Nutritional Properties of Different Millet Types and their Selected Products

by

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ABSTRACT

NUTRITIONAL PROPERTIES OF DIFFERRENT MILLET TYPES AND THEIR SELECTED PRODUCTS

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This study investigated the nutrient quality of different millet types in their whole and decorticated forms. The documentation on the nutrient composition of millets suggested that they are rich in unsaturated fatty acids, phenolic acids and insoluble dietary fibre. The nutrient composition and in vitro starch digestibility varied widely among the different millet types. Decortication leads to a significant loss in nutrients, however the percent decrease depends on the millet type. The change in expected glycemic index after decortication was not very high except for kodo millet. The second part of the study evaluated the effect of parboiling on the decortication yield and nutritional quality of millets. Parboiling method used for pearl and proso millets increased the yield of decorticated millets by 28-35%. Parboiling significantly altered the nutrient composition and in vitro digestibility of millet products. Porridge and steam-cooked couscous prepared from parboiled millets showed lower in vitro starch and protein digestibility when compared to native millets products. Significant increases in the resistant starch and phenolic acids were also observed in the millet products from parboiled grains. The study demonstrated that parboiling may be an effective way of improving decortication yield without deteriorating nutritional quality of millets.
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1. CHAPTER ONE: INTRODUCTION

Millets are small-seeded cereals having excellent nutritional quality. They are comparable or superior to some commonly consumed cereals like wheat and rice (Ragaee et al. 2006). Despite its superior nutritional quality it has received less attention compared to the major cereals. They are gradually gaining importance in the North American and European countries due to its gluten-free and hypoglycemic property. A few studies have focussed on the nutrient quality of pearl millet however documentation on the other types is limited. Millets are also preferred to be decorticated to improve sensory quality and bioavailability of nutrients (Lestienne et al. 2005; Shobana and Malleshi 2007). Decortication removes the germ and pericarp reducing the anti-nutrients but at the same time resulting in a decrease of fibre, lipid, minerals and phenolic acids (Lestienne et al. 2005; Shobana and Malleshi 2007). However, limited information exists on the comparison of nutrient composition in whole and decorticated millets. Millets are known to have a low glycemic index as suggested by some in vivo studies however all of these studies have mainly focussed on millet products from composite flour (Anju and Sarita 2010; Thathola et al. 2010; Shukla and Srivastava 2011). Starch digestibility studies on the 100% cooked millet flour have been rarely done. Dietary fibre, phenolics and lipids which are mainly lost during decortication may also affect in vitro starch digestibility (Singh et al. 2010; Venn and Mann 2013). Removal of protein and lipid or both has shown to significantly increase the expected glycemic index (eGI) (Annor et al. 2013a). However there are no studies to compare the in vitro starch digestibility of cooked millet flour from whole and decorticated grains. The first part of the study evaluated the nutrient composition and in vitro starch digestibility of different types of whole and decorticated millets.
Due to difference in the grain morphology between millets and other cereals, the efforts to decorticate millet by known cereal milling methodologies including abrasion, friction mills or other dehulling techniques have not been successful to date (Shobana and Malleshi 2007). Parboiling can be an effective way to increase decortication yield of millets, as shown by few studies on finger and pearl millet (Clegg et al. 1991; Dharmaraj and Malleshi 2011). Moreover improvement of shelf-life and sensory properties has been observed after parboiling (Nantanga et al. 2008). The physico-chemical changes occurring during parboiling may also affect the nutritional properties of millets (Dharmaraj and Malleshi 2011). However there is a dearth of information on the changes in nutritional quality after parboiling of millets. As the parboiled grains are re-cooked to prepare varied products, hence studying the nutritional properties of the final edible product is important. Differences in starch and protein digestibility were observed between cooked rice from parboiled grains and cooked rice from native grains (Casiraghi et al. 1992; Devi et al. 1997; Larsen et al. 2000; Widowati et al. 2010). Changes in the \textit{in vitro} digestibility of millet products from parboiled and native grains have not been done. Porridge and steam cooked couscous from millets have been some major traditional products consumed in different parts of India and Africa (FAO 1995). These two food matrices will be different in terms of their moisture conditions, cooking time and the form (flour versus intact grain) in which they are cooked. The second part of the proposed study will evaluate the compositional and \textit{in vitro} digestibility of some products (porridge, couscous) prepared from decorticated raw and parboiled millets. Moreover to evaluate the effect of millet types on the nutritional quality of the parboiled products, two types of millets namely pearl and proso millets were considered. The results of this study evaluates the application of parboiling as a potential method to increase decortication yield and improve nutritional quality of millets.
2.1 Millet production and importance

Millets play a major role in the food security and economy of many less developed countries in the world. They are commonly cultivated in India, Africa and China. Millet is thought to be one of the first grains cultivated by man. The first recorded reports on the cultivation of millet dates back to about 5,500 BC in China (Crawford 2006). They are extremely important crops in semi-arid regions where other crops normally do not survive. The world total production of millets in 2007 was reported to be 32 million tonnes, with the top producer being India (10,610,000 tonnes) (FAO 2009). Millets ranks as the sixth most important cereal and feeds one third of the total world population (Saleh et al. 2013). They are easy to cultivate, inherently bio-diverse and can be grown together with varied crops (Rachie 1975; Dendy 1995). Another attributes of millets that make them a preferred choice in areas where they are cultivated, are their short harvest period (45-65 days) (Bukhari et al. 2011).

In North American and European countries, millets are mainly used as an ingredient in composite mixes, to produce gluten-free and low glycemic index (GI) food products. Millet products from 100% millet flour are rarely manufactured. However in African and Asian countries, millets serve as the main ingredient for preparation of traditional foods and beverages (Saleh et al. 2013). Pearl millet is the most commonly consumed millet, grown in the arid and semi-arid tropical regions of Asia, Africa and Latin America. India is the largest producer of pearl millet in Asia and is mainly grown in northwestern parts (Dendy 1995; Obilana 2003). It is also the major millet grown in Nepal and Bhutan (Mal et al. 2010). China however, mainly
produces foxtail millet. Finger millet is cultivated in more than 25 countries in eastern and southern Africa, and across Asia, with the major producers being Uganda, India, Nepal and China. In Africa, pearl millet production is concentrated in Sahara and drier areas of northern and eastern Africa (ICRISAT 1996; Obilana 2003). Proso millet is mainly grown in developed countries like Australia and America (FAO 2005).

Millets have excellent nutritional quality and are comparable to some commonly consumed cereals like wheat and rice (Ragaee et al. 2006). Millets also offer several health benefits to consumers. These crops lack gluten and hence can be consumed by people suffering from celiac disease (Gabrovska et al. 2002). Millet consumption can also lower glycemic response, which can be helpful for the treatment of type II diabetes (Choi et al. 2005). Inclusion of millet in the human diet can also lower the risk of duodenal ulcers, anemia and constipation (Jayaraj et al. 1980; Nambiar et al. 2011). For patients suffering from allergic diseases such as atopic dermatitis, Japanese barnyard millet grains have been recommended to replace rice and wheat grains (Watanabe 1999). Dietary fibre content in pearl and finger millet was found to be higher than that in sorghum, wheat and rice (Kamath and Belavady 1980). Millets are also rich in phenolic acid and has high anti-oxidant activity (Chandrashekhar and Shahidi 2010). They are valuable sources of some essential minerals such as potassium, magnesium, calcium, iron and zinc (Ravindran 1991). Despite their beneficial nutritional properties and tolerance for adverse growing conditions, millet consumption has been less compared to major cereals such as rice, wheat and corn. Among millets, small millets have been most neglected. There is a need to increase awareness about the superior nutritional quality of millets and make them one of the important commodities in our food basket.
2.2 Millet grain structure and classification

Millet are small seeded grains from the grass family and belong to the order Poales and family of Gramineae (Dendy 1995). They cover ten genera and at least 14 species. The most commonly grown millets are pearl and small millets. Small millet types include finger, proso, foxtail, barnyard, little and kodo millet. Fonio, teff, browntop and Australian millets are the less commonly grown millet types (Rachie 1975). Within the millet types there can be different varieties. These varieties within the types may differ depending on many factors namely seed properties, region grown, grain composition, breeding and genetics (Colosi and Schaal 1997; Gelinas and Mckinnon 2006). Millet grain structure is similar to other cereal grains with three principal parts namely endosperm, germ and pericarp. Pericarp is the outermost component of the grain and is composed of three sublayers: epicarp, mesocarp and endocarp. Epicarp can be 1-4 layers thick and may contain pigments which give color to the grains. Underneath the endocarp is the testa or seed-coat (Mcdonough and Rooney 1989). The endosperm consists of the outer aleurone layer and starchy endosperm. The aleurone cells are located beneath the seed coat. The starchy endosperm can be classified into peripheral, floury and corneous components. The corneous part is hard and vitreous-like and mainly found in the outer layer while the floury component is soft and floury, predominating the centre of the endosperm (Mcdonough et al. 1986). Starch granules in the endosperm are embedded in a protein network and the protein matrix is continuous in the peripheral and corneous zones while discontinuous in the floury zone. The number of protein bodies decreases as the starch content increases from the peripheral zone to the central core, where the floury endosperm is located. The shape or size of the starch granule and the nature of protein matrix differ according to the endosperm zone (Mcdonough and
Rooney 1989). The ratio of all these three components can vary among different millet types and may thereby affect kernel hardness and also enzyme susceptibility of the grains (Hadimani 2001; FAO 1995). Pearl millet kernel comprises of 75% endosperm, 17% germ and 8% pericarp (Salvidar and Rooney 1995). Pearl millet has a larger germ compared to other cereals and the endosperm to germ ratio is 4.5:1. Botanically millets are separated into caryopses and utricles. The seed coat in utricles, is covered by the pericarp which is attached at only one point resulting in easy removal of the pericarp. In a caryopsis, the pericarp is strongly attached to the seed. Pearl millet is caryopsis-type while proso, foxtail and finger millets are is utricle type grain (Mcdonough and Rooney 2000). The embryos of proso and finger millets are small with an endosperm to germ ratio of 11-12:1 (FAO 1995; Zarnkow et al. 2007). Millets usually have a single layer thick seed coat except finger millet which is unique with a very thick seed coat with 5 cell layers. The seed coat of finger millet is tightly attached to the aleurone layer and the starchy endosperm (Mcdonough et al. 1986).

Millet endosperm like other cereals is mainly composed of starch followed by protein and lipids (FAO1995; Sramkova et al. 2009). The starch in the endosperm can contribute almost 94% to the total starch in the grain. Cereal germ usually is relatively high in protein, lipid and it contains no starch. The pericarp is a very important source of fibre, lipids and phenolic compounds (Abdelrahman and Hoseney 1984; FAO 1995; Dykes and Rooney 2006). Vitamins and minerals are mainly concentrated in the aleurone, germ and pericarp (Taylor 2004). The proteins in millets were reported to be distributed approximately with the following percentages: 61 % in the endosperm, 31 % in the germ and 10% in the bran (pericarp+aleurone) while lipids were
distributed as: 87% in germ, 6% in the endosperm and 5% in the bran. This distribution may vary in different millets types (Abdelrahman and Hoseney 1984; FAO 1995).

2.3 Nutritional composition of millets

It has been reported that millets are rich source of nutrients and contain 60–70% dietary carbohydrates, 6–19% protein, 1.5–5% fat, 12–20% dietary fibre, 2–4% minerals, and several other phytochemicals (Haldimani et al. 1995). The available information on the compositional and biochemical properties of different millet types is discussed in this section.

2.3.1 Sugars and starch

The free sugars found in millet are glucose, fructose, sucrose and raffinose and their contents ranges from 1-1.4% with sucrose (0.3-1.2%) being the predominant sugar (Malleshi 1986). Total sugars in small millets ranged from 1.4-2% with proso having highest contents. Millets have total starch ranging from 64-79% (Krishnakumari and Thayumanavan 1995; Geervani and Eggum 1999). Amylose contents in millets ranges from 26-30% and amylopectin 69-74% (Krishnakumari and Thayumanavan 1998).

2.3.2 Protein composition

The average protein content of small millet is reported to be from 7.7-11.8% (Hulse et al. 1980). Pearl millet protein ranged from 8-19% (Salvidar et al. 1991). Protein in millets has three main fractions: Fraction I- albumin+globulin, Fraction II-true prolamin+prolamin like, Fraction III-
true glutelin+glutelin like. The albumin and globulin fraction forms 8.5-16.26%, prolamin fraction forms 15-30%, while glutelin forms 45-55% of the total protein in small millets except foxtail which had higher prolamin (60%) than glutelin (15.23%) content. Pearl millets had prolamins from 33-49.5%, glutelins 30-45% and globulins plus albumins from 18-26% (Chanda and Matta 1990; Parmeswaran and Thaymanavan 1995). Differences in the amino acid composition have been shown in different millet types. Lysine is the limiting amino acid in millets similar to other cereals. Glutamic acid (16-23%) and leucine (12-22.3%) were the major amino acids in the prolamin fraction however, barnyard had higher content of alanine (18%) than leucine (Parameswaran and Thayumanavan, 1995; Kumar and Parameswaran 1998).

2.3.3 Lipid profile

Most of the lipids in millets are present as free lipids (60-70%) followed by bound and structural lipids. Unlike other millet types, finger millet has almost equal proportions of free and bound lipids (Sridhar and Laxminarayana 1994). The free lipid content for kodo, finger, barnyard, little, proso, foxtail millet have been reported to be 3.4%, 5.2%, 5.7%, 5.4%, 5.6% and 5% respectively (Sridhar and Laxminarayana 1992, 1994). Pearl millet has free lipid content from 6-8% (Lai and Martson 1980). Bound and structural lipids of small millets were reported to be 1.3-5% and 0.4-0.9%, respectively. Linoleic (38-40%), oleic (27-37%), palmitic (16-22%) and linolenic (1-4%) are the major fatty acids found in millets. Unsaturated fatty acids account for more than 85% of the total fatty acid content in millets (Lai and Martson 1980; Sridhar and Laxminarayana 1992). Millet pericarp and germ have considerable amount of lipids hence the total lipid content and fatty acid profile can be affected by the extent decortication of millets.
(Liang et al. 2010). However there is dearth information on evaluating the changes in lipid content and fatty acid profile of millets after decortication.

2.3.4 Dietary Fibre

Millets are rich sources of insoluble (IDF) and soluble (SDF) dietary fibre and has comparable or even higher total dietary fibre (TDF) than other cereals. Decortication significantly decreases millet TDF. Studies on barnyard, kodo, foxtail and little millets have reported the IDF as 18-30% and SDF as 0.6-2% in whole form and decortication decreased the amount of IDF to 1.5-3% and SDF to 0.3-0.9% (Geervani and Eggum 1989). Reports on proso millets have shown that TDF of 12–20% in whole grain varieties decreased to 3–5% after decortication (Bagdi et al. 2011). Wide variations (7–21.2%) in TDF content of ten varieties of whole grain finger millet have been reported (Premavalli et al. 2004). Therefore, millet type, variety and extent of decortication have an important effect on the IDF and SDF content, however more studies are needed in this aspect.

2.3.5 Phenolics and antioxidant capacity

Phenolic content of millet has been reported to be higher than some major cereals like barley and wheat (Chandrashekhar and Shahidi 2010). Millets contain phenolic acids, which are located in the pericarp, testa, aleurone layer and endosperm (McDonough and Rooney 2000). Studies have reported a high antioxidant activity in the extracts from bran rich fraction compared to refined flour (Suma and Urooj 2010). Effects of processing namely fermentation and germination on the anti-nutrients (tannins and phytates) have been mainly studied (Khetarpaul and Chauhan 1989; Sade 2009). Studies on the effect of decortication on the free and bound phenolic acids have
been limited. In general, major phenolic acids in millets are ferulic, $p$-coumaric and cinnamic acids (McDonough and Rooney 2000). Millets with dark brown pigmented testa and pericarp (kodo, finger) possess a higher phenolic content than those with white or yellow testa and pericarp (pearl, proso, foxtail, little). Highest phenolic content is reported for kodo (368 mg/g) followed by finger (brown variety), little, foxtail and barnyard millet (Hegde and Chandra 2005). Phenolic acids in finger millet are present mostly in free form (71%). Ferulic and $p$-coumaric acid are the major bound phenolic acid (19 mg/100 g) identified, whereas protocatechuic acid is reported as the major free phenolic acid (45 mg/100 g) in finger millet. The antioxidant activity of a free phenolic acid mixture of finger millet is higher compared to that of a bound phenolic acid mixture (Rao and Muralikrishna 2002). Studies on phenolics of millets have mainly focussed on finger and kodo millet hence there is a need to document the phenolic acid profile of the other types.

2.4 Starch digestibility

Finger millet based diet has shown to reduce blood glucose levels when compared to a wheat or rice diet. Lakshmi and Sumathi (2002) reported a lowering of glycemic response in type II diabetic patients on consumption of finger millet roti when compared to wheat or rice roti. Shobana et al. (2007) also showed a lowering of blood glucose level in healthy subjects, by consumption of a product made from composite flour of finger millet and legumes. In vivo studies on millet have mainly considered millets products from composite flour (Anju and Sarita 2010; Thathola et al. 2010; Shukla and Srivastava 2011). Studies on starch digestibility of 100% cooked millet flour have been limited. Decorticated cooked kodo millet flour has been shown to
have lower expected glycemic index (eGI) than rice or wheat (Annor et al. 2013a). *In vitro or in vivo* starch digestibility studies on all the millet types are limited. Epidemiological studies have shown that consumption of whole grains products when compared to refined products, have lower glycemic response (Heaton et al. 1988; Meyer et al. 2001). Presence of higher levels of dietary fibre, anti-nutrients and enzyme inhibitors may be responsible for lower starch digestibility of whole grain products (Singh et al. 2010; Venn and Mann 2004). Starch-protein-lipid interaction has also shown to affect glucose response. The removal of lipid, protein or both in kodo millet flour, has shown to increase *in vitro* starch digestibility significantly (Annor et al. 2013a). As most of the lipids and protein are concentrated in the germ and pericarp of millets, the removal of the outer layers by decortication may lead to an increase in the starch digestibility (Annor et al. 2013a). However, a comparison of the starch digestibility of whole and decorticated millets types has not been done.

From the studies on the nutritional quality of millets as discussed in section 2.3, it is evident that type and variety are important factors affecting the nutrient composition of millets. Studies done on the nutrient composition of millets have mainly focussed on pearl millet, the other types have not been extensively studied. As discussed in section 2.5, starch digestibility of millets have been mainly evaluated for millet products from composite flour, starch digestibility of 100% cooked millet flour has been scarce. Millet pericarp and germ are rich sources of phenolics, fibre and lipid, decortication removes most of these components, thereby possibly leading to significant nutrient loss. Changes in nutrient composition namely lipids, and phenolics after decortication been limited. Similarly, changes *in vitro* starch digestibility of different millet types after
Decortication has also not been investigated. Though some studies have evaluated the changes in IDF and SDF after decortication but they have not been done on all the millet types.

2.5 Factors affecting millet consumption

There are some limiting factors that contribute to the lower consumption of millets. Due to the small size and uniqueness in the grain morphology, commercially available decorticating techniques have not been successfully employed on millets so far (Shobana and Malleshi 2007). The unavailability of processing technologies to manufacture millet products at a commercial scale has confined its consumption only as traditional foods (Shobana and Malleshi 2007). Millets are high in unsaturated fatty acids (Lai and Marston 1980; Sridhar and Laxminarayana 1992, 1994). Thus pearl millet flour is susceptible to rancidity within a few days of storage, owing to lipolysis followed by oxidation of the de-esterified fatty acids. Hence storage of millet grains for long periods in hot and humid conditions results in rancidity and off-flavors (Nantanga et al. 2008). Presence of significant amounts of phytates, phenols, tannins and enzyme inhibitors may limit maximum utilization of the nutrient potential in millets (Pushparaj et al. 2011; Singh and Raghuvanshi 2012).

2.6 Millet processing

Due to the various limitations in millet consumption as discussed in section 2.5, millets like other cereals are usually processed before consumption. Processing technologies employed, improve the edible, nutritional and sensory properties of millet (Shobna et al. 2012). Parboiling,
decortication, popping, extrusion, roasting, pressure cooking, autoclaving, germination and fermentation are some processing techniques used for millets.

2.6.1 Dry-heat and wet treatments

The main purpose of fermentation and germination is to reduce anti-nutrients in millet and improve nutrient bio-availability. Fermentation can synthesize certain amino acids and increase availability of vitamins (Chavan et al. 1989). It also sets optimum pH conditions for enzymatic degradation of phytate which is present in millets as complexes with polyvalent cations such as iron, zinc, calcium, magnesium and proteins. The reduction in phytate may increase the amount of soluble iron, zinc and calcium in many folds (Mahajan and Chauhan 1988; Khetarpaul and Chauhan 1989; Kouakou et al. 2008). Improvement of starch, protein digestibility and sensory properties of food products from fermented and germinated flour has also been reported (Khetarpaul and Chauhan 1989; Inyang and Zakari 2008).

Popping, extrusion, flaking and roller drying are some of the dry heat treatments applied to millets and these methods are based on High temperature short time treatment (HTST) methodology. Ready-to-eat millet products are prepared using these processing techniques. Different physico-chemical changes occur during these dry heat processes. Changes occurring in starch properties during the HTST process, depends on the extent of starch gelatinisation and retrogradation, which may thereby effect resistant starch formation and starch digestibility (Roopa and Premavalli 2008). Flaked millet had lower starch digestibility than extruded, popped and roller dried product which may be due to higher resistant starch formation (Ushakumari et al. 2004). A considerable increase in the unsaturated fatty acids (linoleic, oleic) was observed in the case of popping and extrusion, whereas flaking and roller drying reduced unsaturated (oleic) and
increased saturated (palmitic) fatty acid (Ushakumari et al. 2004; Dharmaraj et al. 2011). The severity of the processing conditions controls the extent of changes in the starch granule, protein matrix and lipids of millets which thereby affect the biochemical properties. Minor changes in protein, insoluble & soluble fibre, phosphorous and calcium content may also occur (Ushakumari et al. 2004).

2.6.2 Parboiling

2.6.2.1 Parboiling process
Hydrothermal treatment or parboiling process basically involves steeping the grains for bringing them to equilibrium moisture content, steaming or boiling to gelatinize the starch and finally dehydrate the grains, to bring its moisture to a safe storage level (Clegg et al. 1991). This entire process brings about various changes in the physico-chemical properties, which leads to an increase in yield of decorticated millet and nutritional value of the grains (Young et al. 1990). There are three major steps in the parboiling process namely soaking, boiling and drying which are described below.

Soaking
Soaking is a slow process which involves diffusion of water into the grain. The moisture content of grain is significantly affected by the soaking time and temperature. Higher temperature increases diffusion rate and decreases the time required to reach equilibrium moisture content (30-40%) (Young et al. 1990; Clegg et al. 1991). Soaking time varies from 10-24 hrs. The temperature of the soaking water should not be above gelatinisation temperature (70°C) as the
grain may burst open, if the gelatinisation temperature is exceeded (Dharmaraj and Malleshi 2011).

**Boiling and drying**

The soaked grains are boiled or steamed and the boiling time depends on the grain morphology. It would be longer if the pericarp and outer layers of the grain are tightly adhered to the endosperm and shorter if the pericarp is loosely adhered. Optimum boiling time for finger millet is 30 min while for pearl it is 5 min (Clegg et al. 1991; Dharmaraj and Malleshi 2011). Drying is one of the major steps in parboiling. Drying lowers the moisture content of the grains for safe storage and milling of the grains. A safe storage level for cereals would be 10-12% moisture (Young et al. 1991). There are different methods of drying: air-drying, sun-drying and oven-drying. Though the air drying method takes longer approximately 72 hr, it is more preferred due to higher yield of intact kernels. Longer drying time at lower temperatures helps avoiding fissures and deformations in the grains (Young et al. 1991).

Soaking-boiling (SB) method is the most common and simplest method for parboiling. However different parboiling methods have been also employed for cereals. Soak-Boil-Soak (SBS), Boil-soak- Boil (BSB) are some other methods of parboiling. It has been found that BSB process gave the highest decortication yields with least broken kernel followed by SB and SBS methods (Clegg et al. 1991; Young et al. 1991).
2.6.2.2 Importance of parboiling

Milling yield

Due to difference in the grain morphology between millets and other cereals, the efforts to
decorticate millet by known cereal milling methodologies including abrasion, friction mills or
other dehulling techniques have not been successful to date (Shobana and Malleshi 2007). The
purpose of decortication is to have the most complete separation of germ, pericarp and
endosperm (Abdelrahman et al. 1983). The small size of the grains is one of the major issues
while decorticating any type of millet. The unique morphological features of finger millet such
as soft and fragile endosperm to which a tough seed coat is rigidly attached, leads to the
crumbling of the grain into fine grits when decorticated (Shobana et al. 2012). For pearl millet, a
firmly embedded germ and a very hard endosperm makes it difficult to decorticate
(Abdelrahman et al. 1983). Therefore, decortication or complete removal of pericarp from the
endosperm of millet has been difficult to achieve by normal milling methods. Each millet type
has its own unique structural properties which reduces its decortication efficiency. Parboiling of
rice has shown to increase the head rice yield by 25-30% (Tirawanichakul et al. 2012; Gunaratne
et al. 2013). Parboiling can be an effective way to increase milling yield of millets too, as shown
by few studies on finger and pearl millet (Clegg et al. 1991; Dharmaraj and Malleshi 2011).

When the grains are boiled during the parboiling process, gelatinisation of the starch granules
and disintegration of the protein bodies takes place, which leads to expansion and filling up the
internal spaces in the grain. Due to this expansion, the granules of starch gets closely pressed
together resulting in a strong cohesion between them. All these changes lead to the hardening of the grain during drying, which thereby increases milling yield (Ali and Pandya 1974; Bakshi and Singh 1980).

Increase in shelf life

Enzyme inactivation takes place during the boiling process in parboiling (Luh and Mickus 1991). Studies have reported lower fat acidity values upon storage of parboiled grain flour, in comparison to untreated flour. This may be due to inactivation of lipoxygenase and peroxidase enzyme which improves shelf life of the grains (Silva et al. 2006, Nantanga et al. 2008).

Improvement of sensory properties

A study by Nantanga et al. (2008) showed that porridge made from parboiled pearl millet flour was preferred over porridge from untreated flour. They suggested that bitter taste of porridge is clearly associated with flour fat acidity, resulting from lipase activity. They suggested that the bitter taste of the porridge from flour of untreated grains was mainly due to free fatty acids produced by lipase and their further oxidation. Lowering of the fat acidity by parboiling reduces the bitter effect of the millet porridge, thereby improving its sensory quality (Nantanga et al. 2008).

2.6.2.3 Physico-chemical changes and in vitro digestibility

There are various physico-chemical changes that occur after parboiling of the millet grains. Generally, the major purpose of parboiling is to increase the milling yield of grains, which makes decortication a necessary step after parboiling. Therefore, studying the biochemical changes of the parboiled decorticated millet can be more practical than studying the changes in whole grain
parboiled millet. A study on parboiled decorticated finger millet showed that the gross composition of the millet flour did not change appreciably compared to the native decorticated millet, however it altered the profiles of carbohydrates, proteins and lipids (Dharmaraj and Malleshi 2011). Studies on biochemical changes after parboiling and milling has been primarily focussed on rice and to some extent sorghum, however literature on millet has been very limited.

During parboiling starch gelatinizes losing its crystallinity and birefringence partially or fully depending on the severity of the process (Dutta and Mahanta 2012). The cooling step in parboiling leads to the re-association of some parts of the gelatinised starch forming retro-graded starch (Rao and Juliano 1970; Bhattacharya and Ali 1985). Starch digestibility of the parboiled decorticated product will depend on the severity of the processing conditions. Starch digestibility is increased or decreased after parboiling, increased owing to complete gelatinization of the starch, or decreased owing to subsequent retrogradation upon cooling (Larsen et al. 2000). The formation of undigested starch (resistant starch) and its subsequent metabolic responses depends on the extent of starch gelatinization and retrogradation which takes place during parboiling (Mangala et al. 1999). The carbohydrate digestibility increased from 61% for native finger millet to 78% for decorticated parboiled millet (Dharmaraj and Malleshi 2011). Parboiled milled rice has shown to have lower starch digestibility and higher resistant starch than native milled rice (Widowati et al. 2010; Casiraghi et al. 1992). However, this may not be always true as studies have shown that the increase or decrease in starch digestibility and resistant starch after parboiling, depends on the severity of processing and also on the type or variety of rice used (Panlasigui et al. 1991; Larsen et al. 2000; Kim et al. 2006).
Dharmaraj and Malleshi (2011) showed an increase in protein digestibility from 79 to 98% for parboiled decorticated millet. They found a significant increase in extractability of globulins and prolamin-like proteins and a decrease in glutelin-like proteins. However protein digestibility of rice and sorghum has shown to decrease after parboiling (Hamaker et al. 1986; Devi et al. 1997). As the literature on parboiling of millets is scarce, it will be difficult to predict whether the biochemical changes in starch and protein of millets will mimic the changes observed in other cereals. The amount of free phenolic acid mainly p-coumaric is higher in parboiled milled rice than native milled rice. The free phenolics may be formed from the breaking down of the bound phenolics and also due to the migration of the free phenolics from the outer layers of the grain into the endosperm during the parboiling process (Kato et al. 1983; Pauda and Juliano 1974). There is not much information on changes in free and bound phenolics for millets. Millets have a high phenolic content compared to other cereals and to study the changes in these components due to parboiling will be a novel aspect.

2.6.3 Millet Products

The parboiled decorticated millet is a quick cooking cereal which can be cooked as discrete grains like rice or it can be further processed to make value added product like expanded, extruded or baked products (Saleh et al. 2013). As the parboiled grains are re-cooked to prepare varied products, hence studying the nutritional properties of the final edible product is important.

Studies on processed products from millets have mostly focussed on fermented and extruded products. For instance Akinbala et al. (2002) worked on fermented porridge from pearl,
Palaniswamy et al. (2011) on fermented flat bread from finger and Thapa and Tamang (2004) on fermented beverage from finger millet. Other products such as popped, flaked and extruded products have also been studied (Ushakumari et al. 2004; Dharmaraj et al. 2011; Roopa and Premavali 2009). The millet products studied so far have mainly focused on finger millet. There are no studies to evaluate the compositional and physico-chemical properties of traditional products made from parboiled decorticated millet flour. Commonly consumed traditional millet products including porridge, flat bread, steam cooked couscous and fried products can be made from native as well as parboiled millet flour (FAO 1995). A study on comparison of the chemical composition of these traditional products, made from native and parboiled decorticated millet grains would be interesting and has not been conducted. In vitro digestibility of the products is also an important aspect to consider, as previous studies on rice and sorghum have shown significant changes in the digestibility of protein and starch after parboiling (Hamaker et al. 1986; Casiraghi et al. 1992; Devi et al. 1997; Larsen et al. 2000; Widowati et al. 2010). Cooked rice from parboiled grains had lower eGI when compared to native grains. However there are mixed results on this aspect as it has been shown that the changes would mainly depend on the parboiling conditions, amylose content of the grains and the variety of cereal chosen (Hamaker et al. 1986; Casiraghi et al. 1992; Devi et al. 1997; Larsen et al. 2000; Widowati et al. 2010). In vitro protein digestibility of rice and sorghum also decreased after cooking or parboiling however there is not much information on the same (Hamaker et al. 1986; Devi et al. 1997). Therefore, to compare the in vitro digestibility of millet products from parboiled and native grains would be a novel aspect. As millet products have not yet been established as confectionary/breakfast/ready to eat products at an industrial scale, therefore, focus on the traditional products would be more beneficial.
2.7 Conclusions

Despite their excellent nutritional quality, millet grains have received less attention compared to some major cereals like rice, wheat and corn. Recently, millets are gaining importance in the production of gluten-free and low GI food products. Documentation of the composition and biochemical properties of different types of millets has been limited. To improve bio-availability, sensory properties and storage quality of millets, they are preferred to be decorticated. As most of the phenolics, fibre and lipids in millets are concentrated in the outer layers and germ, decortication possibly changes their composition markedly. However, information on this aspect is scarce. The first part of the proposed study will be evaluating the nutritional quality of different types and varieties of millets in their whole and decorticated forms. The unique morphology of millet grains makes it difficult to decorticate. This is a major limiting factor for millet consumption. Parboiling has been shown to be an efficient method to increase milling yield of cereal grains. Few studies have focussed on changes in the nutritional quality occurring in the parboiled millet grain but none of them have investigated the changes in products made from parboiled millet flour. The second part of the proposed study will evaluate the compositional and \textit{in vitro} digestibility of some products (porridge, couscous) prepared from decorticated raw and parboiled millets. The results of this study evaluate the application of parboiling as a potential method to increase decortication yield and improve nutritional quality of millets. This study is a part of the project undertaken by International development Research Centre (IDRC) and Foreign Affairs, Trade and Development Canada (DFATD) to improve nutritional status of millets in South Asia. The results of the proposed study will contribute to this project and increase awareness for millet consumption.
Fig. 2.1: Grain structure of a pearl millet grain (McDonough and Rooney 1989).
3. CHAPTER THREE: NUTRIENT COMPOSITION AND IN VITRO STARCH DIGESTIBILITY OF DIFFERENT TYPES OF WHOLE AND DECORTICATED MILLETS

3.1 Abstract

The current study evaluated the chemical composition and nutritional properties of different types and varieties of millet, present in their whole grain (WG) or decorticated (DC) form. Five millet types namely little CO4, proso, kodo, barnyard and foxtail were studied in both their WG and DC forms while pearl, little landrace and four finger varieties were studied in their WG form only. The expected glycemic index (eGI), phenolic content (free and bound), DPPH quenching activity (free and bound) and lipid content for whole grain millets varied as follows: 43-58; 87-2518 µg/g, 1028-7210 µg/g; 32-91%, 85-93% and 6.7-53 mg/g respectively while decorticated millets had the following values: 47-61; 12.9-117 µg/g, 107-325 µg/g; 15-45%, 47-76% and 10-45 mg/g respectively. Significant differences were observed in the composition and in vitro starch digestibility of different whole and decorticated millet types. Decortication of millets reduced the phenolic acid content, antioxidant activity, insoluble dietary fibre, lipid and fatty acid contents significantly while the eGI increased. Phenolic content positively correlated with DPPH activity while insoluble dietary fibre had significant positive correlations with bound phenolic content and DPPH activity.

Key words: millet, in vitro starch digestibility, composition
3.2 Introduction

Millets are small-seeded cereal crops which play a major role in the food security and economy of many Asian and African countries. Studies on millets have showed that they have similar or higher phenolics, antioxidant activity, fibre, vitamins and minerals than wheat and rice (Ragaee et al. 2006). Millets lack gluten and can be consumed by people suffering from celiac disease (Gabrov ska et al. 2002). Some in vivo studies by Shobana et al. (2007), Thathola et al. (2010), Anju and Sarita (2010), Shukla and Srivastava (2011) showed significant lowering of blood glucose level by millet based diet when compared to a wheat or rice diet. However, most of the in vivo studies on millets have mainly considered millets products from composite flour. Studies on starch digestibility of 100% cooked millet flour has been limited, hence there is a need to document the same. Epidemiological studies have shown that consumption of whole grains products when compared to refined products, have lower glycemic response which may be due to presence of higher amounts of fibre, anti-nutrients and enzyme inhibitors (Heaton et al. 1988; Meyer et al. 2001; Venn and Mann 2004; Singh et al. 2010). The removal of lipid, protein or both in kodo millet flour, has shown to increase in vitro starch digestibility significantly (Annor et al. 2013a). As most of the lipids and protein are concentrated in the germ and pericarp of millets, the removal of the outer layers by decortication may lead to an increase in the starch digestibility (Annor et al. 2013a). However, a comparison of the starch digestibility of whole and decorticated millets types has not been done. The current study focusses on this missing aspect.

Due to its superior nutritional quality and as a valuable food source for celiac and diabetic patients, millet is gradually gaining importance in European and North American countries. The
most commonly consumed millets are pearl and small millet. Small millets include: finger, proso, foxtail, barnyard, little and kodo millet. Few studies have reported major differences in the nutritional quality of different types and varieties of millets (Geervani and Eggum 1989; Roopa and Premavalli 2008). Even though the millets are well known for their superior nutritional qualities, the acceptability of millet food products are largely limited by its dark colour, chewy texture and bitter taste imparted by the pericarp or outer layers of the grain (Shobana and Malleshi 2007). Significant amount of phytates, tannins present in the outer layers may also limit maximum utilization of the nutrient potential in millets (Lestienne et al. 2007). Decortication removes the germ and pericarp reducing the anti-nutrients but at the same time resulting in a decrease of fibre, lipid, minerals and phenolic acids (Lestienne et al. 2007; Shobana and Malleshi 2007). The physical state (whole grain versus decorticated) of millet is an important factor determining its nutritional quality apart from its type and variety. However, the effect of all these three factors namely type, variety and state on the nutrient composition millet has not been extensively studied. The objective of the study was to compare nutrient composition and \textit{in vitro} starch digestibility of different whole and decorticated millet types, procured from Canada, India and Nepal.

\section*{3.3 Materials and Methods}

Five millet types little (CO4, landrace varieties), barnyard (landrace variety), kodo (market variety) and foxtail (market variety) were provided by Tamil Nadu Agricultural University, Coimbatore, India, in both their whole and decorticated forms. The decortication was done with a modified rice pearler. Four whole grain finger millet varieties: Seto Jhape (seto) and Dalle
were procured from Nepal while Katti Ragi (katti) and Dalle were obtained from Tamil Nadu Agricultural University, Coimbatore. Whole grain pearl millet was provided by Agriculture Environmental Renewal Canada Inc (ARC) while whole and decorticated proso millet was obtained from Bunge milling, St. Louis, United States of America. Samples were milled in Cyclone Sample Mill (UDY Corp., Fort Collins, CO) equipped with a 1.0 mm screen.

### 3.3.1 Total starch
Total starch content was measured according using a Megazyme assay kit (K-TSTA, Megazyme International Ireland Ltd, Ireland). The amount of glucose produced by the hydrolysis of starch was estimated by measuring the absorbance at 510 nm (Cary 1-Bio UV-visible spectrophotometer, Ontario, Canada).

### 3.3.2 Lipid content and fatty acid profile
Free lipids were extracted using AOAC method 991.36 (1995) with some modifications. Briefly, extraction of free lipids was done in a soxhlet apparatus for 6 hr with petroleum ether as solvent, and then dried overnight at 50°C in a dry air oven. Extracted free lipids were esterified using method by Lai and Marston (1980). Fatty acid methyl esters were analysed in an Agilent Series 6890 gas chromatograph (Agilent Technologies, Waldbonn, Germany) with CP Sil 88FS column, having a Flame Ionization detector (FID) (Jahaniaval et al. 2000).
3.3.3 Phenolics

Free and bound phenolic content

Extraction of free and bound phenolic was done according to the procedure described by Ragaee et al. (2012). Quantification of free and bound phenolic content was done by Folin-Ciocalteau reagent using procedure by (Ragaee et al. 2012). Absorbance was measured at 725 nm by spectrophotometer (Cary 1-Bio UV-visible spectrophotometer, Ontario, Canada). Ferulic acid concentration in the range of 50 to 350 µg/mL was used as the standard and to construct regression equation for quantification.

Antioxidant activity as DPPH

Scavenging Capacity Radical 2, 2-diphenyl-1-picrylhydrazyl radical (DPPH) was used to estimate the scavenging capacity of the extract of free and bound phenolic fraction as explained by Ragaee et al. (2012). The absorbance was read at 517 nm wavelength by spectrophotometer (Cary 1-Bio UV-visible spectrophotometer, Ontario, Canada).

Free and bound phenolic acid profile

Agilent Series 1100 series high performance liquid chromatography (HPLC) (Agilent Technologies, Waldbronn, Germany) was used for detection and quantification of phenolic acids of free and bound extracts as described by Ragaee et al. (2012). HPLC was equipped with a diode array detector (DAD) and a Supelcosil LC-18 column (Supelco Analytical, Bellefont, PA, U.S.A). A gradient elution using 6% formic acid and 6% formic acid in acetonitrile was used at a flow rate of 1 mL/min.
3.3.4 Insoluble and soluble dietary fibre
Insoluble Dietary Fibre (IDF) and Soluble Dietary Fibre (SDF) was measured using gravimetric procedure by AACC (32-07) (2008).

3.3.5 In vitro starch digestibility
Starch digestibility was estimated by Englyst et al. (1992). 10 % slurry of millet flour containing 750 mg of starch was cooked for 10 min with constant stirring with a magnetic stirrer. A mixture of enzymes was prepared with pancreatin from porcine pancreas (Sigma-Aldrich Co. LLC, USA: P-1625, activity 3 X USP/g), invertase from baker’s yeast (S. cerevisiae) (Sigma-Aldrich Co. LLC, USA: 1450) and amyloglucosidase (200 U/mL p-nitrophenyl β-maltoside) (Megazyme International Ireland Ltd, Ireland). 10 ml of 0.1M sodium acetate buffer (pH 5.2) was added to the cooked slurry and 5 ml of the enzyme mixture was then added. The samples were incubated in a shaking water bath at 37°C for 2 hrs. Aliquots of 0.1 ml was pipetted every 20 min into 80% ethanol solution to stop enzyme hydrolysis. Glucose oxidase (GOPOD) (Megazyme International Ireland Ltd, Ireland) assay was used to estimate the amount of glucose released every 20 min. A conversion factor of 0.9 was used to convert glucose to starch. Three hydrolyzed fractions of starch: Rapidly Digestible Starch (RDS), Slowly Digestible starch (SDS) and Residual Starch (RS) were calculated. They were calculated as: RDS= Glucose conc at 20min x 0.9, SDS= (Glucose conc at 120min - Glucose conc at 20min) x 0.9 and RS = TS-(RDS+SDS) according to Englyst et al. (1992). Expected glycemic index (eGI) was calculated by the formula eGI= 8.198+(0.862 x HI) as described by Granfeldt et al. (1992). HI is the hydrolysis index and calculated using method by Goni et al. (1997).
3.3.6 Statistical analysis
All analyses were conducted in duplicates and mean values are reported. ANOVA was performed and Duncan’s multiple range test was used to determine significant differences between means at the level of P < 0.05. Pearson product-moment correlation analysis was used to correlate data at the level of P < 0.05. All the analysis was performed by using Statgraphics Centurion XV, version 15.1.02 (StatPoint, Warrenton, VA, U.S.A.).

3.4 Results and Discussion

Five millet types: little CO4, proso, barnyard, kodo and foxtail were studied in both their whole grain (WG) and decorticated (DC) forms whereas pearl, little landrace and four varieties of finger millet namely G.P 28, Katti, Seto and Dalle were evaluated only in their WG form. Considering the nature of all these selected samples, three factors: type, variety and state (WG versus DC) were considered for analyzing the results. The effect of these three factors on the nutrient composition and in vitro starch digestibility of millet is discussed in this section.

3.4.1 Total Starch
The total starch contents in decorticated millets are shown in Table 3.1 and the amounts ranged from 74 to 84%. The total starch of the whole grain millet ranged from 53 to 65%.

3.4.2 Lipids

Free lipid content
Whole grain millet had free lipid content from 26 to 53 mg/g while finger varieties showed the least contents varying from 6.7 to 12 mg/g. As shown in Table 3.1, lipid content among the WG...
millet types had the following order: Pearl > little landrace > little CO4 > barnyard > foxtail > proso > kodo > finger katti > finger G.P 28 > finger seto > finger dalle. Lipid content of decorticated millets ranged from 10-45 mg/g with barnyard having the highest content. The lipid content of DC millets varied as: barnyard > foxtail > proso > little > kodo (Table 3.1). Decortication lowered the lipid content by 44 to 78% with little CO4 showing the highest decrease.

**Fatty acid profile**

Linoleic (18:2) was present in highest amounts in whole grain millets followed by oleic (18:1), palmitic (16:0), stearic (18:0) and linolenic (18:3) acid. Linoleic, oleic, palmitic, stearic and linolenic ranged from 10-30 mg/g, 8.7-19.4 mg/g, 3-8.9 mg/g, 0.8-2.7 mg/g and 0.2-1.8 mg/g respectively in whole grain millets (Fig 3.2a, b). Finger millet varieties had the lowest fatty acid contents and showed a different fatty acid profile than the other whole grain types (Fig 3.3a, b).

Oleic (3.1-5.2 mg/g) was present in highest amount followed by linoleic (1.8-3.2 mg/g), palmitic (1.3-3 mg/g), linolenic (0.15-0.28 mg/g) and stearic (0.1-0.24 mg/g) in the finger varieties however finger GP 28 showed higher palmitic (2.6 mg/g) than linoleic (1.8 mg/g). Among finger varieties, finger seto showed higher fatty acid contents. Pearl showed higher content for all the fatty acids among whole grains owing to the higher lipid content, except oleic and linoleic acid. Whole grain foxtail showed the highest contents of linoleic (30 mg/g) and linolenic (0.7 mg/g) (Fig 3.2a, b). Kodo, little CO4 and little landrace showed similar ratio of oleic and linoleic in their WG form. Whole grain foxtail, proso, pearl and barnyard millet had higher linoleic acid than oleic and they were higher by 70%, 68%, 48% and 30% respectively. As shown in Fig 3.1a and 3.1b, decorticated millets had linoleic (4.3-18.4 mg/g) in highest amounts followed by oleic
(2.6-12.9 mg/g), palmitic (1.1-7 mg/g), stearic (0.3-1.8 mg/g) and linolenic (0.1-0.4 mg/g). The ratio of oleic to linoleic acid was similar in DC little CO4 and kodo while DC proso and foxtail had 65-70% more linoleic than oleic. The trend in the ratio of oleic to linoleic is similar in both WG and DC forms. Among decorticated millets, palmitic, oleic, linoleic and stearic were higher in barnyard than foxtail, proso, little and kodo, due to its higher lipid content. However, linoleic and the longer chain fatty acids were higher in DC foxtail than DC barnyard. Long chain fatty acids namely arachidic (20:0), eicosonic (20:1), behenic (22:0) and lignoceric (24:0) were present in all the whole and decorticated millet types (Fig 3.1-3.3), the amount of arachidic was highest among the long chain fatty acids followed by behenic, lignoceric and eicosonic. However, in kodo and finger millet varieties eicosonic was higher than lignoceric.

As suggested from these fatty acid results, the fatty acid profile of whole grain millets were almost similar to its decorticated form and had linoleic, oleic and palmitic as the major fatty acids present. This may imply that the fatty acid profile of lipid present in the germ, endosperm and outer layers of millet grain may not be different. However, after decortication, the fatty acids did not show a relative decrease based on their lipid content which may be due to the varying distribution of fatty acids in the grain from the outer layers into the endosperm (Liu et al. 2011). The unsaturated fatty acids oleic, linoleic and linolenic accounts for more than 85% of the total fatty acid present in both whole and decorticated millets. Kodo and little millets were different than the other types by having similar oleic to linoleic ratio. Finger varieties were the most unique showing a different fatty acid profile than the other millet types. Apart from the lipid content, the distribution of the fatty acids in the grain would also influence the fatty acid contents hence higher lipid content may not always lead to an increase of all the fatty acids in the grain.
As seen from the results discussed above, there are wide variations in the fatty acid profile among different types of millet however the varietal effect was not very high. Whole grain millets mainly pearl, barnyard, foxtail and little millet have higher lipid and fatty acid content than some major cereals like wheat, rye and barley (Price 1975; Morrison 1978; Liu 2011). Therefore, millets can be considered as rich sources of unsaturated fatty acid in our diet. Lipid content and types of fatty acids can affect the storage quality, sensory properties and in vitro starch digestibility of millets (Nantanga et al. 2008; Annor et al. 2013). The results from this section will be helpful in further studying the inter-relationship of lipid profile with these attributes.

### 3.4.3 Phenolics

**Free phenolic content and phenolic acid profile**

As shown in Table 3.2, free phenolic content of whole grains varied from 87-2518 µg/g with kodo and finger varieties having higher contents. Gallic acid was the major free phenolic acid for barnyard (22.2 µg/g), pearl (78.3 µg/g) and finger varieties (88-104 µg/g) whilst p-coumaric for kodo (40.8 µg/g) (Table 3.4a, b). Protocatechuic was present in the free fraction of all whole grain millet types and ranged from 1.25-26.8 µg/g except proso. Finger varieties showed higher vanillic (27.9-56.5 µg/g) content compared to the other WG types. Finger seto showed presence of p-hydroxybenzoic, syringic and 3-hydroxybenzoic which were not present in the other finger varieties. Gentistic was present in WG free extract of kodo and finger (seto, G.P 28) and not in the other millet types. Barnyard showed the highest free phenolic content (117 µg /g) among the decorticated millets. Free phenolic content of DC proso, kodo, foxtail and little CO4 ranged from 12.9-43.7 µg /g. Gallic (5.6-20.7 µg/g) and protocatechuic (2.3-6.1 µg/g) were the major
phenolic acids in the DC free extract (Table 3.4a, b). Syringic, gentistic, caffeic and p-coumaric were not detected in the DC free fraction.

**Bound phenolic content and phenolic acid profile**

Bound phenolic content in whole grains ranged from 1028 to 7210 µg/g with kodo having the highest values (Table 3.2). Ferulic was the major phenolic acid present in the WG bound fraction ranging from 407 to 4268 µg/g (Table 3.5a, b). However, p-coumaric was present in foxtail and proso as the main bound phenolic acid. Bound fraction of WG kodo showed the presence of most phenolic acids analysed. Whole grain kodo showed the highest contents of ferulic (4268 µg/g), syringic (713 µg/g), gentistic (178 µg/g), sinapic (190 µg/g) and caffeic (95 µg/g) acid. Gentistic was detected in WG kodo and finger varieties (46-57 µg/g) while it was not detected in the other WG millet types. The phenolic acid content varied among the finger varieties with 3-hydroxybenzoic and vanillic being absent in all finger varieties. The bound phenolic content of decorticated grains ranged from 107-325 µg/g with barnyard showing the highest phenolic content (Table 3.2). Ferulic acid was the major phenolic acid ranging from 75-195 µg/g in the DC bound extract as shown in Table 3.5a and 3.5b. Sinapic, gentistic, gallic, 3-hydroxybenzoic and caffeic were not detected in the bound extract of all DC millets P-coumaric was the second major phenolic acid present in DC foxtail (15.7 µg/g) and barnyard (51.8 µg/g), while it was not detected in the other DC types. The finger millet varieties showed similar free and bound phenolic content unlike the other millet types.

As suggested from the results above, there were wide variations in the free and bound phenolic content and phenolic acid profile among different millet types. Varietal effect on the phenolic
acid can also be seen in the finger millet varieties. Decortication lost 76-99% of free and bound phenolic content resulting in high losses of phenolic acid, however the relative decrease in phenolic acid depends on the millet type, which may be due to the varying distribution of phenolic acid in the outer and inner layers of the grain (Hahn et al. 1984). Whole grain kodo and finger millet showed highest phenolic acid contents among all the millet types, while proso and little millets had lowest amounts. Unlike other millet types whole grain kodo had $p$-coumaric as the major free phenolic while other millet types had gallic as the main free phenolic acid. Whole grain proso and foxtail had $p$-coumaric acid as the major bound phenolic acid while other millet types had ferulic as the major one. Therefore, millets cannot be generalised in terms of their phenolic profile as each millet type has different phenolic contents and phenolic acid profile.

**DPPH scavenging activity**

Different phenolic acids have been shown to have varying antioxidant activity (Williams et al. 1995; Velkov et al. 2007). Factors namely the extraction procedure, polarity of extracting solvent, synergistic activity of several phenolic compounds in the extract, the position and extent of hydroxylation of the phenolic rings and structural features of phenolic compound have also shown to effect antioxidant activity (Meyer et al. 1998; Hegde and Chandra 2002). Hence higher phenolic content may not always predict a high antioxidant activity. The current study uses the free radical diphenylpicrylhydrazyl (DPPH) for estimating the antioxidant potential of the phenolic acids in millets. It has an absorption band at 515 nm and loses this absorption when reduced by an antioxidant or free radical species. This method has been widely used to determine antiradical or antioxidant activity of phenolic compounds (Williams et al. 1995; Velkov et al. 2007). DPPH scavenging potential of free and bound extract from whole grains varied from 32-
91% and 85-93% respectively (Table 3.3). Free extract from decorticated grains had DPPH activity from 19-32% while the bound extract quenched DPPH by 47-69%. Finger millet varieties had higher DPPH activity for both free and bound extract compared to other WG types. Similar to previous studies (Dykes et al. 2005; Mpofu et al. 2006) a significant positive correlation was observed between free phenolic content & DPPH activity of free extract (r=0.75) and between bound content & DPPH activity of bound extract (r=64), for whole and decorticated millet types. Total phenolic content of whole grain barley, rice, wheat and rye ranged from 450-1346 µg/g, 197-396 µg/g, 560-1371 µg/g, 1362-1366 µg/g respectively. Whole grain wheat had DPPH scavenging activity of 3.8-13% and 74-86% for free and bound extract respectively (Ragaee et al. 2006; Dykes and Rooney 2007; Ragaee et al. 2012). These values may vary depending on the variety of cereal chosen. As seen from the results of this study, whole grain millets especially kodo, finger millet varieties, barnyard and pearl have higher phenolic content and antioxidant activity than some of the major cereals.

3.4.4 Insoluble and soluble dietary fibre
Insoluble dietary fibre (IDF) of whole grain millet ranged from 11-32% and soluble dietary fibre (SDF) from 2.0-3.7% as shown in Table 3.1. Whole grain kodo and barnyard had higher IDF than other WG millet types. Pearl millet had the lowest IDF among WG types. SDF of little CO4, finger G.P28 and finger katti millets were higher than the other WG millet types and ranged from 3.5-3.7%. IDF and SDF of finger millet varieties were significantly different, with G.P 28 and katti ragi having higher contents than seto and dalle. IDF and SDF of whole grain little CO4 were higher than little landrace. Decorticated millet had insoluble dietary fibre (IDF) varying from 2.4-5.5 % and soluble dietary fibre (SDF) from 0.4-3.5 % (Table 3.1). Barnyard showed highest IDF and little CO4 had the highest SDF among decorticated millets.
The results of this study indicate wide variation in the IDF contents among the whole grain millets while SDF contents were similar for most millet types. Decortication decreased the IDF from 66-92% with kodo showing the maximum loss after decortication. However, the percent decrease in SDF was lower compared to IDF. SDF decreased by 3.7%, 11%, 17% and 55% for foxtail, proso, barnyard and little CO4 respectively after decortication. Kodo showed the highest reduction of 82% in SDF after decortication. IDF consist of lignin, cellulose and hemi-cellulose while SDF comprise of β-glucan and arabinoxylan. These five components are distributed in varying proportions from outer to the inner layers of the grain. The proportions of these fibre components may vary depending on the grain type (Marlett 1990; Charalampopoulos et al. 2002). This indicates that decortication will reduce the IDF and SDF in varying amounts depending on the millet type. Since SDF is generally found more in the inner layers compared to IDF, hence the percentage decrease in SDF was much lower than IDF, except for kodo. The IDF in some whole grain cereals like wheat, rye and barley are reported to be 10-12%, 14-16%, 18.8-22% while SDF to be 2.8-3.8%, 3.6-3.8%, 2.6-3.9% respectively (Nyman et al. 1984; Ragaee et al. 2006). The results from this study suggests that IDF values of whole grain millet types were comparable or higher than these major cereals while SDF content were similar or lower.

As discussed in section 3.4.3, high losses in phenolic content was observed after decortication, this may suggests that the phenolics are mainly concentrated in the outer layers of the grain. Insoluble dietary fibre (IDF) showed significant positive correlation with bound phenolic content (r=0.83) and bound antioxidant activity (r=0.82) while IDF had weaker correlation with free phenolic content (r=0.55) and free antioxidant activity (r=0.57). SDF did not significantly
correlate with phenolic content and weakly correlated with DPPH activity. Previous studies have suggested that 95% of the phenolic acids are esterified to the plant cell walls which constitute major part of IDF. Therefore, it may be suggested that bound phenolics are major parts of the IDF while SDF contributes little to the phenolic content and antioxidant activity in millets. Previous studies on other cereals have also shown similar correlations (Rybka et al. 1992; Guo and Beta 2013).

3.4.5 In vitro starch digestibility
The rapidly digestible starch (RDS), slowly digestible starch (SDS), residual starch (RES) and expected glycemic index (eGI) values of cooked whole grain flour varied from 19-28%, 31-45%, 31-51% and 43-58 respectively (Table 3.6). Whole grain kodo showed the least RDS, highest RS and least eGI. Pearl had the highest eGI of 58 among WG millets. RDS, SDS, RS and eGI of finger millet varieties ranged from 23-26%, 39-44%, 32-35% and eGI 53-56 respectively. Finger (seto, dalle) millet varieties were significantly different from finger (G.P28, katti) millets however the extent of variation was not high. Little landrace had higher eGI (49) than little CO4 (45). Cooked decorticated millet flour had RDS from 21-31%, SDS 34-44 %, RS 29-44 % and eGI 47-61 (Table 3.6). Kodo showed the highest RDS, least RS and highest eGI. Starch hydrolysis rate for the WG forms were in the order: proso > foxtail > barnyard > little CO4 > kodo (Fig 3.5). The rate of starch hydrolysis of DC millets was in the following order: kodo > proso > barnyard > foxtail > little CO4 (Fig 3.4). At 120 min of hydrolysis, the starch hydrolyzed in DC little CO4, proso, barnyard and kodo was higher than their WG forms by 5.3%, 6.5%, 19.6% and 46% respectively. Based on these results, decortication had an effect on the starch hydrolysis kinetics.
Significant differences were found in the starch digestibility of different whole grain and decorticated millets. Varietal effect on the IVSD was not very high as observed in the finger and little millet varieties. Expected glycemic index (eGI) and RDS for WG pearl, proso and finger millets were higher than the other whole grain types. The differences in the IVSD of the different millet types may be due to the varying starch granular structure, amylose to amylopectin ratio and the resistant starch content (Panlasigui et al. 1991; Sagum and Arcot 2000; Annor et al. 2013b). Kodo millet showed a substantial increase in eGI by 42% after decortication while the other millet types showed an increase less than 6%. The increase in the eGI of decorticated millets maybe due to the changes in IDF, phenolics and lipid contents after decortication. The substantial decrease in IVSD for kodo millet may be due to the decrease in these components. A significant negative correlation of eGI with lipid content ($r=-0.38$), bound phenolic ($r=-0.39$) and IDF ($r=-0.45$) was observed in this study however the correlations were not strong. Therefore, lipid, phenolics and IDF may have some effect on the starch digestibility of millets. Further studies should be done to evaluate the effect of each component on the in vitro starch digestibility. The eGI values of some major cereals like rice, barley and oats in their cooked form are 60-102, 55-65 and 77-100 respectively (Grandfeldt et al. 1994; Frie et al. 2003; Hu et al. 2004; Kim and White 2012). It can be inferred from the current study that the eGI range of these major cereals are higher compared to the whole or decorticated millet types. Therefore, millets with its hypoglycemic property can be a potential food source for controlling diabetes.

3.5 Conclusion

Whole grain millets were found to be rich sources of phenolics, IDF and unsaturated fatty acids. Whole grain kodo and finger millet varieties showed higher phenolic content and DPPH activity
in both free and bound extracts. The phenolic acid profile showed wide variations among the millet types. Phenolic content (free & bound) and antioxidant activity showed high reduction after decortication with kodo and foxtail showing the highest decrease. Among the whole grains, IDF was highest in kodo and barnyard while pearl and foxtail showed high amount of unsaturated fatty acids. The fatty acid profile for finger, kodo and little millets were different than the other types. Decortication lowered the lipid content of millets by 44-78% however the decrease in fatty acid content was not relative based on the lipid content. The fatty acid profile of the whole grain and decorticated millet were not different. Significant positive correlations were observed between- phenolic content and DPPH activity; IDF and bound phenolic content; IDF and DPPH activity. In vitro starch digestibility varied significantly among the whole grain types, with pearl, proso and some finger millet varieties showing higher values than other types. Kodo millet showed the highest increase in IVSD after decortication. It may be suggested that lipids, phenolics and IDF can affect in vitro starch digestibility, however further studies should be done to study the impact of each component. Varietal effects on the composition were also observed however the ranges of variations were not high. The results of the study suggest that the extent of variation of each nutrient component mainly depends on the millet type. Most of the IDF, phenolic content, antioxidant activity and unsaturated fatty acids are lost during decortication, however the hypoglycemic property holds for both the WG and DC forms.
### Table 3.1: Proximate composition of whole and decorticated millets*

<table>
<thead>
<tr>
<th>State</th>
<th>Sample</th>
<th>Total Starch (%)</th>
<th>Free lipid (mg/g)</th>
<th>Insoluble Dietary Fibre (%)</th>
<th>Soluble Dietary Fibre (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>DC**</td>
<td>Little CO4</td>
<td>84.6±1.3h</td>
<td>10.9±0.1c</td>
<td>2.6±0.07a</td>
<td>1.6±0.2b</td>
</tr>
<tr>
<td></td>
<td>Foxtail</td>
<td>77.8±0.2g</td>
<td>26.3±0.2e</td>
<td>4.9±0.2b</td>
<td>2.6±0.08cd</td>
</tr>
<tr>
<td></td>
<td>Barnyard</td>
<td>74±0.6f</td>
<td>45.2±0.3g</td>
<td>5.5±0.06b</td>
<td>2.4±0.2cd</td>
</tr>
<tr>
<td></td>
<td>Kodo</td>
<td>83.2±2.1h</td>
<td>8.8±0.2b</td>
<td>2.4±0.01a</td>
<td>0.4±0.02a</td>
</tr>
<tr>
<td></td>
<td>Proso</td>
<td>78.4±0.7h</td>
<td>12.2±0.2d</td>
<td>5.4±0.1b</td>
<td>2.1±0.04bcd</td>
</tr>
<tr>
<td>WG***</td>
<td>Little C04</td>
<td>55.6±0.7b</td>
<td>49.7±0.06i</td>
<td>21.8±0.3h</td>
<td>3.5±0.1e</td>
</tr>
<tr>
<td></td>
<td>Little Landrace</td>
<td>62.4±0.8cde</td>
<td>53.1±0.01j</td>
<td>19.2±0.5f</td>
<td>2.8±0.1d</td>
</tr>
<tr>
<td></td>
<td>Foxtail</td>
<td>55.1±0.3ab</td>
<td>46.7±0.02h</td>
<td>22.9±0.07i</td>
<td>2.7±0.09d</td>
</tr>
<tr>
<td></td>
<td>Barnyard</td>
<td>55.8±0.6b</td>
<td>47.7±0.1h</td>
<td>26.1±0.2j</td>
<td>2±0.03bc</td>
</tr>
<tr>
<td></td>
<td>Kodo</td>
<td>52.9±0.7a</td>
<td>26.5±0.2e</td>
<td>31.7±0.2k</td>
<td>2.2±0.04cd</td>
</tr>
<tr>
<td></td>
<td>Proso</td>
<td>64.5±1.1e</td>
<td>37.1±0.1f</td>
<td>16.1±0.07e</td>
<td>2.4±0.02d</td>
</tr>
<tr>
<td></td>
<td>Pearl</td>
<td>60.6±0.6cd</td>
<td>56.7±0.9k</td>
<td>11.5±0.4c</td>
<td>2.6±0.02cd</td>
</tr>
<tr>
<td></td>
<td>Finger Seto</td>
<td>62.8±0.5de</td>
<td>6.7±0.2a</td>
<td>15±0.3d</td>
<td>2.2±0.03cd</td>
</tr>
<tr>
<td></td>
<td>Finger Dalle</td>
<td>60.3±0.2c</td>
<td>6.8±0.3a</td>
<td>15±0.3d</td>
<td>2.3±0.03cd</td>
</tr>
<tr>
<td></td>
<td>Finger GP 28</td>
<td>63.1±0.6e</td>
<td>9.3±0.1b</td>
<td>20.4±0.2g</td>
<td>3.7±0.02e</td>
</tr>
<tr>
<td></td>
<td>Finger Katti</td>
<td>62.6±0.8cde</td>
<td>12.1±0.2cd</td>
<td>20.6±0.01g</td>
<td>3.5±0.03e</td>
</tr>
</tbody>
</table>

*Values with different letters within a column are significantly different (P < 0.05)

**Decorticated millet grain, ***Whole grain millet
<table>
<thead>
<tr>
<th>State</th>
<th>Sample</th>
<th>Free Phenolic content (µg/g)</th>
<th>Bound Phenolic content (µg/g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>DECORTICATED</td>
<td>Little C04</td>
<td>43.8±1.8ab</td>
<td>107±2.3a</td>
</tr>
<tr>
<td></td>
<td>Foxtail</td>
<td>15.6±1.4a</td>
<td>244±3.2bc</td>
</tr>
<tr>
<td></td>
<td>Barnyard</td>
<td>117±3.8c</td>
<td>325±5.4c</td>
</tr>
<tr>
<td></td>
<td>Kodo</td>
<td>12.9±0.1a</td>
<td>171±1.3ab</td>
</tr>
<tr>
<td></td>
<td>Proso</td>
<td>30.2±1.3a</td>
<td>210±7.1b</td>
</tr>
<tr>
<td>WHOLE</td>
<td>Little CO4</td>
<td>187±4.2e</td>
<td>1107±21d</td>
</tr>
<tr>
<td></td>
<td>Little Landrace</td>
<td>242±2.6f</td>
<td>1028±13d</td>
</tr>
<tr>
<td></td>
<td>Foxtail</td>
<td>122±1.9c</td>
<td>2773±40i</td>
</tr>
<tr>
<td></td>
<td>Barnyard</td>
<td>127±2.1c</td>
<td>2324±46h</td>
</tr>
<tr>
<td></td>
<td>Kodo</td>
<td>2518±19i</td>
<td>7210±68j</td>
</tr>
<tr>
<td></td>
<td>Proso</td>
<td>87.5±0.4bc</td>
<td>1414±18e</td>
</tr>
<tr>
<td></td>
<td>Pearl</td>
<td>227±2.4de</td>
<td>1948±21f</td>
</tr>
<tr>
<td></td>
<td>Finger Seto</td>
<td>1346±12f</td>
<td>1371±15e</td>
</tr>
<tr>
<td></td>
<td>Finger Dale</td>
<td>1486±11g</td>
<td>2246±23gh</td>
</tr>
<tr>
<td></td>
<td>Finger G.P 28</td>
<td>2229±25h</td>
<td>2778±25i</td>
</tr>
<tr>
<td></td>
<td>Finger Katti</td>
<td>1473±12g</td>
<td>2159±28g</td>
</tr>
</tbody>
</table>

*Values followed by different letters within a column are significantly different (P <0.05)*
Table 3.3: Antioxidant activity as % DPPH scavenged in whole and decorticated millets*  

<table>
<thead>
<tr>
<th>State</th>
<th>Sample</th>
<th>% DPPH free**</th>
<th>% DPPH bound***</th>
</tr>
</thead>
<tbody>
<tr>
<td>DECORTICATED</td>
<td>Little C04</td>
<td>26.8±1.2b</td>
<td>47.1±1.3a</td>
</tr>
<tr>
<td></td>
<td>Foxtail</td>
<td>19.2±0.2a</td>
<td>67.3±1.8c</td>
</tr>
<tr>
<td></td>
<td>Barnyard</td>
<td>44.9±1.6e</td>
<td>76.7±2.2e</td>
</tr>
<tr>
<td></td>
<td>Kodo</td>
<td>23.8±0.3b</td>
<td>59.4±1.4b</td>
</tr>
<tr>
<td></td>
<td>Proso</td>
<td>27.7±0.7b</td>
<td>68.6±2.3c</td>
</tr>
<tr>
<td>WHOLE</td>
<td>Little CO4</td>
<td>40.5±0.8d</td>
<td>80.5±0.5f</td>
</tr>
<tr>
<td></td>
<td>Little Landrace</td>
<td>45.5±1.5e</td>
<td>88.2±0.9h</td>
</tr>
<tr>
<td></td>
<td>Foxtail</td>
<td>31.6±0.3c</td>
<td>90.8±2.6i</td>
</tr>
<tr>
<td></td>
<td>Barnyard</td>
<td>43.6±0.3de</td>
<td>91.1±1.9i</td>
</tr>
<tr>
<td></td>
<td>Kodo</td>
<td>71.2±0.9f</td>
<td>93.1±2.3j</td>
</tr>
<tr>
<td></td>
<td>Proso</td>
<td>35.9±0.5c</td>
<td>85.8±0.6g</td>
</tr>
<tr>
<td></td>
<td>Pearl</td>
<td>72.7±1.5f</td>
<td>91±1.7i</td>
</tr>
<tr>
<td></td>
<td>Finger Seto</td>
<td>88.3±2.3g</td>
<td>86±2.4gh</td>
</tr>
<tr>
<td></td>
<td>Finger Dale</td>
<td>90.1±1.8g</td>
<td>85.7±1.9gh</td>
</tr>
<tr>
<td></td>
<td>Finger GP 28</td>
<td>89.5±2.1g</td>
<td>86.2±1.1gh</td>
</tr>
<tr>
<td></td>
<td>Finger Katti</td>
<td>89.9±1.3g</td>
<td>86±0.9gh</td>
</tr>
</tbody>
</table>

*Values followed by different letters within a column are significantly different (P <0.05)

**% DPPH scavenged in free phenolic extract, ***% DPPH scavenged in bound phenolic extract
## Table 3.4a: Free phenolic acid content (µg/g) in whole and decorticated millets

<table>
<thead>
<tr>
<th>State</th>
<th>Sample</th>
<th>Vanillic</th>
<th>Syringic</th>
<th>Gentistic</th>
<th>Gallic</th>
<th>Protocatechuic</th>
</tr>
</thead>
<tbody>
<tr>
<td>DC</td>
<td>Little C04</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>5.6±0.03</td>
<td>2.3±0.01</td>
</tr>
<tr>
<td></td>
<td>Foxtail</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>13.3±0.05</td>
<td>6±0.02</td>
</tr>
<tr>
<td></td>
<td>Barnyard</td>
<td>1.5±0.01</td>
<td>-</td>
<td>-</td>
<td>20.7±0.4</td>
<td>4.3±0.03</td>
</tr>
<tr>
<td></td>
<td>Kodo</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>6.7±0.02</td>
<td>2.6±0.04</td>
</tr>
<tr>
<td></td>
<td>Proso</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>10.6±0.06</td>
<td>6.1±0.04</td>
</tr>
<tr>
<td></td>
<td>Little C04</td>
<td>4.5±0.02</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>6±0.02</td>
</tr>
<tr>
<td></td>
<td>Little Landrace</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>1.3±0.01</td>
</tr>
<tr>
<td></td>
<td>Foxtail</td>
<td>5.6±0.02</td>
<td>8.8±0.07</td>
<td>-</td>
<td>-</td>
<td>3.8±0.01</td>
</tr>
<tr>
<td></td>
<td>Kodo</td>
<td>20.8±0.4</td>
<td>38.9±0.9</td>
<td>30.3±0.8</td>
<td>-</td>
<td>9±0.04</td>
</tr>
<tr>
<td></td>
<td>Proso</td>
<td>2.2±0.03</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>WG**</td>
<td>Pearl</td>
<td>1.5±0.03</td>
<td>27.5±0.2</td>
<td>-</td>
<td>78.3±1.1</td>
<td>26.6±0.3</td>
</tr>
<tr>
<td></td>
<td>Barnyard</td>
<td>4.9±0.06</td>
<td>5.4±0.04</td>
<td>-</td>
<td>22.2±0.4</td>
<td>8.2±0.02</td>
</tr>
<tr>
<td></td>
<td>Finger Seto</td>
<td>27.9±0.3</td>
<td>20.5±0.4</td>
<td>8.3±0.05</td>
<td>88.2±1.3</td>
<td>26.8±0.4</td>
</tr>
<tr>
<td></td>
<td>Finger Dalle</td>
<td>34.7±0.4</td>
<td>-</td>
<td>-</td>
<td>91.2±1.4</td>
<td>21.4±0.5</td>
</tr>
<tr>
<td></td>
<td>Finger G.P 28</td>
<td>56.5±0.5</td>
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<td>6.1±0.02</td>
<td>100±2.1</td>
<td>25±0.3</td>
</tr>
<tr>
<td></td>
<td>Finger Katti</td>
<td>32.4±0.2</td>
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<td>-</td>
<td>104±2.3</td>
<td>20.1±0.6</td>
</tr>
</tbody>
</table>

Decorticated millet grain, **Whole grain millet
Table 3.4b: Free phenolic acid content (µg/g) in whole and decorticated millets

<table>
<thead>
<tr>
<th>State</th>
<th>Sample</th>
<th>$p$-hydroxy***</th>
<th>$p$-coumaric</th>
<th>Ferulic</th>
<th>Sinapic</th>
<th>Caffeic</th>
</tr>
</thead>
<tbody>
<tr>
<td>DC</td>
<td>Little C04</td>
<td>-</td>
<td>-</td>
<td>3.3±0.01</td>
<td>3.0±0.04</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>Foxtail</td>
<td>0.8±0.01</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>Barnyard</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
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<tr>
<td></td>
<td>Kodo</td>
<td>1.2±0.03</td>
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<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>Proso</td>
<td>0.8±0.03</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>WG</td>
<td>Little C04</td>
<td>1.3±0.01</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>Little Landrace</td>
<td>2.1±0.02</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>1.2±0.01</td>
</tr>
<tr>
<td></td>
<td>Foxtail</td>
<td>2.1±0.04</td>
<td>3.6±0.02</td>
<td>4.1±0.1</td>
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<tr>
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<td>Kodo</td>
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<td>73±1.2</td>
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<tr>
<td></td>
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<td>1.8±0.0</td>
<td>-</td>
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<td>-</td>
</tr>
<tr>
<td></td>
<td>Pearl</td>
<td>4.5±0.02</td>
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<td>2.4±0.1</td>
<td>1.9±0</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>Barnyard</td>
<td>2.1±0.03</td>
<td>3.7±0.01</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>Finger Seto</td>
<td>24.1±0.2</td>
<td>-</td>
<td>-</td>
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<td>-</td>
</tr>
<tr>
<td></td>
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<td>-</td>
<td>-</td>
<td>0.88±0</td>
<td>0.35±0</td>
<td>-</td>
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<td>Finger G.P 28</td>
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<td>1.5±0.01</td>
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<td>-</td>
</tr>
<tr>
<td></td>
<td>Finger Katti</td>
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<td>1.02±0</td>
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Decorticated millet grain, **Whole grain millet, ***$p$-hydroxybenzoic acid
Table 3.5a: Bound phenolic acid content (µg/g) in whole and decorticated millets

<table>
<thead>
<tr>
<th>State</th>
<th>Sample</th>
<th>Vanillic</th>
<th>Syringic</th>
<th>Gentistic</th>
<th>Gallic</th>
<th>Protocatechuic</th>
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</tr>
<tr>
<td>DC*</td>
<td>Little C04</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>Foxtail</td>
<td>9.9±0.02</td>
<td>7.4±0.03</td>
<td>-</td>
<td>-</td>
<td>10±0.1</td>
</tr>
<tr>
<td></td>
<td>Barnyard</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
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</tr>
<tr>
<td></td>
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<td>-</td>
<td>-</td>
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<td>-</td>
</tr>
<tr>
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<td>Proso</td>
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<td>-</td>
</tr>
<tr>
<td>WG**</td>
<td>Little C04</td>
<td>14.2±0.2</td>
<td>11.2±0.03</td>
<td>-</td>
<td>4.2±0</td>
<td>-</td>
</tr>
<tr>
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<td>Little Landrace</td>
<td>13.3±0.3</td>
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<td>-</td>
<td>12.6±0.02</td>
</tr>
<tr>
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<td>Foxtail</td>
<td>77.7±1.2</td>
<td>47.9±1.1</td>
<td>-</td>
<td>9.6±0.02</td>
<td>10.4±0</td>
</tr>
<tr>
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<td>Barnyard</td>
<td>47.1±0.9</td>
<td>33.6±1.2</td>
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<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>Kodo</td>
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<td>713±10</td>
<td>178±2.3</td>
<td>27±0.1</td>
<td>17.3±0.03</td>
</tr>
<tr>
<td></td>
<td>Proso</td>
<td>23.3±0.3</td>
<td>131±6.4</td>
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<td>-</td>
<td>31.3±0.07</td>
</tr>
<tr>
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<td>Pearl</td>
<td>12.3±0.03</td>
<td>11.4±0.03</td>
<td>-</td>
<td>16±0</td>
<td>4.2±0</td>
</tr>
<tr>
<td></td>
<td>Finger Seto</td>
<td>-</td>
<td>6.2±0.02</td>
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<td>83.0±1.8</td>
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<td>Finger Dalle</td>
<td>-</td>
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</tr>
<tr>
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<td>Finger G.P 28</td>
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<td>45.7±0.6</td>
<td>66.2±0.5</td>
<td>22.9±0.4</td>
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<td>Finger Katti</td>
<td>-</td>
<td>14.6±0.08</td>
<td>47.8±0.4</td>
<td>58.1±0.6</td>
<td>78.8±0.8</td>
</tr>
</tbody>
</table>

*Decorticated millet grain, **Whole grain millet
Table 3.5b: Bound phenolic acid content (µg/g) of whole and decorticated millets

<table>
<thead>
<tr>
<th>State</th>
<th>Sample</th>
<th>$p$-hydroxy***</th>
<th>$p$-coumaric</th>
<th>Ferulic</th>
<th>Sinapic</th>
<th>Caffeic</th>
</tr>
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<tr>
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<td>15.7±0.1</td>
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<tr>
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<td>Barnyard</td>
<td>-</td>
<td>51.8±1.2</td>
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<td>-</td>
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</tr>
<tr>
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<td>Kodo</td>
<td>-</td>
<td>-</td>
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<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>Proso</td>
<td>-</td>
<td>-</td>
<td>160±1.6</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
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<td>7.3±0</td>
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<td>525±16</td>
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</tr>
<tr>
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<td>12.3±0.01</td>
<td>28.3±0.04</td>
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<td>Finger Seto</td>
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<td>450±1.9</td>
<td>8.7±0</td>
<td>46±0.3</td>
</tr>
<tr>
<td></td>
<td>Finger Dalle</td>
<td>12.5±0.04</td>
<td>45.3±0.08</td>
<td>664±14</td>
<td>8±0.06</td>
<td>93.2±0.8</td>
</tr>
<tr>
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<td>Finger G.P 28</td>
<td>85.4±1.4</td>
<td>44.5±0.09</td>
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<td>8.5±0.02</td>
<td>85.1±1.1</td>
</tr>
<tr>
<td></td>
<td>Finger Katti</td>
<td>12.2±0.6</td>
<td>15.2±0.04</td>
<td>407±8.7</td>
<td>7.6±0</td>
<td>50.9±0.7</td>
</tr>
</tbody>
</table>

*Decorticated millet grain, **Whole grain millet, *** p-hydroxybenzoic acid
Table 3.6: Rapidly digestible starch (RDS), slowly digestible starch (SDS) residual starch (RES) and expected glycemic index (eGI) of cooked millet flour

<table>
<thead>
<tr>
<th>State</th>
<th>Sample</th>
<th>RDS (%)</th>
<th>SDS (%)</th>
<th>RES (%)</th>
<th>eGI</th>
</tr>
</thead>
<tbody>
<tr>
<td>DC**</td>
<td>Little CO4</td>
<td>21.9±0.6bcd</td>
<td>33.7±0.9b</td>
<td>44.1±0.6h</td>
<td>46.8±0.5bc</td>
</tr>
<tr>
<td></td>
<td>Foxtail</td>
<td>22.5±0.3cde</td>
<td>37.2±0.3cde</td>
<td>40.4±0.4g</td>
<td>49.4±0.4de</td>
</tr>
<tr>
<td></td>
<td>Barnyard</td>
<td>22.6±0.7cde</td>
<td>43.8±0.8h</td>
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</tr>
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<td>30.6±0.6f</td>
<td>40.8±0.3fg</td>
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<td>60.8±0.6k</td>
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<td>Proso</td>
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</tr>
<tr>
<td>WG***</td>
<td>Little CO4</td>
<td>20.2±0.4ab</td>
<td>32.1±0.3ab</td>
<td>47.7±0.2i</td>
<td>44.8±0.3ab</td>
</tr>
<tr>
<td></td>
<td>Little Landrace</td>
<td>21.1±0.4bc</td>
<td>40.6±0.2fg</td>
<td>38.3±0.05fg</td>
<td>48.6±0.1cd</td>
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<td>40.7±0.1g</td>
<td>46.8±0.2b</td>
</tr>
<tr>
<td></td>
<td>Barnyard</td>
<td>24.8±0.3fg</td>
<td>30.7±0.2a</td>
<td>44.6±0.5h</td>
<td>49.9±0.3c</td>
</tr>
<tr>
<td></td>
<td>Kodo</td>
<td>19.2±0.08a</td>
<td>29.6±0.09a</td>
<td>51.2±0.6j</td>
<td>42.7±0.1a</td>
</tr>
<tr>
<td></td>
<td>Proso</td>
<td>27.3±0.05ij</td>
<td>36.4±0.3c</td>
<td>36.4±0.09ef</td>
<td>55.1±0.7ghi</td>
</tr>
<tr>
<td></td>
<td>Pearl</td>
<td>28.7±0.03j</td>
<td>40.3±0.4fg</td>
<td>31±0.3ab</td>
<td>58.3±0.3j</td>
</tr>
<tr>
<td></td>
<td>Finger Seto</td>
<td>23.4±0.1def</td>
<td>44.5±0.2h</td>
<td>32.1±0.6bc</td>
<td>52.9±0.6fg</td>
</tr>
<tr>
<td></td>
<td>Finger Dalle</td>
<td>24±0.1efg</td>
<td>42.6±0.3gh</td>
<td>33.4±0.5bcd</td>
<td>53.1±0.5fgh</td>
</tr>
<tr>
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<td>Finger GP 28</td>
<td>25.3±0.3gh</td>
<td>39.2±0.4def</td>
<td>35.5±0.2de</td>
<td>56.1±0.8ij</td>
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<tr>
<td></td>
<td>Finger Katti</td>
<td>26.4±0.06hi</td>
<td>39.7±0.2ef</td>
<td>33.9±0.4cde</td>
<td>55.3±0.8hi</td>
</tr>
</tbody>
</table>

*Values with different letters within a column are significantly different (P < 0.05)

**Decorticated millet grain, ***Whole grain millet
Fig 3.1: Free fatty acid contents (a) 16:0, 18:0, 18:1, 18:2 (b) 18:3, 20:0, 20:1, 22:0, 24:0 in decorticated millets.
Fig 3.2: Free fatty acid content (a) 16:0, 18:0, 18:1, 18:2 (b) 18:3, 20:0, 20:1, 22:0, 24:0 in whole grain millets.
Fig 3.3: Free fatty acid content (a) 16:0, 18:0, 18:1, 18:2 (b) 18:3, 20:0, 20:1, 22:0, 24:0 in whole grain finger millet varieties.
Fig.3.4: Starch hydrolysis kinetics of cooked flour from decorticated millets.
Fig. 3.5: Starch hydrolysis kinetics of cooked flour from whole grain millets.
4. CHAPTER FOUR: EFFECT OF PARBOILING ON THE NUTRIENT COMPOSITION AND IN VITRO DIGESTIBILITY OF MILLET PRODUCTS

4.1 Abstract

Parboiling is a common method used for rice to improve its milling yield and nutritional quality. However, limited information exists on millet parboiling. The current study evaluates the impact of parboiling on the decortication yield and nutritional value of millets. Two types of product namely steam cooked couscous and porridge were prepared from native and parboiled millet. Pearl and proso millet types were considered for the study. Parboiling significantly increased the resistant starch contents in both pearl and proso products. Resistant starch of proso products was significantly higher than the pearl millet products. Free phenolic acid contents increased 3-13 times and bound phenolics had a 25-60% increase after parboiling. There was a significant decrease in RDS and eGI of the products from parboiled millets, however the extent of change was not very high. The eGI of all the products from native or parboiled flour showed lower eGI than most cereal products. Parboiling reduced the in vitro protein digestibility by 13-16%. The type of millet mainly affected the composition and in vitro digestibility of the millet porridge and couscous, rather than the product type. The results of the study suggest that parboiling improved the yield of decorticated millets and also changed the nutritional composition and in vitro digestibility of the products significantly. However the extent of changes in the nutritional properties of the parboiled product may depend on the type of millet and the parboiling conditions used.

Key words: parboiling, millet, composition, in vitro digestibility
4.2 Introduction

Commercially available decorticating techniques have not been successfully employed on millets, the small size and uniqueness in the grain morphology of millet makes it difficult to decorticate (Shobana and Malleshi 2007). Parboiling has been shown to improve milling yield of rice by 25-30% and is a common method used for rice to improve nutritional quality and yield (Tirawanichakul et al. 2012; Gunaratne et al. 2013), however there is dearth of information on millet parboiling. Few studies on parboiling of finger and pearl millet have shown to improve its decortication yield, storage quality, sensory properties and nutritional quality (Clegg et al. 1991; Nantanga et al. 2008; Dharmaraj and Malleshi 2011). The hydrothermally decorticated millet is a quick cooking cereal which can be cooked as discrete grains like rice or it can be further processed to make traditional or value-added products (Saleh et al. 2013). As the parboiled grains are re-cooked to prepare varied products, hence studying the nutritional properties of the final edible product is important. Porridge and couscous from millets have been some major traditional products consumed in different parts of India and Africa (FAO 1995). As millet products have not yet been established as confectionary, breakfast or ready to eat product at an industrial scale, therefore, focus on the traditional products from native and parboiled flour would be more beneficial. Porridge is usually prepared by cooking millet flour in excess water while couscous is steamed as intact grains. These two food matrices will be different in terms of their moisture conditions, cooking time and the form (flour versus intact grain) in which they are cooked. Moreover these products would be prepared from 100% millet flour and water, there are no other ingredients added to these product matrix. This would ensure that there are no interfering factors to affect the physico-chemical changes occurring in the parboiled products. The current study compared the nutritional properties of millet porridge and couscous made from
native and parboiled decorticated millet. Pearl and proso millets were considered for the study owing to its morphological and compositional differences. Botanically, millets are separated into caryopses and utricles. The seed coat is covered by the pericarp which is attached at only one point, resulting in easy removal of the pericarp. In a caryopsis, the pericarp is strongly attached to the seed. Pearl millet is a caryopsis while proso is utricle type grain (McDonough and Rooney 2000). Wide variations in starch properties, protein and phenolics were also observed in these two grain types (Belelia et al. 1980; Chanda and Matta 1990; Yanez et al. 1991; Parmeswaran and Thaymanavan 1995; Dykes and Rooney 2006). The results of the current study evaluates the application of parboiling as a potential method to increase decortication yield and improve nutritional quality of millets.

4.3 Materials and methods

Pearl CGMPH 90 was provided by Agriculture Environmental Renewal Canada Inc (ARC) and Proso Colorado from Bunge milling, St. Louis, United States of America. The samples were decorticated using Satake TM5 mill by Bunge milling, St. Louis, United States of America.

4.3.1 Preparation of sample

Parboiling process

Parboiling process as described by Clegg et al. (1991) was used with some modifications. The process is described as below:
Grains were soaked in water (grain:water 1:3) for 12 hr at room temperature

\[ \text{Drain water} \]

Proso millet grains were poured in boiling water and boiled for 2 min

Pearl millet grains were poured in boiling water and boiled for 5 min

Grains were air-dried for 24-48 hr by spreading them on steel trays, until the moisture content came to 11-13%

Decorticate

**Product preparation:**

**Porridge:** The native and parboiled millet grains were ground into flour and a slurry was made by adding the millet flour to cold water (flour:water 1:10). The mixture was boiled at medium to high heat for 10 min in a non-stick pan with intermittent stirring. Product was cooled for 10-15 min and freeze dried.

**Couscous:** The native and parboiled grains were soaked (grain:water 1:3) for 3 hr. The soaked water was drained and the grains are steam-cooked. Steam cooking was done by boiling water in a steam cooker, the soaked grains are then poured into the cooker and cooked for 50 min. After removing excess water from the steamed grains, it was cooled for 10-15 min and freeze dried. The freeze dried porridge and couscous were ground in a coffee grinder and passed through a 0.5 mm sieve. These samples were stored at -20°C freezer until further analysis.
4.3.2 Total Starch
Megazyme assay kit (Bray, Ireland) was used for the quantification of total starch. It is based on AACC method 76.13 (2003). Absorbance was measured at 510 nm by spectrophotometer (Cary 1-Bio UV-visible spectrophotometer, Ontario, Canada).

4.3.3 Resistant starch
Megazyme resistant starch kit (Bray, Ireland) was used to estimate resistant starch. It is based on AACC 32-40 method (2003). The principle of this method is removing the non-resistant starch by hydrolysis with α-amylase and amyloglucosidase for 16 h at 37°C. Recovery of resistant starch was done as a pellet by centrifugation and washed with ethanol. This pellet was then dissolved in potassium hydroxide solution and quantitatively hydrolyzed to glucose by amyloglucosidase (Ragaee et al. 2006). Absorbance was measured at 510 nm wavelength by spectrophotometer (Cary 1-Bio UV-visible spectrophotometer, Ontario, Canada).

4.3.4 Phenolics

Free and bound phenolic content
This procedure of extraction of free and bound phenolic mostly isolates the phenolic acids (Khoddami et al. 2013). Extraction of free and bound phenolics was done according to the procedure described by Ragaee et al. (2012). Quantification of free and bound phenolic content was done by Folin-Ciocalteau reagent (Ragaee et al. 2012). Absorbance was measured at 725 nm by spectrophotometer (Cary 1-Bio UV-visible spectrophotometer, Ontario, Canada). Ferulic acid concentration in the range of 50 to 350 µg/mL was used as the standard and to construct regression equation for quantification.
**Free and bound phenolic acids**

High Performance Liquid Chromatography (HPLC) (Agilent Series 1100, Waldbronn, Germany) was used for detection and quantification of phenolic acids of free and bound extracts as described by Ragaee et al. (2012). HPLC was equipped with a diode array detector (DAD) and a Supelcosil LC-18 (Supleco Analytical, Bellefont, PA) column. A gradient elution using 6% formic acid and 6% formic acid in acetonitrile was used at a flow rate of 1 mL/min.

**4.3.5 In vitro starch digestibility**

Starch digestibility was estimated by Englyst et al. (1992). A mixture of enzymes was prepared with pancreatin from porcine pancreas ((Sigma-Aldrich Co. LLC, USA: P-1625, activity 3 X USP/g)), invertase from baker’s yeast (S. cerevisiae) (Sigma-Aldrich Co. LLC, USA: 1450) and amylglucosidase (200 U/mL p-nitrophenyl β-maltoside) (Megazyme International Ireland Ltd, Bray, Ireland). A sample containing 750 mg of starch was weighed into round bottom flasks and 10 ml of 0.1M sodium acetate buffer (pH 5.2) was added followed by addition of the enzyme mixture. The samples were incubated in a shaking water bath at 37°C for 2 hrs. Aliquots of 0.1 ml was pipetted every 20 min into 80% ethanol solution to stop enzyme hydrolysis. Glucose oxidase (GOPOD) (Megazyme) assay was used to estimate the amount of glucose released every 20 min. A conversion factor of 0.9 was used to convert glucose to starch. Three hydrolyzed fractions of starch: Rapidly Digestible Starch (RDS), Slowly Digestible starch (SDS) and Residual Starch (RS) were calculated. They were calculated as: RDS= Glucose conc at 20min x 0.9, SDS= (Glucose conc at 120min - Glucose conc at 20min) x 0.9 and RS = TS- (RDS+SDS) according to Englyst et al. (1992). Expected glycemic index (eGI) was calculated by the formula eGI= 8.198+ (0.862 x HI) as described by Granfeldt et al. (1992). HI is the hydrolysis index and calculated using method by Goni et al. (1997).
4.3.6 In vitro protein digestibility
Protein digestibility was estimated by using the method by described by Gauthier et al. (1986) with some modifications. Pepsin from porcine gastric mucosa (Sigma-Aldrich Co. LLC, USA: P-7012) and pancreatin from porcine pancreas (Sigma-Aldrich Co. LLC, USA: P-1625, activity 3 X USP/g) was used in this two-step digestion procedure. A sample containing 250 mg of protein was weighed into conical flasks and 30 ml of 0.1 N HCl was added. The first digestion was conducted on this mixture by adding 1 ml pepsin prepared in 0.1N HCl (1mg/ml) at pH 1.9 and 37°C for 30 min. After adjusting the pH of this digest to 7.5 by NaOH, the second digestion was carried out with 2.5 ml of pancreatin prepared in 0.01M sodium phosphate buffer at 37 °C for 6 hr. The digest was then transferred into centrifuge tubes and trichloroacetic acid (TCA) (20g/100 ml) was added in a ratio 1:1 (v/v) to stop the enzymatic reaction and to precipitate the undigested protein. The tube content was then centrifuged at 10,000 rpm for 10 min. After centrifuging both the pellet and supernatant were obtained to measure the undigested and digested protein respectively. The nitrogen content in the pellet and supernatant was done using Dumas (FP-528 Leco Instrument Ltd Mississauga, ON, Canada). A factor of 5.7 was used to convert %nitrogen to protein. Sodium caseinate was used as reference protein in the digestibility experiments.

4.3.7 Statistical Analysis
All analyses were conducted in duplicates and mean values are reported. ANOVA was performed and Duncan’s multiple range test was used to determine significant differences between means at the level of P < 0.05. All the analysis was performed by using Statgraphics Centurion XV, version 15.1.02 (StatPoint, Warrenton, VA, U.S.A.).
4.4 Results and discussion

4.4.1 Decortication yield
As shown in table 4.1, decortication yield of parboiled grains were significantly different and higher than the raw grains for both pearl and proso millet. Pearl millet showed a 35% increase and proso a 28% increase in yield upon decortication. Therefore, parboiling method used was successful in significantly increasing yield of decorticated millets. When the grains are boiled during the parboiling process, gelatinisation of the starch granules and disintegration of the protein bodies takes place, which leads to expansion and filling up the internal spaces in the grain. Due to this expansion, the granules of starch gets closely pressed together resulting in a strong cohesion between them. All these changes lead to the hardening of the grain during drying, which thereby increases milling yield (Ali and Pandya 1974; Bakshi and Singh 1980). Pearl millet had higher yield of decorticated millets than proso millets which may due to the difference in the grain morphology (as discussed in section 4.1) and also owing to the difference in boiling time. The boiling time for proso and pearl millet was 2 min and 5 min respectively. However when the boiling time for proso millet exceeded 2 min, a splitting of the kernels and oozing out of the endosperm was observed. Therefore, 2 min was fixed at the optimum boiling time for proso millets. Unlike pearl millet, proso millet has the pericarp loosely adhered to the endosperm which may have facilitated the easy removal of the endosperm from the pericarp during boiling, leading to the splitting of the kernels.

4.4.2 Total Starch
The total starch in porridge and couscous of pearl and proso millet ranged from 71.7-81% as shown in table 4.2. The porridge and couscous from parboiled grain had lower starch content
than the raw grains. This may be due to the leaching out of some starch during the soaking and boiling of the grains during parboiling.

4.4.3 Resistant Starch
As shown in table 4.2, the resistant starch (RS) of porridge and couscous ranged between 2.13-5.3% and 2.53-5.53%. Significant differences were found in the RS content among pearl and proso millet products. RS of porridge and couscous made from proso millet (5.13-5.52%) were higher than pearl (2.11-2.51%). This difference may be due to the varying amylose to amylopectin ratio in both millet types. It was reported that higher amylose rice formed more resistant starch after processing when compared to rice having low or intermediate amylose content (Sagum and Arcot 2000). The gelatinisation and subsequent cooling of this starch leads the amylose molecules to align themselves or associate with each other forming a rigid gel. This process is called retrogradation and resistant starch is formed as the insoluble crystallite (Eggum et al. 1993). The higher amylose content of proso millet in the current study might have resulted in higher RS content compared to pearl millet. Some studies have reported higher amylose content for proso millet (29.2-32.6%) than pearl (20-22%), however this may not be always true as wide variations among different varieties has also been observed (Belelia et al. 1980; Yanez et al. 1991; Wankhede et al. 1990; Kim et al. 2012). The difference in the starch granular structure between proso and pearl millets may also be responsible for the varying levels of resistant starch in both types (Belelia et al. 1980; Yanez et al. 1991).

The RS contents between the two products (couscous versus porridge) did not show any significant differences, suggesting that the type of product did not affect the RS formation. The soaking of grains prior to steaming and higher cooking time for couscous might have caused
similar changes in starch properties as in porridge, thereby resulting in similar RS contents for both products. Parboiling lead to a significant increase in RS for all products however the percentage increase was not very high ranging from 4-17%. Some re-association of amylose during retrogradation might be the reason for this increase (Russell et al. 1989). An increase in resistant starch has been shown in parboiled raw and parboiled cooked rice. A higher parboiling temperature (120°C) increased the RS formation (Eggum et al. 1993; Mangala et al. 1999). Few studies have also shown no change in the resistant starch after parboiling which may be due to the mild processing conditions (Gunaratne et al. 2013). The results of these studies may suggests that RS formation would mainly depend on the parboiling conditions such as moisture, temperature and time which would thereby affect the starch granular structure and its interactions (Eggum et al. 1993; Hoover 2010). RS contents of the parboiled products in the current study did not show substantial increases which may be due to the mild parboiling conditions employed.

4.4.4 Phenolic content and phenolic acid profile

Free and bound phenolic content
The free phenolic content in the raw and parboiled products of pearl millet ranged from 25-117 μg/g (Table 4.3). Proso millet products had free phenolic content from 3.5-33 μg/g. Previous studies have suggested that pearl millet has higher phenolic content than proso millets (Dykes and Rooney 2006). Similar observations have also been found in this study with pearl millet products having higher phenolics than proso. There was a drastic increase in the free phenolic content of all parboiled products. Parboiling increased the free content of pearl millet porridge by almost three times while for proso porridge, the increase was almost 8 times. Pearl and proso couscous showed an increase in free content by approximately three times after parboiling. The
increase in the free phenolic content in the current study may be due to the migration of the free phenolics from the outer layers of the grain into the endosperm and also owing to the breakdown of bound phenolics during the parboiling process (Harris and Hartly 1980; Kato et al. 1983). The bound phenolic content in the raw and parboiled product of pearl millet varied from 298-541 µg/g while proso millet products had bound content from 195-300 µg/g. Parboiling increased the bound phenolic content in the products by 25-60%, with porridge from parboiled pearl millet showing the highest increase. Some of the migrated free phenolics from the pericarp into the endosperm during parboiling, might have formed complexes with the grain components in the endosperm leading to an increase in bound content. The type of product also affected the free and bound phenolic content. Pearl and proso porridge had higher bound phenolic content than couscous. Contrary to this, free content was higher in pearl and proso couscous than porridge. The cooking time, moisture conditions, form (grain vs flour) and temperature maybe some of the factors controlling the release and formation of free and bound phenolics in both products (Dimberg et al. 1996).

**Free and bound phenolic acids**

Protocatechuic (2-9.6 µg/g) and gallic (0.6-13.2 µg/g) were the major phenolic acids detected in the free extract of all products (Table 4.4a, b). There was an increase in gallic and protocatechuic acid contents in the free extract of pearl and proso parboiled products. *P*-coumaric acid was detected in the free extract of all parboiled products except couscous from parboiled proso millet, however products from native flour did not show presence of *p*-coumaric. Parboiling also lead to some loss in free phenolic acids as seen in pearl porridge. The slight losses in the free phenolic acids may be due to the leaching out of some phenolic acids during the soaking and boiling
process of the parboiling method. Couscous from parboiled pearl millet showed higher contents and variety of phenolic acids in the free extract when compared to the other products. Caffeic, vanillic, gentistic and 3-hydroxybenzoic was not detected in the free extract of any products. Ferulic was the major bound phenolic acid present in all products and ranged from 187-352 µg/g (Table 4.4a, b). The increase in ferulic acid in the parboiled products ranged from 10-27%. Gentistic and caffeic acid were not present in the bound extract of any product. Parboiling increased the gallic, sinapic and p-hydroxybenzoic acid contents in pearl millet porridge by approximately 3-7 times while other phenolic acids had a 38-73% increase. The bound extract of proso porridge showed a 2-4 times increase in gallic and protocatechuic after parboiling while contents of p-coumaric and syringic decreased slightly (8%). Vanillic, syringic and p-hydroxybenzoic were present in the bound extract of couscous from parboiled proso but were not found in couscous from native proso millet. Rice parboiling has also shown an increase in free phenolic acid after parboiling. There was an increase in p-coumaric, vanillic, ferulic and caffeic acid however p-hydroxybenzoic and syringic acid showed mixed results depending on the variety of rice chosen (Kato et al. 1983).

The increase in the free and bound phenolic acid in the parboiled products are clearly due to the increase in free and bound phenolic content as seen from the results above. The changes in the phenolic acids may also be due to the thermal degradation of some phenolic acids. For instance vanillic acid is formed through the thermal decomposition of ferulic acid (Fiddler et al. 1967). Breakdown of conjugated polyphenolic compounds (tannins) during parboiling might also have increased ferulic, syringic, vanillic and p-coumaric contents in the free and bound extract of
parboiled products (Cheng et al. 2006). Therefore, parboiling can be an efficient way of increasing the free and bound phenolic acid content in millet products.

4.4.5 *In vitro* starch digestibility (IVSD)
The rapidly digestible starch (RDS), slowly digestible starch (SDS) and residual starch (RES) for millet products ranged from 17.4-19.1%, 32.8-36.7% and 44.4-49.1% respectively (Table 4.6). The RDS values of the products from parboiled millets were significantly lower than the native millets while the SDS of the parboiled products were not significantly different. RES values showed slight increases after parboiling, however the increase was significant only for pearl porridge and proso couscous. The expected glycemic index (eGI) of porridge and couscous ranged from 41.7-44.5 and showed significant differences. The eGI of the products from parboiled millets were significantly lower than the products from native millets. The eGI values of couscous and porridge made from native or parboiled millet were lower than those of wheat, corn, barley or rice products (Powell et al. 2002). This indicates that these products can be potential low GI foods.

A lowering of glycemic indices has been shown by consumption of cooked parboiled rice when compared to cooked rice from native grains (Casiraghi et al. 1992; Larsen et al. 2000; Widowati et al. 2010). It was shown that pressure parboiled (PP) rice had lower glycemic indices than the traditional parboiled (TP) rice (Larsen et al. 2000). Therefore, the severity of the treatment has significant impact on IVSD. Though significant differences were observed in RDS, RES and eGI values of raw and parboiled products, however the extent of changes were not very high. This may be due to the lower severity of the current parboiling method. The lower IVSD in parboiled
rice has been attributed to the amylose-lipid complexes, amylose and amylopectin retrogradation (Larsen et al. 2000; Erlingen et al. 1994; Alsaffar et al. 2010). In the current study, it will be difficult to cite the reasons for the differences in the starch digestibility of the raw and parboiled products as no study was done to evaluate the structural changes during parboiling and re-cooking of the grains. The formation of amylose-lipid complex, amylose and amylopectin retrogradation might have occurred during parboiling, which may have reduced the eGI and and RDS in the parboiled products. However further changes in the starch properties might also have occurred when the parboiled grains were cooked into porridge and couscous. The severe cooking conditions in the preparation of the products might have minimised the effect of retrogradation leading to slight changes in the IVSD. Further studies should be conducted to throw more light on the molecular changes in starch structure during re-cooking of the parboiled grain and relate them to starch digestibility. The increase in resistant starch in the products from parboiled millet (section 4.4.3) might also be responsible for the decrease in the eGI and RDS in these products. Previous studies have shown strong negative correlations of RS with RDS and eGI (Rosin et al. 2002; Deepa et al. 2010).

The food particle size has also been shown to affect starch digestibility (Bjorck et al. 1994). In the current study couscous was cooked as whole intact form and porridge was grounded into flour however this difference in form did not affect IVSD. Couscous had a higher cooking time of 50 min compared to a 10 min cooking time of porridge, additionally the couscous grains were soaked before cooking. This severe cooking conditions of couscous compared to porridge might have resulted in similar starch properties in both products.
4.4.6 In vitro protein digestibility (IVPD)
The in vitro protein digestibility of native millet products ranged from 51 to 63% and that of parboiled products varied from 44 to 57% (Table 4.7). Pearl products from native millet showed higher digestibility amongst all. Parboiling decreased the IVPD in pearl porridge, pearl couscous, proso porridge and proso couscous by 17%, 16%, 13% and 16% respectively. Proso millet products had lower digestibility than pearl products. The difference in the IVPD between the two millet types may be due to the differences in the distribution of protein fractions. Prolamins are reported to have lesser digestibility than the glutelin and albumin+globulin fraction (Hamaker et al. 1989; Stennson and Sathe 1995). Few studies have reported pearl and proso millet has varied protein distributions which may have resulted in the difference in IVPD in both types (Chanda and Matta 1990; Parmeswaran and Thaymanavan 1995). Previous studies on rice, sorghum and pearl millet have shown a reduction in IVPD after parboiling. Raw rice was shown to have an average IVPD of 76% which decreased to 66% after parboiling. Recooking the parboiled grains led to a further decrease to 55% (Devi et al. 1997). Sorghum protein digestibility has shown to decrease by approximately 15 % after cooking (Hamaker et al. 1986). Few studies have shown wide variations in the decrease from 4-40% after cooking of pearl millet (Ejeta et al. 1987; Pushparaj et al. 2011). This may be due to the enzymatic digestion procedure followed. It has been suggested from previous studies that the digestion assay procedure (One- step versus two-step), type and variety of enzymes used affect the IVPD values (Saunders et al. 1972; Abdel-al 2007). A study by Ejeta et al. (1987) has shown pepsin digestibility (one step) of pearl millet to decrease from 91% to 85% upon cooking. In another study by Pushparaj et al. (2011) pepsin-pancreatin (two step) digestibility of native pearl millet was shown to be 46% which reduced to 33% upon boiling and to 44% upon pressure cooking. However another pearl millet variety showed mixed results in the same study. Therefore, millet variety, cooking conditions and
enzymatic digestion procedure are some important factors that affect IVPD (Devi et al. 1997; Abdel-al 2007; Pushparaj et al. 2011). The current study follows a two-step digestion procedure and the IVPD values have shown a significant decrease upon parboiling. Parboiling has shown to reduce extractability of protein by 45% in rice while finger millet has shown to decrease the extractability of protein fractions from 94% to 82% (Rao and Juliano 1970; Dharmaraj 2011). The reduction in extractability of protein fractions has been mainly attributed to the formation of disulphide cross-links and changes in secondary structure of protein (Hamaker et al. 1987; Duodu et al. 2003). Parboiled product might have higher intensities of these changes than the native product which resulted in lower IVPD. The increase in free and bound phenolic content as shown in section 4.4.4 after parboiling, might also have reduced IVPD. Phenolic acids contain hydroxyl groups and therefore, may also interact with and form complexes with proteins. The oxidation of phenolic compounds may lead to formation of peroxides which are highly reactive species and may oxidise amino acid residues and cause polymerisation of proteins (Damodaran 1996; Duodu et al. 2003). However extensive studies have not been conducted so far to relate phenolic acid content and IVPD.

**4.5 Conclusion**

The yield of decorticated grains was significantly increased after parboiling. Parboiling significantly reduced the eGI and RDS however the extent of changes were not very high. *In vitro* protein digestibility was significantly reduced in the products from parboiled millets. Lowering of protein digestibility by parboiling can limit the nutritional quality of millet products, however further studies should be conducted to minimize this effect. The type of product did not affect the nutritional properties however the millet type did. Therefore, the two product matrices
were not very different to create significant differences in the resistant starch and *in vitro* digestibility. The difficulty in decorticating millets grains can be overcome by parboiling, as shown by the increase in yield of decorticated grains from parboiled millets. In addition, it can improve the nutritional properties of millet products made from these parboiled grains, as suggested by the significant lowering of eGI and increase in resistant starch as well as phenolic acids. However, the extent of these changes may depend on the type of millet and the parboiling conditions used.
### Table 4.1: Yield of decorticated native and parboiled millets

<table>
<thead>
<tr>
<th>Sample</th>
<th>State</th>
<th>Yield (%)**</th>
<th>% Increase in yield</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pearl</td>
<td>Native</td>
<td>56.0 ± 0.6&lt;sup&gt;a&lt;/sup&gt;</td>
<td>37</td>
</tr>
<tr>
<td></td>
<td>Parboiled</td>
<td>76.8 ± 0.2&lt;sup&gt;c&lt;/sup&gt;</td>
<td></td>
</tr>
<tr>
<td>Proso</td>
<td>Native</td>
<td>61.1 ± 0.2&lt;sup&gt;b&lt;/sup&gt;</td>
<td>28</td>
</tr>
<tr>
<td></td>
<td>Parboiled</td>
<td>77.9 ± 1.6&lt;sup&gt;c&lt;/sup&gt;</td>
<td></td>
</tr>
</tbody>
</table>

<sup>*Values followed by different letters within a column are significantly different (P < 0.05)</sup>

<sup>**Yield of decorticated millets**</sup>
Table 4.2: Total starch (%) and resistant starch (%) content of millet products*

<table>
<thead>
<tr>
<th>Sample**</th>
<th>State</th>
<th>Total starch</th>
<th>Resistant starch</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pearl Porridge</td>
<td>Native</td>
<td>80.1±2.3cd</td>
<td>2.11±0.02a</td>
</tr>
<tr>
<td></td>
<td>Parboiled</td>
<td>71.7±1.5a</td>
<td>2.37±0.01b</td>
</tr>
<tr>
<td>Pearl Couscous</td>
<td>Native</td>
<td>81.4±2.1c</td>
<td>2.13±0.04a</td>
</tr>
<tr>
<td></td>
<td>Parboiled</td>
<td>72.2±1.6a</td>
<td>2.51±0.06b</td>
</tr>
<tr>
<td>Proso Porridge</td>
<td>Native</td>
<td>81.1±1.9c</td>
<td>5.28±0.04cd</td>
</tr>
<tr>
<td></td>
<td>Parboiled</td>
<td>77.2±1.2bc</td>
<td>5.52±0.01e</td>
</tr>
<tr>
<td>Proso Couscous</td>
<td>Native</td>
<td>80.4±1.8c</td>
<td>5.13±0.04c</td>
</tr>
<tr>
<td></td>
<td>Parboiled</td>
<td>75.9±0.9b</td>
<td>5.37±0.03de</td>
</tr>
</tbody>
</table>

*Values followed by different letters within a column are significantly different (P < 0.05)

**Millet type followed by product type
Table 4.3: Free and bound phenolic content (µg/g) in millet products *

<table>
<thead>
<tr>
<th>Sample**</th>
<th>State</th>
<th>Free phenolics</th>
<th>Bound phenolics</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pearl Porridge</td>
<td>Native</td>
<td>25±0.1b</td>
<td>337±3.2e</td>
</tr>
<tr>
<td></td>
<td>Parboiled</td>
<td>74.8±1.2d</td>
<td>541±4.5g</td>
</tr>
<tr>
<td>Pearl Couscous</td>
<td>Native</td>
<td>71.4±1.6d</td>
<td>298±2.5d</td>
</tr>
<tr>
<td></td>
<td>Parboiled</td>
<td>117±2.4e</td>
<td>437±1.6f</td>
</tr>
<tr>
<td>Proso Porridge</td>
<td>Native</td>
<td>3.5±0.04a</td>
<td>220±1.2b</td>
</tr>
<tr>
<td></td>
<td>Parboiled</td>
<td>29±0.9c</td>
<td>300±2.3d</td>
</tr>
<tr>
<td>Proso Couscous</td>
<td>Native</td>
<td>12.3±0.3b</td>
<td>195±1.3a</td>
</tr>
<tr>
<td></td>
<td>Parboiled</td>
<td>32.7±0.4c</td>
<td>245±3.2c</td>
</tr>
</tbody>
</table>

*Values followed by different letters within a column are significantly different (P < 0.05)

**Millet type followed by product type
Table 4.4a: Free phenolic acid content (µg/g) in millet products*

<table>
<thead>
<tr>
<th>Sample*</th>
<th>State</th>
<th>$p$-hydroxybenzoic</th>
<th>Syringic</th>
<th>$p$-coumaric</th>
<th>Ferulic</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pearl Porridge</td>
<td>Native</td>
<td>2.5±0.1</td>
<td>4.7±0.2</td>
<td>-</td>
<td>0.3±0</td>
</tr>
<tr>
<td></td>
<td>Parboiled</td>
<td>-</td>
<td>-</td>
<td>2.9±0.1</td>
<td>-</td>
</tr>
<tr>
<td>Pearl Couscous</td>
<td>Native</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>5.6±0.3</td>
</tr>
<tr>
<td></td>
<td>Parboiled</td>
<td>-</td>
<td>11.6±0.4</td>
<td>8.06±0.6</td>
<td>3.8±0.5</td>
</tr>
<tr>
<td>Proso Porridge</td>
<td>Native</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>Parboiled</td>
<td>-</td>
<td>-</td>
<td>12.5±1.0</td>
<td>-</td>
</tr>
<tr>
<td>Proso Couscous</td>
<td>Native</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>3.6±0.2</td>
</tr>
<tr>
<td></td>
<td>Parboiled</td>
<td>1.28±0</td>
<td>3.6±0.3</td>
<td>-</td>
<td>4.2±0.2</td>
</tr>
</tbody>
</table>

Millet type followed by product type
Table 4.4b: Free phenolic acid content (µg/g) in millet products*

<table>
<thead>
<tr>
<th>Sample**</th>
<th>State</th>
<th>Sinapic</th>
<th>Gallic</th>
<th>Protocatechuic</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pearl Porridge</td>
<td>Native</td>
<td>0.1±0</td>
<td>0.9±0.0</td>
<td>5.6±0.3</td>
</tr>
<tr>
<td></td>
<td>Parboiled</td>
<td>-</td>
<td>3.1±0.3</td>
<td>9.6±0.8</td>
</tr>
<tr>
<td>Pearl Couscous</td>
<td>Native</td>
<td>-</td>
<td>12.9±0.9</td>
<td>4.1±0.4</td>
</tr>
<tr>
<td></td>
<td>Parboiled</td>
<td>1.7±0.1</td>
<td>13.2±0.6</td>
<td>3.8±0.6</td>
</tr>
<tr>
<td>Proso Porridge</td>
<td>Native</td>
<td>-</td>
<td>0.6±0.1</td>
<td>3.9±0.5</td>
</tr>
<tr>
<td></td>
<td>Parboiled</td>
<td>-</td>
<td>1.4±0.5</td>
<td>7.3±0.5</td>
</tr>
<tr>
<td>Proso Couscous</td>
<td>Native</td>
<td>-</td>
<td>6.9±0.4</td>
<td>3.4±0.3</td>
</tr>
<tr>
<td></td>
<td>Parboiled</td>
<td>-</td>
<td>4.8±0.4</td>
<td>2.0±0.3</td>
</tr>
</tbody>
</table>

*Caffeic, vanillic, gentistic and 3-hydroxybenzoic acids were not detected in the free extract of any product

**Millet type followed by product type
Table 4.5a: Bound phenolic acid content (µg/g) in millet products

<table>
<thead>
<tr>
<th>Sample</th>
<th>State</th>
<th>$p$-hydroxybenzoic</th>
<th>Vanillic</th>
<th>Syringic</th>
<th>$p$-coumaric</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Pearl Porridge</strong></td>
<td>Native</td>
<td>4.0±0.3</td>
<td>5.0±1.1</td>
<td>11.2±0.1</td>
<td>8.3±0.2</td>
</tr>
<tr>
<td></td>
<td>Parboiled</td>
<td>8.0±1.7</td>
<td>6.9±2.6</td>
<td>17.2±1</td>
<td>13.7±1.3</td>
</tr>
<tr>
<td><strong>Pearl Couscous</strong></td>
<td>Native</td>
<td>-</td>
<td>7.7±0.2</td>
<td>7.5±0.2</td>
<td>2.4±0.9</td>
</tr>
<tr>
<td></td>
<td>Parboiled</td>
<td>-</td>
<td>11.4±0.5</td>
<td>11.4±1.7</td>
<td>9.7±1.3</td>
</tr>
<tr>
<td><strong>Proso Porridge</strong></td>
<td>Native</td>
<td>-</td>
<td>-</td>
<td>8.4±0.4</td>
<td>6.4±0.6</td>
</tr>
<tr>
<td></td>
<td>Parboiled</td>
<td>0.9±0.1</td>
<td>3.3±0.6</td>
<td>7.7±0.7</td>
<td>5.6±0.3</td>
</tr>
<tr>
<td><strong>Proso Couscous</strong></td>
<td>Native</td>
<td>-</td>
<td>-</td>
<td>4.5±0.7</td>
<td>2.9±0.1</td>
</tr>
<tr>
<td></td>
<td>Parboiled</td>
<td>-</td>
<td>-</td>
<td>5.5±0.1</td>
<td>2.2±0.2</td>
</tr>
</tbody>
</table>

Millet type followed by product type
Table 4.5b: Bound phenolic acid content (µg/g) in millet products*

<table>
<thead>
<tr>
<th>Sample**</th>
<th>State</th>
<th>Ferulic</th>
<th>Sinapic</th>
<th>Gallic</th>
<th>3-hydroxy benzoic</th>
<th>Protocatechuic</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pearl Porridge</td>
<td>Native</td>
<td>276±5.1</td>
<td>3.1±0</td>
<td>15.7±1.7</td>
<td>-</td>
<td>22.3±1.5</td>
</tr>
<tr>
<td></td>
<td>Parboil</td>
<td>352±15</td>
<td>20.8±1.5</td>
<td>35.7±0.6</td>
<td>18.2±1.2</td>
<td>38.5±2.1</td>
</tr>
<tr>
<td>Pearl Couscous</td>
<td>Native</td>
<td>276.3±2.4</td>
<td>1.5±0.3</td>
<td>7.3±0.8</td>
<td>-</td>
<td>16.4±0.3</td>
</tr>
<tr>
<td></td>
<td>Parboil</td>
<td>344±20</td>
<td>13.2±0.3</td>
<td>33±2.1</td>
<td>34.7±2.1</td>
<td>15.1±1.2</td>
</tr>
<tr>
<td>Proso Porridge</td>
<td>Native</td>
<td>198±9</td>
<td>-</td>
<td>1.8±0.4</td>
<td>-</td>
<td>15.4±0.1</td>
</tr>
<tr>
<td></td>
<td>Parboil</td>
<td>250±9.8</td>
<td>-</td>
<td>6.7±0.5</td>
<td>-</td>
<td>29.4±0.8</td>
</tr>
<tr>
<td>Proso Couscous</td>
<td>Native</td>
<td>177±1.3</td>
<td>-</td>
<td>4.8±0.8</td>
<td>-</td>
<td>10.8±0.9</td>
</tr>
<tr>
<td></td>
<td>Parboil</td>
<td>216±2.7</td>
<td>-</td>
<td>4.0±0.2</td>
<td>-</td>
<td>20.4±0.5</td>
</tr>
</tbody>
</table>

*Gentistic and caffeic acid were not present in the bound extract of any product

**Millet type followed by product type
Table 4.6: Rapidly digestible starch (RDS), slowly digestible starch (SDS), residual starch (RES) and expected glycemic index (eGI) of millet products*

<table>
<thead>
<tr>
<th>Sample**</th>
<th>State</th>
<th>RDS (%)</th>
<th>SDS (%)</th>
<th>RES (%)</th>
<th>eGI</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pearl Porridge</td>
<td>Native</td>
<td>18.9±0.03e</td>
<td>36.7±0.7b</td>
<td>44.4±0.8a</td>
<td>44.5±0.4e</td>
</tr>
<tr>
<td></td>
<td>Parboiled</td>
<td>17.6±0.02ab</td>
<td>36.6±0.3b</td>
<td>45.8±0.2c</td>
<td>42.7±0.2bc</td>
</tr>
<tr>
<td>Pearl Couscous</td>
<td>Native</td>
<td>18.8±0.02de</td>
<td>36.7±0.2b</td>
<td>44.5±0.7a</td>
<td>44.4±0.5e</td>
</tr>
<tr>
<td></td>
<td>Parboiled</td>
<td>18.3±0.05cd</td>
<td>36.6±0.5b</td>
<td>45±0.4bc</td>
<td>43.7±0.6d</td>
</tr>
<tr>
<td>Proso Porridge</td>
<td>Native</td>
<td>18.2±0.06c</td>
<td>33.9±0.4a</td>
<td>47.8±0.5de</td>
<td>42.8±0.2c</td>
</tr>
<tr>
<td></td>
<td>Parboiled</td>
<td>17.4±0.07a</td>
<td>33.8±0.3a</td>
<td>48.9±0.8ef</td>
<td>41.7±03a</td>
</tr>
<tr>
<td>Proso Couscous</td>
<td>Native</td>
<td>19.1±0.09e</td>
<td>33.8±0.6a</td>
<td>47.1±0.6d</td>
<td>43.9±0.4de</td>
</tr>
<tr>
<td></td>
<td>Parboiled</td>
<td>17.9±0.04bc</td>
<td>32.8±0.8a</td>
<td>49.1±0.8f</td>
<td>42.2±0.5ab</td>
</tr>
</tbody>
</table>

*Values followed by different letters within a column are significantly different (P < 0.05)

**Millet type followed by product type
Table 4.7 Total protein and *in vitro* protein digestibility (IVPD) of millet products *

<table>
<thead>
<tr>
<th>Sample**</th>
<th>State</th>
<th>Total Protein (%)</th>
<th>IVPD (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pearl Porridge</td>
<td>Native</td>
<td>8.1±0.02a</td>
<td>62.9±0.3c</td>
</tr>
<tr>
<td></td>
<td>Parboiled</td>
<td>9.3±0.05c</td>
<td>51.9±0.2b</td>
</tr>
<tr>
<td>Pearl Couscous</td>
<td>Native</td>
<td>8.2±0.06a</td>
<td>60.9±0.09c</td>
</tr>
<tr>
<td></td>
<td>Parboiled</td>
<td>9.1±0.03c</td>
<td>51.9±0.3b</td>
</tr>
<tr>
<td>Proso Porridge</td>
<td>Native</td>
<td>8.9±0.04b</td>
<td>52±0.08b</td>
</tr>
<tr>
<td></td>
<td>Parboiled</td>
<td>9.6±0.06d</td>
<td>44.6±0.2a</td>
</tr>
<tr>
<td>Proso Couscous</td>
<td>Native</td>
<td>8.9±0.04b</td>
<td>52.7±0.01b</td>
</tr>
<tr>
<td></td>
<td>Parboiled</td>
<td>9.5±0.01d</td>
<td>44.3±0.1a</td>
</tr>
<tr>
<td>Sodium Caseinate***</td>
<td>-</td>
<td>88.7±1.2</td>
<td>84.8±1.1</td>
</tr>
</tbody>
</table>

*Values followed by different letters within a column are significantly different (P < 0.05)

**Millet type followed by product type

***Sodium caseinate was used as the reference protein
5. CHAPTER FIVE: CONCLUSION

Millet type is a very important factor affecting the nutritional properties and \textit{in vitro} starch digestibility of millets. The documentation on the nutrient composition of millets suggested that they have high unsaturated fatty acid content, phenolic acid content, antioxidant activity and insoluble dietary fibre contents. The information obtained on the fatty acid content and phenolic acid profile may help in future research to explain the lower starch digestibility of millets. Decortication significantly reduced the nutrient contents while the increase in the \textit{in vitro} starch digestibility was not very high except kodo millet. Therefore, owing to its hypoglycemic property both whole and decorticated millets may be used as potential food source for diabetics. The losses in the nutrients after decortication may also depend on the distribution of the nutrient from the outer layers into the endosperm. Further research on the distribution of nutrients namely phenolic acids, fatty acids and dietary fibre in millet grain should be done to minimise the losses from decortication. The finger and little millet varieties showed significant differences however the ranges of variation were not very high. Further studies to understand the reasons for type and varietal differences in millets should be done. Several factors like genetic background, grain morphology, environmental and breeding factors may be considered.

The difficulty in decortication of millets can be overcome by parboiling as suggested from the significant increase in decortication yield after parboiling in this study. Products from parboiled millet had lower eGI than the products from native grain. Hence this finding can be utilised to prepare low GI food products from parboiled millet. The increase in the resistant starch and phenolic acids in the millet products can also suggest an improvement in nutritional quality after
parboiling. However the extent of all these changes may depend on the parboiling conditions applied and type of millet chosen. The reduction in the in vitro protein digestibility of the parboiled millets may limit its nutritional quality. Further studies should be conducted to minimize this effect. Parboiling can be effectively used to increase yield of decorticated millets without deteriorating its nutritional quality. Future research should be emphasized on the various physico-chemical changes occurring during parboiling followed by product preparation, and relate them to the nutrient composition and in vitro digestibility of the products. This would also help to set up optimum parboiling conditions to produce higher nutrient quality millet products. The effect of parboiling should also be studied for other food matrices which should be considerably different from the ones used in this study. For instance products like extruded, popped, flaked, fried, flat breads or baked products should be considered. In summary, the current study set up a complete documentation of the nutritional properties of different types of whole and decorticated millets and also indicated that parboiling may be used as an effective way to improve decortication yield and nutritional quality of millets.
6. REFERENCES CITED


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