Research Journal of Food Science and Quality Control (RJFSQC) E-ISSN 2756-5483
P-ISSN 2695-2459 Vol 9. No. 2 2023 www.iiardjournals.org

The Effect of Pre-Treatment in the Development and Quality Attributes of Extrudates from Nigerian Pigeon Pea

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DOI: 10.56201/rjfsqc.v9.no2.2023.pg111.125

Abstract

Consumption of pigeon pea, a drought tolerant legume with adequate nutritional composition has been limited due the prolonged time required during cooking. With high production capacity, the transformation of this crop into a ready to eat extruded snacks would increase its consumption while strengthening Nigerian food processing industries. Through this research driven innovation, a long shelf life extruded snacks from 100% whole pigeon pea (a legume) were developed following the use of native and pre-treated seeds as extrusion feed materials. The pre-treatment involved a short time hydrothermal treatment at 90 ^{0}*C and alkaline treatment with 0.5% sodium bicarbonate which targeted hydration of starch and cell wall degradation. The extruded snacks were produced at a high temperature of 140* ^{0}*C and short time (22 seconds) using co-rotating twin screw extruder which extrusion conditions influenced the quality characteristics of the expanded snacks. The sectional expansion index (SEI) significantly (P<0.05) increased from 1.09 in NNPHME (extrudate from high (22%) moisture native pigeon pea) to 3.42 in BBE (extrudate from dry (11% moisture content) milled alkaline treated pigeon pea) while the bulk density (BD) decreased mostly in BBE. The peak viscosity ranged from 168 cP in NNPHME to 1661 cP in BBHME (extrudate from wet (22% moisture content) milled alkaline treated pigeon pea). The cold water viscosity, an indication of starch gelatinised during extrusion increased greatly to 849.33 cP in BBE compared to 36.66 cP in native non-extruded pigeon pea. Hence, the expansion, textural and pasting properties of extrudates from treated feeds was improved compared to extrudates from non-treated feeds. Considering the good quality attributes of some of the extruded snacks such as expansion ratio, bulk density, textural characteristics and long shelf-life, it would be recommended as fast-moving consumer goods to industrialists.*

***Keywords**: Extrudates, Hydration, Pigeon Pea, Expansion and Starch*

1 Introduction

Pigeon pea is a drought-tolerant legume mainly eaten in Nigeria as a protein rich food (protein alternative). The nutritional composition of whole dry seed of pigeon pea consists of protein:18.8%, starch: 53%, fat: 1.9% (majorly unsaturated fats), crude fibre: 6.6% and soluble sugar: 3.1% (Saxena *et al*., 2010). Within the starch content, about 60% are resistant starch thatdiffers digestion. Similar to other legumes, the high content of the resistant starch and the dietary fibres lowers glycaemic index and results to prevention of digestive and coronary diseases.

Despite the health benefits, many factors have limited processing of pigeon pea at domestic and industrial level. For it to be safe to eat and acceptable as a nutritious and quality product, it requires extensive heat treatment. This is because like other legumes, the pigeon peas seed is hard to hydrate. Hydration is essential for food applications and to negate the potential of the anti-nutritional factors that occur in this seed and to increase the digestibility of nutrients. If the seed is not adequately hydrated, then extensive thermal processing is required, and this uses extensive energy and can cause a negative impact on the material that is hydrated. The major chemical components of pigeon pea; starch, non-starch polysaccharides and protein need hydration for adequate cooking before consumption.

This difficulty in hydration and softening of pigeon pea seeds during cooking results to phenomenon generally referred to as the “hard to cook defect.” The hard to cook (HTC) defect is a textural defect developed by legume seeds during post-harvest storage and exhibited during cooking in which the seeds are hard to hydrate and cotyledon cells fail to separate. This defect could lead to a delay in starch gelatinisation, protein denaturation, softening of seed, an increase in cooking time and seed hardness when compared to the fresh seed. Cooking would normally be associated with the loss of starch native structures. As the gelatinisation of starch (starch conversion) is influenced by moisture, temperature and shear, these critical factors influences starch functionality during processing and subsequent digestion (Aguilera and Rivera, 1992).

Due to the thermoplastic properties of starch, in which starch crystalline structures can melt and soften when heated and hardened on cooling, varieties of ready-to-eat snacks from starch-based crops could be developed. A process method to achieve this is by thermo-mechanical extrusion, a short time (5-200 second) continuous cooking at high pressure (above the vapour pressure of water) that combines moisture (10-25%), high temperature (above 100 °C) and mechanical shear (250-500 rpm screw speed) for the development of uniform food products, especially expanded (puffed) snacks and textured foods. Generally, this food processing technique referred to as high temperature short time cooking (HTST) and is carried out using an extruder. It is an efficient low-cost production technique involving mixing, shearing, cooking and forming (Moraru and Kokini, 2003; Moscicki and Zuilichem, 2011; Robin*et al*., 2014). Extrusion products are enriched with nutrient and bioavailability of nutrients. It significantly increased *in vitro* starch digestibility of extrudates (Altan *et al*., 2009). Through extrusion cooking, materials of different components could be blended as feed and use in the production of varieties of ready to eat products.

Many Nigerian authors have undergone studies on the use of blends from cereals, legumes, tubers and vegetables to produce locally extruded ready to eat snacks. These extrusion feed blends include: African yam bean, pearl millet and tigernut (Sotunde *et al*., 2021); millet-cowpea based Fura (Filli *et al*., 2012); cassava and sesame (Olorode and Sobowale, 2021); sorghum and charamenya (Eze *et al*., 2020); yellow maize, soybean and amaranth leaf flour (Nkesiga and Okafor, 2015), bambara groundnut, cassava starch and corn bran (Ogunmuyiwa *et al*., 2017); whole millet, African walnut and corn starch (Sobowale *et al*., 2021a). Their reports show that extrudates were formed at temperature of 70 to 170^{0}C using different branded extruders configured as bench-top and single screw in addition to locally fabricated extruders (Filli *et al*., 2012; Eze *et al*., 2020). It could be possible that prolonged conventional processing of pigeon pea grain through overnight (12h) soaking (hydration) and cooking period (2-3h) could be reduced through high temperature short time extrusion cooking. Therefore, extrusion of 100% whole pigeon pea (pigeon pea with all components intact including seed coat) would be a great innovative snack with high prospect in terms of its nutritional benefits and value addition to pigeon pea. The extrudates when produced would contribute greatly to higher utilisation of pigeon pea (drought tolerant legume pulse) in the food industry for achievement of Nigerian food security.

Since there is paucity of evidence on the successful extrusion of 100% whole pigeon pea, this study explored the functionality of native and pre-treated Nigerian pigeon pea and applied it in the production of quality extruded ready to eat snacks products.

It has been suggested that twin-screw extruder has operational efficiency, degree of mixing and ability to handle the different combinations of food material (Sobowale *et al* 2021b). Depending on the formulation of extrusion blends and some extrusion conditions with critical effects on the quality of the extruded products (extrudates) such as die diameter, extrusion temperature, feed moisture, feed rate, screw configuration and screw speed have to be monitored and adjusted. However, quality control parameters for the evaluation of the extruded products attributes would include expansion ratio, bulk density, hardness and pasting properties that measures the degree of cook of starch (starch gelatinisation).

2 Materials and methods

2.1 Pre-treatment and production of extruded products

The pre-treatment was a hydrothermal treatment (HTT) chosen for the hydration of the seed at 90 °C for 5 min in a jacketed vessel with continuous stirring. Following the hydration treatment, the hydrated seeds had increased in moisture to 22% and then were wet milled (HTTHME) after cooling in the cooled jacketed vessel and used directly as the extruder feed. To obtain the low moisture feed from HTT, the hydrated 22% moisture seeds were then dried at 50 °C and dried milled. The resulting powder (HTTE) had a moisture content of 11% dwb (dry weight basis) and this was used directly as dry feed. No further water was added in the barrel during extrusion.

In the last batch of the feed preparation, the seeds had undergone the HTT to hydrate and soften the seed components, but to enhance cellular disruption, the hydration occurred in 0.5% sodium bicarbonate (alkaline) solution with an increase in the seed moisture content to 22%. Like the previous HTT, some portion of the hydrated (22% moisture content) seed in the sodium bicarbonate (alkaline) solution were wet milled (BBHME) while the other (BBE) was dried to 11% moisture content and then milled.

The extrusion was carried using co-rotating twin screw extruder (Prism TSE 24 MC,Thermo Scientific, Germany) at 140 ^{0}C under screw speed of 200-250 rpm (high sear rate), residence time of 4 min, die of 4 mm diameter and 5 cm length, screw length/diameter ratio of 40 (diameter: 22.5 mm, length:980 mm), motor power 5.5 kW and output 50 kg/h . The extrudates produced were formulated from six feed blends (batches) shown in Table 1. The feed blends include native and pre-treated pigeon pea as the ground native pigeon pea powder seemed difficult to hydrate within the time frame of the extrusion (the short residence time of 22 secs).

Table1: Feed formulations used in production of pigeon pea extruded products

Sample	**Non-treated native pigeon pea (NPP)**	**Hydrothermal treatment (HTT)**	**Alkaline treatment with bicarbonate (BB)**	**Wet (W)/ Dry (D) milling**	**Moisture content of the feed (% DWB)**	Moisture (%) addition in the barrel
NPPHME	Yes	No	No	D	11	Yes
NPPE	Yes	No	No	D	11	No
HTTHME	No	Yes	No	W	22	No
HTT	No	Yes	No	D	11	No
BBHME	No	Yes	Yes	W	22	No
BBE	No	Yes	Yes	D	11	No

NPPHME: extrudate from high moisture (22% MC) native pigeon pea, NPPE: extrudate from (11% MC) native pigeon pea, HTTHME: extrudate from wet (22% MC) milled HTT treated pigeon pea, HTTE: extrudate from dry (11% MC) milled hydrothermally treated pig`1eon pea, BBHME: extrudate from wet (22%MC) milled alkaline treated pigeon pea, BBE: extrudate from dry (11% MC) milled alkaline treated pigeon pea.

2.2 Quality control analysis of pigeon pea extrudates

The parameters used for the evaluation of the extruded products qualities includes expansion ratio, bulk density, shear strength (measured with texture analyser) and pasting properties determined through a viscosity profile of a Rapid Visco Analyser (RVA) that measure the degree of cook of starch (starch gelatinisation).

2.2.1. Extrudate expansion properties

2.2.1.1 Extrudate bulk density

The bulk density of extrudate was determined by method of Lazou and Krokida (2010) using equation (1). The density was calculated as mass (g) per unit volume. Assuming the extrudate with cylindrical shape and volume as $(\pi d^2 l/4)$, the diameter (d) and length (l) were measured with digital vernier caliper(Mitutoyo, Japan)while its mass was measured with an analytical balance.An average of 10 replicates was measured.

Bulk density (g/cm^3) =4m/ ($\pi d^2 l$) (1)

2.2.1.2 Extrudate sectional expansion index (SEI)

The sectional expansion index (SEI) of the extrudate was obtained with the method of Alvarez *et al* (1988) and Lazou and Krokida (2010) by dividing the cross-sectional diameter of the extrudate with the diameter of the die. The cross-sectional diameter was determined as the average of 10 replicate measurement of a roughly 10 cm extrudatewith a digital vernier caliper (Mitutoyo, Japan). The results were obtained using equation (2).

$$\text{Sectional expansion index} = \frac{\text{cross sectional diameter of extrudate}}{\text{diameter of die}} \qquad (2)$$

2.2.1.3.Extrudate specific mechanical energy

The specific mechanical energy (SME) of the extrudate was calculated using the equation (3) described by Lai and Kokini (1991).The SME is the energy provided by the motor drive to the extruding material in the extruder per unit mass.

$$\text{SME (Wh/kg)} = \frac{\text{screw speed (rad s}-1)*\text{torque (Nm)}}{\text{feedrate}\left(\frac{\text{kg}}{\text{h}}\right) \quad *2} \qquad (3)$$

Screw speed in rad $^{s-1}$ = screw speed in rpm * $2\pi/60$

2.2.4 Texture analysis of the extrudate

The extrudate texture was measured according to the method described by Ding *et al* (2006) and Da silva *et al* (2014). The texture of the extrudate was measured as the maximum peak deformation force. It is the maximum force required for the cylinder probe to penetrate the extrudate and relates to the sample hardness, hence imitating the force required for human mastication (chewing). The test was carried out with a Texture Analyser, (TA.XT Plus, Stable Micro System, Surrey UK) fixed with a 30 kg load cell and a cylindrical probe of 2 mm diameter. The cylindrical probe was programmed to approach the extrudate at 1 mm/s and on detection of the snacks' surface, penetrated 60% of the cross-sectional diameter (cross sectional diameter was set at 2 mm for less expanded products another 3 mm was used for highly expanded extrudates) at 1 mm/s test speed. Finally, the cylindrical probe returned to its initial position at 10 mm/sec (post speed). The degree of deformation and fracture is shown in the test profile curve as force (N) distance (mm) curve and it represents the deformation force.

2.2.4 Extrudate pasting properties

The pasting characteristics of the extrudates were determined using Rapid Visco Analyser super 4 models by Newport Scientific Ltd, Australia. The protocol was modified from Carvalho and Mitchell (2001) to detect cold water viscosity. The profile applied consisted of a starting temperature of 25 °C which was kept constant for 5 min before it was raised to 95 °C in 4min, kept constant at 95 °C for 2 min, decreased to 25 °C in 4min and finally kept at this temperature for 5min.

Ground extrudate 5 g (dry basis) was weighed into canisters and was solubilised with 2 ml-100% absolute ethanol to prevent lump formation. The mixture was made up to 28 g with deionised water. Each sample was prepared and analysed in triplicate and the results of cold water viscosity was determined at 5 min of the starting time followed by the peak viscosity at 10 min of the pasting period. All values were mean of triplicate analysis.

The measured cold water peak viscosity of the extrudate is an indication of starch gelatinisation during the extrusion processing. It is expected that the cold water viscosity of the extrudates will increase if the degree of cook (gelatinisation) during the extrusion increases and then decreases at higher pasting temperature due to granular rupture and dextrinization. However, if the extrudate final viscosity from the pasting profile is higher, it will indicate that lower gelatinisation of starch occurred during the extrusion.

Statistical method

The significant difference ($P<0.05$) of the mean of all the data generated during this study was assessed using two-way Anova (multivariate) under General linear model of IBM SPSS statistics 24 software. Following the analysis of variance, the mean values were compared and separated into letter (alphabets) subscripts using Tukey *post Hoc* test.

3 Results and Discussion

The qualities attributes of extrudates produced from the 100% whole pigeon pea were evaluated based on their expansion ratio, swelling index, textural and pasting properties.

3.1 Extrusion responses of pigeon pea extrudates

The extrusion responses in Table 2 shows that at higher moisture content (22%), the torque required to rotate the screw and the feed decreases and consequently there is a lowering of the SME. In contrast, at low moisture extrusion of both treated and non-treated materials, the increase in torque increased the SME. An indication that as the workload increases on the screw, the torque also increases.

Table 2: Extrusion conditions and responses

Sample	Temp (°C) of barrel last zone	Torque (Nm)	Pressure (Bar)	Melt temp	SME (Wh/kg)
NPPHME	120	19	34	158	28
NPPE	121	53	21	70	79
HTTHME	120	23	8	63	34
HTTE	123	52	21	66	77
BBHME	120	25	23	76	37
BBE	132	68	23	67	101

NPPHME: extrudate from high moisture (22% MC) native pigeon pea, NPPE: extrudate from (11% MC) native pigeon pea, HTTHME: extrudate from wet (22% MC) milled HTT treated pigeon pea, HTTE: extrudate from dry (11% MC) milled hydrothermally treated pig`1eon pea, BBHME: extrudate from wet (22%MC) milled alkaline treated pigeon pea, BBE: extrudate from dry (11% MC) milled alkaline treated pigeon pea.

The extrusion of the low moisture alkaline treated feed (BBE) showed the highest torque in contrast to high moisture extrusion at the same constant feed rate of 8 kg/h, higher temperature (120 °C) and screw speed (400 rpm. With these results, it seems that the torque depends on modifications of the viscoelasticity of the extruding material as it changes from solid elastic material to rubbery-liquid. This is in agreement with Filli *et al* (2012) and Singha *et al*.(2017) in an extrusion of high protein-fibre feed material, where an increase in moisture content decreases the torque.

3.2 Sectional expansion index and bulk density

The sectional expansion index (SEI) depicted in figure 1 significantly (P<0.05) increased from 1.09 in NNPHME to 3.42 in BBE while the bulk density (BD) decreased mostly in BBE. As shown in Figure 1, the expansion properties of extrudate from treated feed were improved compared to extrudates from non-treated feed. The degradation of rigid-insoluble polysaccharide (hydrocolloids) of the pigeon pea seed coat through the chemical treatment with sodium bicarbonate and hydrothermal treatment may have improved starch hydration.

Degraded hydrocolloids (cold-water soluble hydrocolloids) from the pigeon pea seed coat mucilage (non-starch polysaccharides) may have enhanced the volume expansion of the extrudates from treated feed. It was reported that soluble seed coat mucilages can improve texture, appearance and stability of food products (Liu *et al.*, 2021).

Wagner *et al*. (2023) observed that the expansion ratio (ER) of extrudate from native corn starch reached a maximum of 3.73 with a 2.5% tamarind seed gum (TSG) level when extruded at 150 rpm ($p < 0.05$). From this reported observation, small inclusions of TSG can improve the direct expansion properties of starch, whereas larger inclusions result in a lubrication effect that mitigates the shear-induced depolymerization of starch.

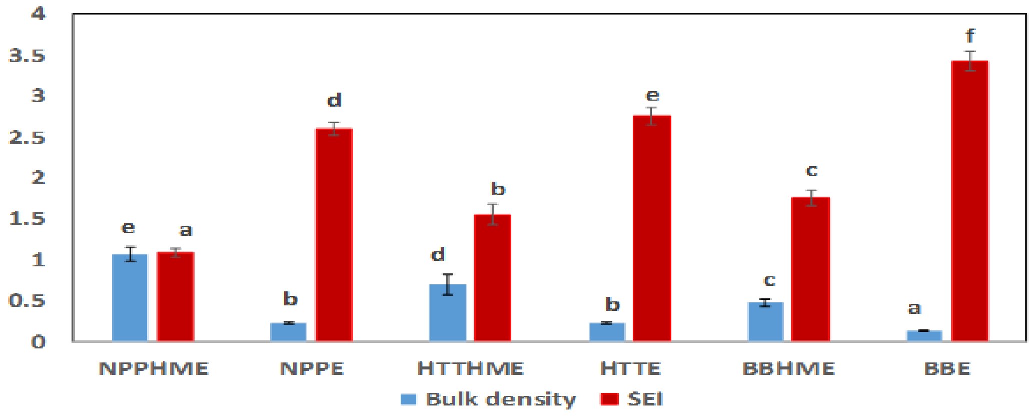

Figure1: Expansion properties of extrudate from treated feed
The columns are mean value of ten replicates. The error bar represents the standard deviation while the column with different letters are significantly different ($P<0.05$).

(SEI: Sectional expansion index, BD: Bulk density, MC: Moisture content).
NPPHME: extrudate from high moisture (22% MC) native pigeon pea, NPPE: extrudate from (11% MC) native pigeon pea, HTTHME: extrudate from wet (22% MC) milled HTT treated pigeon pea, HTTE: extrudate from dry (11% MC) milled hydrothermally treated pig`1eon pea, BBHME: extrudate from wet (22%MC) milled alkaline treated pigeon pea, BBE: extrudate from dry (11% MC) milled alkaline treated pigeon pea.

In addition to result in Figure 1, the image of NPPHME (extrudate from high moisture untreated feed) in Figure 2A indicates that the extrudate size is similar to the size of the extruder die. The low SEI and high BD are evidence of limited starch conversion during the extrusion cooking due to high moisture content feed. High moisture extrusion feed acts like lubricant and reduces the production of superheated steam necessary for expansion during flash vaporisation (Mishra *et al*., 2014). Ditodumpo *et al*. (2016) has shown that increasing the feed moisture content resulted in increase in bulk density and decrease in porosity and expansion ratio ($p < 0.05$) of extruded corn starch. Usually, extrudate such as NNPHME is termed a half product as it requires a second heating or cooking process for the starch crystalline structure to be fully melted and sufficient starch conversion to occur to achieve product expansion.

Sometimes, extrudate made from high protein and insoluble fibre material could shows restricted expansion due to inhibition of gelatinisation.This implies that higher proportion of protein and fibre breaks the cell walls and prevents the formation of air bubbles and maximum expansion (Altan *et al*., 2009). This feature can be remedied if additional starchy material is included in the feed blend (Osibanjo *et al*., 2022). Therefore, it is important to determine the properties of flours of different varieties when selecting feed materials for extrusion processing as it affects the development of direct-expanded products (Ek *et al*., 2021).

The Pigeon pea extrudate can be considered a complex extrudate due to the basic components which consists of starch (45%), protein (20%) and fibre (26%). It is expected that the non-starch components, when not-treated, would act as a diluent and will influence the expansion. Although the hydrothermal and the drying treatment that follows made no difference to the expansion of HTTE compared to NPPE but considerable differences were observed in SEI and BD after alkaline treatment in extrudate BBE.

Figure2: A-C: extrudates from high moisture (22%) feed (A) non-treated: NNPHME (B) hydrothermally: HTTHME and (C) alkaline treated: BBHME, D-F extrudates from low moisture (11%) feed (D) non-treated: NPPE, (E) hydrothermally: HTTE and (F) alkaline treated: BBE

Since, the expansion properties of starch based extrudate is related to the extent of starch conversion, extrusion of the alkaline (sodium bicarbonate) treated feed material at low moisture content seems to increase the starch conversion which favours increase in SEI and decrease in BD. It was stated that addition of sodium bicarbonate to bean flour feed was effective in increasing expansion ratio to two-fold. The mechanism of expansion by sodium bicarbonate in the bean flour extrudate was attributed to the numerous air cells created by the evolution of CO_2 from sodium bicarbonate at temperature higher than 100 °C. Sodium bicarbonate which acts as a nucleating agent enhances expansion, creation of air cells and swelling of melt on exit the extruder (Navale *et al*., 2015). Contrasting effects of the expansion of extrudates following sodium bicarbonate treatment of extrusion feeds has been reported. The effect of sodium bicarbonate in wheat flour extrusion was observed to have uneven influence on bulk expansion properties (Robin *et al*., 2010).

Two major phenomena are known to control expansion at die exits. They are expansion through vapour flash-off and by die swell. The die swell, which is more prevalent in synthetic extrusion, occurs due to elastic recovery of deformation on the extruding melt. In food, it is a characteristic of melts with low gas bubble units and those occurring at lower temperature (approximately 100 °C) that prevents the flash-off of vapour. If a product swells at the die, to hold the expanded form, the product must regain a stable state whilst expanded. For biopolymers, this normally means loss of water acting as the plasticiser, and lowering of temperature so the product changes from a rubbery material into the stable glassy state.

Sample	Cold-water viscosity (cP)	Peak viscosity (cP)

3.3 Pasting properties of extruded pigeon pea snacks

The extrudate (BBE) produced from alkaline treated feed developed high cold peak viscosity in Figure 3 following the high starch conversion from the extrusion feed with high degree of cell wall degradation. A high cold-water viscosity at 25 °C, 5 min, low hot peak, high breakdown and low setback viscosities were exhibited by extrudate BBE created with low moisture (11%) bicarbonate and hydrothermal treated feed. This type of viscosity profile is often an indication of starch without crystalline structure especially where the starch was converted through extrusion cooking. The high breakdown shows the instability of the paste due to breakdown and disrupture of swollen granules while the reduced setback indicates lesser affinity to retrogradation (Wani and Kumar, 2019; Munoz-Pabon *et al*., 2022)

NPP (native-non extruded pigeon pea flour suspension) without any measurable cold-water viscosity, exhibited high hot peak viscosity (Figure 3), following the gelatinisation of starch during pasting as expected for a product containing native starch. It is only starchy material with high water absorption capacity that enables starch granules to swell into higher hot peak viscosity when heated during pasting (gelatinisation) due to their higher accessibility to water (Okpala *et al*., 2020). The absence of cold water peak viscosity in native pigeon pea is attributed to non-hydrothermal treatment. Cold water peak viscosity profile expresses the presence of gelatinised starch which had occurred during the primary cooking stage of the starchy material.

As a legume, the native pigeon pea flour (NPP) was predominated with high level of resistant starch which couldn’t easily disrupt during pasting heating and shearing except with extrusion shear. This resulted to minimal breakdown viscosity as shown in Fig 3 compared with BBE which displayed high breakdown viscosity profile after extrusion cooking. The impact of high extruder’s screw speed in increasing the instability of starch that leads to high breakdown viscosity has been confirmed (Mitrus *et al*., 2020).

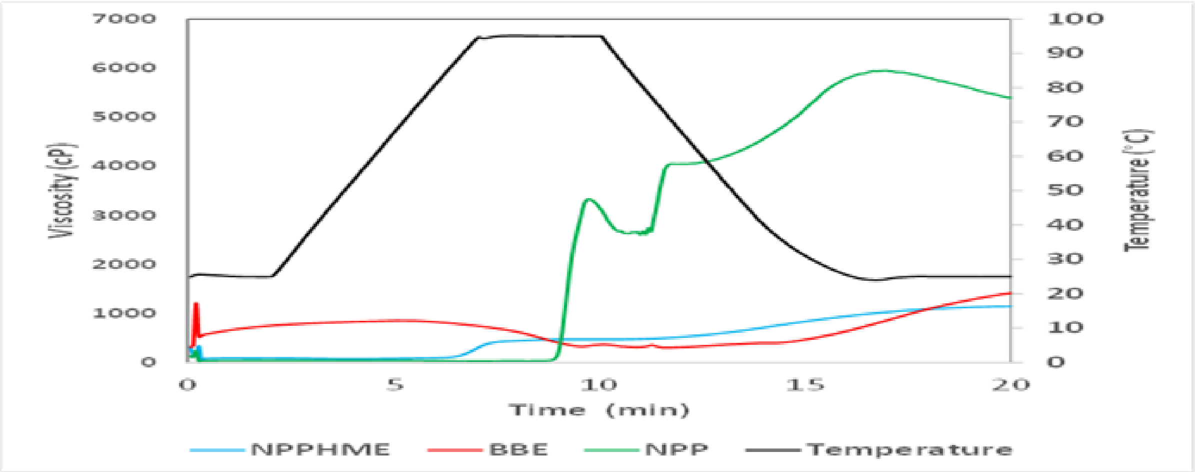

Figure 3: Pasting profile of native pigeon pea (NPP), extrudates from high moisture non-treated native pigeon pea (NPPHME) and low moisture alkaline treated (BBE) feed.

Table 3: Effect of treatment on cold water and peak viscosities

NPP	36.66±2.49^{a}	3162.33±17.13^{e}
NPPHME	75.66±1.24^{a}	467.66±14.57^{b}
NPPE	441.33±13.02^{b}	168.33±8.5^{a}
HTTHME	3195±41.73^{d}	1069.60±14.04^{c}
HTTE	811.33±42.08^{c}	494.66±34.64^{b}
BBHME	899.66±10.47^{c}	1661.66±13.59^{d}
BBE	849.33±12.81^{c}	357.66±6.42^{ab}

NPPHME: extrudate from high moisture (22% MC) native pigeon pea, NPPE: extrudate from (11% MC) native pigeon pea, HTTHME: extrudate from wet (22% MC) milled HTT treated pigeon pea, HTTE: extrudate from dry (11% MC) milled hydrothermally treated pig`1eon pea, BBHME: extrudate from wet (22%MC) milled alkaline treated pigeon pea, BBE: extrudate from dry (11% MC) milled alkaline treated pigeon pea.

In extrudate NPPHME produced from untreated feed with high moisture, the maximum swelling known as peak viscosity valued at 467 cP occured during the pasting phase at the highest (peak) regime temperature of 95 °C. Its pastingviscosity curve in Figure 3 shows no cold-water peak throughout the pasting cycles. Already, from previous assessment of sectional expansion index (SEI) and bulk density (BD), NPPHME has been identified as an extrudate with high levels of non-gelatinised starch and therefore has very limited starch conversion. It could be expected that this non-converted starch would hydrate and impact on the viscosity during the RVA pasting. However, the poor hydration of the extrudate from untreated pigeon pea may indicate that the components (starch, protein and fibre) are unable to swell highly as they are entrapped in the matrix. This behaviour in which the presence of fiber or bran inhibits starch gelatinization has been confirmed (Wani and Kumar, 2019; Okpala *et al*., 2020; Tensiska *et al*., 2021).

Though NPPE extrudate was produced with non-treated pigeon pea feed at low moisture (11%), it displayed some cold water peak viscosity lower than treated feeds. Probably, the frictional force and vapour pressure due to extrusion at low moisture content permits the degradation of starch granule and disrupture of crystalline structure.

Sample HTTHME created using high moisture (22%) in the extruder with the hydrothermally treated feed still shows an increase (two-fold) in cold water viscosity (3195 cP) despite the HTTE having a far greater SME. It does appear that the normal expectation of breakdown of all structures of pigeon pea in the extruder for the samples to be easily hydrated in post extruder was met by HTTHME. The balance for the thermal and shear breakdown of the starch seems to be confounded by the other materials within the cotyledon. These other materials in pigeon pea which have undergone hydration and then extrusion seem to be resilient to expansion and hydration. It would be possible to create a product such as HTTE even if it will not be readily expanded, but should show more cold water hydration or viscosity so it would serve well as cold gruel without further heating.

As starch granules pass the different stages of extrusion, both in the barrel and in the die, its mode of conversion differs. At low temperature zone of the barrel even with much kneading, native starch may be protected and co-exist with the molten starch. Similar mixtures of fully converted starch can interact with much degraded starch as the SME increases from the shearing process. Therefore, the variations from the co-existence of starch in different structural and molecular levels (native, gelatinised and degraded) affected all the extrudate pasting behaviour (Ozcan and Jackson 2005).

With this pasting behaviour of pigeon pea, it can be confirmed that only starch conversion in BBE with high cold water viscosity, low hot peak viscosity and higher SME (> 130 Wh/kg) can cause an increase in sectional expansion index and be available for consumption as ready to eat snacks.

3.4 Extrudate textural properties

The distribution of peak deformation force as shown in Figure 4 was used to evaluate the textural properties of the extrudates from treated and non-treated feed. The deformation force measures the force required by the testing probe to penetrate into the interior cells of the extrudate from exterior surface. The hardness of expanded extrudate is a perception of the human being and is associated with the expansion and cell structure of the product (Shruthi *et al*., 2019). It corresponds to the force required for the chewing and biting of the products.

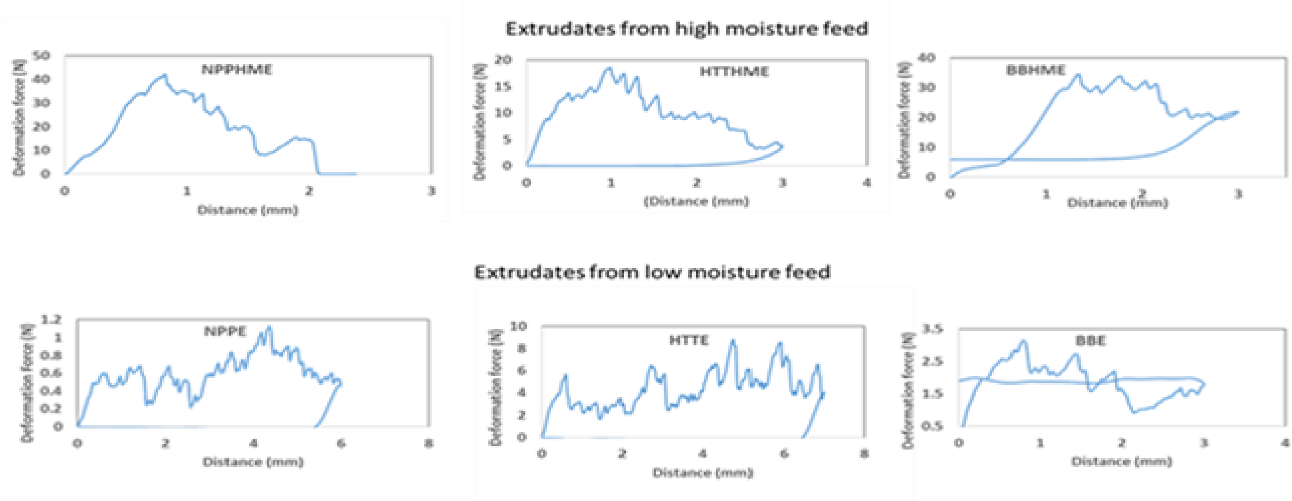

Figure 4: Extrudate deformation force (chewing force)

NPPHME: extrudate from high moisture (22% MC) native pigeon pea, NPPE: extrudate from (11% MC) native pigeon pea, HTTHME: extrudate from wet (22% MC) milled HTT treated pigeon pea, HTTE: extrudate from dry (11% MC) milled hydrothermally treated pig`1eon pea, BBHME: extrudate from wet (22%MC) milled alkaline treated pigeon pea, BBE: extrudate from dry (11% MC) milled alkaline treated pigeon pea.

Surprisingly, HTTHME with the highest cold-water viscosity recorded the highest peak deformation force of 35.57 N (more hardness) compared to samples with lower cold-water viscosities. Although it is expected that the initial high cold water viscosity which relate to high starch conversion would result to low deformation (low hardness) but the low formation of air cells due to reduced super heating of high water feed impacted high deformation force.

Earlier, during the assessment of physical features of HTTHME, the presence of thick cell walls and coalesced cellular structures were observed.Normally, starch conversion influences viscoelastic properties of the melt and mechanical properties of extrudates. High puffing of feed material would result to high volumetric expansion and creation of more air bubbles which is related to low hardness (Jia *et al*., 2021). However, with this result of HTTHME, it seems that the type, size and shape of the extrudate cellular structures (cells and cell wall) mostly affect peak deformation force rather than the extent of starch conversion. However, increase in hardness occurs in extrudate made from high fibre and high protein feed material due to reduced expansion (Kaushal *et al*., 2019; Munoz-Pabon *et al*., 2022).

Shruthi *et al*. (2019) observed that high extrusion temperature (130 ^{0}C) and low moisture content (17.5%) feed decreased the hardness of corn-based-pigeon pea snacks due to more bubble formation which is easy to disrupt during penetration of textural analysis testing cylindrical probe. This report confirms the low deformation force (2.5 N) of BBE with highest extrusion temperature which is related to high crispy texture of the snack.

4 Conclusion

But to optimise pigeon pea extrusion cooking and obtain more stable products, the thermomechanical extrusion was best carried out with low moisture (11%) treated feed material. With these conditions, the expansion properties of extrudate from treated feed improved compared to extrudates from non-treated feed. As a good indication that less force is required during chewing/biting of this extrudate, a low deformation peak force was obtained when puncturing these extrudates (NPPE, HTTE, and BBE) from low moisture feed. At the low moisture extrusion, especially as it pertains to treated feeds, the more the extrusion cooking solubilises and degrades the melt components (starch, protein and fibre), the more the extrudate sectional expansion index increases. The low bulk density of extrudate from sodium bicarbonate treated feed (BBE) would offers both the manufacturer and consumers the convenience in handling.

Acknowledgement

I appreciate the PhD scholarship funding received from NigerianTetfund through which this research was sponsored. Also, my profound gratitude goes to Prof Emeritus Sandra Hill for her supervision and to all research associates and technical staff, Department of Food Science, University of Nottingham UK where this study was carried out between 2013-2017.

Conflict of interest

There is no conflict of interest among the contributors

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