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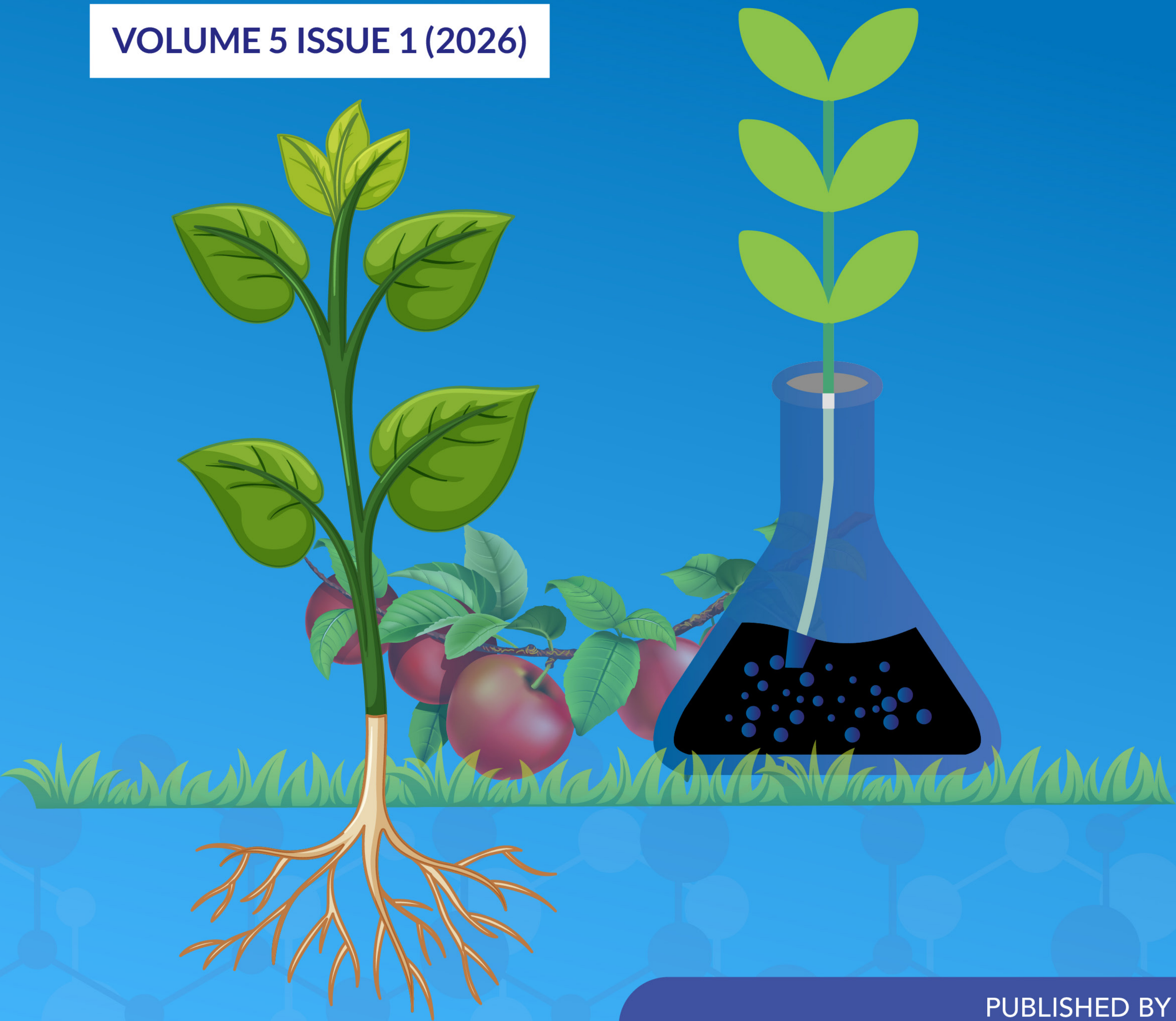

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Effect of Extrusion, Milling And Nature of Ingredient on The Microstructure of Egg-Based Whole Wheat Snack

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ABSTRACT

This paper aims to evaluate the effect of extrusion, milling and the nature of the ingredient on the microstructure of the extrudates from whole-wheat flour and chicken egg. The whole-wheat flour was mixed separately either with the raw whole egg, egg yolk or egg albumen, a twin-screw extruder was used for the extrusion of the samples. After production, the microstructure of the extrudates were determined using a scanning electron microscope (SEM). From the SEM micrograph, microstructure of extrudates were changed by extrusion and samples containing egg yolk (emulsifier) were changed to a greater extent compared with other samples. Milling had a slight effect on the microstructure of the extrudates.

INTRODUCTION

Extrusion cooking is conventionally a high temperature short time process which involves unit operations such as mixing, shaping, forming and sometimes cooking depending on the finished product. The desired products determines the extrusion temperature, for pasta production, cold extrusion is used whereas for snack production hot extrusion is used.

In most cases of extrusion cooking, the microstructure of the extrudate is different from that of the raw materials. Water determines the quality of food to a large extent. The relationship between food microstructure and water affects food texture. The reason is that water determines the physical state of food such as staling, solubilization and melting (García-García *et al.,* 2018). Type of ingredients in extruded foods affects its microstructure, Chassagne-Berces *et al.* (2011) reported that fibre incorporated in cereal may damage the microstructure thereby resulting in quality issues and consequent consumer rejection of the product. Jiddere & Filli (2015) used favourable extrusion conditions to develop an extruded product which is rich in protein and possess desirable physio-chemical and sensory properties.

The increase in awareness in the health benefits of whole grain foods has led to advancements in the control of microstructure of extruded foods and improvement in their sensory quality (Cui *et al.,* 2024). Foods with better product quality has been developed using extrusion technology with special focus on some parameters which affects product quality characteristics such as barrel temperature, feed moisture, screw speed of extruder and co-ingredients (Yadav *et al.,* 2022). The nutritional value of extruded foods and its acceptability to consumers can be improved by altering these extrusion parameters. Hou *et al.* (2024) reported that the double helix structure of starch including the crystalline zone of starch are damaged more as temperature or moisture content are increased during extrusion cooking. Dar *et al.* (2014) reported that with respect to microstructure, extrudates had a harder and compact texture with temperature increase during extrusion cooking. Téllez-Morales *et al.* (2025) investigated the microstructure of extrudates from mixtures of whey protein isolate and corn starch and determined the microstructure using X-ray diffractometry (XRD), differential scanning calorimeter (DSC), Raman spectroscopy, Fourier transform infrared spectroscopy (FTIR), confocal laser scanning microscopy (CLSM) and scanning electron microscopy (SEM) and reported the following: DSC showed 100 % gelatinization. XRD showed that crystalline structure was lost. SEM confirmed the results from DSC and XRD for starch granule gelatinization and protein denaturation. Raman and FTIR showed that the intensity of the peaks decreased with the absence of newly formed functional groups and a decrease in viscosity. CLSM presented no direct interaction between components.

The microstructure of food may be natural or imparted by processing. It is worthy of note that foods having similar chemical composition can exhibit different mechanical behavior which largely depends on the nature of processing given to the foods that determines its structure. Relevant properties of food such as mechanical and rheological properties are structure sensitive (Aguilera, 2000). Food microstructure has to do with

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how food components are arranged. Such components range from water, fat, air and cells. These components are crucial because they define some properties such as the texture of the food, the release of flavor, nutrient bioavailability (absorption), the stability of the food, and most importantly, the overall quality of the food. Food structure is linked to the function and the stability of the food. Food microstructure enables rational food design which culminates in a healthier and a more stable product which goes a long way to influence the taste of food in the mouth and the digestibility of food in the body. The study of food microstructure with regards to the relationship between the structure and property of the food helps researchers and food processors to be in control of the behavior of food during processing and subsequent storage. A good understanding of food microstructure results in better products and solving certain challenges at the industry. Food microstructure relates to how food constituents are organized and their interaction. These organization and interaction occurs in different material phases resulting in a visible spatial partition which is microscopic (Verboven *et al.,* 2017).

The microstructure of food have been determined by different microscopy techniques such as light microscope and more advanced techniques such as electron, confocal laser scanning, and atomic force microscopy. Aguilera (2005) reported that in the past, scientists neglected the effect of microstructure on the properties of food for two reasons, firstly, the concept of structure was not firmly established in chemical engineering and therefore not transferred to food engineering, secondly, foods are systems with multiple complex components which makes it difficult to observe them both in the natural and transformed states. Aguilera (2005) concluded that in order to understand the behavior of foods it is very important to understand the structure.

Nwadi & Okonkwo (2025) in a review stated that different food processing conditions affect the microstructure of food. Yang *et al.* (2020) reported that extrusion process altered the microstructure of rice.

Zambrano *et al.* (2022) investigated the microstructure of rice-flour pellets using X-ray microtomography (micro-CT) and reported that several structural changes takes place during extrusion which may be influenced by different processing conditions such as initial moisture content, screw speed, formulation and cooking temperature.

Milling affects microstructure in the sense that intact cells are broken down, protein matrix are altered starch granules are shattered, these gives rise to an increase in surface area and smaller particles which are irregularly shaped. These ultimately affects properties such as digestibility, nutrient release, enzymatic activity, texture, water absorption and functional properties. Type of milling technique, stone, roller or hammer produces different effect on products such as rough, smooth or uniform particles. These fractured surfaces have starch-protein interactions which varies. All these attributes affects the characteristics of the product which includes the microstructure. Liu *et al.* (2022) reported that the degree of milling affects microstructure. Lu *et al.* (2022) reported that colloid milling affected microstructure. Jiang *et al.* (2025) reported that milling technique affects microstructure.

Most researchers have not paid attention to microstructural changes which takes place during extrusion cooking (Nwadi & Okonkwo, 2018;Muthukumarappan & Swamy, 2018), however, lately, many researches now investigate the microstructure of extruded food. High extrusion temperatures results in numerous tiny air cells, decline in extrudate brittleness, better crunchiness, rough and pervious cell walls.

Many snacks are produced through extrusion cooking. Extrusion cooking especially of snacks involves high temperature which may alter the microstructure and sensory properties of the raw materials on extrusion. However, there is paucity of information on the microstructural properties of extruded egg-based wheat snacks. Therefore, there is the need to investigate the microstructural properties of egg-based wheat snack products.

MATERIALS AND METHODS

Materials

Four bags of 50 kg each of whole-wheat flour were purchased from Supreme Flour Mills, 6, President Burgers Street, Pretoria West 0183, Pretoria, South Africa. Thirty-two crates of thirty eggs each of freshly laid eggs were purchased from Northwest University farm, Mmabatho Unit 5, Mafikeng 2790, Mafikeng, South Africa.

Methods

The samples (Table 1) were prepared using the method of Nwadi *et al.* (2025). Egg whites were separated from the egg yolk for samples requiring either egg yolk or egg white using an egg separator. The whole-wheat flour and raw whole egg or raw egg yolk or raw egg white were mixed using a 50-litre paddle mixer constructed by Centre for Advanced Manufacturing (CFAM), Potchefstroom, South Africa, in different proportions (Table 1). After mixing, extrusion of the samples was done in TX-32 Laboratory Scale (300 kg/h maximum) twin screw extruder made by CFAM. The extrusion was done in a batch size of 20 kg (using a Platform Scale, Model: Micro A12E in CFAM) per run for each of the samples and the extrusion parameters were constant for all the samples at a screw speed of 700 rpm, feed rate of 53.6 – 78.9 kg/h (50 – 60 %) driven by a 6 – 9.7 kW motor, 20.8 – 24.1 AMP, 50 – 55 % Torque, temperature of 139 – 153 oC and 20 % feed moisture content. Each run lasted 14.22 – 15.02 minutes. A spaghetti die of 1.8 mm (2 rings) with a 40 – 60 % cutter was used in each run. The microstructure of the samples were determined using the scanning electron microscope.

Determination of microstructure using scanning electron microscope (SEM)

The microstructure was determined using SEM as described by Hardy & Jideani (2018). A VEGA TESCAN, Model TC 100 Scanning Electron Microscope (SEM) at Rhodes University, Grahamstown, South Africa was used. Prior to Imaging, the milled extrudates were placed on a double sided stub having carbon tape on both sides and spinned in an Ashford Kent England, Model Q150R Gold Coater at Rhodes University, South Africa. The essence of coating with a thin layer of Gold was to ensure the samples (milled extrudates) were electrically conducting. During surface analysis, the beam conditions were 20.00 KV. The micrographs were viewed at a magnification of 2000 x

Table 1: Ingredient combinations for products

Sample	Ratio (percentage of whole wheat flour to chicken egg)	Quantity of whole wheat flour (kg)	Quantity of chicken egg (kg)	Total quantity (kg)
RI (Whole wheat flour)	100:0	20	0 (no egg)	20
R2 (Whole wheat flour and raw whole egg)	85:15	17	3 (60 whole eggs)	20
R3 (Whole wheat flour and raw whole egg)	80:20	16	4 (80 whole eggs)	20
R4 (Whole wheat flour and raw egg yolk)	85:15	17	3 (187.5 egg yolks)	20
R5 (Whole wheat flour and raw egg yolk)	80:20	16	4 (250 egg yolks)	20
R6 (Whole wheat flour and raw egg white)	85:15	17	3 (81 egg whites)	20
R7 (Whole wheat flour and raw egg white)	80:20	16	4 (108 egg whites)	20

One whole egg = 50 g, one egg white = 37 g, one egg yolk =16 g, 1000 g = 1 kg

RESULTS AND DISCUSSION

Extruded Egg-Based Wheat Snacks

The colour of the control sample (extrudate from 100% whole wheat flour) was brown (Plate 1). This is not surprising because whole wheat flour is naturally brown in colour. Whole wheat flour also contains high amount of carbohydrate (70 – 75 %) and 10 – 15 % protein in addition to about 2.0 % lipid (Cornell, 2012). When heated as in baking or hot extraction (both of which are dry heat cooking) further browning takes place (especially on the surface) resulting from the caramelisation and Maillard reactions. On substitution of whole wheat flour with 15 % raw whole egg, the extruded products became darker brown (plate 2). This is not unexpected since raw whole egg contains, among other things, 12 % protein (from the egg white and yolk) and 12 % lipid (from the yolk) but very negligible amount of sugar (Zhu *et al.,* 2018). All these component of egg take part in browning reactions with the starch. The wheat which has high amount of carbohydrate, is provided with more proteins and lipids (from the egg) for the reactions to proceed at a greater rate, resulting to the formation of darker product compared to that obtained from wheat alone. With the substitution using 20% raw whole egg, the extrudate became even darker brown (Plate 3) because larger amounts of proteins and lipids (from the whole egg) provided greater amount of substrate for the formation of more Maillard pigments in addition to caramelisation. The extrudate (Plate 4) obtained from the substitution of the whole wheat flour with 15 % raw egg yolk was as dark brown as that obtained from the substitution with 15 % raw whole egg. This could be explained by the fact that the different between protein contents of raw egg yolk (50 %) and that of raw egg white (40 %) is only 10 % and therefore negligible. Hence, 15 % raw egg yolk substitution of whole wheat flour appeared to produce similar level of browning as whole egg substitution. Also, substitution of whole wheat flour with 20 % raw egg yolk did not produce remarkably different degree of browning from that extrudate containing 20 % raw whole egg (Plate 5) for the same reasons as explained above for 15 % raw egg yolk substitution. The brown colour developed in the extruded products when whole wheat flour is substituted with 15 % raw egg white (Plate 6) and 20% raw egg white (plate 7) were not noticeably different from their corresponding products extruded with 15 % and 20 % raw whole egg. However, on extrusion of whole wheat flour substituted with 15 % raw egg white, the product developed low level stringy appearance (Plate 6) in addition to the brown colour. The stringy appearance was now pronounced when substitution of whole wheat flour was increased to 20 % raw egg white. Since the quantities of the raw egg white added did not differ from those of others, the formation of stringy appearance has been attributed to clumping as a result of the high moisture content and foamy nature of raw egg white. Indeed massive clumping was observed on substitution with higher quantities (>20 %) of raw egg products and this made it impossible to use substitution higher than 20 % raw egg products.

Microstructure of Extrudates Using Scanning Electron Microscope (SEM)

Physical properties of extrudates are influenced by microstructure (Zarzycki *et al.,* 2015), hence the need to investigate the extent extrusion affected microstructure.

Cell wall: Samples R1, R2, R3, R6 and R7 (Figure 10, 11, 12, 15 and 16) had thin cell walls very similar to

Figure 1: R1 - 100:0 (100 % Whole wheat flour)

Figure 2: R2 - 85:15 (85 % Whole wheat flour and 15 % raw whole egg)

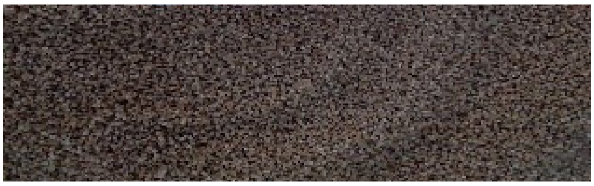

Figure 3: R3 -80:20 (80 % Whole wheat flour and 20 % raw whole egg)

Figure 4: R4 - 85:15 (85 % Whole wheat flour and 15 % raw egg yolk)

Figure 5: R5 - 80:20 (80 % Whole wheat flour and 20 % raw egg yolk)

Figure 6: R6 - 85:15 (85 % Whole wheat flour and 15 % raw egg white)

Figure 7: R7 - 80:20 (80 % Whole wheat flour and 20 % raw egg white)

the control sample (whole wheat flour (not extruded). Samples R4 and R5 appeared to have a thicker cell wall compared with the control sample.

Size: The extrudates were larger and had no small particles unlike the control, however samples R4 and R5 appeared a little bit lumpy but still clumped together.

Shape: Compared with the control, the extrudates did not contain particles of different shapes but appeared more continuous and uniform, this may be described as dough-like but cooked.

Air spaces: The control contained more air spaces compared with the extruded samples (R1, R2, R3, R4, R5, R6 and R7, Figure 10 to 16). There were occasional pin holes in the surfaces of the extrudates. Samples R6 and R7 showed a shallow-to-deep concave depression in the center of the granule. The depressions may be due to strains developed within the granules during extrusion cooking.

From the SEM Micrograph (Figure 10 to 16), the whole wheat flour contained round to disc (oval) granules (the round granules were small while the disc granules were thin and large, spherical shaped and semi-crystalline as was also reported by Singh *et al.* (2009). These may be endosperm tissues which broke up during milling as suggested by Roman-gutierrez *et al.* (2002). These were described as irregular protein fragments, endosperm lumps, whole starch granules and damaged granules by (Lin *et al.,* 2019). The surfaces of the granules were relatively smooth which is in agreement with the report of Hall & Sayre (1970). The extrusion was carried out under same conditions for all the extrudates. The extrudates had porous structures. After extrusion cooking, most of these features were lost and this also suggests that gelatinization had occurred as a result of extrusion cooking. This was also suggested by Kaushal *et al.* (2019). The oval shape of starch granules in whole wheat flour, control (Plate 8) disappeared after the extrusion cooking as seen in the extrudates. This is in agreement with the report of Bdour *et al.* (2014) that reported loss in the oval shape after extrusion. The extrudates showed a regular network structure, which may be attributed to uniform mixing during extrusion cooking, Choudhury *et al.* (2014) also reported a regular network structure of extrudates. However, in comparing the surface appearance such as colour, all the extrudates were similar and also, in expansion and microstructure.

The cell structure of wheat granule was greatly affected by the mixture of egg yolk and whole wheat flour in R4 and R5 (Figure 13 and 14). This could be attributed to the fact that egg yolk is an emulsifier. This is in agreement with Ryu & Walker (1994) that reported significant change in cell structure parameters when wheat flour is mixed with an emulsifier. This is also in agreement with (Muthukumarappan & Swamy, 2018) that reported microstructure of extrudates to be influenced more by the raw materials compared with the extrusion process. Apart from R4 and R5 (Figure 13 and 14) other samples (R1, R6 and R7, Figure 10, 15 and 16) respectively were similar. Samples R2 and R3 (Figure 11 and 12) containing whole egg were moderately affected as a result of the presence of egg yolk. R1 (100 % whole wheat flour), Plate 8, which served as control looked very smooth which could be attributed to higher quantity of gluten per unit area (Bressiani *et al.,* 2017). It showed a well-compacted organized structural orientation having no hollows and ditches which is in agreement with the findings of Xu *et al.* (2017).

After extrusion, the extrudates were milled through 0.1 mm sieve using a hammer mill (Model 3100, Perten instruments, 05 Kunens Kurva, Sweden) in CFAM. Based on the SEM Micrographs of the milled extrudates, milling reduced the particle sizes of the extrudates and also had a slight effect on the microstructure as can be seen from the visible cracks on the surface of the milled extrudates. This is in line with the findings of Jekle & Becker (2015) in a review that milling results in microstructural changes.

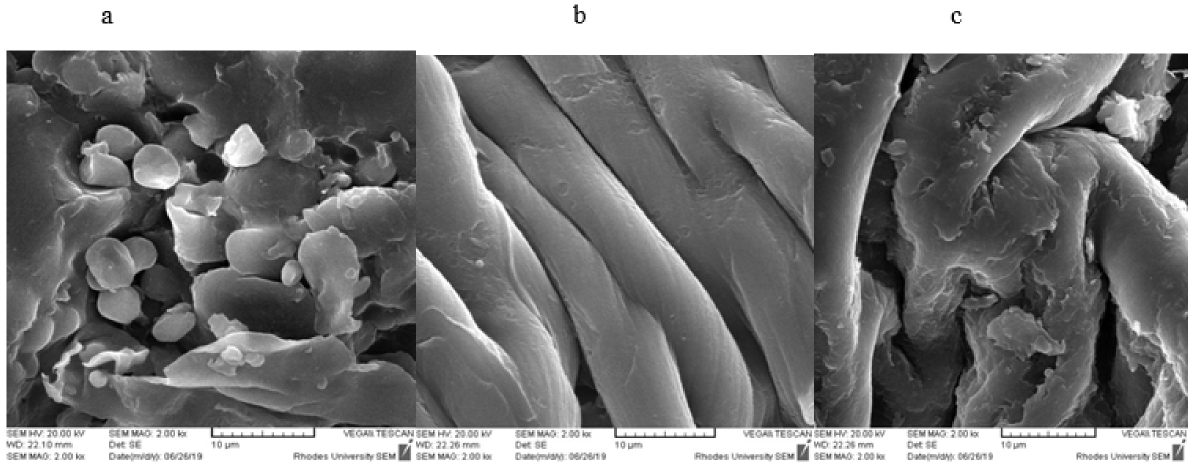

Figure 8: R1: Whole wheat flour (a-Control (not extruded), b-extrudate, c-milled extrudate

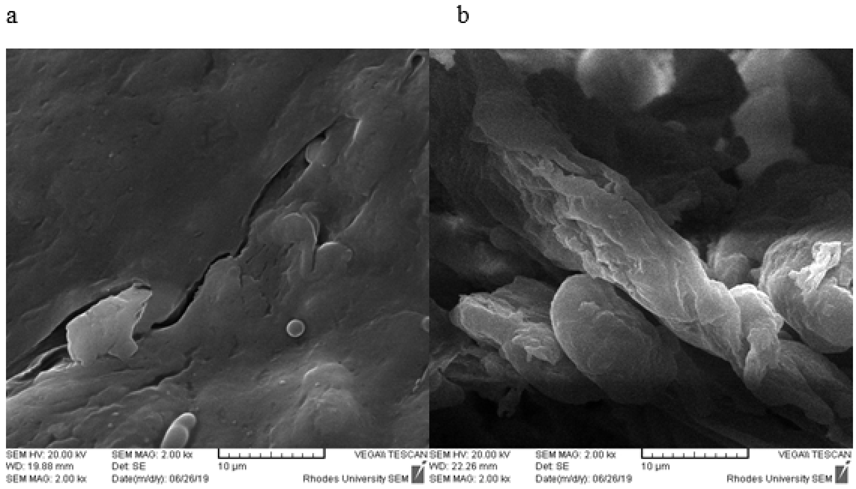

Figure 9: R2: Whole wheat flour (85 %) and raw whole egg (15 %): a-extrudate, b-milled extrudate

a b

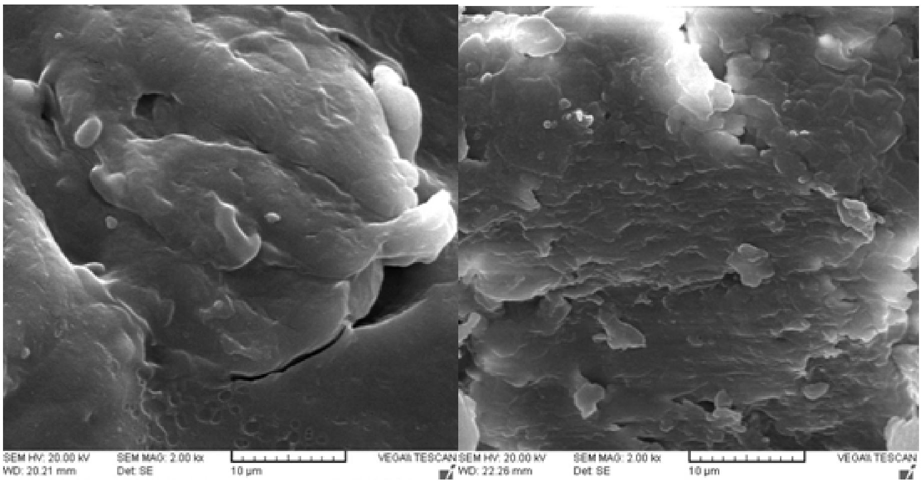

Figure 10: R3: Whole wheat flour (80 %) and raw whole egg (20 %): a-extrudate, b-milled extrudate

a b

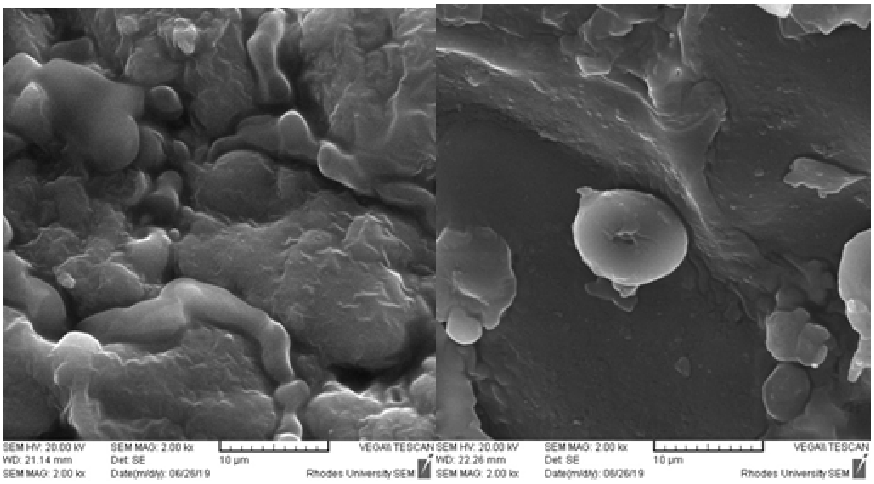

Figure 11: R4: Whole wheat flour (85 %) and raw egg yolk (15 %): a-extrudate, b-milled extrudate

a b

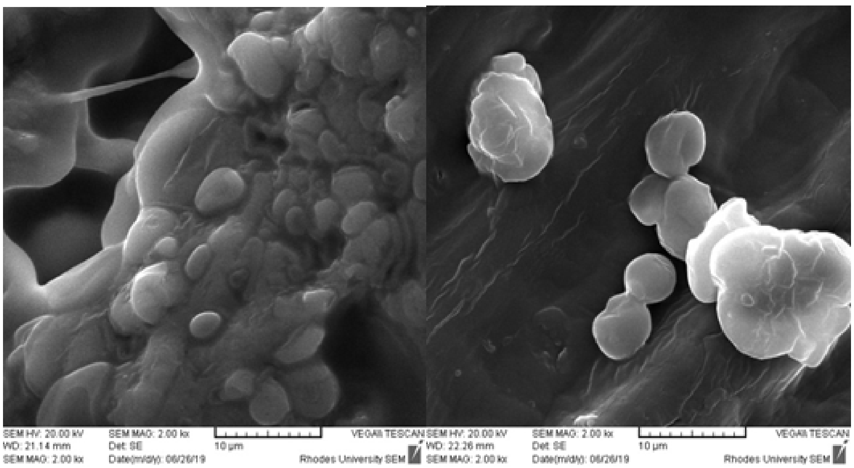

Figure 12: R5: Whole wheat flour (80 %) and raw egg yolk (20 %): a-extrudate, b-milled extrudate

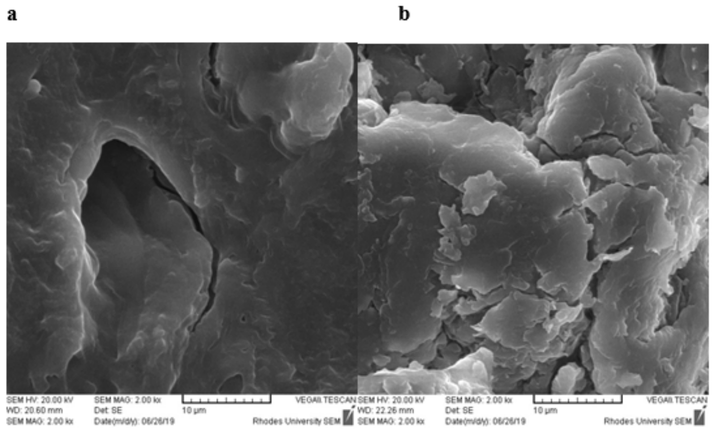

Figure 13: R6: Whole wheat flour (85 %) and raw egg white (15 %): a-extrudate, b-milled extrudate

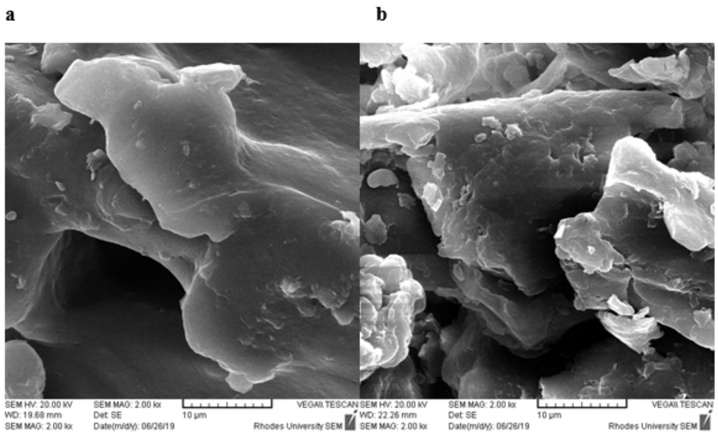

Figure 14: R7: Whole wheat flour (80 %) and raw egg white (20 %): a-extrudate, b-milled extrudate

CONCLUSION

The microstructure of the extruded snack produced from chicken egg and whole wheat flour was affected by extrusion, however, the microstructure of the extrudates were affected more by ingredient (egg yolk) than the extrusion cooking process. Milling had a slight effect on the microstructure of the extrudates. Hence extrusion, milling, and ingredient affected the microstructure of the extrudates; however, this occurred to different extents as shown on the micrographs.

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