysis (PCA) was performed to illustrate the variation among composite porridge samples and to explore multivariate relationships among molar mass parameters, rapidly digestible starch (RDS), pasting behaviour, and rheological properties (Fig. 5). The first two principal components (PC1 and PC2) explained 63.5 % and 26.8 % of the total variance, respectively, and together accounted for 90.3 % of the overall variation.

The score plot illustrates clear clustering among formulations. Composite porridges containing germinated pearl millet were located on the positive side of PC1, accounting for the greater variation. On the other hand, PC2 further separated formulations according to the presence of cowpea. Composite porridges containing fermented cowpea were located on the negative side of PC2, whilst those with soaked cowpea clustered on the positive side. The explained variance can be further understood by examining the variables presented in the loading plot.

The loading plot illustrates the relationships among variables. Variables associated with the solubilised starch fractions were found at the positive end of PC1, together with phase angle at 10 rad/s and tan δ at 2.5 % strain and were well explained by it. These features reflect the

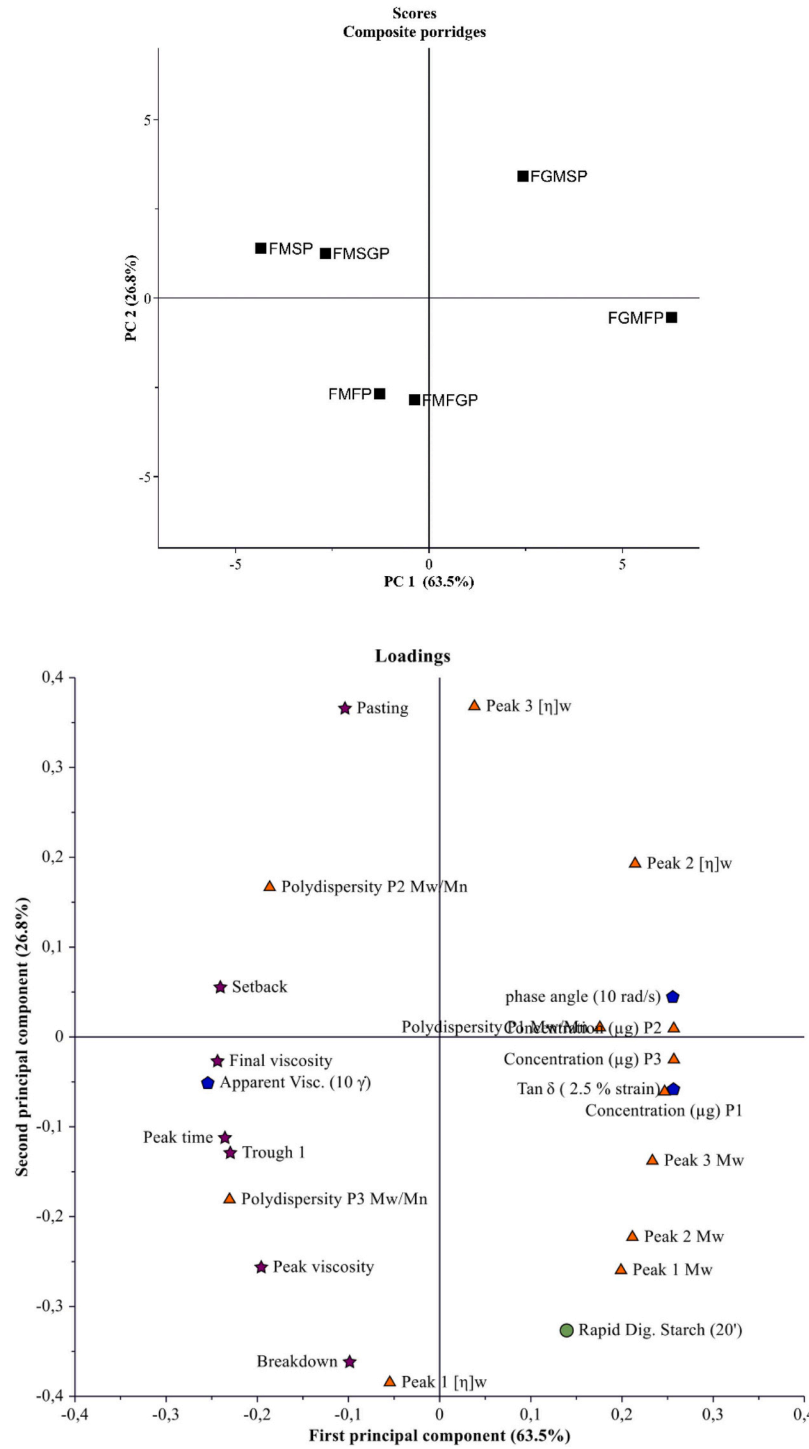

Fig. 5. Score and loading plots of the first two principal components of composite porridges. Orange represent molar mass distribution, blue rheological behaviour, violet pasting properties, and green represent rapidly digestible starch. For sample codes, see Table 1.

strong influence of germinated pearl millet in the formulations. Germination hydrolyses starch, producing more starch fragments. Both soluble and insoluble starch fractions affect porridge viscosity. The insoluble (but hydrated) starch fraction becomes smaller under pre-treatments such as germination and thus contributes less to thickening, whilst the soluble fraction, if degraded into small sugars, also significantly decreases viscosity. On the other hand, if soluble fractions are long enough to entangle may significantly increase the viscosity. In contrast, apparent viscosity at 10 s^{-1} shear rate and final viscosity were found on the negative end of PC1. Thus, porridges with hydrolysed starch fragments exhibited lower viscosity.

Along PC2, the intrinsic viscosity of Peak 1, the weight-average molar mass of Peaks 1 and 2, the breakdown value, and RDS were located at the negative end, indicating that these variables were strongly associated with formulation loaded on the negative side of PC2, these formulations, including FMFP, FMFGP, and FGMFP.

The PCA reveals that germination and fermentation systematically influenced the molecular and functional characteristics of the composite porridge. Formulations such as FMFP, FMFGP, and FGMFP demonstrated favourable functional characteristics, suggesting potential porridges for feeding children in low-income countries such as Mozambique. Further investigation is needed to explore their sensory properties and to identify the most acceptable formulation within Mozambican communities.

4. Conclusion

This study demonstrated that all composite porridges exhibited desirable properties intended for feeding undernourished children. All formulations showed shear-thinning behaviour and viscoelastic solid-like properties. Porridges containing germinated pearl millet exhibited the lowest final and apparent viscosities, measured using both a Rapid Visco Analyser and rheometer. These lower viscosities suggest that such formulations could accommodate higher solids content without compromising the acceptable viscosity suitable for children's consumption.

Porridges made from fermented pearl millet and fermented cowpea, either together or combined with germinated pearl millet or cowpea (FMFP, FMFGP, and FGMFP), showed higher concentrations of solubilised starch fragments, a secondary population of larger molecules, and higher intrinsic viscosity. All composite porridges were classified as rapidly digestible starch (RDS), with 60–62 % DM hydrolysed within 20 min, indicating high starch accessibility and rapid energy availability.

Overall, the findings demonstrate that low-cost pre-treatments can modulate the rheological behaviour, molecular characteristics, and digestible starch profile of composite porridges. These processing strategies may support the development of nutrient-dense, easy-to-swallow composite porridges suitable for feeding undernourished children in Mozambique and other low-income countries facing similar challenges.

4.1. Limitations

This study had certain limitations, as enzymatic activity (e.g., α-amylase levels) was not directly measured. Future research should examine energy density and maximum solids tolerance to better translate rheological findings into practical feeding recommendations.

Declaration of generative AI in scientific writing

During the preparation of this work, the authors used Grammarly in order to improve text clarity. After using this tool/service, the authors reviewed and edited the content as needed and take full responsibility for the content.

Ethical statement

The authors declare that the study has not involved humans or animals

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CRediT authorship contribution statement

Sunera Zulficar Nurmomade: Writing – original draft, Visualization, Investigation, Formal analysis, Conceptualization. **Janicka Nilsson:** Writing – review & editing, Methodology, Data curation. **Irene De Carvalho:** Writing – review & editing, Supervision. **Maria Eduardo:** Writing – review & editing, Supervision. **Santanu Basu:** Writing – review & editing, Validation, Supervision, Methodology, Formal analysis, Conceptualization. **Roger Andersson:** Writing – review & editing, Visualization, Validation, Supervision, Data curation, Conceptualization.

Declaration of competing interest

The authors declare no conflict of interest.

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.afres.2025.101625.

Data availability

Data will be made available on request.

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