PHYSICOCHEMICAL, NUTRITIONAL AND FUNCTIONAL PROPERTIES OF POPPED FINGER MILLET (*Eleusine coracana*) AND ITS APPLICATION IN PRODUCT DEVELOPMENT

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DECLARATION

This thesis is my original work and has not been presented for a degree in any other University.

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This thesis has been submitted for examination with our approval as the University Supervisors:

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DEDICATION

I dedicate this work to my beloved father, William Kipkoros, and my precious daughter, Abigail Jemosop. They are my greatest source of strength, inspiration and motivation.

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ABSTRACT

Finger millet (*Eleusine coracana*) is a highly nutritious grain with significant health benefits; however, its traditional processing methods have not been fully optimized for modern applications to enhance commercialization. This study evaluated the physicochemical, nutritional, and functional properties of popped finger millet and its application in cereal bar development. Finger millet grains were sourced from Jamhuri Market in Thika Town. The grains were sorted, cleaned, and dried, with an initial moisture content of 10.01%. The moisture content was subsequently adjusted to 15%, 18%, and 21% (in triplicates) and popped at chamber pressures of 120, 140, and 160 psi. The popped grains were analyzed for selected physicochemical, nutritional, functional, and microstructural properties. Grains popped at 21% moisture content and 160 psi were used to formulate five cereal bar variants with varying concentrations of guar gum and honey, which were then subjected to sensory, physicochemical, and microbiological analyses. Results indicated that increasing moisture content and pressure significantly ($p \leq 0.05$) enhanced popping yield and expansion ratio while reducing bulk density. The interaction between pressure and moisture content also had a significant ($p \leq 0.05$) effect on these parameters. Increasing moisture content from 15% to 21% significantly ($p \leq 0.05$) increased lightness and total color difference, while redness and browning index decreased significantly with increasing moisture content and pressure. Crude fat and moisture content of the popped grains decreased significantly ($p \leq 0.05$) with increasing pressure and moisture, whereas crude protein content increased significantly with pressure. Mineral analysis showed significant ($p \leq 0.05$) increases in zinc and iron content with increasing pressure and moisture levels. Total phenolic content also increased significantly, while phytates and tannins decreased significantly ($p \leq 0.05$), indicating improved nutritional quality. Functional properties were significantly influenced by processing conditions, with water absorption capacity, swelling power, and viscosities increasing, while bulk density decreased when popping pressure and moisture content were raised. Particle size distribution was also significantly affected by pressure, moisture, and their interaction. For the developed cereal bars, color attributes (lightness, redness, yellowness, and hue angle) varied significantly ($p \leq 0.05$), with increased lightness and yellowness observed at higher honey levels (10%–50%). Water activity ranged from 0.391 to 0.776 and decreased with increasing honey concentration, remaining within safe microbial limits. Bulk density and texture decreased significantly ($p \leq 0.05$) with increasing honey levels, improving handling and packaging characteristics. Proximate composition showed moisture content ranging from 3.47% to 11.35%, crude fiber from 2.31% to 2.70%, crude protein from 7.17% to 8.39%, and carbohydrates from 70.02% to 78.24%, all significantly influenced by formulation. Microbial analysis of the developed cereal bars revealed total viable counts ranging from 2.2007 to 2.7253 log CFU/g, within acceptable limits for ready-to-eat foods. No coliforms were detected, indicating satisfactory hygienic practices. *Staphylococcus aureus* was detected in two cereal bars, although no immediate health risk was indicated, while yeast and mold counts remained within acceptable limits. Sensory evaluation showed significant differences ($p \leq 0.05$) in appearance, flavor, taste, texture, and overall acceptability. Samples B1 and B5 were the most preferred, with overall acceptability scores above 7.0. Honey and guar gum significantly influenced sensory attributes, with higher honey levels enhancing flavor and consumer acceptance. In conclusion, popping pressure and moisture content significantly affect the nutritional, functional, and physicochemical properties of finger millet and demonstrates strong potential for value addition. The developed cereal bars exhibited acceptable sensory and microbial quality, supporting their potential as nutritious snack products. These findings highlight the role of popped finger millet in enhancing food and nutrition security and promoting the utilization of this underutilized indigenous crop.

CHAPTER ONE

INTRODUCTION

1.1 Background Information

Finger millet (*Eleusine Coracana*) is an annual small-seeded cereal crop belonging to the Poaceae family of the monocotyledon group, mostly grown for its grain that is used for food and brewing (Ramashia *et al*., 2018). Its origin can be traced to Ethiopia and is now produced in most parts of the world including Kenya. It can grow in varied agro-climatic conditions and performs better than wheat and rice for its ability to grow in drylands (Chandra et al., 2016). Traditionally, it has been a staple food in most African and Asian diets, consumed as a non-alcoholic beverage (porridge), stiff porridge (*ugali*), local brew (*busaa*), and flatbread. It is the fourth most important millet after sorghum, pearl, and foxtail millet (Shobana *et al*., 2013).

Finger millet contains nutrients such as carbohydrates (59%), protein (7.3%), ash (3.0%), fat (1.3%), total dietary fiber (19.1%), calcium (344mg/100g), and potassium (443 mg/100g), among others. It can contribute to the United Nation's resolution of ending all forms of malnutrition by the year 2030 (Kumar *et al.,* 2018). Furthermore, its remarkably high polyphenol and dietary fiber content have been associated with health benefits such as antimutagenic, antioxidative, and anti-glycemic activities (Devi *et al*., 2014).

Finger millet has received relatively less attention from the research community as compared to other major staple crops such as maize, wheat, and rice. As such, its worldwide production and commercialization remain low, accounting for 0.13% of all the cereals produced (Ceasar *et al.*, 2023). In developed countries, finger millet is used as animal feed and as human food in developing countries and is considered a poor man's food (Maharajan *et al*., 2021). Nevertheless, it is an important source of sustenance in most marginalized areas such as the arid and semi-arid areas (Abah *et al*., 2020).

Over the years, various researchers have studied the possibilities of developing finger millet-based foods to promote their consumption in urban areas with the major focus being on composite flours and extruded products (Saleh *et al*., 2013) Furthermore, its realization as a neglected crop is currently drawing attention as it can alleviate hunger and food shortage in developing countries. Accordingly, the various processing methods are aimed at reducing the antinutritional factors such as phytic acid and increasing the bioavailability of zinc and iron (Saleh *et al*., 2013). Popping, fermentation, cooking, milling, malting germination, roasting, and extrusion has been performed to improve nutritional quality, improve starch digestibility, preserve, soften, improve functionality, improve sensory quality and reduce antinutritive factors of finger millet products (Kakade, 2014).

Popping or puffing is a traditional processing method that is used to prepare expanded cereals and grain legumes resulting in shelf-stable and crunchy products used as ready-to-eat convenience foods. It is performed by conditioning the grains through defined moisture addition followed by tempering to defined conditions and exposure to a high-temperature short time (HTST) conditions to result in grain explosion and subsequent expansion. The popped products have improved aroma, taste, starch digestibility and solubility, reduced antinutritive factors, and can be consumed directly or used to make enriched snack bars and composite flours (Ramashia *et al*., 2019; Saleh *et al*., 2013; Thapliyal & Singh, 2015; Wanjala *et al*., 2016). There is a need for further scientific application of traditional processing methods in modern processing methods to enhance the commercialization of the finger millet grain (Ramashia *et al*., 2019)).

The incorporation of finger millet in food products can increase the nutrient content, improve palatability and reduce the glycemic index of the products. The bulky fibers and slow digestion rates, provide prolonged satiety and reduced calorie intake. These features make it suitable for feeding the elderly, convalescents, and invalids. Cereal snack bars are prepared from multiple ingredients including cereals, fruit, nuts, sugars and have a long shelf-life of 6-12 months. They offer a fast, convenient food source that requires no preparation, long shelf life and requires no refrigeration (R. Singh *et al*., 2021).

According to the World Bank, approximately 815 million people still face hunger globally (Kumar *et al*., 2018). Food and nutrition insecurity is also a concern for policymakers in Kenya as about 2 million people lack food access and therefore require urgent food aid (USAID, 2019). About 31% of Kenyan households are faced with a lack of food availability or access as evidenced by poor dietary diversity (consume under four food groups per day) (Kabura & Kwamboka, 2019)

There's been an exponential increase in the incidence of metabolic disorders such as diabetes globally, thus necessitating an increase in demand for foods that have complex carbohydrates and phytochemicals to combat them (Devi *et al*., 2014). There's also a growing consumer awareness of the relationship between nutrition and healthcare, thus enhancing the potential for phytochemicals such as polyphenols and dietary fiber (Thapliyal & Singh, 2015). This study was therefore aimed at optimizing the popping conditions for popping finger millet; establishing the effect of moisture and pressure on selected physico-chemical and functional properties; and establishing the sensory, physicochemical and microbial parameters of popped finger millet cereal bar, to improve its utilization base for the development of nutritious and healthy products.

1.2 Problem Statement

Despite the recognized nutritional and agronomic advantages of finger millet, its utilization in Kenya remains largely confined to traditional food products such as porridge and local beverages (Onyango, 2016). While these applications are culturally significant, they do not align with the rapidly evolving consumer demand for convenient, ready-to-eat, and nutritionally enhanced food products, particularly in urban settings (FAO, 2019). At the same time, Kenya is experiencing a dual burden of malnutrition, characterized by both micronutrient deficiencies and an increasing prevalence of diet-related non-communicable diseases (WHO, 2021; Kenya Demographic and Health Survey, 2014) This necessitates diversification of diets using nutrient-dense crops such as finger millet (Kumar *et al*., 2018).

Snacks account for 15-30% of the world's total energy intake. Snacks made from refined cereals such as biscuits, deep-fried and extruded products that are relatively cheap and convenient dominate the Kenyan market. Without indigenous ingredients such as finger millet. They are energy dense and nutrient-poor and have been implicated in cases of poor diet quality and metabolic disorders such as obesity, diabetes, and hypertension (FAO 2019). This presents a missed opportunity for incorporating underutilized, nutrient-rich and drought-tolerant crops such as finger millet into mainstream food systems (Kabura & Kwamboka, 2019).

Furthermore, the local production of maize grain in Kenya is experiencing a downward trend from 3.9 million metric tonnes in 2018 to 3.3 million metric tonnes in 2022 (USDA, 2024). On the other hand, its consumption has increased from 3,250,000MT to 3,450,000MT over the same period. This has led to a maize shortage and subsequent food insecurity because it is the main staple food in Kenya. The Ministry of Agriculture has proposed that millers should blend maize flour with locally produced crops such as millet, cassava, and sorghum to enhance sufficient food production (Kariuki *et al.*, 2025) .

Although previous studies have documented the nutritional composition of finger millet and explored processing techniques, there is limited research on the application of modern processing methods such as popping to enhance its physicochemical and functional properties for use in value-added products (Ramashia *et al*., 2018). More importantly, there is a notable gap in integrating these processing improvements into the development of commercially viable and consumer-acceptable food products such as snack bars within the Kenyan context (Ramashia *et al*., 2019).

1.3 Justification

Maize is the main staple food in Kenya. During the past 10 years, its production in Kenya has been experiencing a downward trend due to the reduction of land under cultivation, unfavorable weather conditions, and pest and disease attacks (Mogeni, 2019). At the same time, the population has been increasing geometrically from 40.9 to 52.57 million in 2009 and 2019 respectively. This has led to a shortage of food, thus necessitating the Ministry of Agriculture, Livestock, Fisheries, to direct millers to blend maize flour with locally produced crops such as millet, cassava, and sorghum for adequate food supply (Kariuki *et al*., 2025).

The development of popped finger-millet-based products is expected to reduce the over-reliance on maize, improve nutritional value, provide convenience, reduce micronutrient deficiency and enhance dietary diversity and overall food and nutrition security. Finger-millet is rich in polyphenols and its application in food formulation can impart anti-glycemic, anti-mutagenic, anti-microbial, and anti-oxidative properties in the foods. Its application in product development adds to the portfolio of healthy products that are particularly useful for vulnerable individuals such as invalids and convalescents.

There is a growing consumer awareness of nutrition and healthcare research, which enhances the potential for phytochemicals such as polyphenols and dietary fiber. Millet has several health benefits attributed to its polyphenol and dietary fiber composition (Saleh *et al*., 2013). This makes it useful in the management of various physiological disorders such as diabetes mellitus, hypertension, vascular fragility, hypercholesterolemia, prevention of oxidation of low-density lipoproteins (LDLs) and improves gastrointestinal health (Am *et al*., 2021). The development of a ready-to-eat finger millet-based snack bar will provide a healthy alternative for diabetic, sick and convalescing individuals.

This study will increase the availability and awareness of finger millet-based food products in rural and urban areas as it has been considered a neglected crop and yet it is very nutritious. The results will contribute to evidence for driving the nutritional advocacy that would promote its consumption, leading to the reduction of hunger and food shortage, and improvement of nutrition and livelihoods.

1.4 Objectives

1.4.1 Overall Objective

To evaluate the physicochemical, nutritional and functional properties of popped finger millet and evaluate its potential in snack bar development.

1.4.2 Specific Objectives

i. To determine the effect of pressure and moisture content on the physical properties and microstructure of popped finger millet grain.
ii. To determine the effect of pressure and moisture content on the physico-chemical, nutritional, functional properties and anti-nutrients of popped finger millet flour.
iii. To formulate a popped finger millet-based cereal bar and evaluate its physicochemical properties, sensory attributes and microbial safety.

1.5 Hypotheses

i. Pressure and moisture content have no effect on the physical properties and microstructure of popped finger millet grain.
ii. Pressure and moisture content have no effect on the physico-chemical, nutritional and functional properties, and anti-nutrients of popped finger millet.
iii. A popped finger millet-based snack bar cannot be formulated and characterized for physicochemical properties, sensory attributes and microbial safety.

CHAPTER TWO

LITERATURE REVIEW

2.1 Overview of Finger Millet

The name 'millet' was derived from the French word "mille'' meaning "thousand", as a handful of millet contains up to 1000 grains (Chandr, 2013). The growth of finger millet forms panicles that take the form of several fingers (Sood *et al*., 2017). There are different cultivars of finger millet that is brown, light brown and white, with grain colour being used as the distinct means of cultivar differentiation (Devi *et al*., 2014; Kumar *et al*., 2018).

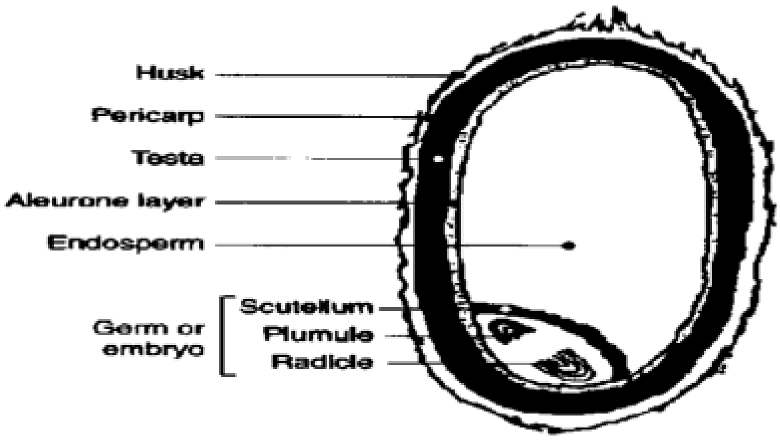

Figure 2.1: Structure of Finger Millet Grain (Ramashia et al., 2017a)

Finger millet grains are globular in shame with diameters ranging from 1.0 to 1.5 mm with a unique grain characteristic of having an utricle instead of a true caryopsis (Gull *et al*., 2014; Siwela, 2009). The pericarp is not completely fused with the testa. The finger millet grain allows the pericarp to be removed with ease upon rubbing with a mortar and pestle (Shobana *et al*., 2018). They have a five-layered testa that has been implicated as one of the likely reasons for the presence of a high dietary fibre content in the grain. The anatomical parts of the finger millet grains are the pericarp, germ and endosperm (Figure 2.1). The pericarp is the outer thin layer that covers the grain and is also called the glume. The grain pericarp consists of the epicarp, mesocarp and endocarp (Ramashia *et al*., 2017a; Siwela, 2009). The pericarp is the non-edible tissue and is removed from the kernel prior to processing (Patel & Verma, 2015). The endosperm is attached to the seed coat and forms the largest anatomical component of the kernel and is used in the production of flour (Palanisamy *et al*., 2012).

2.2 Nutritional and Health Benefits of Finger Millet

Finger millet (*Eleusine coracana*) grains are gluten-free, non-acid-forming, easily digestible, and with a low glycemic index (Am et al., 2021; Muthamilarasan et al., 2015). Its low glycemic index food property is reported to be a good choice for people with celiac disease and diabetes as its consumption regulates blood glucose levels. Finger millet nutrient profile includes dietary fiber, carbohydrates, iron, and calcium in high concentrations as compared to other cereal grains (Shobana *et al*., 2013) Finger millet also contains magnesium and phosphorus. The utilization of these nutrients has been associated with the reduction of non-communicable and chronic disorders such as type II diabetes, obesity, hypertension, ischemic strokes, and cardiovascular diseases (Ramashia *et al*., 2019). Its proximate composition is summarized in table 2.1.

Table 2.1: Summary of the Proximate Composition of Finger Millet (Amadou et al.,2013).

Component	Quantity
Protein (%)	7.3
Fat (%)	1.3
Crude fiber (%)	3.6
Ash (%)	3.0
Starch	59
Total dietary fiber (%)	19.1
Total phenols mg/100g	102

In comparison with other millet species, finger millet grains contain the highest calcium content and range from 162.0-358.0 mg/100 g. Calcium plays an essential role in growing children, expectant women, the elderly as well as in people suffering from obesity, diabetes, and malnutrition. Finger millet-based foods can therefore be used to alleviate calcium deficiency. Its phosphorus content ranges from 130.0-283.0 mg/g, while iron content was found to be between 3-20 mg/100 mg (Gull *et al*., 2014)

Finger millet also contains vitamin A and B complex vitamins, and the dried grains lack vitamin C (Devi *et al*., 2014). They contain methionine, cysteine, tryptophan, lysine, isoleucine, leucine, phenylalanine, and threonine which constitute 44.7% of the essential amino acids and have been associated with lowered cholesterol levels by modulating low density lipoprotein receptor activity and altering cholesterol transport and clearance mechanisms (Fassini *et al*., 2011; Vijayan *et al*., 2022) and reduced cancer and obesity risks in the body (Zeidan *et al.*, 2017). Its methionine content (194 mg/g) is the highest among the millet species. Additionally, it contains the linolenic and palmitic fatty acids that play a vital role in brain and neural tissue development. Fat is low in finger millet and this enhances its storage properties, reduces the risk of obesity and helps to maintain normal body weight. The low-fat content, high dietary fiber, and non-starchy polysaccharides provide hypocholesterolemic and hypoglycemic effects. The dietary fiber in the forms of lignin, cellulose, β-glucan, arabinoxylan, cellulose, and pectin contributes to the millet's high nutritional and functional significance and determines the final quality of cereal-based food products (Devi *et al*., 2014; Ramashia *et al*., 2019).

Finger millet is more nutritious as compared with other species of millet, by exceptionally high calcium content, substantial dietary fiber, and rich phytochemical profile, although variations exist across specific nutrients among millet types (Devi *et al*., 2014; Saleh *et al*., 2013) and yet the grain is still neglected and widely underutilized. There are limited studies and innovations on finger millet grains and flours as compared to conventional cereal grains such as maize, sorghum, rice and wheat. It is still relatively neglected and underutilized. The limiting nutrients that are found in relatively low concentrations in finger millets such as proteins (6-8%), vitamin A (negligible), C (negligible), zinc and iron can be improved by incorporating some fruits, vegetables, cereals, legumes and edible insects (Saraswathi & Rs, 2022).

2.3 Finger Millet Processing Technologies

Traditional and modern technologies have been applied to finger millet grain processing. Traditional methods are mostly low-cost, require inexpensive equipment, and have been predominant in rural areas and include soaking, germination, malting and grinding among others. Soaking is done to reduce anti-nutritional factors and improve zinc bioavailability and is applied by adding distilled water to the grains under defined conditions, then dried and milled to flour (Saleh *et al*., 2013). Germination is performed by soaking the grains for 2-24 hours, covered on a damp cloth, and incubating at 30^{o}C for 48 hours to soften the structure of the kernel, improve the nutritional composition and, functional properties of the grains. Malting is aimed at improving nutritional values, starch digestibility, and sensory properties and, reducing antinutritive factors (Rurinda *et al*., 2014). It has been used in traditional brewing of traditional local brews for refreshment during traditional ceremonies and farming activities. Malting is accomplished by steeping, germinating, drying, toasting, grinding, and sieving finger millet grains (Ramashia *et al*., 2019).

Milling involves a series of processes of converting dried or moistened grains to flour using a mortar and pestle to remove the coarse bran, some phytochemicals, and improve iron bioavailability. Modern milling is currently performed using milling machines, hammer, and ball mills. The finely milled flour is used to prepare *chapati* while coarse flour is used to prepare thin porridge and *ugali* (Patel & Verma, 2015). Finger millet can be fermented under defined conditions to produce fermented foods and refreshment beverages for consumption. Commercial industries have applied this technology using specific micro-organisms to produce value-added products targeted at the urban population. Fermentation provides preservation, improved nutritional values, and reduced anti-nutritive compounds such as tannins, phytic acid, trypsin, and amylase inhibitors (Shobana *et al*., 2013)

Cooking is performed by either boiling whole finger millet grains in water followed by mashing the softened grains and mixing with water to produce a soup product, or by mixing a defined ratio of flour and water and then cooking to produce porridge.

This reduces the microbial loads and improves the sensory properties of finger millet. Roasting is another processing method applied mostly in rural areas and helps to reduce antinutritive and toxic elements such as goitrogenic agents, saponins, glycosides, alkaloids, hemagglutinin, and trypsin inhibitors. It also extends the shelf life of the grain and improves the nutritional quality (Thapliyal & Singh, 2015). Extrusion is a modern processing method accomplished by gelatinizing and cooking finger millet grains completely to full cooking to produce different forms of finger millet products of desired shapes such as noodles and macaroni. It improves product parameters such as quality, functionality, and shelf life (Ramashia *et al*., 2019).

Popping or puffing has been accomplished traditionally by first moisture conditioning the finger millet grains to about 18-20% followed by tempering for about 4-6 hours under a shed. The grains are then popped by agitation on a hot sand surface at 230-250 ^{o}C for a short time. The sugars in the aleurone layer react with the amino acids in the millet through the Maillard reaction to yield a desirable aroma. The vapor pressure of the grain increases as the moisture transforms to steam, starch gelatinization occurs, and the grain explodes. This reduces the grain's moisture content to about 3-5% for prolonged shelf life. The puffed finger millet grains can be milled and used to develop enriched composite flours (Thapliyal & Singh, 2015). Modern air puffing machines have been developed for the mass production of popped millets (Ramashia *et al*., 2019). The application of popped finger millet in producing ready-to-eat foods has not been fully exploited in research and empirical data is therefore limited.

2.4. Effect of Processing Methods on the Physical, Chemical and Functional Properties of Finger Millet

Processing significantly alters the physical and chemical characteristics of finger millet, including color, density, starch structure, and microstructure. Thermal processing methods such as roasting, extrusion, and popping induce starch gelatinization, protein denaturation, and structural breakdown of the grain matrix. For instance, popping under high temperature and pressure leads to rapid moisture vaporization, causing expansion and formation of porous structures, which lowers bulk density and enhances crispness (Thapliyal & Singh, 2015). Similarly, extrusion cooking results in complete gelatinization of starch and formation of homogeneous products with improved texture and digestibility (Gull *et al*., 2014)

Processing also influences color parameters. High-temperature treatments promote Maillard reactions between reducing sugars and amino acids, leading to browning and development of desirable flavors and aromas. However, excessive heating may increase browning index and reduce lightness (Pathare et al., 2012). Milling affects particle size distribution and surface area, which in turn influences hydration properties and digestibility. Fine milling increases surface area, enhancing water absorption and enzymatic susceptibility, while coarse milling retains more structural integrity and fiber (Patel & Verma, 2015).

Processing has both beneficial and adverse effects on the nutritional composition of finger millet. Finger millet contains antinutritional compounds such as phytates, tannins, and polyphenols that limit mineral bioavailability (Sood *et al.*, 2017). Processing methods such as soaking, germination, and fermentation significantly reduce these compounds. For example, fermentation activates endogenous phytases that degrade phytic acid, thereby improving the bioavailability of iron, zinc, and calcium (Saleh *et al.*, 2013). Germination similarly reduces tannins and enhances mineral accessibility (Rurinda *et al*., 2014). Germination and malting improve the bioavailability of proteins and minerals by activating hydrolytic enzymes such as amylases and proteases. These enzymes break down complex macromolecules into simpler, more digestible forms (Devi *et al.*, 2014). Additionally, fermentation enhances vitamin content, particularly B-vitamins, due to microbial synthesis (Chandra *et al.*, 2016). Thermal processes such as popping and roasting may reduce moisture and fat content due to volatilization and oxidation, while protein digestibility often increases due to denaturation (Thapliyal & Singh, 2015). However, excessive heat can lead to losses of heat-sensitive nutrients such as certain vitamins. Processing also improves starch digestibility, particularly in popped and extruded products, by disrupting crystalline starch structures and increasing enzymatic accessibility (Saraswathi & Rs, 2022).

Functional properties such as water absorption capacity, swelling power, viscosity, and bulk density are crucial for food formulation and are significantly influenced by processing. Processing methods like extrusion, popping, and germination enhance water absorption capacity (WAC) and swelling power due to starch gelatinization and breakdown of the protein-starch matrix. This improves the suitability of finger millet flour in bakery and weaning foods (Ramashia *et al.*, 2017a). Bulk density generally decreases with processes such as popping and extrusion due to expansion and formation of porous structures. Lower bulk density is desirable in complementary foods as it allows higher nutrient density per unit volume (Muthamilarasan *et al.*, 2015). Processing alters the pasting behavior of finger millet flour. Germination reduces viscosity due to enzymatic hydrolysis of starch, making it suitable for infant foods. In contrast, extrusion and popping may increase viscosity depending on the degree of gelatinization (Shobana *et al*., 2013). Improved functional properties enhance the incorporation of finger millet into various products such as porridge, snack bars, baked goods, and extruded snacks. For instance, popped finger millet flour exhibits better solubility, dispersibility, and sensory acceptability, making it suitable for ready-to-eat products (Dharmaraj *et al.*, 2012).

2.5 Development of Finger Millet-Based Products

Finger millet has the capability of blending with other food ingredients without imparting an off-flavor (Devi *et al*., 2014). The usage of finger millet has been limited to flour-based products. Popped finger millet has a high potential for use as snacks and allied food products (Dharmaraj *et al.*, 2013). Traditionally, it has been applied in the preparation of food products that include *roti*, porridge, and alcoholic drinks. Its ability to complement well with other ingredients has made it possible to combine with other nutrient-dense ingredients such as legumes in the formulation of nutrient-balanced composite products with high biological value such as noodles (Shukla & Srivastava, 2011) and cereal nut bars (Himaja & Meera, 2020).

Finger millet has recently gained importance due to its nutritional quality in terms of high calcium, iron and dietary fiber content and can be exploited in the development of various products (Shukla & Srivastava, 2011). Finger millet can’t adequately meet nutritional requirements for a whole family setup (Feyera *et al*., 2021) because it has low energy, nutrient density and limited amino acids (Barugahara *et al*., 2015). This thus necessitates the need to enrich it with legumes, roots and tubers to improve its nutrient density and acceptability. In addition to nutritional value, the use of composite flours also saves money, promotes high-yielding indigenous crops and enhances the utilization of local crops in flour (Shobana *et al*., 2018). The value addition and improvement of health benefits of finger millet by combining with other legumes, grains, fruits and vegetables with the application of advanced processing technologies of preservation creates new avenues for product diversification (Feyera *et al.*, 2021). Research findings by (Shukla & Srivastava, 2011) indicated that the incorporation of 30% finger millet in noodles yielded the highest results for sensory evaluation while the noodles with 50% finger millet had the highest dietary fiber content.

2.5.1 Snack Bars

Cereal snack bars are convenient, nutrient-dense foods that can be consumed between meals, complement main meals and healthily provide energy. They are prepared from multiple ingredients such as nuts, fruits, cereals, sugars and have a long shelf life of 6-12 months and no refrigeration (Karuppasamy, 2020). Snack bars are presented in various forms such as packaged snack foods, processed foods, or items prepared from fresh ingredients. Most snack labels usually emphasize parameters that have been perceived to be unhealthy such as the calorie and fat (saturated and trans-fat) composition. Vital information on health-benefiting components such as minerals, dietary fiber and vitamins is less emphasized leading consumers to make misinformed nutritional choices. It is therefore vital for all stakeholders to provide extensive dietary guidance to shift the snack choice criteria to nutrient density. It has been found that cereals used in snack formulation are beneficial for human health (Hess *et al*., 2017) Kabura & Kwamboka, 2019)

Some of the cereals supply resistant starch that health-promoting effects such as prebiosis and complement the limiting amino acids in legumes such as methionine, cysteine, and tryptophan. Recently, composite foods have been formulated using legumes and traditional cereals. Such combinations result in nutrient-diversified products for reducing the incidences of malnutrition among vulnerable groups such as invalids and convalescents (Usman & Okafor, 2016). Peanut is an important protein-rich legume that is used in most diets in developing countries. It is also a good mineral, vitamin, and dietary fiber source. However, the peanut is limited in sulfur-containing amino acids (Bonku & Yu, 2020). The use of popped finger millet as a ready-to-eat snack is not fully exploited and yet it can create much-needed convenience in food preparation and consumption. (Karuppasamy, 2020)**,** prepared a snack bar using roasted finger millet, pearl millet, puffed sorghum, jaggery and β-carotene enriched mango at various proportions and reported high acceptability and nutritional values and shelf life of 60 days at room temperature storage.

2.5.2 Multi-Purpose Flour

Unprocessed or processed millet grains have been milled into flour and used in various recipes such as thin porridge (*Uji*), thick porridge (*Ugali*), biscuits, cakes and *chapatti* (Ramashia *et al*., 2019; Saleh *et al*., 2013). Thin porridge (*Uji*) is prepared using unblended or composite flours of finger millet, maize, sorghum and cassava, in their neural or fermented form. It is prepared by combining 10 % w/v flour and water and heating to gelatinize the starch and form a thin slurry that can be eaten with a spoon (Wanjala *et al*., 2016). It serves as an ideal low-calorie product for all age groups especially infants, expectant women, and the elderly (Jain *et al*., 2017). *Uji* is mostly used as a breakfast meal, children's complementary food, or refreshment drink at any time of the day. It doesn't require chewing, helps in improving appetite and has thus been recommended for use in complementary feeding of children under the age of five years and invalids and convalescents (Wanjala *et al*., 2016).

Previous studies have shown that nutrient-dense ingredients can improve the nutritional quality of finger millet-based *Uji* (Agrahar-Murugkar *et al*., 2020). The preparation of composite porridge using finger millet, sprouted grain and sprouted legumes increased the protein, and mineral contents of the beverage (Agrahar-Murugkar *et al*., 2020). Similarly, *Moringa oleifera* and *Curcuma maxima* (pumpkin) improved the protein, zinc, and vitamin A contents of the porridge (Barugahara *et al*., 2015). Sensory test results of composite porridge from fermented finger millet, *Moringa oleifera* and pumpkin seeds and leaves had better acceptability (Barugahara *et al*., 2015).

Thick porridge (*ugali*) is made by combining 30 % w/v flour and heating to gelatinize the starch and form a thick slurry that is consumed with vegetables or meat and must be chewed before swallowing. Pure or composite flours of whole-meal finger millet, maize, sorghum and cassava are commonly used to develop *ugali*. It is consumed as a main meal at lunch or dinner and has been used by local communities as a functional food to manage some non-communicable diseases such as type II diabetes and cardiovascular diseases (Wanjala *et al*., 2016). Maize, finger millet, sorghum and cassava flours are the main flours that have been used to make ugali, either singly or as composite flours (Wanjala *et al*., 2016).

2.6 Consumer Preference and Sensory Acceptability of New Products

The major determinants of food intake are food acceptance and the development of preferences. This is largely driven by the food quality and sensory properties. These include color, appearance, smell, thickness, flavor, taste and texture. These factors are determined by processing and combination protocols applied during new product development. Sensory evaluation is critical to the development of food products. The obtain accurate information, the panelists should have past knowledge or training. For any new product, sensory evaluation is important because it helps in the collection of the best-desired attributes to enable adjustment of a product to fit consumer liking (Gitau *et al*., 2019).

CHAPTER THREE

METHODOLOGY

3.1. Study Design

The study was performed at the Jomo Kenyatta University of Agriculture and Technology. An experimental research design was used. A factorial arrangement in a completely randomized design was used to investigate the three levels of pressure (120,140 and 160 psi) and the three levels of moisture content (15, 18, 21 %).

3.2. Preparation of Popped Finger Millet Grains

Finger millet grains were purchased from Jamhuri market in Thika Town and transported to the JKUAT food processing unit. It was then cleaned, dried sorted for best quality. The initial moisture content of the finger millet grains was determined using AOAC 2000 method as described by (Momanyi et al., 2020). The samples were raised to 15%, 18%, or 21% moisture content by adding predetermined amounts of water followed by confirmatory moisture content tests. These moisture levels were picked after conducting preliminary studies with conditions found in published literature by Lewis *et al.*, (1992). The amount of water required to adjust grain moisture content was calculated using the standard conditioning equation:

$$W_a = \frac{(Mf - Mi)}{(100 - Mf)} \times W_s$$

Where W_a = Water added

M_i = Initial moisture content

M_f = Final moisture content

W_s = Sample weight. This equation is based on the principle of dry matter conservation during moisture adjustment (Mohsenin, 1986).

Triplicate 200g samples were weighed for each level and popped in an enclosed puffing chamber (Lewis *et al.*, 1992). The puffing chamber was pre-heated and charged with the sample. Its temperature and pressure were allowed to equilibrate for 2 minutes or until a pressure of 60 psi was attained. Heating continued to raise the internal pressure to 120, 140 and 160 psi and discontinued once the desired pressure was attained. The chamber was pointed to a bin and the popped grains were discharged, collected, cooled and packed in airtight zip-lock bags then kept at room temperature until subsequent analyses. Popped finger millet flour was prepared by pulsing in a grinder (Omniblend I TM.767, Japan) for 60 seconds followed by passing through a 1 mm sieve, packing in airtight HDPE pouches and storing in a cool and dry place awaiting analysis.

3.3 Determination of Popped Yield, Expansion Ratio and Density

The popped yield was established using the method described by Sharma *et al.*, (2014) with slight modifications. Popped finger millet grains were separated from unpopped grains and weighed. The popped yield was then obtained using the formula:

Popped yield = Popped weight grain (g)/Total discharged grain (g)×100

The expansion ratio was determined according to the method described by Sharma *et al*. (2014) with slight modifications. Popped grains were filled up to the 100 ml mark in a 100 ml cylinder and weighed. The volume of unpopped grain (in ml) of equal weight (in grams) for the sample was then determined. An average of three measurements were taken and the expansion volume was calculated as:

Expansion ratio = 100 ml of popped grain/volume of equal weight of unpopped grain.

The density of popped grain was established using the method described by Lewis *et al*., (1992). A 100 ml beaker was filled to the 100 ml mark with popped grain and weighed and density was computed using the formula:

Density= Mass of known volume of popped grain/known volume of popped grain

3.4 Determination of Colour

Colour was quantified with a method described by (Pathare *et al*., 2012) A hunter color difference meter was calibrated using a standard white plate (L=98.5, a= 0.1, b=4.9) and used to read the L*, a* and b* values of the popped and unpopped finger millet samples directly. The samples were evenly spread in a single layer in a petridish to completely cover the measurement area of the colorimeter and the measurements done in triplicate at different positions of the sample. The procedure was repeated to get three values that were averaged.

Values were displayed on the color meter screen as L* for lightness/darkness (100 for perfect lightness, 0 for black), a* for chromaticity from red (+) to green (-) axis, and b* for chromaticity from yellow (+) to blue axis (-). The values were then tabulated and used to calculate hue angle, Chroma values (purity) and total color difference.

The colour purity, expressed as chroma (c) was obtained using the formula $(a^{*2} + b^{*2})^{0.5,}$ and the hue angle was determined using $\tan^{-1}(b^*/a^*)$. If $a^* > 0$ and $b^* > 0$, then $h^o = \tan^{-1}(b^*/a^*)$; if $a^* < 0$ and $b^* > 0$, then $h^o = \tan^{-1}(b^*/a^*)] + 180$; if $a^* > 0$ and $b^* < 0$, then $h^o = \tan^{-1}(b^*/a^*)] + 360$. The total colour difference ΔE was determined using the formula $[(L_o^* - L^*)^2 + (a_o^* - a^*)^2 + (b_o^* - b^*)^2]^{0.5}$ (Bolade *et al*., 2009)

L* =value (0 = black=high value, 100 = white)

The browning index (*BI*) was determined using the formula below which was adapted from (Dharshini & Meera, 2023).

$$BI = 100 \times (x - 0.31)/0.17$$

$$x = \frac{(a* + 1.75L*)}{(5.645 + a* - 0.3012b*)}$$

Where L*, a*, and b* represent lightness, redness and yellowness, respectively.

3.5 Scanning Electron Microscopy

The microstructure of popped finger millet grain was studied according to the method described by Oladunmoye *et al*., (2010) with slight modification. Whole and transversely sliced popped finger millet were mounted onto a sample holder using a double-side scotch tape and mounted into a scanning electron microscope (JOEL Advanced Lab Solutions, Japan) and observed at an accelerating voltage of 5.0kV under 20, 60 and 100 magnification levels respectively.

3.6 Determination of Proximate Composition

The proximate composition for the popped finger millet was performed according to the Association of Official Analytical Chemists (AOAC 2000) method as described by Momanyi *et al*., (2020).

3.6.1 Moisture Content

The moisture content was quantified by oven drying method**.** Moisture dishes were cleaned, dried, cooled, and weighed accurately. Three grams of the samples were weighed into the dishes in 3 replicates. The test samples and dishes were oven (Memmert UF 110, Germany) dried at 105^{o}C for 3 hours to a constant weight, and then removed quickly and placed in a desiccator for cooling. After cooling, the dishes together with the samples was be weighed accurately. Moisture content was obtained through differences in weight before and after moisture drying to a constant weight and the obtained values expressed as percentage moisture content using the formula below:

$$Moisture\ (\%) = \frac{(W1 - W2)}{W1} * 100$$

Where: W_1= weight before drying; W_2= weight after drying.

3.6.2 Determination of Crude Ash

Ashing dishes were heated in a muffle furnace at 550^{o}C for 1 hour then cooled to room temperature in a desiccator. After cooling, the dishes were weighed with an analytical balance and recorded as W_0. 2 grams of sample was weighed into the ashing dishes in triplicates and recorded as W_1. The dishes and test samples were then charred on a hot plate in a fume chamber until smoking stopped and incinerated in a muffle furnace (Adventic KL-420) at 550^{o}C for 5 hours. The charred sample was cooled to room temperature and weighed. The values obtained were expressed as percentage ash content using the formula:

% Crude ash = (Weight of ash remained/weight of sample) × 100

3.6.3 Crude Fibre Content

Two grams of the sample was boiled in 200 ml of 1.25% sulfuric acid under reflux conditions for 30 minutes. The mixture was then transferred into a glass wool-fitted Büchner funnel, cooled and filtered. This was followed by washing the residue with boiling water and boiling it in 200 ml of hot 1.25% sodium hydroxide solution for 30 minutes. It was then filtered in a Büchner funnel, rinsed with 1% hydrochloric acid and hot water and washed twice using alcohol and thrice using petroleum ether. The resultant residue was oven-dried at 105^{o}C in a crucible for 1 hour, placed in a muffle furnace to incinerate for 3 hours, cooled and weighed. Crude fiber was quantified as the difference in weight after ignition using the formula below:

$$\% \text{ Crude fiber} = \frac{W1 - W2}{W} \times 100$$

W_1= Digestion residue

W_2= Weight of ash

W= Original sample weight

3.6.4 Crude Protein Determination Using the Semi-Micro-Kjeldahl Method

One gram of test samples was weighed in triplicates into digestion flasks using an analytical balance. Five grams of potassium sulfate and 0.5 grams of copper sulphate were added to the samples to catalyze the digestion process. Fifteen ml of conc sulphuric acid was also added to the test samples and digested at 400^oC for one hour until the solution turned green. This was followed by cooling the digest to room temperature and diluted to 100ml in a volumetric flask using distilled water. A 10ml aliquot of the digest was taken into a distilling flask, neutralized using 15 ml of 40% NaOH, and distilled into 25 ml of 4% boric acid with 2-3 drops of mixed indicator until 40-50 ml of distillate was collected. The distillate containing ammonium borate ions was titrated with 0.02N Hydrochloric acid. The Nitrogen content was translated to be the protein content. The assumption was that a mixture of pure protein would contain 16% Nitrogen. Hence,

% Protein= N%× Protein Factor (6.25)

3.6.5 Determination of Crude Fat

Clean 250ml extraction flasks were dried, cooled, and weighed. 3 grams of test samples were weighed in triplicates, placed in dry extraction thimbles, and covered with cotton wool. 150 ml of petroleum ether was placed in the extraction flasks. The extraction flask, Soxhlet flask, and the condenser were assembled and extraction flask heated for 4 hours in a heated water bath at 40-60^oC. After extraction, the petroleum ether was removed from the extraction flask by evaporating on a rotary evaporator. The extraction flask was then oven-dried at 105°C for one hour and cooled to room temperature in a desiccator and weighed to the nearest 0.001 grams. The total fat content was expressed in percent using the formula below:

$$\% \text{ Total crude fat} = \frac{(W2-W1)}{w0} * 100 \%$$

Where:

W_1= Empty extraction flask weight

W_0= Sample weight

W_2= Extraction flask and dried fat weight

3.6.6 Determination of Carbohydrates

The carbohydrate content was quantified by subtracting the sum of moisture, ash, protein, crude fiber, and crude fat content from 100% (Momanyi *et al.*, 2020).

3.7 Determination of Calcium, Iron, and Zinc

Mineral analysis was carried out by dry ashing and atomic absorption spectrophotometer (AAS) (Shimadzu AA-7000), as per AOAC 2000 method (Momanyi et al., 2020). A clean and dry crucible was weighed. 2 grams of samples were then added into the crucible and charred on a hot plate in a fume hood, while slowly increasing the temperature until smoking ceased. The charred samples were incinerated in a muffle furnace set at 550 · C for 5-18 hours. The ash was allowed to cool in a desiccator, after which it was quantitatively transferred into a 100 mL volumetric flask. It was then dissolved in 20 mL of 0.5 N HNO_3, and the solution was made up to the mark with 0.5 N HNO_3. For Calcium determination, 1ml of lanthanum chloride solution was added to achieve 0.5% in the sample and standard solutions. Insoluble matter was filtered and the filtrate kept in a labeled polyethylene bottles. The absorbances of the solutions was read by Atomic Absorption

Spectrophotometer (AAS). Calcium, iron, and zinc absorbances were read at 422.7nm, 248nm and 213nm, respectively. Sample absorbance was compared to standard absorption using standard curves for calcium, zinc, and iron to determine the contents of the respective mineral elements.

3.8 Determination of Anti-Nutritive Factors

3.8.1 Phytates

Phytates were determined by the HPLC technique described by Camire (Camire, 1982). Approximately 0.5 g of sample was extracted using 10 mL of 3% sulphuric acid in triplicates. The contents were filtered and placed in a boiling water bath for 5 minutes and 3 mL of $FeCl_3$ solution was added. This was followed by heating for 45 minutes to completely precipitate the ferric-phytate complex. Centrifugation of the contents was carried out at 4500 rpm for ten minutes and then the supernatant was discarded. The resultant precipitate was washed using 30 ml distilled water then centrifuged, and the supernatant was disposed of. Into the residues, 3 mL of 1.5 N sodium hydroxide was added and topped up to 30 mL using distilled water. Heating was then performed for 30 minutes using a bath of boiling water for precipitation of the ferric hydroxide. The samples were cooled, centrifuged and the supernatant poured in a 50 mL volumetric flask. The sample was subsequently microfiltered and injected into a HPLC (Shimadzu Refractive Index Detector RID-6A), using 0.005 N sodium acetate as the mobile phase at a flow rate of 0.5 µL/min.

3.8.2 Tannins

The vanillin-hydrochloric acid technique was used to analyze condensed tannins (Price *et al.*, 1978). Approximately 0.25 grams of the sample was extracted in triplicates with 10 ml of 4% hydrochloric acid in methanol by shaking for 20 minutes with a shaker and separation was performed using a centrifuge for 10 mins at 4,500 revolutions per minute at 25°C. The residue was subjected to a second extraction using 5 mL of 1% hydrochloric acid in methanol. The 2 supernatants were transferred into a 25 ml volumetric flask and topped up to the mark with 1% hydrochloric acid in methanol. Catechin standards were prepared using catechin hydrate at concentrations of 0, 10, 20, 40, 60, 80, and 100 ppm. 1 mL of each sample was placed into duplicate test tubes, one serving as the sample blank. 5 mL of vanillin-HCL reagent was reacted with both the samples and standard solutions and then permitted to rest for 20 minutes. 5 mL of 4% HCL in methanol was added into the sample blanks. All solutions' absorbance was read at 500 nm using a double-beam UV spectrophotometer (Shimadzu model UV-VIS1800, Kyoto, Japan). The tannin content was quantified from the standard calibration curve as mg/100g catechin equivalent (CE).

3.8.3 Total Polyphenols

The Folin-Ciocalteu method as documented by (Nino *et al.*, 2021), with slight modifications was used to establish the total phenols. Polyphenol-containing samples produce a blue-colored complex due to the reduction by the Folin-Ciocalteu reagent. 1 g of sample was weighed into clean centrifuge tubes in triplicates. 25 ml of pure methanol was added and incubated at 25^{o}C in a dark place for 72 hours. The content was filtered using Whatman filter paper no. 1, then the filtrate was centrifuged at 13000g for 10 minutes. The supernatant was collected and microfiltered into clean test tubes. 2 ml of 10% Folin-Ciocalteu reagent was added, vortexed, and 4 ml of saturated sodium carbonate added. It was then left to rest for 60 minutes in the dark. The standards for creating the calibration curve were prepared using methanolic gallic acid at 0, 5, 10, 20, 30, 40, 50, 100, and 125 ppm and mixed with 2 ml of 10 % Folin–Ciocalteu reagent and 4 mL of saturated sodium carbonate and left to rest for 30 minutes at 25^{o}C. The absorbance for standards and samples was obtained using a UV Spectrophotometer (Shimadzu model UV-VIS1800, Kyoto, Japan) at 765 nm. The quantification of total phenol content was performed from the calibration curve, and the results were expressed as mg/100 g of gallic acid equivalent.

3.9 Determination of Functional Properties of Popped Finger Millet Flour

3.9.1 Water Absorption Capacity

Five grams of the sample were weighed into pre-weighed centrifuge tubes in triplicate. Thirty millilitres of distilled water were added, and the mixture was stirred and allowed to stand for 30 minutes, followed by the addition of a further 10 mL of distilled water. The samples were then centrifuged at 1600 rpm for 25 minutes, after which the supernatant was discarded and the tubes reweighed. Water absorption was determined as the difference between the initial and final weights of the centrifuge tubes (S E Ramashia *et al*., 2017).

3.9.2 Bulk Density

Bulk density was determined using the method described by (Ramashia *et al*., 2017) A 10 mL capacity graduated cylinder was weighed and recorded. The flour sample was filled into the 10 ml graduated cylinder and tapped gently for 30 times from the bottom till no further change in sample dimension was observed and the volume recorded (Ramashia *et al*., 2017). The equation below was used to estimate the bulk density:

Bulk density (g/ml) = Weight of flour/flour volume after tapping

3.9.3 Particle Size Distribution

Particle size distribution was established according to the method described by Patwa (Patwa *et al*., 2014). A set of 5 test sieves, that is 2mm, 1mm, 750 µm, 500µm and 250µm was arranged in decreasing order of aperture size and 100 g of flour was weighed onto the topmost sieve and shaken for 30 minutes. The weight of the flour remaining on the sieve and that of the flour going through the sieves was recorded and quantified as a percent of the total flour. This was be accomplished in triplicate.

3.9.4 Swelling Power

Swelling power was determined by the procedure of Eke-Ejiofor *et al*., (2021). The sample was initially dried in an oven at 44°C and subsequently homogenized. One gram of the sample flour was then mixed with 15 mL of distilled water in a centrifuge tube to form a slurry. The mixture was stirred, and the tube was gently placed in a water bath maintained at 70°C for 15 minutes, with continuous gentle stirring to prevent clumping. Thereafter, the sample was centrifuged at 3000 rpm for

10 minutes, and the weight of the sediment was recorded. Swelling power was then calculated as follows:

Swelling power = Weight of wet mass of sediment/weight of dry matter in the gel

3.9.5 Viscosity

Viscosity was established according to the method described by Snr *et al*., (2022)with slight modifications. A 10% (w/v) slurry was prepared by dispersing 10 g of flour in 90 mL of distilled water and thoroughly mixing. The mixture was equilibrated at 30°C for 30 minutes with occasional stirring, after which its viscosity was measured using a Brookfield Viscometer (Model RV, Brookefield Engineering Inc., Stoughton, MA, USA) with appropriate spindles (RV-3, 50 rpm) to obtain the cold paste viscosity. The slurry was then heated in a water bath at 95°C for 10 minutes until fully cooked, and the viscosity was measured again. Thereafter, the sample was cooled to 30°C, and the final (cooked paste) viscosity was recorded.

3.10 Development and Evaluation of Popped Finger Millet-Based Cereal Bar

3.10.1 Snack Bar Development

Popped finger millet grain from the treatment that had the highest puffing quality based on expansion ratio and popped yield (21% moisture and 160 psi) was used to develop the cereal bar. Guar gum was constituted by adding 1 gram of powder 10 ml of water. Five types of cereal bars (B1-B5) were prepared using popped finger millet and varied proportions of honey and guar gum. Popped finger millet, guar gum and honey were measured according to the stated proportions is Table 3.1. Guar gum was mixed with honey in a cooking pot, and heated to 85 ^{o}C to melt the honey and achieve a smooth consistency (Himaja & Meera, 2020). The popped grains were then added into the honey and guar gum mixture and stirred to a homogenous mix, compacted in a greased paper-lined pan to assume the pan’s shape, baked in an oven set at 100^{o}C for 20 minutes, cooled and diced into definite shapes and sizes of length 6 cm width 4 cm and thickness 1.5 cm and packaged using airtight LDPE pouches.

Table 3.1: Cereal Bar Formulation

Sample ID	Finger millet pops (%)	Guar gum (%)	Honey (%)
B1	50	50	0
B2	50	40	10
B3	50	30	20
B4	50	20	30
B5	50	10	40

B1: Bar 1, B2: Bar 2, B3: Bar 3, B4: Bar 4, B5: Bar 5.

3.10.2. Colour Analysis

The colour properties of the cereal bars were established using the method described by (Pathare *et al*., 2012) A calibrated hunter color difference meter (Minolta, Chroma Metre CR-200; Minolta Camera Co., Ltd., Osaka, Japan) was used to read the L*, a*, and b* values of the snack bar sample directly. Color measurements were done in triplicate at different positions of the sample. The procedure was repeated to get six values that were averaged. The values were then tabulated and used to calculate hue angle, Chroma values (purity), using the formulas below.

Chroma value = $(a^{*2} + b^{*2})^{0.5}$

Hue angle = $\tan^{-1}(b^*/a^*)$. if $a^* > 0$ and $b^* > 0$, then $h^o = \tan^{-1}(b^*/a^*)$; if $a^* < 0$ and $b^* > 0$, then $h^o = \tan^{-1}(b^*/a^*)] + 180$; if $a^* > 0$ and $b^* < 0$, then $h^o = \tan^{-1}(b^*/a^*)] + 360$

3.10.3 Bulk Density, Texture and Water Activity

Bulk density of the samples was determined using the method described by Aboshora *et al*. (2014). Each sample was crushed using a mortar and pestle and filled into a 10 ml measuring cylinder. The bottom of the cylinder was gently tapped on a laboratory bench until there was further diminution of the sample after filling to 0ml mark. Bulk density was estimated as mass per unit volume of the sample (g/ml).

The texture was established using the TA.TX2 type texture analyzer (Stable Microsystems, Godalming, UK) as described by (Momanyi et al., 2020). The maximum compression force of the cereal bar was used to determine the hardness when cutting through a blade. At a test speed of 500 mm per minute and distance of 0.50 mm, a vertical force was applied to the snack and the maximum peak force recorded in Newtons. The higher the maximum peak forces, the harder the snacks.

The water activity for the cereal snack was established using hygropalm HP23-AW-A-portable water activity analyzer (Rotronic AG, Bassersdorf Switzerland) as described by (Momanyi et al., 2020). The samples with established moisture contents were sealed in a ziplock bag that ensured an airtight condition. About 5 grams of the sample was put into a sample cup. The water activity meter was set at Aw Quick mode where sealed samples were kept at relatively constant temperature (22±3°C) for 5 minutes that allowed temperature conditions of the sample and the probe to be stabilized before the displayed a^w reading was recorded

3.10.4 Sensory Evaluation of the Snack Bar

A 9-point hedonic scale was used to test for the appearance, texture, taste, flavor and overall acceptability of the snack bar. The five (5) samples were evaluated by a group of 30 panelists from the Department of Food Science and Technology. Participants were selected based on their availability for repeated testing sessions and willingness to provide honest and unbiased feedback. Twenty grams of the samples was served in identical plates, blind-labeled in random 3-digit codes, and presented randomly to prevent bias during testing. The panelists were instructed to assign their scores as follows: 1=dislike extremely, 2= dislike very much, 3= dislike moderately, 4= dislike slightly, 5= neither like nor dislike, 6= like slightly, 7= like moderately, 8= like very much, 9= like extremely. To avoid masking the sensory attributes and minimize error, portable water was supplied and panelists requested to rinse the mouth before and after tasting the samples (Momanyi *et al*., 2020).

3.10.5 Snack Bar Proximate Composition Determination

The proximate composition of the developed snack bars was be determined as per the Association of Official Analytical Chemists (AOAC 2000) procedures outlined in section 3.6. The total energy was determined according to the method by Momanyi *et al*., (2020) using the formula below:

Total energy (kcal/100g) = [(%carbohydrates *4) + (% protein *4) + (% fat *9)]

3.10.6 Microbiological Analysis

The standard plate count method as described by Kiranmai *et al*., (2017) was used to establish the total viable counts of microorganisms present in the snack bar and flour as follows. Approximately 10 grams of each of the samples was be weighed and transferred into sterile beakers. 90 ml of sterile peptone water was added to each beaker. A series of serial dilutions up to 10^4 was be prepared in sterile test tubes. 0.1ml of each dilution was aseptically pipetted onto the pre-poured, solidified agar plates and inoculum spread with a sterile, bent glass rod. Total coliforms were enumerated on MacConkey agar, *Staphylococcus aureus* on Mannitol salt agar, and total plate count (TPC) on Plate count agar, with all plates incubated at 37°C for 48 hours. The yeast and mold plates were incubated at 25ºC for 48 hours on Sabourand dextrose agar. The colonies formed on the plates were counted after 48 hours. The results were reported in log CFU/g (colony forming units per gram)

3.10 Statistical Data Analysis

The results were expressed as mean values ±SD of 3 replicates using Microsoft Excel 2019. Analysis of variance (ANOVA) to detect statistical significance was performed in the Stata software version 13.0. Means separation to detect significant differences in each treatment was carried out using Bonferroni's method with statistically significant differences established at $p \leq 0.05$. Micrographs were annotated using coloured arrows, where red arrows indicated starch granules and yellow arrows indicate pores or air spaces.

CHAPTER FOUR

RESULTS

4.1 Popped Yield, Expansion Ratio and Density of Popped Finger Millet

The results for popped yield, expansion ratio and density are shown in Table 4.1. Pressure, moisture and pressure-moisture interactions had a significant ($p \leq 0.05$) effect on the puffing yield. The popping yield increased when the moisture content of the grain was increased from 15% to 21% at popping pressures of 140 psi and 160 psi. At 15% moisture content, water was not sufficient for the grains to achieve superheated steam which is the driving force for optimal grain popping. At 18% and 21% moisture, the grains achieved relatively higher superheated steam which was sufficient for optimal puffing (Lewis *et al*., 1992). Similarly, the yield generally increased when the pressure was increased from 120 psi to 140 psi, or 160 psi. A drop in popping yield was observed when grain moisture was raised from 18% to 21% at 120 psi. This is because heating time was insufficient for the moisture in the grain to achieve superheated state that enable popping, as compared to lower moisture contents of 15% and 18%.

Table 4.1: Popping Yield, Density and Expansion Ratio of Popped Finger Millet

Pressure (psi)	Moisture(%)	Popping yield (%)	Density (g/cm^3)	Expansion ratio
120	15	25.03±2.05^{c}	0.21±0.01^{f}	3.34±0.15^{c}
	18	37.96±1.30^{d}	0.13±0.00^{ac}	5.51±0.09^{be}
	21	15.81±0.59^{e}	0.17±0.00^{cd}	4.21±0.04^{a}
140	15	43.85±1.67^{f}	0.18±0.01^{e}	3.82±0.21^{ac}
	18	61.15±0.58^{ab}	0.12±0.01^{ab}	5.79±0.37^{b}
	21	64.63±1.25^{a}	0.12±0.00^{ab}	5.04±0.09^{de}
160	15	57.03±2.58^{b}	0.16±0.01^{d}	4.43±0.35^{ad}
	18	62.82±0.63^{a}	0.11±0.01^{b}	6.19±0.06^{bf}
	21	78.16±013^{g}	0.13±0.00^{ac}	6.63±0.37^{f}
P values	Pressure	<0.001	<0.001	<0.001
	Moisture	<0.001	<0.001	<0.001
	Pressure-Moisture	<0.001	<0.001	<0.001

Values based on means ± SD of triplicate measurements. Mean values within the same column with different letters are significantly different ($P \leq 0.05$).

A similar inference was drawn in a study to establish the effect of hydration and pan-roasting pre-treatments on the puffing characteristics of the *ragi* (finger millet) variety ‘MR1’ (Bawa & Organisation, 2021). Water and buttermilk hydration improved puffing yield but water conditioning was more economical. Popping of conditioned pearl millet using heated sand at 250 ^{o}C resulted in a yield of popped grains ranging from 8.3-77.1% (Saraswathi & Rs, 2022).

The expansion ratio in a grain is determined by the conversion of water to superheated steam and the difference in pressure between the vessel and the atmosphere (S. Singh *et al*., 2007). A general increase in the expansion ratio was observed when the puffing vessel pressure increased from 120 psi to 160 psi with the lowest and highest being 3.34 and 6.63 at 120 psi and 160 psi, respectively (Table 3). Pressure, moisture, and pressure-moisture interactions had significant ($p \leq 0.05$) effects on the expansion ratio ($p \leq 0.05$).

The expansion ratio of popped finger millet increased when the moisture content of the grains was raised from 15% to 18% at 120 psi and 140 psi and dropped when it was raised to 21 %. At 160 psi, the expansion ratio increased when moisture content was progressively raised from 15% to 21%. A moisture content of 15% was inadequate for optimal expansion of the grain, whereas 21% moisture content was adequate, having produced the highest expansion ratio of 6.63 at 160 psi. Insufficient moisture generates insufficient steam pressure during heating (Taylor *et al.*, 2009).

The results agree with previous studies that obtained expansion ratios within the range achieved (Athmaselvi, 2019). An increase in pressure and moisture yielded an increase in the expansion ratio because gelatinization increases and starch expands increasing the expansion ratio (Athmaselvi, 2019). An expanded decorticated finger millet product prepared at a high-temperature short-time treatment had an expansion ratio of 5.64 (Dharmaraj *et al*., 2012). Popping of conditioned pearl millet using heated sand at 250 ^{o}C resulted in an expansion ratio of 2.3 to 11.3% (Saraswathi & Rs, 2022). The expansion ratio of grain is important in the food industry because it can help to predict the shelf life of grain-based products. For instance, highly expanded flour can absorb free water released during the staling of bread and maintain its softness for longer (Dharmaraj *et al*., 2012b). Highly expanded flour possesses a porous structure and high-water absorption capacity due to starch gelatinization and structural disruption during HTST processing. During bread storage, water released from the starch-gluten matrix as a result of retrogradation is reabsorbed by the expanded flour matrix (Cheng *et al*., 2022). This reduces moisture migration and limits crumb firming, thereby maintaining bread softness over an extended storage period (Yan et al., 2021).The puffing index of wheat increased significantly when puffing pressure was increased from 690kPa to 1240kPa (Subramani *et al*., 2023).

The density of popped products may be influenced by process conditions such as grain moisture content before puffing. The popped grain densities ranged from 0.11g/cm^3 to 0.18g/cm^3 (Table 3). There was a significant effect of pressure, moisture content, and their interaction on the density of popped finger millet ($p \leq 0.05$). The densities exhibited a generally decreasing trend when moisture content was increased from 15% to 18% or 21%, and pressure was increased from 120 psi to 140 psi or 160 psi. This can be attributed to popping producing highly expanded and less dense products Lewis *et al.*, 1992). The 18% and 21% moisture tempering produced mostly highly expanded and therefore lowest in density. (Dharmaraj *et al.*, 2012) obtained a density of 0.14 g/cm^3 after subjecting decorticated finger millet to a high-temperature short-time process. Farahnaky *et al.*, (2013) observed that a moisture content lower than 18% yielded higher popcorn density in their investigation on the effect of moisture content on density.

4.2 Color Properties of the Popped Finger Millet Grain and Flour

Colour is an important characteristic of popped finger millet. Colour affects the appearance, acceptance and likely purchase of a product by consumers (Pathare *et al*., 2012). Color changes during processing give data about the level of browning reactions such as Maillard reaction, caramelization, the degree of cooking and pigment deterioration during the cooking process (Athmaselvi, 2019). Upon heating, a Maillard reaction occurs and, in this case, the sugars in the aleurone layer react with the amino acids in the millet grain (Saraswathi & Rs, 2022) which changes the pigment of the popped product.

Table 4.2: Colour Properties of Popped Finger Millet Grain

Pressure (psi)	Moisture (%)	L*	a*	b*	Chroma	Hue angle	Color difference	Browning index
120	15	65.23±2.71^{a}	3.73±0.12^{a}	8.17±1.15^{a}	8.97±0.98^{a}	65.13±3.52^{ac}	35.81±2.66^{a}	5.33±0.27^{c}
	18	70.17±1.50^{ab}	3.60±1.04^{a}	7.00±0.69^{a}	7.87±1.09^{a}	63.20±4.85^{c}	40.41±1.90^{ab}	5.36±0.02^{c}
	21	73.07±3.93^{ab}	3.00±1.21^{a}	6.97±2.14^{a}	7.53±2.37^{a}	67.27±2.71^{abc}	43.05±4.62^{ab}	4.87±0.01^{ce}
140	15	67.13±1.25^{ab}	2.60±0.75^{a}	8.00±0.52^{a}	8.40±0.70^{a}	74.23±1.23^{ab}	36.95±1.28^{ab}	3.58±0.39^{ab}
	18	70.67±4.65^{ab}	2.50±0.72^{a}	8.07±0.60^{a}	8.47±0.55^{a}	72.77±5.25^{abc}	39.98±3.92^{ab}	4.05±0.42^{ae}
	21	74.87±1.85^{b}	2.03±0.06^{a}	7.13±0.64^{a}	7.43±0.64^{a}	74.00±1.91^{ab}	44.82±1.81^{b}	2.90±0.07^{bd}
160	15	65.2±2.59^{a}	2.33±0.58^{a}	9.60±0.35^{a}	9.90±0.17^{a}	76.30±3.81^{b}	35.68±2.14^{a}	3.61±0.02^{ab}
	18	67.83±3.58^{ab}	2.37±0.12^{a}	8.60±0.17^{a}	8.93±0.23^{a}	74.90±0.01^{ab}	38.24±3.01^{ab}	3.76±0.36^{a}
	21	70.83±2.15^{ab}	2.20±0.66^{a}	7.07±0.40^{a}	7.43±0.49^{a}	72.83±4.46^{abc}	40.56±2.10^{ab}	2.72±0.39^{d}
P value	Pressure	0.1290	0.0043	0.0776	0.3220	<0.001	0.2031	0.0315
	Moisture	<0.001	0.3176	0.0091	0.0114	0.6215	0.0010	0.0535
	Pressure. Moisture	0.9338	0.9581	0.4113	0.6344	0.5960	0.8406	0.9813

Values based on means ± SD of triplicate measurements. Mean values within the same column with different letters are significantly different ($P \leq 0.05$).

The colour properties of popped finger millet grain are indicated in Table 4.2. The raw finger millet grain was brown. Popped finger millet was relatively lighter because popping exposed the white endosperm that is white. The L* values obtained ranged from 65.2 - 74.87, a* values 2.03 - 3.73, and b* values 6.97 - 9.60.

The effect of pressure was not significant ($p>0.05$) on the lightness of finger millet pops while that of moisture content was significant ($p\leq 0.05$). Pressure and moisture content interaction was not significant ($p>0.05$) on the lightness of popped finger millet grain. The lightness generally increased when puffing moisture was raised from 15% to 18% or 21%. This is because, at 15%, the moisture did not generate enough steam for puffing to expose the endosperm as it escaped when the grains were discharged from the puffing chamber. On the other hand, at 18% or 21% moisture content, sufficient superheated steam was generated, and it provided optimum explosion and exposure of the endosperm.

There were significant ($p\leq 0.05$) differences in the redness of finger millet puffs due to pressure, whereas moisture content and pressure-moisture content interactions had no significant ($p>0.05$) effects. When the pressure was increased from 120 psi to 140 psi or 160 psi, the redness increased. Moisture content had a significant ($p\leq 0.05$) effect on the yellowness of puffs, whereas pressure and pressure-moisture content interactions had no significant effects. The yellowness generally decreased when moisture was increased from 15% to 18% or 21%.

The Hue angle represents the qualitative property of colour seen by the naked eye. It aids in differentiating particular colours and grey colour with the same luminance. Large hue angles indicate weak yellow components (Dharshini & Meera, 2023). 0^o, 90^o, 180^o, and 270^o represent redness, yellowness, green-ness, and blueness respectively (S E Ramashia *et al.*, 2017). The hue angles ranged from 63.20^o to 76.30^o (Table 4). Pressure significantly affected the hue angle ($p\leq 0.05$) while moisture content and pressure-moisture content interactions had no significant effect. The total colour difference for popped finger millet grains ranged from 35.68 to 44.82 (Table 4). These are distinctive colour changes because they are greater than 3 and can be easily perceived with the naked eye (Dharshini & Meera, 2023).

Chroma is the quantitative measure of colorfulness and measures how different a hue is from a grey colour of the same luminance (Pathare *et al.*, 2012). The chroma values ranged from 7.43 to 9.90 (Table 4.2). Moisture content significantly affected the chroma values, while pressure and pressure moisture-content interactions had no significant effect ($p>0.05$).

Similar results for lightness were observed in previous studies. In a study to investigate the effect of moisture content on colour of popcorn, Farahnaky *et al*. (2013) reported an increase in lightness when moisture content was increased from 10% to 12, 14, 16, 18, or 20%. Colour of popped samples is largely affected by material volume and density. Higher volumes cause the inclusion of more air bubbles and a reduction of the percentage of sample surface covered by dry substance.

Browning index indicates non-enzymatic reactions in food due to protein and starch interactions and is obtained using colour changes during processing (Dharshini & Meera, 2023). The browning index of popped finger millet grain ranged from 2.72 to 5.36 (Table 4). When the lightness increased, the browning index dropped. There was a significant effect ($p\leq0.05$) of pressure on the browning index of popped millet grain. Moisture and pressure-moisture interactions had no significant effect ($p>0.05$) on the browning index of popped finger millet grain. The increase in lightness (L^*) and decrease in browning index with increasing popping pressure and moisture content can be attributed to multiple factors. High moisture levels reduce Maillard reaction rates due to dilution of reactants and unfavorable water activity conditions. Additionally, increased pressure promotes rapid expansion under high-temperature short-time conditions, limiting the duration of thermal exposure required for browning reactions. The resulting porous structure enhances light scattering and dilutes pigment concentration, contributing to a lighter appearance (Dharmaraj *et al*., 2012; S. Singh *et al*., 2007a). In a study to evaluate the influence of popping and milling on the chemical properties of finger millet, (Dharshini & Meera, 2023) obtained a browning index of 5.59 after popping finger millet grains on dry heat on an open pan and also observed a drop in browning index when lightness increased.

4.3 Scanning Electron Microscopy

Scanning electron microscopy facilitates the study of surface and internal characteristics to indicate the transformation of grain structure due to any given processing technique (Dharshini & Meera, 2023). Figures for popped finger millet show loosened starch granules which are spherical as indicated in Figures 4.2- 4.10. The starch in the raw grain was intact as shown in Figure. 4.1. The popped samples contained no intact starch granules, probably because these are altered due to the heat of popping (Figure 2-10). When puffing pressures and moisture were increased from 120 psi to 140 psi or 160 psi and 15% to 18% or 21% respectively, the size and number of air spaces in the grain matrix increased. This could be due to higher vapor generation during the puffing process (Farahnaky *et al*., 2013). The gelatinization is responsible for the differences in the holes/air spaces. As the pressure and moisture content are raised, the degree of gelatinization increases thus making the air spaces bigger. The bigger air spaces indicate a high degree of expansion that will improve the shelf life of popped finger millet-based products by re-absorbing excess moisture released during storage to maintain softness and texture stability thus slow down the staling of bread for instance (Dharmaraj *et al*., 2012a).

The microstructure of popped starch granules becomes spherical (Saraswathi & Rs, 2022) Popping changes the microstructure of cereal grains due to the loss of water from the inner structure and surrounding surface during the heating process (Snr et al., 2022). Processing methods such as soaking and drying of grain can cause alterations in microstructure (Snr *et al*., 2022) In a study performed by(Dharmaraj *et al*., 2013) popping of a finger millet-based extruded snack elicited several visible changes in the structure of starch, related to loss of granule shapes, such as gelatinization, and rupture of intermolecular bonds. The outer surface of the finger millet which has a cellular matrix formed a honeycomb-like structure, as it underwent popping (Dharshini & Meera, 2023).

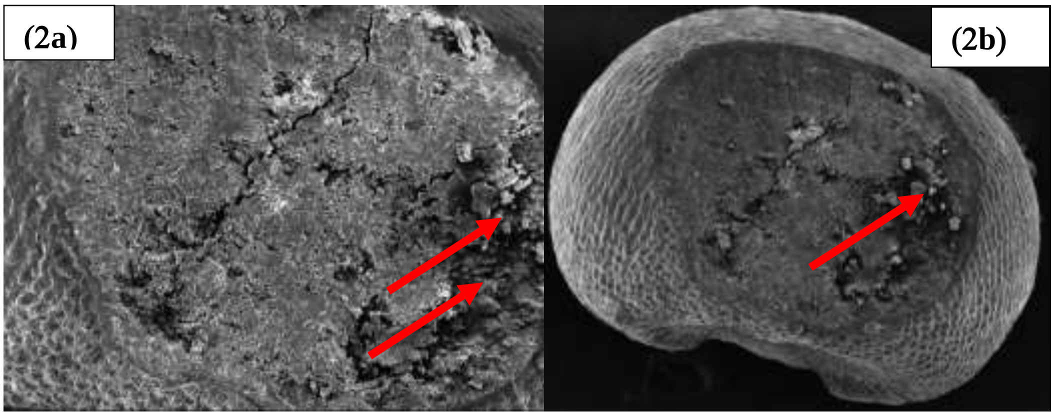

Figure 4.1: Unpopped Finger Millet Grain Under: (2a) Magnification of 100 Times × 100 µm and (2b) Magnification of 20 Times × 100 µm. Red Arrows Indicate Intact Starch Granules.

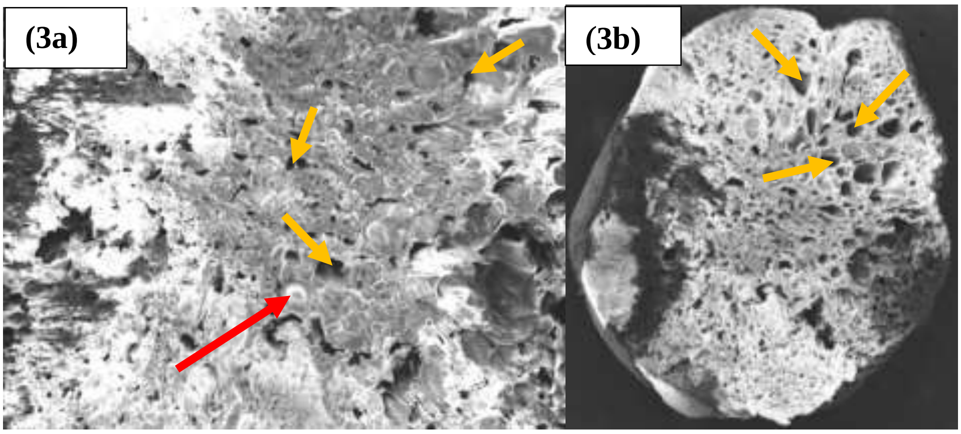

Figure 4.2: Finger Millet Grain Popped at 120 psi Pressure and 15% Moisture Content Under (3a) Magnification of 100 × 100 µm and (3b) Magnification of 20 Times × 100 µm. Red Arrows Indicate Disrupted Starch Granules, Yellow Arrows Indicates Pores or Air Spaces.

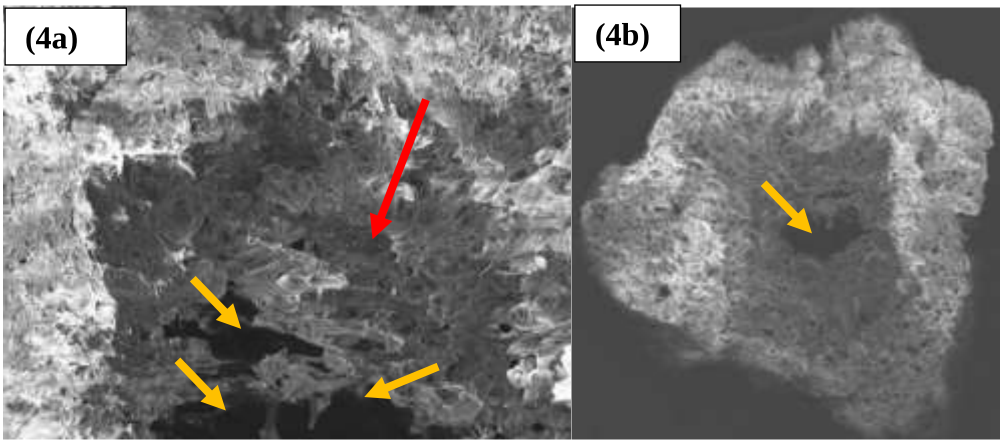

Figure 4.3: Finger Millet Grain Popped at 120 psi Pressure and 18% Moisture Content Under: (4a) Magnification 100 Times ×100 µm, and (4b) Magnification of 20 Times × 100 µm. Red Arrows Indicate Disrupted Starch Granules, Yellow Arrows Indicate Pores or Air Spaces.

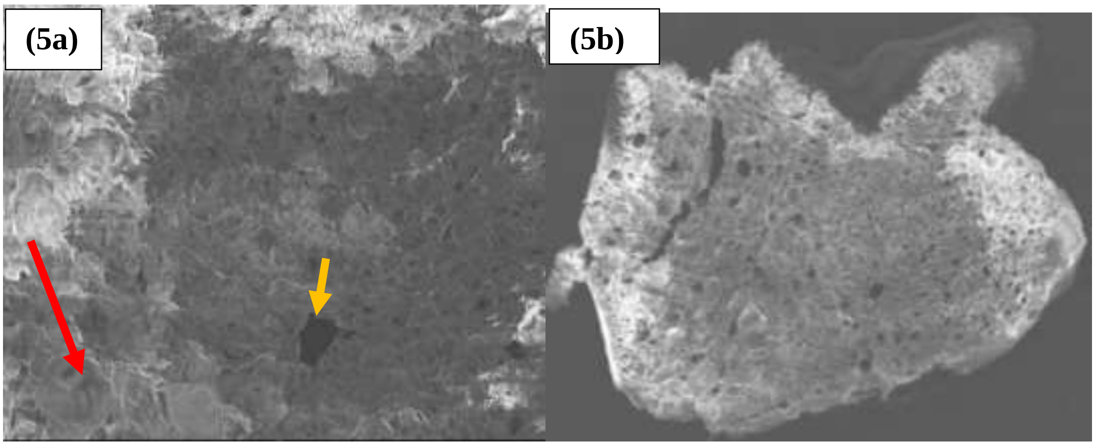

Figure 4.4: Finger Millet Grain Popped at 120 psi Pressure and 21% Moisture Content Under: (5a) Magnification of 100 Times ×100 µm and (5b) Magnification of 100 Times 100 µm. Red Arrows Indicate Disrupted Starch Granules, Yellow Arrows Indicate Pores or Air Spaces.

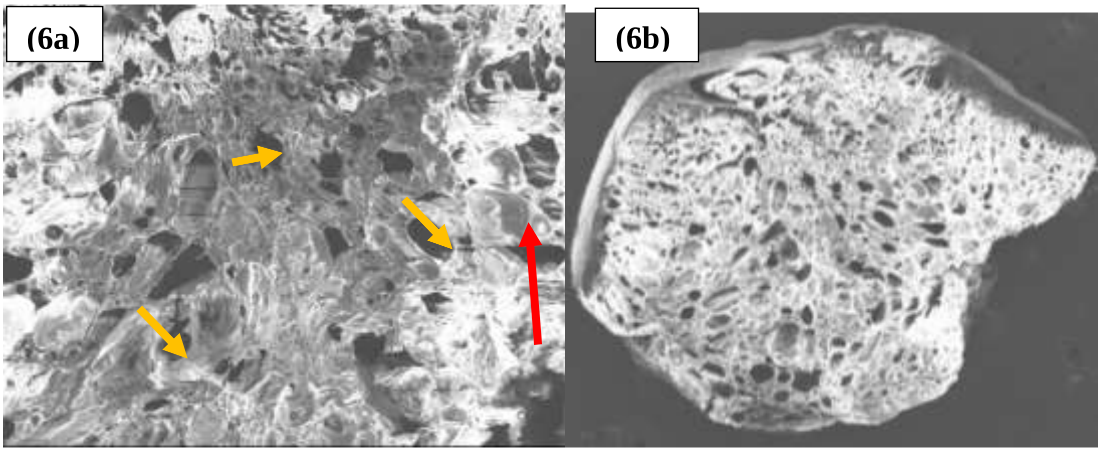

Figure 4.5: Finger Millet Grain Popped at 140 psi Pressure and 15% Moisture Content Under (6a): Magnification of 100 Times × 100 µm and (6b) Magnification Levels of 20 Times × 100 µm. Red Arrows Indicate Disrupted Starch Granules, Yellow Arrows Indicate Pores or Air Spaces.

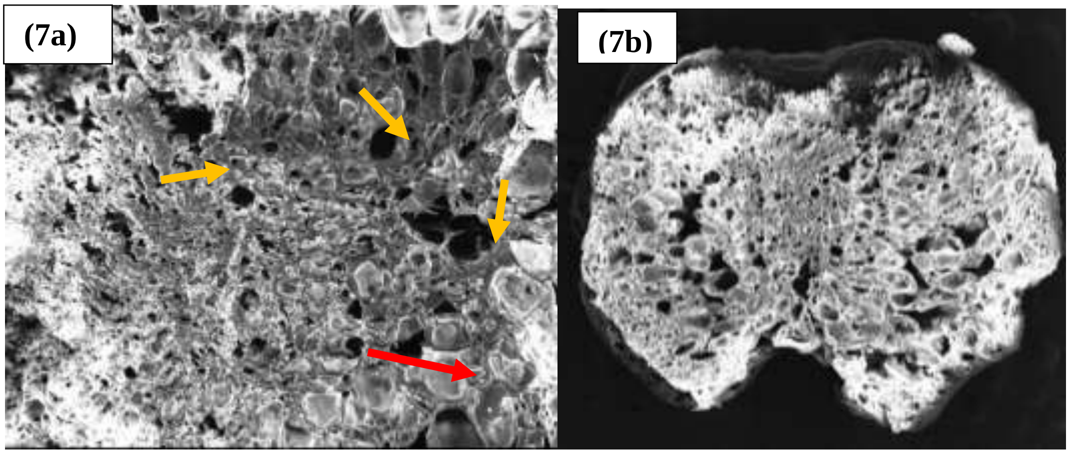

Figure 4.6: Finger Millet Grain Popped at 140 psi Pressure and 18% Moisture Content Under: (7a) Magnification of 100 Times × 100 M and (7b) Magnification of 20 Times × 100 µm. Red Arrows Indicate Disrupted Starch Granules, Yellow Arrows Indicate Pores or Air Spaces.

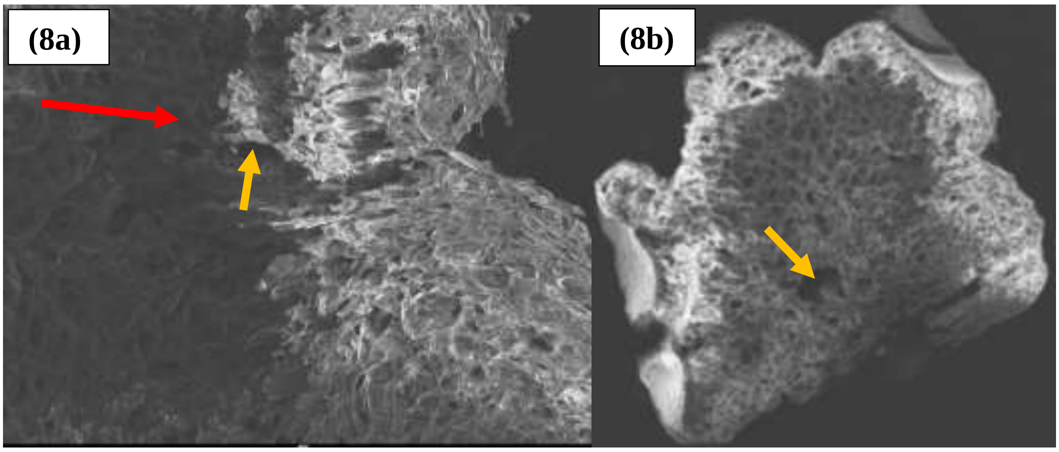

Figure 4.7: Finger Millet Grain Popped at 140 psi Pressure and 21% Moisture Content Under: (8a) Magnification of 100 Times × 100 , and (8b) Magnification of 20 Times × 100 µm. Red Arrows Indicate Disrupted Starch Granules, Yellow Arrows Indicate Pores or Air Spaces.

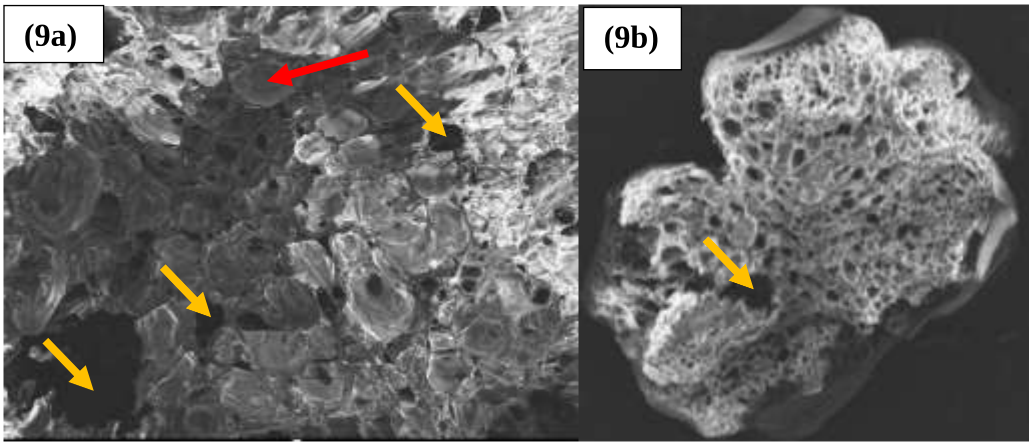

Figure 4.8: Finger Millet Grain Popped T 160 psi Pressure and 15% Moisture Content Under: (9a) Magnification of 100 Times × 100 µm and (9b) Magnification of 20 Times × 100 µm. Red Arrows Indicate Disrupted Starch Granules, Yellow Arrows Indicate Pores or Air Spaces.

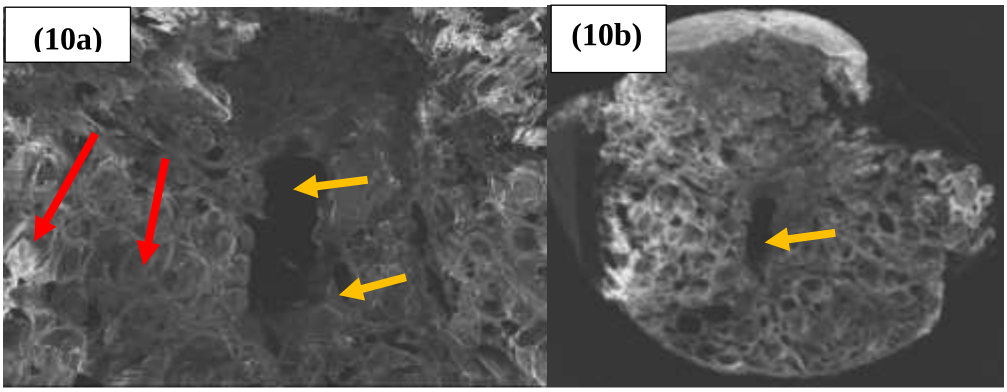

Figure 4.9: Finger Millet Grain Popped at 160 psi Pressure and 18% Moisture Content Under: (10a) Magnification of 100 Times × 100 µm, and (10b) Magnification of 20 Times × 100 µm. Red Arrows Indicate Disrupted Starch Granules, Yellow Arrows Indicate Pores or Air Spaces.

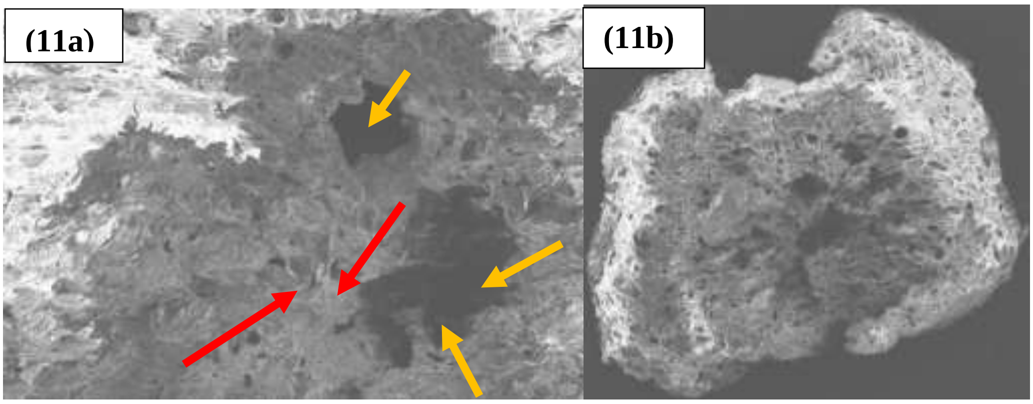

Figure 4.10: Finger Millet Grain Popped at 160 psi Pressure and 21% Moisture Content Under: (11a) Magnification of 100 Times× 100 µm, and (11b) Magnification of 20 Times × 100 µm. Red Arrows Indicate Disrupted Starch Granules, Yellow Arrows Indicate Pores or Air Spaces.

4.4 Proximate Composition of Popped Finger Millet

The proximate composition of the popped finger millet is shown in Table 4.3. The moisture content of popped finger millet flour ranged from 6.06±0.04% to 7.98±0.02%. This is within the range for the effective flour storage (Oladunmoye et al., 2010).

Table 4.3: Proximate Composition of Popped Finger Millet (wb)

Pressure (psi)	Moisture (%)	Proximate Composition					
		Moisture (%)	**Crude fibre (%)**	**Crude ash (%)**	**Crude fat (%)**	**Crude protein (%)**	**Carbohydrates(%)**
120	15	7.12±0.01[a]	2.93±0.34[a]	2.44±0.50[a]	0.95±0.02[e]	7.15±0.16[b]	79.40±0.30[ab]
	18	7.68±0.03[b]	2.46±0.38[a]	2.02±0.30[a]	0.73±0.04[ab]	8.27±0.96[abc]	78.83±0.72[ab]
	21	7.98±0.02[c]	2.56±0.61[a]	1.83±0.60[a]	0.84±0.05[c]	6.96±0.35[b]	79.83±1.21[b]
140	15	6.47±0.02[d]	3.20±0.67[a]	1.81±0.42[a]	0.80±0.06[ac]	9.15±0.19[a]	78.55±0.69[ab]
	18	7.02±0.01[e]	3.40±0.45[a]	2.35±0.14[a]	0.77±0.01[ac]	7.61±0.34[bc]	78.85±0.84[ab]
	21	7.77±0.05[f]	3.37±0.23[a]	2.46±0.36[a]	0.71±0.01[ab]	8.23±0.67[abc]	78.45±0.63[a]
160	15	6.06±0.04[g]	3.52±0.18[a]	2.84±0.93[a]	0.65±0.04[bd]	9.16±0.10[a]	77.77±0.75[ab]
	18	6.28±0.03[h]	3.12±0.27[a]	2.44±0.12[a]	0.71±0.02[ab]	8.96±0.07[ac]	78.49±0.36[ab]
	21	7.14±0.03[a]	3.02±0.28[a]	2.17±0.31[a]	0.57±0.01[d]	8.86±0.33[ac]	78.22±0.81[ab]
P value	Pressure	<0.001	0.0059	0.2341	<0.001	<0.001	0.0059
	Moisture	<0.001	0.4073	0.6402	<0.001	0.1075	0.8162
	Pressure. Moisture	<0.001	0.5446	0.1368	<0.001	0.0012	0.0909

Values based on means ± SD of triplicate measurements. Mean values within the same column with different letters are significantly different (p≤0.05).

Low moisture content in popped grain and flour could be due to extreme dehydration during the puffing process as water is converted to steam and made to escape during expansion (Sreenatha *et al.*, 2023). Puffing results in reduced moisture in the end product. The moisture content of 12-15.5% has been recommended for cereal flour storage, failure to which moisture absorption from the atmosphere can take place and lead to caking. The pressure and moisture content effect was significant ($p \leq 0.05$). The moisture content of popped grain increased when the puffing moisture was raised from 15% to 18 % or 21% at constant pressure. A general decline in moisture content of popped grain was observed when the popping pressure was increased from 120 psi to 140 psi or 160 psi. This could be due to the extended time that is taken to raise the pressure to 140 psi or 160 psi and this gives more time for enhanced conversion of water to steam for subsequent expulsion when the grain is discharged from the puffing vessel. The results indicated a significant decline in moisture content when popping pressure and moisture content were raised. This can be attributed to high temperature during processing and is consistent with findings by Dharmaraj *et al*., (2012) who reported similar moisture reduction in popped cereals due to thermal dehydration.

Crude protein content ranged between 6.96 and 9.16. Proteins in the diet provide cellular structures, promote movement and regulate body fluid balance. The effect of pressure and pressure-moisture interaction was significant ($p \leq 0.05$). A general increase in protein was observed when pressure was increased from 120 psi to 140 or 160 psi. This could be due to the progressive loss of moisture during popping that could have resulted in the rise of dry matter content in the grain and hence higher levels of detectable crude protein. No significant ($p > 0.05$) differences due to moisture content were observed. Similar trends have been reported in studies on thermally processed grains, where nutrient concentration increases as water content decreases (Anjitha *et al*., 2021).

Crude ash refers to the inorganic residue remaining after either ignition or complete oxidation of organic matter in a foodstuff. It is a measure of the total amount of minerals present within a food (Verma *et al*., 2022). In this study, crude ash content ranged between 1.81% and 2.84%. Pressure and moisture content had no significant effect ($p>0.05$) on the crude ash content of popped finger millet. There is no significant change in crude ash because minerals are generally heat stable therefore thermal processes like popping don't destroy them chemically (Adebowale *et al*., 2005). Crude fat content ranged from 0.57% to 0.95%. The effect of pressure and moisture on crude fat was significant ($p \leq 0.05$). A general decline in crude fat was noted as the pressure was increased from 120 psi to 140 psi or 160 psi. This could be attributed to the interactions of lipids with other grain constituents such as protein and carbohydrates that render lipids less available for extraction (Lewis *et al*., 1992). These interactions may include lipid oxidation, hydrolysis, and the formation of starch-lipid complexes, which reduce lipid extractability during analysis. Lipids are relatively small and mobile molecules that can melt, migrate, and undergo thermal degradation during processing. Furthermore, the formation of amylose–lipid complexes during heat treatment can limit lipid availability, resulting in lower measured lipid content (S. Singh *et al*., 2007b). Fats or lipids are organic compounds primarily composed of fatty acids esterified to alcohols (such as glycerol), forming triglycerides. They serve as a major source of energy in the diet and play essential structural and functional roles in the body, including being key components of cell membranes and contributing to the structure and function of nervous and visual (eye) tissues. (Gaikwad *et al*., 2024).

Crude fiber content ranged from 2.46% and 3.40%. Pressure had a significant ($p \leq 0.05$) effect, but no significant differences ($p>0.05$) were observed due to moisture and moisture-pressure interactions on the crude fibre content of popped finger millet. The relatively stable fibre content across moisture treatments agrees with Onipe *et al*. (2024), who highlighted that dietary fibre in cereals is largely resistant to thermal degradation. These components provide the bulk necessary for proper peristaltic action in the intestinal tract and lower post-meal glucose in the bloodstream because they are slowly absorbed and assimilated in the body (Onipe *et al*., 2024).

Carbohydrate content of popped finger millet flour ranged from 77.77% and 79.40%. Pressure had a significant effect ($p \leq 0.05$) on the carbohydrate content of popped finger millet. Carbohydrates are generally not lost during thermal processing;

instead, they undergo physicochemical transformations such as starch gelatinization, where heat and moisture disrupt the crystalline structure of starch granules, leading to swelling and loss of granular integrity (Singh *et al*., 2006). Carbohydrates are mainly used as a source of energy in nutrition (Gaikwad *et al*., 2024).

4.5 Calcium, Iron and Zinc Composition

The calcium, zinc, and iron contents of popped finger millet are illustrated in Table 4.4. The calcium content of popped finger millet in this study ranged from 1030.42 to 1164.40 mg/100 g, which is substantially higher than values commonly reported in the literature (approximately 300–370 mg/100 g) (Devi *et al*., 2014). This variation may be attributed to differences in cultivar, soil mineral composition, agronomic practices, and environmental conditions (Chandra *et al*., 2016). There were no significant differences ($p>0.05$) in calcium content due to pressure and moisture content. Zinc and iron contents ranged between 2.45mg/100g and 4.47mg/100g and 1.05mg/100g and 1.58mg/100g, respectively. Significant ($p\leq0.05$) differences in zinc content due to pressure and moisture content were observed, and the effect of pressure-moisture interactions was not significant. Pressure, moisture, and their interaction had significant ($p\leq0.05$) effects on the iron content. The iron content generally increased when the pressure and moisture were increased from 120 psi to 140 psi or 160 psi and 15% to 18% or 21 %, respectively. This could be due to the simultaneous reduction of antinutritive factors such as phytates and tannins during the popping process that could have otherwise bound the iron and zinc and made them unavailable. In a study by (Krishnan *et al*., 2012) on the effect of popping on finger millet, the calcium, zinc, and iron contents were 369mg/100g, 12.7mg/100g, and 2.2mg/100g, respectively. The observed increase in iron content with increasing popping pressure and moisture content may be attributed to the reduction of antinutritional factors such as phytates and tannins, which are known to chelate divalent minerals including iron, calcium, and zinc. However, the effect is more pronounced for iron due to its stronger interaction with phytates and its lower initial bioavailability, making its release more detectable following processing (Abera *et al*., 2023)

Table 4.4: Calcium, Iron and Zinc Composition of Popped Finger Millet

Pressure (psi)	Moisture (%)	Calcium (mg/100g)	Zinc (mg/100g)	Iron (mg/100g)
120	15	1030.42±93.09[a]	1.05±0.06[b]	2.48±0.01[a]
	18	1047.85±94.59[a]	1.25±0.06[ab]	2.45±0.17[a]
	21	1048.86±30.02[a]	1.29±0.01[a]	3.38±0.09[b]
140	15	1122.33±75.40[a]	1.23±0.11[ab]	2.41±0.16[a]
	18	1087.94±54.25[a]	1.28±0.05[a]	2.73±0.45[a]
	21	1055.38±49.48[a]	1.45±0.05[ac]	3.78±0.13[b]
160	15	1092.97±81.15[a]	1.32±0.12[a]	3.28±0.39[b]
	18	1164.40±72.08[a]	1.38±0.06[ac]	4.20±0.17[c]
	21	1128.89±82.96[a]	1.58±0.07[c]	4.47±0.08[c]
*P v*alue	Pressure	0.07	0.02	<0.001
	Moisture	0.79	0.03	<0.001
	Pressure-Moisture	0.68	0.06	<0.001

Values based on means ± SD of triplicate measurements. Mean values within the same column with different letters are significantly different (P≤0.05).

The role of calcium in the diet is to renew the skeleton, facilitate calcium and muscular contractions, transmit nerve impulses, and facilitate hormone release. A deficiency of calcium leads to joint and cardiovascular problems, and osteoporosis. Zinc maintains the structural integrity of proteins, regulates gene expression, and contributes to the development of the male sexual organs. A zinc deficiency can cause male sterility (Momanyi et al., 2020). Iron plays the role of manufacturing hemoglobin and binds with myoglobin, a protein involved in muscle oxygenation. An iron deficiency will cause anemia, and this affects about 33% of women in the reproductive age bracket, and 25 % of children under the age of five globally (Momanyi *et al*., 2020).

4.6. Tannins, Total Polyphenols and Phytates Composition

The tannin content of popped finger millet flour ranged from 0.0158 to 0.0738mg/100g catechin equivalent (Table 4.5). Moisture content had a significant effect on the tannin content, whereas pressure and pressure-moisture content effects had no significant effect ($p>0.05$).

The polyphenol content of popped finger millet ranged from 0.0802 and 0.1226mg/100g gallic acid equivalent (GAE) (Table 7). Pressure, moisture content and their interactions had significant effects ($p\leq0.05$) on the polyphenol content of popped finger millet. The phytate content of popped finger millet ranged from 219.00mg/100g to 247.00mg/100g (Table 4.3). Significant ($p\leq0.05$) differences due to pressure were observed. The phytate content generally declined when popping pressure was increased from 120 psi to 140 psi or 160 psi. Moisture content and pressure-moisture content interactions had no significant ($p>0.05$) effect on the phytate content.

The levels of tannins, total phenols, and phytates observed in this study were comparable to values reported in previous studies on finger millet, although some variations were noted. Reported tannin content in finger millet ranges from approximately 0.3 to 3.0%, depending on variety and processing conditions, while total phenolic content has been reported to vary widely due to genetic and environmental influences (Devi *et al*., 2014; Shahidi & Chandrasekara, 2013). Similarly, phytate content in finger millet is typically reported within the range of 0.5 to 1.5%, with variations attributed to cultivar differences and post-harvest handling practices (Abioye *et al*., 2022).

The differences between the values obtained in this study and those reported in the literature may be attributed to variations in grain variety, growing conditions, and analytical methods used. In addition, processing conditions such as popping pressure and moisture content may influence the levels of these anti-nutritional factors. Thermal processing has been reported to reduce tannins and phytates through degradation and complex formation, while phenolic compounds may either decrease due to thermal breakdown or increase in extractability due to cell wall disruption (Abioye *et al*., 2022; Shahidi & Chandrasekara, 2013).

Table 4.5: Tannins, Total Phenols and Phytate Content of Popped Finger Millet

Pressure (psi)	Moisture (%)	Tannins (% CE)	Total Phenols (mg/100g) GAE	Phytates (mg/100)
120	15	0.0762±0.002[a]	0.1070±0.002[bc]	247.00±9.64[b]
120	18	0.0329±0.008[bcd]	0.1033±0.004[abc]	247.00±5.29[b]
120	21	0.0234±0.003[bc]	0.0974±0.007[ab]	239.33±6.51[ab]
140	15	0.0565±0.016[ad]	0.0802±0.000[e]	231.67±7.57[ab]
140	18	0.0738±0.005[a]	0.0942±0.001[a]	242.00±5.57[ab]
140	21	0.0523±0.003[acd]	0.0937±0.001[a]	229.33±8.08[ab]
160	15	0.0678±0.003[a]	0.1083±0.003[c]	238.67±4.51[ab]
160	18	0.0346±0.003[bcd]	0.1188±0.002[d]	222.33±9.61[a]
160	21	0.0158±0.002[b]	0.1226±0.002[d]	219.00±10.00[a]
P value	Pressure	0.0561	<0.001	<0.001
	Moisture	0.0024	<0.001	0.0323
	Pressure-Moisture	0.0606	<0.001	0.0891

Values based on means ± SD of triplicate measurements. Mean values within the same column with different letters are significantly different ($P \leq 0.05$)

Popping improves the nutritional value of food by inactivating some of the antinutritive factors. The breakdown of phytic acid in finger millet can lead to the bioavailability of iron and other minerals (Subramani *et al*., 2023). Anti-nutritive factors can cause poor protein and carbohydrate digestion by inhibiting digestive enzymes and reducing the bioavailability of minerals such as calcium and iron. Majorly, phytates and tannins have been associated with the reduced bioavailability of vital nutrients, therefore reducing them in the popped finger millet increases the nutritional value of the product (Gaikwad *et al*., 2024).

4.7 Water Absorption Capacity, Swelling Power and Bulk Density

4.7.1 Water Absorption Capacity

Water absorption capacity is the ability to absorb and retain water without necessarily swelling to achieve the desired consistency (Dharmaraj *et al*., 2012). The water absorption capacity of popped finger millet flour ranged from 5.42 mL/g to 6.23 mL/g (Table 4.6). Significant ($p \le 0.05$) differences due to pressure and moisture content and their interactions were observed. The water absorption capacity of popped finger millet flour generally increased when the pressure was raised progressively from 120 psi to 160 psi and moisture increased from 15% to 18% or 21%.

Table 4.6: Water Absorption Capacity, Bulk Density and Swelling Power of Popped Finger Millet

Pressure (psi)	Moisture (%)	Water absorption Capacity (mL/g)	Bulk density (g/mL)	Swelling power
120	15	5.42 ±0.08[a]	0.47±0.02[ef]	5.48±0.02[a]
120	18	5.45 ±0.09[ab]	0.43±0.02[de]	5.59±0.04[ab]
120	21	5.77±0.16[c]	0.37±0.01[a]	5.87±0.02[ab]
140	15	5.57±0.09[abc]	0.48±0.02[f]	5.75±0.01[ab]
140	18	5.76±0.02[bc]	0.37±0.01[a]	5.71±0.02[ab]
140	21	6.18±0.15[d]	0.36±0.005[ac]	5.92±0.07[ab]
160	15	5.66±0.11[abc]	0.42±0.02[d]	6.07±0.01[abc]
160	18	5.54±0.03[abc]	0.32±0.01[bc]	6.15±0.18[bc]
160	21	6.23±0.09[d]	0.31±0.01[b]	6.69±0.60[c]
P Values	Pressure	<0.001	<0.001	0.0835
	Moisture	<0.001	<0.001	0.0075
	Pressure. Moisture	0.0185	<0.001	<0.001

Values based on means ± SD of triplicate measurements. Mean values in the same column with the same letter are not significantly different in each column ($p \le 0.05$).

Grains with relatively higher moisture content might be prone to starch damage during high-pressure processing. High pressure damages the starch granules within the grains. Damaged starch granules absorb water more readily than intact ones due to gelatinization (Dharmaraj *et al.*, 2012). When starch absorbs moisture, it swells, gelatinizes, and gets damaged as a rearrangement of its intermolecular structure takes place. The extent of starch damage increases when the moisture and pressure are increased. High pressure increases starch swelling and gelatinization. This is useful for improving the textural and shelf-life properties of popped finger millet flour because it may preferentially absorb free water in the popped finger millet product and release it later during storage hence retaining the texture of baked products (Dharmaraj *et al*., 2012)

4.7.2 Swelling Power

Swelling power refers to the ability to absorb water and increase in volume or physical size (Ramashia *et al.*, 2017). The swelling power of finger millet results are shown in Table 8. Pressure did not significantly affect the swelling power of popped finger millet ($P>0.05$) moisture and pressure-moisture interaction effects were significant ($p\leq0.05$). A general increase in the swelling power was observed when the moisture content was raised from 15% to 18% or 21%. This could be attributed to the increasing grain porosity of the matrix that is formed when starch is gelatinized. High swelling power makes the popped grain flour suitable for use as a low-calorie food (Dharmaraj *et al*., 2012).

4.7.3 Bulk Density

Bulk density measures how much mass of flour fits into a given volume (Farid *et al*., 2022). It influences its packaging properties and material handling and as such, flour with a high bulk density necessitates packing in a constant volume (June *et al*., 2019). The bulk density of popped finger millet flour observed was in the ranged between 0.31 to 0.48 g/mL (Table 8). Significant effects ($p\leq0.05$) due to pressure, moisture, and pressure-moisture interactions were observed. The bulk density generally dropped when the pressure and moisture were increased from 120 psi to 140 psi or 160 psi and 15% to 18% and 21 % respectively. The observed decrease in bulk density with increasing popping pressure and moisture content can be attributed to enhanced expansion and structural changes within the grain during popping. (Athmaselvi, 2019; (Chanda *et al*., 2014)

Bulk density reflects the load that the flour samples can sustain if allowed to rest directly on one another. Flour with low bulk density would be suitable for preparing instant foods, complementary and weaning foods while that with high bulk density would be suitable in food preparation (Snr *et al*., 2022). In comparison, the bulk density of raw finger millet flour ranged from 0.54-0.67 g/ml (Gull *et al*., 2015), indicating a notable difference between raw and popped flour, likely due to processing conditions such as pressure and moisture levels.

4.8 Viscosity of Popped Finger Millet Flour

The viscosity of cold uncooked paste ranged from 30.00 - 66.67 Mpa (Table 4.7). Hot paste and cooled cooked viscosities ranged from 86.67-230 and 180.00-363.33 MPa, respectively. Significant differences ($p \leq 0.05$) due to the effects of pressure and moisture and their interactions were observed in cold uncooked and hot paste (Table 8). For cooked and cooled paste, pressure and pressure-moisture interactions had a significant effect ($p \leq 0.05$) on the results whereas moisture had no significant effect ($p > 0.05$).

Table 4.7: Viscosity of Popped Finger Millet Flour

Pressure (psi)	**Moisture (%)**	**Cold paste at 30 °C**	**Hot paste at 95°C**	**Cooked and cooled paste at 30⁰C**
120	15	30.00 ± 0.01^{a}	130.00 ± 0.01^{c}	183.33 ± 11.55^{c}
120	18	50.00 ± 0.01^{c}	180.00 ± 0.01^{d}	226.67 ± 5.77^{d}
120	21	60.00 ± 0.01^{d}	100.00 ± 10.00^{a}	240.00 ± 10.00^{ab}
140	15	30.00 ± 0.01^{a}	86.67 ± 10.00^{a}	180.00 ± 10.00^{c}
140	18	30.00 ± 0.01^{a}	110.00 ± 10.00^{b}	246.67 ± 5.77^{ab}
140	21	36.60 ± 5.78^{b}	230.00 ± 0.01^{e}	260.00 ± 0.01^{b}
160	15	40.00 ± 0.01^{b}	90.01 ± 0.01^{a}	206.67 ± 5.77^{cd}
160	18	50.00 ± 0.01^{c}	90.01 ± 0.01^{a}	250.00 ± 0.01^{ab}
160	21	66.67 ± 5.77^{e}	90.01 ± 0.01^{a}	363.33 ± 25.16^{e}
P Values	Pressure	<0.001	<0.001	<0.001
	Moisture	<0.001	<0.001	0.182
	Pressure. Moisture	<0.001	<0.001	<0.001

Values based on means ± SD of triplicate measurements. Mean values in the same column with the same letter are not significantly different in each column ($p \leq 0.05$).

A general rise in viscosity was observed when pressure and moisture content were progressively raised from 120 to 160 psi and 15% to 21 % respectively. This could be due to the elevated levels of starch damage, gelatinization and water absorption capacity that occur when both pressure and moisture content are increased. Heat-induced protein-fiber interactions during popping could have improved the water binding capacities of the flour, contributing to the increased viscosity of the flour. The cold paste viscosities were lower than cooked paste viscosities due to the presence of unprocessed carbohydrates in their original unaltered form (Singh *et al*., 2007). Low viscosity indicates the presence of unprocessed low molecular weight carbohydrates. Low molecular weight carbohydrates have less water binding capacity and may be more readily digested and absorbed as required by infants (Snr *et al*., 2022)

4.9 Particle Size Distribution of Popped Finger Millet Flour

The particle size distribution of flour determines the general use and functionality of flour (Hasmadi *et al*., 2020). Milling influences the extent of starch damage and it has been linked to water absorption capacity. The particle size of flour is an essential consideration in food formulation as it affects flour functionality. As such, finer flours are used in the preparation of smooth-textured products such as weaning foods and porridge whereas flour with larger particles is used to formulate coarse-textured products such as baked goods and snack coatings (Oyeyinka & Bassey, 2025). Flour particle size affects bulk density (Abah *et al*., 2020). The flour particle size with the highest proportion for all treatments was below 250 µm (Table 4.7).

Pressure, moisture content, and their interactions had significant effects ($p \leq 0.05$) on the particle size distribution of popped finger millet flour. The proportions of flour with sizes of 1mm and 750 µm increased when pressure and moisture content were increased from 120 psi to 140 psi or 160 psi, and 15 % to 18 % or 21 %, respectively. For 500 µm flour size, the proportions decreased when pressure and moisture were increased from 120 psi to 140 psi or 160 psi, and 15 % to 18 % or 21 %, respectively. On the other hand, the proportions of 250µm flour size generally increased when the pressure was increased from 120 psi to 140 psi or 160 psi.

When moisture content increases, the starch granules absorb more water, making them more prone to expansion and fragmentation under heat and pressure. This results in finer flour particles after milling, as the expanded grain structure is more brittle and easier to break down.

When popping pressure is raised, the grain undergoes rapid expansion, creating a more porous and less dense structure. The larger, more expanded grains are harder to break into uniform fine particles during milling, leading to a broader particle size with more coarse particles. Excessive pressure can cause over-fragmentation, producing a mixture of both fine and coarse particles (Swarnakar *et al.,* 2022).

Table 4.7: Particle Size Distribution of Popped Finger Millet Flour

Pressure (psi)	Moisture (%)	2 mm	1 mm	750 µm	500 µm	250 µm	<250µm
120	15	0.099±0.00[a]	0.18±0.01[c]	3.00±0.00[c]	16.275±0.24[b]	24.32±0.023[c]	56.20±0.05[c]
120	18	0.009±0.00[d]	0.52±0.01[b]	5.52±0.03[a]	12.65±0.037[f]	20.44±0.036[ab]	60.74±0.63[ab]
120	21	0.022±0.00[e]	0.69±0.01[d]	7.32±0.01[g]	11.14±0.033[e]	22.73±0.028[ac]	57.73±0.38[cd]
140	15	0.104±0.01[a]	0.47±0.01[a]	4.86±0.04[f]	13.81±0.001[g]	20.16±0.004[ab]	60.7±0.01[ab]
140	18	0.104±0.00[a]	0.50±0.00[ab]	2.92±0.03[b]	8.57±0.015[a]	18.05±0.009[b]	69.69±0.005[e]
140	21	0.054±0.00[b]	1.33±0.01[g]	7.91±0.02[h]	9.83±0.1[d]	21.65±0.841[abc]	59.23±0.86[bd]
160	15	0.190±0.00[c]	0.99±0.01[e]	3.66±0.01[d]	12.74±0.03[b]	20.72±0.17[abc]	61.99±0.07[a]
160	18	0.185±0.003[c]	1.20±0.001[f]	4.67±0.005[e]	8.53±0.039[a]	19.95±0.02[ab]	68.72±0.22[e]
160	21	0.055±0.003[b]	3.74±0.024[h]	5.53±0.033[a]	6.95±0.006[c]	23.58±3.453[ac]	61.26±0.94[a]
P Values	Pressure	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
	Moisture	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
	Pressure. Moisture	<0.001	<0.001	<0.001	<0.001	0.0499	<0.001

Values based on means ± SD of triplicate measurements. Mean values in the same column with the same letter are not significantly different in each column ($p \leq 0.05$).

4.10 Colour Properties of Popped Finger Millet Flour

The lightness, redness, and blueness of flour ranged between 71-76.2, 1.83-2.93, and 8.37-10.27 respectively (Table 4.8). Moisture content had a significant ($p \leq 0.05$) effect on lightness whereas pressure and pressure moisture interactions did not cause significant differences. Pressure, moisture content, and pressure-moisture content interactions caused significant ($p \leq 0.05$) differences in the redness and yellowness of popped finger millet flour. The lightness of popped finger millet flour decreased when the pressure and moisture content were increased from 120 psi to 140 psi or 160 psi, and from 15 % to 18% or 21%. This can be attributed to the increased extent of browning when starch is exposed to heat and cooking, they undergo Maillard reaction and caramelization (Saraswathi & Rs, 2022)

Table 4.8: Colour Properties of Popped Finger Millet Flour

Pressure (psi)	Moisture (%)	L*	a*	b*	Chroma	Hue angle	Color difference	Browning index
120	15	75.37±0.11^{a}	2.23±0.15^{ac}	10.03±0.5^{a}	10.28±0.49^{ab}	77.43±1.11^{abd}	6.28±0.28^{a}	3.43±0.15^{ab}
120	18	76.2±0.17^{a}	2.3±0.17^{ac}	8.9±0.3^{b}	9.19±0.25^{c}	73.69±2.91^{ce}	4.90±0.10^{c}	3.25±0.09^{a}
120	21	72.67±0.40	2.93±0.06d	8.37±0.06^{b}	8.86±0.07^{c}	70.68±0.30^{e}	7.75±0.41^{b}	4.02±0.08^{c}
140	15	75.67±0.21^{a}	2.07±0.06^{ab}	10.4±0.10^{ac}	10.60±0.11^{bc}	78.76±0.22^{ab}	6.33±0.07^{a}	3.32±0.06^{ab}
140	18	75.7±0.1^{a}	2.03±0.06^{ab}	9.7±0.01^{ad}	9.91±0.01^{ad}	78.16±0.33^{ab}	5.80±0.07^{ad}	3.19±0.09^{a}
140	21	75.7±0.36^{a}	2.5±0.20^{c}	9.0±0.26^{bd}	9.34±0.20^{cd}	74.43±1.61^{cd}	5.36±0.43^{cd}	3.70±0.17^{bc}
160	15	74.23±0.61^{b}	2.1±0.01^{ab}	11.0±0.26^{c}	11.19±0.26^{e}	79.18±0.25^{ab}	7.77±0.29^{b}	3.49±0.02^{ab}
160	18	74.06±0.15^{b}	1.83±0.12^{b}	10.27±0.06^{ac}	10.43±0.08^{ab}	79.88±0.57^{b}	7.38±0.09^{b}	3.39±0.30^{ab}
160	21	71±0.44^{c}	2.57±0.06^{c}	10.03±0.16^{a}	10.36±0.12^{ab}	75.65±0.16^{acd}	9.91±0.41^{e}	4.0±0.09^{c}
P Values	Pressure	0.1290	<0.001	<0.001	<0.001	<0.001	<0.001	0.0091
	Moisture	0.0003	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
	Pressure. Moisture	0.9338	0.0733	0.1238	0.1475	0.0506	<0.001	0.5680

Values based on means ± SD of triplicate measurements. Mean values in the same column with the same letter are not significantly different in each column ($p \leq 0.05$).

Chroma and hue angles of popped finger millet flour ranged between 8.86-11.19 and 73.69-79.88 respectively (Table 4.8). There were significant differences observed ($p \leq 0.05$) due to the effect of pressure and moisture content on the chroma and hue angles while their interaction had no significant effect on these parameters. There was a general decline in hue angle when pressure and moisture were raised from 120 to 140 or 160 psi and 15 % to 18 or 21% respectively. The hue angle was tending towards yellow (90^{o}). Chroma increased when pressure was increased from 120 to 140 or 160 psi and declined when moisture content was increased from 15% to 18% and 21% moisture content.

The total color difference of popped finger millet flour ranged between 4.90.10-9.91 (Table 4.8). Significant ($p \leq 0.05$) differences due to pressure, moisture, and pressure moisture interactions were observed in the color differences for popped finger millet flour. The total color difference was increased when the pressure was increased from 120 psi to 160 psi, and moisture content increased from 15% to 21%.

Browning index indicates non-enzymatic reactions that take place in food due to protein and starch interactions and is obtained using colour changes during processing (Dharshini & Meera, 2023). The browning index of popped finger millet flour ranged from 3.19 to 4.02 (Table 4.8). Pressure and moisture content had significant effects ($p \leq 0.05$) on the browning indices of popped finger millet flour whereas pressure and moisture content interaction had no significant effect($p > 0.05$). When the lightness increased for both popped grain and flour, the browning index dropped. There was a significant effect ($p \leq 0.05$) of pressure on the browning index of popped millet grain. Moisture and pressure moisture interactions had no significant effect ($p > 0.05$) on the browning index of popped finger millet grain. This could be attributed to the greater extent of Maillard and caramelization reactions that occurred when the puffing pressures and moistures were raised. In a study to evaluate the influence of popping and milling on the chemical properties of finger millet, Dharshini and Meera, (2023) obtained a browning index of 5.59 after popping finger millet grains on dry heat on an open pan and also observed a drop in browning index when lightness rose.

4.11 Colour Properties of Finger Millet-Based Cereal Bar

The colour properties of popped finger millet-based cereal bars are illustrated in Table 4.9. The lightness ranged between 26.03 and 41.33. The lightness, redness, yellowness and hue angles were significantly different (P≤0.05). The lightness, yellowness and hue angle generally increased when the proportion of honey were progressively raised from 0% to 50% and simultaneous decrease of guar gum from 50% to 10%. B1, B2 and B3 with hue angles of 38.72 (yellow-orange), 46.01(yellow-orange) and 51.02 (yellow) respectively and would be perceived to be dark-brown. Cereal bars B4 and B5 with hue angles of 67.44 (yellow-green) and 61.49 (yellow green) respectively and would be perceived to be light-brown. The redness generally decreased when guar gum proportions were progressively lowered from 50% to 10% with concurrent addition of honey from 0% to 50%. There were no significant differences (P>0.5) in chroma values. Colour is a critical sensory parameter as it contributes to the physical appearance and acceptance by consumers as it is the first feature that attracts buyers (Dharshini & Meera, 2023).

Table 4.9: Colour Properties of Finger Millet-Based Cereal Bar

Cereal bar	L* value	a* value	b* value	Hue Angle	Chroma
B1	26.03±0.25^{a}	9.10±1.473^{b}	7.23±0.50^{a}	38.72±3.10^{a}	11.63±1.43^{a}
B2	31.30±0.89^{a}	8.07±0.42^{b}	8.37±0.57^{a}	46.01±1.68^{ab}	11.63±0.62^{a}
B3	31.23±2.69^{a}	7.33±1.50^{ab}	9.00±0.79^{ab}	51.02±6.52^{bc}	11.66±1.07^{a}
B4	41.33±2.23^{b}	4.43±0.23^{a}	10.70±0.63^{b}	67.44±2.05^{d}	11.57±0.52^{a}
B5	41.03±1.84^{b}	4.93±0.70^{a}	9.10±1.18^{ab}	61.49±3.09^{cd}	10.36±1.26^{a}
P value	<0.001	<0.001	0.0037	<0.001	0.5061

Values based on mean±SD of triplicate measurements. Values on the same column with different superscripts are significantly different (P≤0.05).

B1: Cereal bar containing 50% finger millet pops, 50% guar gum, and 0% honey.
B2: Cereal bar containing 50% finger millet pops, 40% guar gum, and 10% honey.
B3: Cereal bar containing 50% finger millet pops, 30% guar gum, and 20% honey.
B4: Cereal bar containing 50% finger millet pops, 20% guar gum, and 30% honey.
B5: Cereal bar containing 50% finger millet pops, 10% guar gum, and 40% honey.

4.12 Water Activity, Bulk Density and Texture of Finger Millet-Based Cereal Bar

The water activity of popped finger millet-based cereal bars ranged from 0.391 to 0.776 (Table 4.10). Significant differences among the bars were observed ($P \leq 0.05$). Water activity decreased when honey proportion was progressively raised from 0% to 40% with simultaneous progressive lowering of guar gum proportion from 50% to 10%. B1 and B2 had significantly higher ($P \leq 0.05$) water activities than B3, B4 and B5. This could be attributed to the higher proportion of guar gum that had been constituted with water.

Table 4.10: Water Activity, Bulk Density and Texture of Finger Millet-Based Cereal Bars

Cereal bar	Water activity	Bulk density (g/ml)	Texture (Force, N)
B1	0.776 ± 0.005^{d}	0.3725 ± 0.0229^{a}	0.3366 ± 0.015^{b}
B2	0.743 ± 0.002^{c}	0.3442 ± 0.0006^{a}	0.2233 ± 0.011^{a}
B3	0.557 ± 0.004^{b}	0.3431 ± 0.0113^{a}	0.2367 ± 0.006^{a}
B4	0.392 ± 0.001^{a}	0.2816 ± 0.0026^{b}	0.2233 ± 0.006^{a}
B5	0.391 ± 0.001^{a}	0.2368 ± 0.0005^{a}	0.1433 ± 0.005^{c}
P value	<0.001	<0.001	<0.001

Values based on mean±SD of triplicate measurements. Values on the same column with different superscripts are significantly different ($P \leq 0.05$).

B1: Cereal bar containing 50% finger millet pops, 50% guar gum, and 0% honey.
B2: Cereal bar containing 50% finger millet pops, 40% guar gum, and 10% honey.
B3: Cereal bar containing 50% finger millet pops, 30% guar gum, and 20% honey.
B4: Cereal bar containing 50% finger millet pops, 20% guar gum, and 30% honey.
B5: Cereal bar containing 50% finger millet pops, 10% guar gum, and 40% honey.

Water activity is not the only indicator of microbial safety because there are other factors such as pH, salt, sugar and honey that can also provide preservative effects either alone or in combination (Ryland, 2003). (Ryland, 2003) obtained a water activity range of 0.454-0.622 in micronized flaked lentil-based snack bar. Water activity of below 0.78-0.80 can limit microbial growth and toxin production (Ryland, 2003). Cereal bars are generally formulated to have a water activity level of 0.65 (Loveday *et al*., 2009). The finger millet based cereal bars formulated re therefore within the safe levels of water activity.

Bulk density and texture ranged from 0.2368±0.0005 g/ml to 0.3725±0.0229 g/ml and 0.1433 N to 0.3366 N respectively (Table 13). Bulk density and texture declined when honey proportion was progressively raised from 0% to 40% with simultaneous progressive lowering of guar gum proportion from 50% to 10%. Significant differences (P≤0.05) were observed. Bulk density is an indicator of heaviness and has an influence on product handling and packaging. Products with low bulk density require larger packaging for the same weight compared to high-density products. Products with higher bulk density tend to flow more easily through processing and packaging equipment, reducing blockages and downtime (R. Singh *et al*., 2021). The textures were generally low indicating that the bars were not hard. This can be attributed to the popping of grain that greatly expanded the product, affecting its crispiness causing a decline in the hardness of the final product (Momanyi *et al*., 2020). Moreover, the snack's relatively low fibre content (2.31-2.70g/100g) may have contributed to its reduced hardness. Previous studies have indicated that higher levels of fibre tend to increase the hardness of snacks, as they interfere with the continuous matrix of the product, limiting its ability to expand and maintain an elastic texture during processing (Dlamini, 2016).

4.13 Proximate Composition of Cereal Bars

Proximate values for the cereal bars are illustrated in Table 4.11. The moisture content for the cereal bars ranged from 3.47% and 11.35%. Moisture content influences the shelf-life stability, texture properties and bulk density. This range is within the range for safe storage. Cereal bars are formulated to achieve a moisture of 10-15% to ensure its safety during storage (Loveday *et al*., 2009). Low moisture content additionally gives the cereal bars a low bulk density and crunchy texture (Momanyi *et al*., 2020). Crude fiber and crude ash ranged from 2.31%-2.70% and 1.44%-2.13% respectively, crude protein ranged from 7.17% to 8.39%, carbohydrate content ranged from 70.02% to 78.24%. while the total energy ranged between 338.13 kcal/100g and 376.87 kcal/100g. Significant (p≤0.05) differences were observed in the results. A decrease in ash and protein content was observed was observed when the levels of guar gum were decreased progressively from 50% to 10%. Guar gum enhanced the protein content of the cereal bars. Carbohydrate is one of the major macronutrients of concern in regards to the prevention of Protein-Energy malnutrition. It is the main source of energy and critical in proper blood sugar control (Fao & Consultation, 2005). Carbohydrates provide energy to the cells particularly the brain cells that require glucose for metabolism. Crude fat content significantly ($p \leq 0.05$) rose when the levels of honey were progressively increased from 0% to 40%. A similar trend was observed by (Demirci *et al.*, 2014). The significant increase ($p \leq 0.05$) in crude fat content with increasing levels of honey (0–40%) may be attributed to the presence of minor lipophilic constituents in honey, including waxes and trace fatty substances, which can be co-extracted during crude fat determination. Although honey is predominantly composed of carbohydrates, these minor components may contribute to the measured fat content as their proportion increases in the formulation (Bogdanov et al., 2008). The low fat content in this cereal bar is ideal for individuals who prefer to avoid snacks often associated with high levels of saturated fats. The total energy values increased when honey was progressively increased from 0% to 40% with concurrent reduction of guar gum from 50% to 10%. Energy is essential for sustaining the body's metabolic rate, supporting growth, promoting the synthesis of new tissues, enabling muscular activity, and maintaining physiological functions. Daily energy intake and requirements are determined by factors such as physical activity level, age, body mass index (BMI), and basal metabolic rate (BMR) (Fao & Consultation, 2005).

The combination of finger millet and guar gum provides a moderate amount of plant-based protein, essential for tissue repair and growth. Finger millet provides a moderate amount of plant-based protein, essential for tissue repair and growth. It supplies both simple and complex carbohydrates, offering immediate and sustained energy release. Its dietary fiber content supports digestive health and helps regulate blood sugar levels. Finger millet's rich mineral profile, especially calcium, contributes to bone health (Devi *et al*., 2014).

Finger millet-based foods are considered to have lower glycemic responses and have been recommended for individuals living with diabetes (Devi *et al*., 2014). Dietary fiber imparts a functional benefit such as lower digestibility. Whole grains are considered as healthier options compared to polished grains when glycemic response is concerned (Shobana *et al*., 2017). Products with low glycemic responses has been associated with a reduced risk of chronic illnesses (Barclay *et al*., 2008). Finger millet-based cereal bars provide a healthier alternative for managing chronic illneses like diabetes and obesity.

Honey is majorly composed of fructose and glucose that provide an immediate natural source of energy. It also contains enzymes that aid in carbohydrate digestion and has antioxidant properties (Ajibola *et al*., 2012). Guar gum is a polysaccharide seed flour extracted from the endosperm of *Cyamopsis tetragonoloba* L that has been used as a binder in food products (Tahmouzi *et al*., 2023). Besides its binding property, guar gum has 5-6 % protein, low calories and its fiber gives a feeling of satiety and can benefit people living with type II diabetes by moderating blood sugar spikes (Amir *et al.,* 2013). Its inclusion in the cereal bar improves texture and enhances protein content, contributing to its overall nutritional value (Tahmouzi *et al*., 2023).

The cereal bar formulated with popped finger millet, guar gum, and honey offers a nutritious snack that supports bone health, aids digestion, provides sustained energy, and contributes to overall well-being.

Table 4.11: Proximate Composition of Finger Millet-Based Cereal Bars

Cereal bar	Moisture (%)	Crude ash (%)	Crude fiber (%)	Crude fat (%)	Crude protein (%)	Carbohydrate (%)	Total energy (Kcal/100g)
B1	11.35 ± 0.01^{a}	2.13 ± 0.03^{d}	2.70 ± 0.01^{b}	0.58 ± 0.01^{a}	8.39 ± 0.05^{b}	70.02 ± 0.55^{c}	338.13 ± 0.25^{a}
B2	10.55 ± 0.26^{b}	1.95 ± 0.01^{a}	2.31 ± 0.02^{a}	0.88 ± 0.02^{b}	6.97 ± 0.60^{a}	73.86 ± 0.97^{d}	345.11 ± 0.89^{b}
B3	7.63 ± 0.38^{c}	1.97 ± 0.01^{a}	2.33 ± 0.01^{a}	0.92 ± 0.01^{c}	7.04 ± 0.72^{a}	76.30 ± 0.97^{a}	356.85 ± 1.67^{c}
B4	5.29 ± 0.17^{d}	1.70 ± 0.02^{c}	2.33 ± 0.02^{a}	1.05 ± 0.00^{d}	7.59 ± 0.34^{ab}	76.96 ± 0.09^{ab}	367.97 ± 0.84^{d}
B5	3.47 ± 0.18^{e}	1.44 ± 0.02^{b}	2.31 ± 0.01^{a}	1.14 ± 0.01^{e}	7.17 ± 0.59^{a}	78.24 ± 0.71^{b}	376.87 ± 0.78^{e}
P value	<0.001	<0.001	<0.001	<0.001	0.0497	<0.001	<0.001

Values based on mean±SD of triplicate measurements. Values on the same column with different superscripts are significantly different ($P\leq0.05$) **B1:** Cereal bar containing 50% finger millet pops, 50% guar gum, and 0% honey.

B2: Cereal bar containing 50% finger millet pops, 40% guar gum, and 10% honey.

B3: Cereal bar containing 50% finger millet pops, 30% guar gum, and 20% honey.

B4: Cereal bar containing 50% finger millet pops, 20% guar gum, and 30% honey.

B5: Cereal bar containing 50% finger millet pops, 10% guar gum, and 40% honey.

4.14 Microbial Quality and Sensory Properties of Popped Finger Millet-Based Cereal Bars

Microbial evaluation of food reveals important insights about their safety and quality *(Gitahi et al.*, 2012). Total viable count reflects the general microbial population in the samples. High counts usually indicate poor hygiene practices at production, handling or storage. The results for microbial analysis of the cereal bars are shown in Table 4.12.

Table 4.12: Microbial properties of finger millet-based cereal bars

Cereal bar	Total viable count (log CFU/g)	Total coliforms (log CFU/g)	Staphylococcus aureus (log CFU/g)	Yeast and mold (log CFU/g)
B1	2.4183±0.10[abc]	ND	0.6667±0.09[a]	0.667±1.32[a]
B2	2.5603±0.07[bc]	ND	ND	0.667±1.32[a]
B3	2.7253±0.05[c]	ND	ND	ND
B4	2.3597±0.10[ab]	ND	ND	ND
B5	2.2007±0.17[a]	ND	2.1±0.16[b]	1.434±1.16[a]
P value	0.0014	ND	0.0022	0.3838

Values based on mean±SD of triplicate measurements. Values on the same column with different superscripts are significantly different ($P \leq 0.05$).

B1: Cereal bar containing 50% finger millet pops, 50% guar gum, and 0% honey.
B2: Cereal bar containing 50% finger millet pops, 40% guar gum, and 10% honey.
B3: Cereal bar containing 50% finger millet pops, 30% guar gum, and 20% honey.
B4: Cereal bar containing 50% finger millet pops, 20% guar gum, and 30% honey.
B5: Cereal bar containing 50% finger millet pops, 10% guar gum, and 40% honey.

The total viable count ranged between 2.2007 Log CFU/g-2.7253 Log CFU/g and were significantly ($P \leq 0.05$) different (Table 4.12). These levels were below the acceptable limits of 3-5 log CFU/g for ready-to-eat foods (Gitahi et al., 2012). Total coliforms are indicators of faecal contamination or poor sanitary conditions during production, handling or storage (Mwove *et al.*, 2022). Total coliforms were not detected in all samples ascertaining those sanitary conditions were satisfactory. *Staphylococcus aureus* is a common food pathogen that produces heat-resistant toxins that cause food poisoning. *Staphylococcus aureus* count was 0.6667 Log CFU/g and 2.1 Log CFU/g in B1 and B5 cereal bars respectively and was not detected in B2, B3 and B4. Presence of Staphylococcus aureus in B1 and B5 can be attributed to possible lapses in hygiene practices that led to contamination. Staphylococcus aureus is present in the environment and can contaminate food surfaces, hands and equipment. (Mwove *et al*., 2022). The acceptable limit for Staphylococcus aureus in ready-to-eat foods should be less than 1 log CFU/g (KEBS, 2013). While repeating the development under stricter hygienic conditions could reduce microbial load, this was not conducted due to resource and time limitations. The observation highlights the importance of good manufacturing practices (GMP) for safe commercialization (Geraldo *et al*., 2024) . Cereal bar B5 was offered to panelists, although its *S. aureus* load (2.1 ± 0.16 log CFU/g) exceeded the recommended limit of 1 log CFU/g for ready-to-eat foods. While this presents a potential food safety concern, the exposure was limited to a controlled sensory evaluation, and no adverse effects were reported. Yeast and molds grow in poorly handled and stored foods causing spoilage, off-flavors and potential health hazards if mycotoxins and produced. Yeast and mold were not detected in cereal bars B3 and B4, but were detected in B1, B2 and B5 at 0.667 Log CFU/g and 1.434 Log CFU/g respectively. The acceptable limit for yeast and molds is 2-3 log cfu/g in ready-to-eat foods (KEBS, 2013). The cereal bars were within the acceptable limits for yeast and mold.

Sensory testing is important for establishing the level of liking and improving and selecting cereal bars that were most preferred. Popping generally imparts a desirable aroma in products, making them highly acceptable (Bunkar *et al.*, 2014). The acceptability of food largely depends on flavor, texture, appearance and taste (Shobana *et al*., 2018).The hedonic scores obtained ranged from dislike slightly to like moderately: appearance 6.10-7.34, flavour 5.03-7.34, taste 4.89-7.31, texture 5.38-6.66 and overall acceptance 5.24-7.41 as presented in Table 4.13.

Table 4.13: Sensory Properties of Finger Millet Based Cereal Bars

Sample ID	Appearance	Flavor	Taste	Texture	Overall acceptance
B1	7.34±1.73[a]	7.34±1.43[a]	7.31±1.86[a]	6.66±1.82[a]	7.41±1.73[a]
B2	6.10±1.67[b]	5.03±1.90[b]	4.89±2.00[b]	5.38±1.88[a]	5.24±1.96[b]
B3	6.21±1.44[ab]	6.07±1.73[ab]	6.44±1.54[a]	5.89±1.37[a]	6.38±1.37[ab]
B4	7.07±1.60[ab]	6.93±1.96[a]	7.14±1.30[a]	6.59±1.74[a]	7.21±1.39[a]
B5	7.34±1.63[a]	7.34±1.69[a]	7.31±1.75[a]	6.66±1.89[a]	7.41±1.82[a]
P value	0.0028	<0.001	<0.001	0.0185	<0.001

Values based on mean±SD of triplicate measurements. Values on the same column with different superscripts are significantly different (P≤0.05).

B1: Cereal bar containing 50% finger millet pops, 50% guar gum, and 0% honey.
B2: Cereal bar containing 50% finger millet pops, 40% guar gum, and 10% honey.
B3: Cereal bar containing 50% finger millet pops, 30% guar gum, and 20% honey.
B4: Cereal bar containing 50% finger millet pops, 20% guar gum, and 30% honey.
B5: Cereal bar containing 50% finger millet pops, 10% guar gum, and 40% honey.

B1 and B5 were the most preferred in terms of appearance, flavour, taste, texture and overall acceptance as compared to B2, B3 and B4. Significant differences were observed among the treatments (P≤0.05). The cereal bars were generally accepted by the panelists because their overall acceptability was greater than 5.5. This gives an impression of a good quality product (Momanyi et al., 2020). The difference in the appearance, flavour, taste, texture and overall acceptance could be attributed to the varied concentrations of honey and guar gum that were used in formulating the bars. B1 had 50% popped finger millet, 50% guar gum and 0% honey. B5 had 50% popped finger millet, 10% guar gum and 40% honey. Hedonics is a subjective method that is based on pleasure. The output can be influenced by the sensory properties of the food, consumer expectations, culture and physiological states such as hunger, illness and thirst (Shobana *et al*., 2018).

CHAPTER FIVE

CONCLUSION AND RECOMMENDATIONS

5.1 Conclusion

The results demonstrated that popping conditions significantly influenced the physical properties of finger millet grains. Increasing both *moisture* content and popping pressure resulted in higher expansion ratios and popping yields, alongside a notable reduction in bulk density. These changes can be attributed to increased internal steam pressure during popping, which promotes structural expansion and the formation of porous matrices. The observed microstructural modifications further confirmed the development of expanded and less compact grain structures, which are desirable characteristics in ready-to-eat products. These findings led to the rejection of the first null hypothesis, confirming that popping conditions have a significant effect on the physical attributes of finger millet.

In addition to physical changes, popping significantly altered the physicochemical and nutritional composition of finger millet. The study revealed that protein content increased with increasing pressure, while essential minerals such as iron and zinc were enhanced. At the same time, antinutritional factors, including phytates and tannins, were significantly reduced as a result of the popping process. This reduction improves mineral bioavailability and overall nutritional quality. Moisture and crude fat contents decreased, contributing to improved shelf stability of the processed product. Functional properties such as water absorption capacity, swelling power, and viscosity were also significantly improved, indicating enhanced suitability for various food applications. These findings resulted in the rejection of the second null hypothesis, as popping conditions were shown to significantly influence both nutritional and functional properties.

The development and evaluation of popped finger millet-based cereal bars further demonstrated the practical applicability of the popped finger millet grain. The cereal bars exhibited acceptable physicochemical properties, including water activity levels within safe limits for ready-to-eat foods. The incorporation of honey positively influenced product quality by improving color, texture, and overall palatability, while also contributing to reduced water activity and bulk density. Microbiological analysis indicated that the products were generally safe for consumption, as total viable counts were within acceptable limits and coliforms were absent, reflecting good hygienic practices during processing. Although *Staphylococcus aureus* was detected in some samples, there were no reported cases of foodborne illness. Sensory evaluation revealed that the cereal bars were well accepted, with specific formulations achieving high scores in taste, flavor, and overall acceptability. These results led to the rejection of the third null hypothesis, confirming that acceptable and safe cereal bars can be developed from popped finger millet.

Overall, this study establishes that popping is an effective value-addition technique that significantly improves the physical, nutritional, and functional properties of finger millet while enabling the development of acceptable ready-to-eat products. The findings highlight the potential of finger millet as a nutrient-dense, climate-resilient crop that can contribute to dietary diversification and food security. The successful development of cereal bars further demonstrates its applicability in modern food systems, particularly in meeting the growing demand for convenient and health-promoting foods.

5.2 Recommendations

There is a need for further research to optimize popping conditions at an industrial scale, with emphasis on scalability and commercialization. Future studies should investigate continuous processing systems that can be adapted for commercial production, alongside detailed assessments of energy efficiency, process yield, and cost implications. These parameters are critical for determining the economic viability of large-scale adoption. In addition, product development should be expanded to include diversified food applications such as breakfast cereals, baked products, and extruded snacks. Formulation studies incorporating legumes and other nutrient-rich ingredients are also recommended to improve protein quality, amino acid balance, and micronutrient density, thereby enhancing both nutritional and functional properties of the final products.

Furthermore, future studies should consider sourcing finger millet from well-defined ecological zones. This would allow for better understanding of how agro-ecological conditions influence physicochemical properties, nutritional composition, and popping quality. Such location-specific research would also improve traceability and strengthen the scientific validity of comparisons across studies. This approach would be particularly valuable in addressing limitations associated with market-sourced samples of unknown origin, as was the case in the present study.

Further research should also prioritize shelf-life evaluation as a central component of product development. Given that microbial analysis was conducted in this study, future work should extend these findings by investigating microbial stability, physicochemical changes (such as moisture uptake, rancidity, and texture degradation), and sensory quality over time under different storage conditions. These studies should also include packaging trials to identify suitable materials and storage environments that ensure product safety and quality retention throughout its shelf-life.

From a food safety perspective, the detection of Staphylococcus aureus highlights the urgent need for improved hygienic controls across the value chain. It is therefore recommended that strict adherence to Good Manufacturing Practices (GMP) and Hazard Analysis and Critical Control Point (HACCP) systems be enforced, particularly for ready-to-eat millet-based products. Regulatory agencies should strengthen monitoring and enforcement mechanisms to ensure compliance with food safety standards.

At the policy level, more explicit interventions are required to support the integration of finger millet into mainstream food systems. Governments and relevant stakeholders should promote finger millet through value chain development policies that support production, processing, and marketing. Inclusion of finger millet in institutional feeding programs such as schools, hospitals, and relief food systems is strongly recommended to improve nutrition security while creating stable market demand. Additionally, public awareness campaigns should be implemented to promote the nutritional and climate-resilient benefits of finger millet, thereby encouraging its consumption as part of diversified diets.

Consumer and market-oriented studies are also necessary to support commercialization. Future research should assess consumer acceptability, purchasing behavior, and market segmentation across different demographic groups to inform effective product positioning and scaling strategies.

Finally, sustainability and socio-economic development should be emphasized through policies that encourage smallholder farmers to cultivate finger millet, particularly in drought-prone regions. Strengthening linkages between farmers, researchers, food processors, and government institutions will be essential in building a resilient and inclusive finger millet value chain. Dissemination of research findings through scientific publications, stakeholder workshops, and industry partnerships will further support knowledge transfer and innovation.

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APPENDICES

Appendix I: Sensory Evaluation Form

SENSORY EVALUATION QUESTIONNAIRE FOR CEREAL BAR

RECORDING SHEET

Date:

Panelist name: **Gender:**

Age group (Tick as appropriate): <20: 20-30: 30-40: 40-50: 50-60: >60:

You are provided with coded cereal bars. Please examine, taste, smell, and score them for the selected parameters from 1-9 in the table provided based on how best you feel about them.

1. Dislike extremely 2. Dislike very much 3. Dislike moderately 4. Dislike slightly 5. Neither like nor dislike 6. Like slightly 7. Like very much 8. Like very much 9. Like extremely

SAMPLE CODE	APPEARANCE	FLAVOR	TASTE	TEXTURE	OVERALL ACCEPTABILITY

Appendix II: Abstract of Published Journal

Effect of pressure and moisture content on physicochemical properties of popped finger millet (*Eleusine coracana*)

Abstract

Finger millet (Eleusine coracana) is a nutritious grain whose traditional processing methods have received inadequate application in modern processing to enhance its commercialization. This study investigated how pressure and moisture content affected the puffing yield, density, expansion ratio, colour, proximate composition, selected minerals and antinutritive factors of popped finger millet grain. Grains were equilibrated at 15,18, or 21% moisture content and popped at 120, 140, or 160 psi. The results show that progressively raising the moisture content and pressure significantly ($p \leq 0.05$) increased the popping yield and expansion ratio while reducing density. Pressure and moisture content interactions significantly ($p \leq 0.05$) influenced the popping yield, expansion ratio and density. Popped grain lightness and total colour difference significantly ($p \leq 0.05$) increased when the moisture content was increased from 15% to 21 %. The redness and browning index were significantly ($p \leq 0.05$) reduced when the moisture content and pressure were progressively raised from 15% to 21% and 120 psi to 160 psi respectively. Progressive increase of pressure and moisture content, and their synergistic interactions significantly ($p \leq 0.05$) reduced the crude fat and moisture contents of popped grain. Moreover, crude protein significantly ($p \leq 0.05$) improved when pressure was increased. Zinc and iron and total phenol contents significantly ($p \leq 0.05$) increased when the popping pressures and moisture content were progressively raised from 120 psi to 160 psi, and 15% to 21% respectively. Phytates content declined significantly ($p \leq 0.05$) when pressure was increased from 120psi to 140 psi or 160psi.Tannins significantly reduced ($p \leq 0.05$) when the moisture content was raised from 15% to 21 %. These findings demonstrate that popping finger millet can improve its nutritional value making it a viable avenue for value addition.

Key words: Popped finger millet, Pressure, Moisture content, Physico-chemical properties.