DEVELOPMENT OF A MILLET DEHULLER (HAND – OPERATED) TO REDUCE DRUDGERY IN PROCESSING AND UTILIZATION OF MILLET WASTE (HULLS) IN ANTIOXIDANT EXTRACTION

By

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April 2018

A thesis submitted to McGill University in partial fulfillment of the requirements of the degree of

Master of Science
in
Bioresource Engineering

ABSTRACT

Efficient post-harvest handling practices are important in grain processing, since improper handling of the harvested crops may lead to losses. Post-harvest handling of crops includes a combination of several unit operations including threshing, drying, storage, etc. Among those processes, dehulling is crucial for many cereal grains as it facilitates the removal of the fibrous outer husk layers. Consumption of cereal grains in their natural form and in the form of processed foods like flour and other consumables would not be as palatable without dehulling.

Millets are cereal crops that fall under a category of small seeded grasses. Millets' unique characteristics make them equivalent to other cereal grains in terms of nutrition. Some of their notable properties include drought and temperature resistance, short harvest period and gluten-free nature. In arid and semi-arid regions of the world, millets are the major energy reservoir among the poor. Millet dehulling for human consumption is, however, tiresome due to their small size and the unavailability of suitable processing equipment. Dehulling practices can be made simpler and more efficient by adopting and developing appropriate processing technology.

The primary objective of this study was set to develop a simple and efficient hand operated, table-top millet dehuller that could reduce processing drudgery at household levels, within the Indian context. Its performance was evaluated based on its ability to dehull different millet varieties, namely, foxtail (*Setaria italica*), barnyard (*Echinochloa colona)* and kodo (*Paspalum scrobiculatum*) millets. Friction-Shearing principle was used to loosen and remove the outer hull layer from millets, since presence of hulls makes the grains nearly inedible. A centrifugal blower was also fabricated for aspirating the millet hulls from the dehulled clean grains. The blower functioning is an integral part of the dehuller such that both the rubber rollers and the blower operate simultaneously. The dehulling efficiency of the machine was assessed by passing (1-3

consecutive passes) the whole grains in different rubber roller spacing (0.20, 0.25, 0.30 and 0.35 mm). As kodo millet is the hardest of all the millet varieties, the lowest dehulling efficiency was recorded for this variety, when compared to the other two varieties tested. For foxtail and barnyard millets, complete dehulling was achieved only after 3 consecutive passes. In addition to dehulling efficiency, percentage of broken grains and head rice recovery were also investigated.

The millet hull/husk, generated as a by-product during millet processing, possesses considerable amounts of phenolic compounds with antioxidant potential. It can be utilized as a functional component in nutraceutical and food products. For this purpose, the millet hulls obtained through mechanical dehulling were used in extracting antioxidants. Microwave assisted extraction technique was employed for extraction and response surface methodology was used as a tool for optimizing the extraction conditions. Three parameters at different levels namely, microwave holding time (2, 4 and 6 min), extraction temperature (60°C, 80°C and 100°C) and solvent concentration (30%, 60% and 90% *v/v*) were selected to study their individual and combined effects on the phenolic compounds present in millet hulls. The antioxidative properties of millet hull extracts were evaluated by examining their total phenol content and antioxidant capacity using different assays. The antioxidant potential of the extracts was found to be temperature dependent. Increase in extraction temperature also increased the total phenol content and the antioxidant capacity. From the results it was evident that millet hull fractions can be successfully used for extracting phenolic antioxidants.

RÉSUMÉ

Des pratiques de manutention post-récolte efficaces sont importantes dans le traitement des céréales, car une mauvaise gestion des récoltes peut entraîner des pertes. La manutention post-récolte des cultures se compose d'opérations unitaires incluant le battage, le séchage, le stockage, etc. Parmi ces procédés, le décorticage des céréales facilite l'enlèvement des couches fibreuses de la cosse. La consommation et la transformation des céréales en farine et autres produits alimentaires consommables sont presque impossibles sans décorticage.

Les millets sont des cultures céréalières qui entrent dans la catégorie des petites graminées. Les caractéristiques uniques des millets les rendent équivalentes aux autres céréales en termes de nutrition et d'avantages pour la santé. Certaines de leurs propriétés notables comprennent la résistance à la sécheresse et à la température, la courte période de récolte et la nature sans gluten. Dans les régions arides et semi-arides du monde, les mils constituent le principal apport énergétique, en particulier chez les populations pauvres. Le décorticage du millet est fastidieux en raison de sa petite taille et de l'indisponibilité d'un équipement de traitement approprié. Les pratiques de décorticage peuvent être simplifiées et plus efficaces en développant une technologie de traitement appropriée.

L'objectif principal de cette étude était de mettre au point un simple décortiqueur de millet, pouvant être utilisé pour le décorticage domestique. Sa performance a été évaluée sur la base de sa capacité à décortiquer différentes variétés de millet, à savoir, la sétaire (Setaria italica), la basse-cour (Echinochloa colona) et le kodo (Paspalum scrobiculatum). Le principe de friction-cisaillement a été utilisé pour relâcher et enlever la couche externe de la coque des mils, puisque la présence des coques rend les grains moins comestibles. Un ventilateur centrifuge a également été fabriqué pour aspirer les coques du millet décortiqué. Le ventilateur fait partie intégrante du

décortiqueur, de sorte que les rouleaux en caoutchouc et le ventilateur fonctionnent simultanément. L'efficacité de décorticage de la machine a été évaluée en faisant passer (1-3 passes consécutives) les grains entiers dans différents espacements des rouleaux (0.20, 0.25, 0.30 et 0.35 mm). La dureté et la teneur en humidité des grains affectent significativement la capacité de décorticage. Le millet de kodo étant le plus dur des variétés de millet, l'efficacité de décorticage la plus faible a été enregistrée pour cette variété. Pour les millets de sétaire et de basse-cour, le décorticage complet a été réalisé après 3 passages consécutifs. En plus de l'efficacité de décorticage, le pourcentage de grains cassés et la récupération des grains entiers ont également été étudiés.

La coque de millet produite en tant que sous-produit pendant le traitement du millet possède une quantité considérable de composés phénoliques ayant un potentiel antioxydant. Ces composés phénoliques peuvent être utilisés comme ingrédient fonctionnel alimentaire. De ce fait, les coques de mil ont été utilisées pour extraire des antioxydants. L'extraction assistée par micro-ondes a été utilisée et la méthodologie de surface de réponse a servi pour optimiser les conditions d'extraction. Trois paramètres à différents niveaux, à savoir, temps de maintien des micro-ondes (2, 4 et 6 min), température d'extraction (60°C, 80°C et 100°C) et concentration de solvant (30%, 60% et 90% v/v) ont été utilisés pour étudier leur effet individuel et combiné sur les composés phénoliques présents dans les coques de mil. Les propriétés antioxydantes des extraits de coque de mil ont été évaluées en examinant leur teneur en phénol et leur capacité antioxydante. Le potentiel antioxydant des extraits s'est révélé être dépendant de la température. D'après les résultats, il était évident que les fractions de coque de mil peuvent être utilisées pour extraire des antioxydants phénoliques.

ACKNOWLEDGEMENTS

First of all, I would like to express my sincere gratitude towards my supervisor Dr. Valérie Orsat for her guidance, professional support, encouragement and kindness. I thank her for being patient with my problems and for her timely help throughout my study. Thank you very much for having faith in me and I feel blessed to be your student.

I would like to thank Dr. Vijaya Raghavan for his support and allowing me to use the lab for conducting experiments. Special thanks to Mr. Yvan Gariépy and Dr. Darwin Lyew for providing the necessary technical help to complete the project in time. I gratefully acknowledge Dr. Samson Sotocinal for his mentorship and technical expertise. During the course of my study, he has been of great help and has shared his knowledge and experience with me which cannot be gained elsewhere.

I'm also thankful to Dr. Sriram Jayabal and Dr. Shrikalaa Kannan for clarifying my questions on experimental designs and data analysis. I also thank Mr. Sai Kranthi Kumar Vanga for providing academic advices. I would like to thank all my friends including Yugadhi, Mahsa, Mehran, Renuga, Arun, Bhalamurugan, Sellam, Jyothi, Shalini, Parghat and Gayathri who encouraged me throughout my study.

Words cannot express how thankful I am to my teachers, especially Dr. Varadharaju and Dr. Malathi, who guided and supported me during my undergraduate studies in Tamil Nadu Agricultural University and after coming to McGill University. My heartfelt thanks to my family (Mom, Dad and Sister) for their moral support and prayers.

It would not have been possible to conduct this study without the financial support of the International Development Research Centre (IDRC) and Global Affairs Canada (GAC)

Thank you,

Subhash Palaniswamy.

THESIS FORMAT

This thesis is submitted in the format of papers suitable for journal publication. This thesis format has been approved by the Faculty of Graduate and Postdoctoral Studies, McGill University, and follows the conditions outlined in the Guidelines: Concerning Thesis Preparation, which are as follows:

"As an alternative to the traditional thesis format, the dissertation can consist of a collection of papers of which the student is an author or co-author. These papers must have a cohesive, unitary character making them a report of a single program of research. The structure for the manuscript-based thesis must conform to the following:

1. Candidates have the option of including, as part of the thesis, the text of one or more papers submitted, or to be submitted, for publication, or the clearly duplicated text (not the reprints) of one or more published papers. These texts must conform to the "Guidelines for Thesis Preparation" with respect to font size, line spacing and margin sizes and must be bound together as an integral part of the thesis. (Reprints of published papers can be included in the appendices at the end of the thesis).
2. The thesis must be more than a collection of manuscripts. All components must be integrated into a cohesive unit with a logical progression from one chapter to the next. In order to ensure that the thesis has continuity, connecting texts that provide logical bridges between the different papers are mandatory.
3. The thesis must conform to all other requirements of the "Guidelines for Thesis Preparation" in addition to the manuscripts.

The thesis must include the following

i. A table of contents;

ii. An abstract in English and French;

iii. An introduction which clearly states the rational and objectives of the research;

iv. A comprehensive review of the literature (in addition to that covered in the introduction to each paper);

v. A final conclusion and summary.

4. As manuscripts for publication are frequently very concise documents, where appropriate, additional material must be provided (e.g., in appendices) in sufficient detail to allow a clear and precise judgment to be made of the importance and originality of the research reported in the thesis.

5. In general, when co-authored papers are included in a thesis the candidate must have made a substantial contribution to all papers included in the thesis. In addition, the candidate is required to make an explicit statement in the thesis as to who contributed to such work and to what extent. This statement should appear in a single section entitled "Contributions of Authors" as a preface to the thesis. Since the task of the examiners is made more difficult in these cases, it is in the candidate's interest to clearly specify the responsibilities of all the authors of the co-authored papers".

CONTRIBUTION OF THE AUTHORS

In accordance with the "Guidelines for thesis preparation - manuscript based" set by the Faculty of Graduate and Postdoctoral Studies of McGill University, the manuscripts prepared and contribution of authors are presented below.

All the works presented in this thesis was performed by Subhash Palaniswamy under the supervision of Dr. Valérie Orsat at the Department of Bioresource Engineering, Macdonald campus, McGill University, Sainte-Anne-de-Bellevue, Quebec, Canada. Dr. Samson Sotocinal and Dr. Vijaya Raghavan provided technical support and guidance throughout the research work. Dr. Samson Sotocinal also participated in reviewing the manuscripts for publication. Mr. Yvan Gariépy is a professional associate in the Department of Bioresource Engineering who provided instructions and access to the facilities required for conducting the experiments.

The following are the manuscripts prepared for publication from this thesis

1. **Palaniswamy, Subhash**; Sotocinal, Samson; Orsat, Valérie; Raghavan, Vijaya. Implementation of Mechanized Post-Harvest Processing Technologies of Millets: A Review.
2. **Palaniswamy, Subhash**; Sotocinal, Samson; Orsat, Valérie; Raghavan, Vijaya. Development and performance evaluation of hand operated millet dehuller.
3. **Palaniswamy, Subhash**; Gariépy, Yvan; Orsat, Valérie; Raghavan, Vijaya. Optimization of Microwave-Assisted Extraction (MAE) of phenolic antioxidants from Kodo millet hulls (*Paspalum scrobiculatum*) and evaluation of its antioxidant activity *'in vitro'*.

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CHAPTER I

GENERAL INTRODUCTION

The issues related to food insecurity and malnutrition in the modern world are a major problem, besides other concerning environmental factors like climate change and global warming. These issues are on the rise, as millions of people suffer from starvation and undernutrition, despite the production of foods in sufficient amounts to satisfy their dietary needs (Startdesi.com, 2016; Thevathasan, 2014). This situation is particularly common among the poorest of the poor including small scale farmers (Padulosi, Mal, King, & Gotor, 2015). Occurrence of malnutrition and food insecurity can be due to several reasons like consumption of low nutritious foods, unavailability of foods with high health benefits, etc. Cereal grains like wheat and rice have been cultivated for high yield and profit. However, consuming these cereal grains on a large scale has been found to cause diabetes, obesity, celiac diseases and gluten intolerance (Hejazi & Orsat, 2015; Saleh, Zhang, Chen, & Shen, 2013). Utilization of neglected and highly nutritious crops like millets can be part of the solution to the problem of food insecurity and malnutrition in the developing as well as the developed nations.

Millets have been cultivated and consumed by people as a part of their daily diet even before the domestication of major crop varieties. However, as a consequence of producing high yielding and profitable varieties of cereal crops through different farming practices, consumption of millets has fallen worldwide over the years (Agrawal, 2017). Even in the regions where these crops were the traditional staple crop, millet cultivation has drastically reduced. Resuming millet cultivation and consumption must be encouraged in order to fight malnutrition and better ensure food security. Not only that, it can also benefit small farmers whose income entirely depends on millets.

"*Millet*" is a generic term that refers to a group of small seeded grains which can grow on their own without any special requirements like irrigation facilities, unlike other cereal crops such as wheat and rice. The nutrient composition of millets makes them nutritionally equivalent and sometimes even superior than other grains. Various studies on millets have proven these grains to be highly nutritious with health beneficial properties to humans (Asharani, Jayadeep, & Malleshi, 2010; Bagdi et al., 2011; Bwai, Afolayan, Odukomaiya, & Abayomi, 2014; Geervani & Eggum, 1989; Gull, Prasad, & Kumar, 2015; Hama et al., 2012; Pawar & Machewad, 2006; Suma & Urooj, 2014b; Thilagavathi et al., 2015; Zhang & Liu, 2015). Nevertheless, availability of millets to the urban population as a processed food product in the market is negligible in comparison with the availability of wheat and rice based food products. An overall decrease in processing of millets for food is the governing factor behind the insufficient availability of millet based food products.

1.1 HYPOTHESIS AND IMPLICATIONS

Dehulling or decortication of millets is normally done using mortar and pestle or mill stones, which creates drudgery during processing. Lack of adaptable dehulling machinery forces farmers to dehull millets using traditional methods. And this drudgery has eventually led to the reduction in millet cultivation. Drudgery involved in millet processing is a serious problem especially in the arid and semi-arid regions where the population majorly depends on millets for energy. With this background, we decided to fabricate a hand cranked rubber roller millet dehuller that works on a simple shearing principle. We also utilized the millet hulls generated during dehulling by investigating their antioxidant potential through microwave assisted extraction technique.

1.2 OBJECTIVES

1.2.1 Overall objective

The overall objective of the study was to fabricate a mini rubber roller dehuller (hand operated) for reducing the burden of dehulling millets when using time-consuming traditional methods, and evaluate the effect of changing the rubber roller spacing and number of consecutive passes on the dehulling performance. In addition, the objective was to utilize the produced millet hulls in the extraction of antioxidants and explore its potential to be used as a reliable source of antioxidants.

1.2.2 Specific objectives

1) To design, build and test the performance of a hand operated millet dehuller for different millet varieties.
2) To perform antioxidant extraction from millet hulls through application of microwave assisted extraction (MAE) technique and study the effect of various parameters (time, temperature and solvent concentration) on millet hull phenolics during extraction and optimize the extraction conditions.

CHAPTER II

GENERAL LITERATURE REVIEW

2.1 MILLETS

Millets are one of the most ancient known crops, which are believed to be the first cereal crop in the world (Shahidi & Chandrasekara, 2013). These crops are recognized as a group of small-seeded annual forage grasses and are the sixth most important cereal crops in the world (Saleh et al., 2013; Shahidi & Chandrasekara, 2013). These crops have a short growing period and can be harvested in as little as 65 days (Michaelraj & Shanmugam, 2013), depending on the variety of millet. Once harvested, they can be stored for as long as 4 to 5 years without any quality losses (Bookwalter, Lyle, & Warner, 1987). Millets are among the highly nutritious foods, which provide huge health benefits when consumed. They are an excellent source of protein and fiber and are considered to be good alternatives for wheat due to their non-glutinous nature (Hejazi & Orsat, 2015). Apart from basic nutritional components, millets are also abundant in phenols, antioxidants, flavonoids and other phytochemicals (Shahidi & Chandrasekara, 2013; Suma & Urooj, 2012). These crops serve as the main source of energy in most of the arid and semi-arid regions of the world where there is very little annual rainfall. This is because millets are drought resistant crops (Amadou, Gounga, & Le, 2013; Geetha, Mishra, & Srivastav, 2014) and can grow even in less fertile soils (Geervani & Eggum, 1989).

98.8% of the world's millet production (FAOSTAT online database; MordorIntelligence, 2016) comes from under developed or developing countries in Africa (Amadou et al., 2013; FAO, 2001; Geervani & Eggum, 1989), Eastern Europe (FAO, 2001; Geervani & Eggum, 1989) and few Asian countries including India, Sri Lanka and China due to their topographical conditions that suits the cultivation of millets. Global millet production during the year 2014 was about 28.3 million tonnes with Africa accounting for 43.7% and Asia, 52.3% of the total production (FAOSTAT online database). Table 2.1 shows the leading producers of millets in 2014 (FAOSTAT online database). However, in developed countries like US, Canada and parts of Western Europe these crops are grown especially for hay, while the seeds are sold as a component of birdseed mixes (Bookwalter et al., 1987; Shahidi & Chandrasekara, 2013). These "*coarse*" grains (FAO, 1995; Weber & Fuller, 2008) are sometimes referred to as "*poor people's crops*" due to the crop's resilience and the fact that farmers and poor people consume millets in larger proportions (Weber & Fuller, 2008).

Table 2.1. Leading producers of millets in 2014

Country	Production (million tonnes)
India	11.42
Niger	3.32
China, mainland	2.34
Mali	1.71
Nigeria	1.38
Sudan	1.24
Burkina Faso	0.97
Ethiopia	0.91
Chad	0.69
Russian Federation	0.49

Source: FAOSTAT online database

2.2 HISTORICAL BACKGROUND & CLASSIFICATION OF MILLETS

Millets have been known since before the emergence of the major cereal grains like rice and wheat. It is also believed to be the first ever cultivated crop in the world (Shahidi &

Chandrasekara, 2013). For example, in Northern China, millet remains have been discovered which are dated back to 8200 years before present (Lu et al., 2009). However, the exact origin and emergence of millets as a cereal crop is uncertain. This is likely because of the lower interest shown in studying millets by researchers and scientists worldwide.

Recent archeological findings from Mali (Manning, Pelling, Higham, Schwenniger, & Fuller, 2011) also show that a specific millet variety (pearl millet) has been domesticated 4500 years ago. In addition, proso millet (*Panicum miliaceum L.*) and foxtail millet (*Setaria italica L.*) varieties have been found dating back to well over 5000 year BC in the Yellow River and other regions of North China (Hunt et al., 2008). This implies that China was the first Asian country to domesticate proso and foxtail millets as staple food crop, which then gradually moved to other Asian, Europe and African countries. However, there is lack of sufficient evidence to confirm the origin of cultivation of these crops and the timeline of emergence, which makes it difficult to explain the uses and spread of specific varieties to other regions.

Belonging to the order of *Poales*, millets are typically classified in the grass family *Gramineae*/*Poaceae* (FAO, 2001; Gull et al., 2015; Michaelraj & Shanmugam, 2013; Nazni & Bhuvaneswari, 2015; Shahidi & Chandrasekara, 2013). The common millet varieties grown all over the world are generally classified as major millets (pearl millet) and minor millets or small millets (finger, foxtail, kodo, little, proso, barnyard, fonio, teff and browntop millets) as shown in Fig. 2.1 (FAO/ICRISAT, 1996).

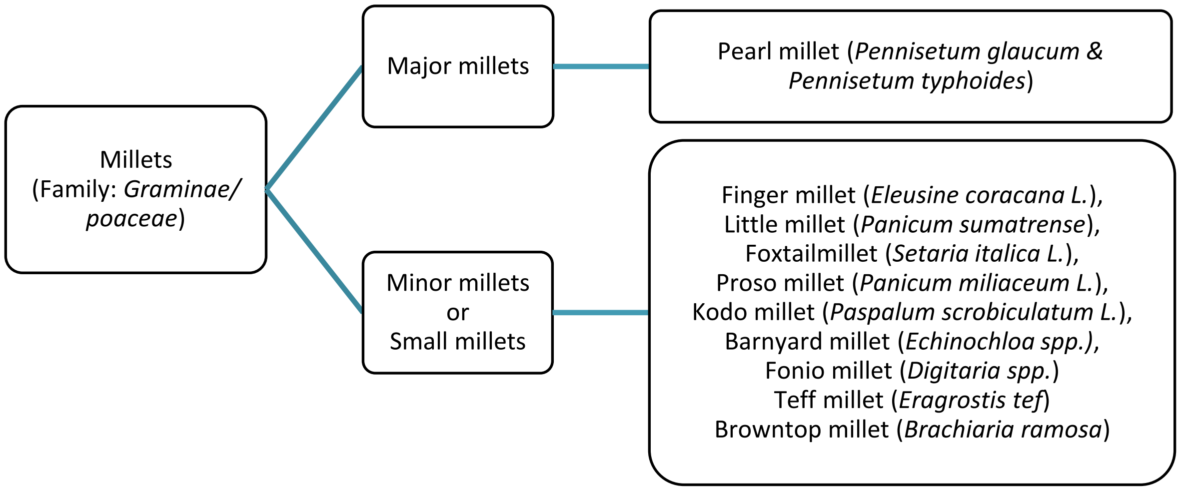


Fig. 2.1 Classification of millets

2.3 MAJOR MILLETS

2.3.1 Pearl millet

Pearl millet (*Pennisetum glaucum & Pennisetum typhoides*), also known as spiked millet, is a staple cereal crop of Africa and parts of India (Manning et al., 2011) accounting for about 40-50% of world's millet production (Amadou, Gounga, Shi, & Le, 2014; Marathee, 1993; Shahidi & Chandrasekara, 2013). It is widely grown in Africa and India as a multipurpose crop (food, forage and feed) (Eltayeb, Hassn, & Babiker, 2016) due to its drought resistant properties but requires special processing in terms of conservation and consumption after harvest (Jain & Bal, 1997). Being called by several different names like bajra, bulrush millet, dark millet, etc. (FAO, 1995), pearl millets are considered to be the sixth most important cereal crop in the world (Gull et al., 2015). Pearl millet is similar to sorghum in terms of its uses and growth but smaller in size than sorghum (Obizoba & Atii, 1994). The shape of the pearl millet grains is considered to be ovoid or cono-spherical in nature (Obizoba & Atii, 1994), coming in different colors like near white, pale yellow, brown, purple and grey (FAO, 1995).

2.4 MINOR MILLETS

2.4.1 Finger millet

Finger millets (*Eleusine coracana L.*), also called as African millet, ragi, telebun, wimbi and bulo, are quite common in Africa, Sri Lanka and India due to their several health benefits (Dharmaraj & Malleshi, 2011). In India, finger millet ranks sixth in the production of cereal crops next to pearl millet (Nazni & Bhuvaneswari, 2015). These millets have been used in making beer and non-alcoholic beverages like "*arake*" or "*areki*", “*togwa*” in African countries (Bwai et al., 2014; Kitabatake, Gimbi, & Oi, 2003). While in India, it is traditionally consumed in the form of thick porridge (muddle, dumplings), thin fermented porridge (ambali) and flat fried pan cakes (roti and dosa) (Antony, Sripriya, & Chandra, 1996)

2.4.2 Proso millet

Proso millet, also called as common millet, comes with many other names like broomcorn millet, hog millet, Russian millet, prove millet and brown corn (FAO, 1995, 2001). Proso millet is mainly grown in Eastern Asia including India, Japan, Manchuria, Mongolia, Eastern and Central Russia. It has been proven to be domesticated first in China about 10,000 years ago after which it slowly moved to other countries (Lu et al., 2009). Proso millet, which matures in 60-90 days, is also found to show the lowest water requirement compared to any other cereals (FAO, 2001).

2.4.3 Foxtail millet

Foxtail millet (*Setaria italica L.*) is one among the minor millets, which is believed to be originating from China approximately 8000 years ago (Lu et al., 2009; Zhang & Liu, 2015). It is also popular in Japan, Bangladesh and India because of its short growing season and low rainfall requirements (Pawar & Machewad, 2006). Foxtail millets are also known for their extended storage period with their pest resistant property during storage (Anju & Sarita, 2010). Foxtail millet ranks second in the world's total production of millets. It is also known as Italian millet, Hungarian millet, Chinese millet, German or Siberian millet (Amadou et al., 2014; Yang et al., 2012) and is considered one of the oldest cultivated crops in the world (Mohamed, Zhu, Issoufou, Fatmata, & Zhou, 2009). The foxtail millet grains can also be found in different shades of colors like pale yellow, red and brown to black (FAO, 1995). In India, it is grown especially as food for the low income strata of the population (Pawar & Machewad, 2006).

2.4.4 Kodo millet

Kodo millet (*Paspalum scrobiculatum L.*) is another important minor millet type, which is of great importance in the tribal regions of India due to its interesting protein and mineral content (Neelam, Kanchan, Alka, & Alka, 2013). It is believed to have been domesticated 3000 years ago in India and an important crop of the Deccan plateau (Kumar, Patel, Naik, & Mishra, 2016). It is mainly grown in Madhya Pradesh, Maharashtra, Uttar Pradesh, Himachal Pradesh, Gujarat, Karnataka and parts of Tamil Nadu. It is considered as the hardest millet grain because of its hard outer shell, which allows it to grow even in high drought regions (Sharma, Sharma, Handa, & Pathania, 2017). It takes almost five to six months for complete maturation of the seeds (Rachie, 1975) which is probably the longest growing duration compared to other millet varieties (FAO, 2001). These millets can be found in colors that vary from light red to dark grey (FAO, 1995).

2.4.5 Little millet

Little millet (*Panicum sumatrense*) is widely grown in Asian countries like India, Sri Lanka, etc. It is indigenous to the Indian subcontinent (Nirmalakumari, Salini, & Veerabadhiran, 2010), where it is grown among the low-income groups, especially among the farmers of South India for its therapeutic value (Rajendran & Thayumanavan, 2000). The maturation period of little millet is between 2.5 to 5 months (FAO, 2001). The different millet varieties with their corresponding scientific and vernacular names are presented in Table 2.2.

2.4.6 Barnyard millet

Available in different names like barnyard millet, Japanese millet, Indian barnyard millet, burgu millet (Africa) and sawa millet, *Echinochloa spp.* is widely grown in Japan, China, Africa, Malaysia, India and parts of the United States (Anju & Sarita, 2010). The Japanese millet (*Echinochloa crus-galli (L.) P.B.*) is a temperate grass which was domesticated over 4000 years ago in Japan (Wallace et al., 2015). These grains have the tendency to mature in as little as 45 days once seeded and can be stored for a long period of time, unlike other major cereal crops.

2.4.7 Fonio

Fonio (*Digitaria exilis or Digitaria iburua*) is of less importance compared to other millet varieties. However, these grains are important in some parts of Africa like Mali, Nigeria, Niger, etc., (FAO/ICRISAT, 1996). Furthermore these grains are considered the oldest among the cereals grown in Western Africa (Marouzé, Thaunay, Fliedel, & Cruz, 2008) and are believed to be cultivated since 5000 BC. Fonio actually comes in two different forms – true or white fonio and black fonio, which are said to have been domesticated in West Africa. These grains are known especially for their short growing periods, i.e. between 40 days to three and a half months (Hitu, M'Ribu, Liang, & Mandelbaum, 1997).

2.4.8 Teff

Teff (*Eragrostis tef*) is another minor millet variety grown for food principally in Ethiopia. The cultivation of these grains in the Ethiopian highlands exceeds even that of major cereals like barley, wheat, etc. (FAO/ICRISAT, 1996; Tadesse, 1993). Information available on teff is sparse, since this crop is not popular outside of Ethiopia (FAO, 2001).

2.5 NUTRITIONAL CHARACTERISTICS OF MILLETS

Balanced nutrition is very much essential in maintaining self-balance and adequate metabolism for healthy life. With a great increase in the demand for nutritious and safe food, people have slowly started to look for nutritive alternatives with potential health benefits. Millets are one such cereal crops, with some superior qualities (Neelam et al., 2013; Shrestha & Srivastava, 2017; Thilagavathi et al., 2015) over that of some major cereal grains. This nutritional trend has started an increased utilization of millets in both developed and developing countries due to the potential health benefits provided by millets. One interesting characteristics of millets is their non-gluten nature (Saleh et al., 2013), which makes them an excellent alternative for people suffering from celiac disease and gluten intolerance. Many studies on millets have demonstrated them to be superior in quality, providing plenty of nutritious and medicinal functions when compared with many other major cereal crops consumed worldwide like rice, wheat, barley, rye, etc. (Amadou et al., 2013).

Table 2.2. Scientific and common names of the most common types of millets

Scientific name	Common names
Pennisetum glaucum	Pearl, bajra, cattail, bulrush, candlestick, sanyo, munga, seno, kambu
Elusinecoracana	Finger, ragi, African, bird's foot, rapoko, hunsa, wimbi, bulo, telebun, koracan, kurakkan, mandua, kelvaragu
Panicum milliaceum	Proso, common, hog, broom, samai, russian, panivarigu, panic, maha meneri, baragu
Setaria italic	Foxtail, Italian, German, Hungarian, Siberian, kangani, navane, thanahal, thinai, korralu
Paspalum scrobiculatum	Kodo, varagu, bastard, ditch, araka, water couch, Indian paspalum, creeping paspalum, amu, varigalu
Panicum sumatrense	Little, blue panic, heen meneri, samai
Echinochola spp.	Barnyard, Japanese, sanwa, sawa, Korean, kweichou, madira, kuthiraivaali, oodalu
Digitaria exilis/ Digitaria iburua	Fonio, fundi, hungry rice, acha, crabgrass, raishan, fonde, findi, polish millet
Eragrostis tef	Teff, abyssinian lovegrass
Brachiaria ramose	Browntop, palapul, chamapothaval, korle

Adapted from: FAO (2001); FAO/ICRISAT (1996); Shahidi and Chandrasekara (2013)

Millets have great potential for being utilized in different food systems due to their nutritional and functional quality. These grains are, in general, a rich source of vitamins, minerals, sulphur containing amino acids, phytochemicals and micronutrients (Ballolli, Malagi, Yenagi, Orsat, & Gariepy, 2014; Chethan & Malleshi, 2007b; Saleh et al., 2013; Shahidi & Chandrasekara, 2013; Takhellambam, Chimmad, & Prkasam, 2016), hence they are also termed as "*nutria-cereals*" or "*nutria-millets*" (Lahangir, 2012; Passi & Jain, 2014; Singh, Mishra, & Mishra, 2012). Millet proteins are good sources of essential amino acids except for lysine and threonine but are high in methionine and cysteine (Mohamed et al., 2009; Saleh et al., 2013). They also contain high proportions of non-starchy polysaccharides and dietary fibre (Chethan & Malleshi, 2007b; Geervani & Eggum, 1989; Hadimani & Malleshi, 1993; Mannuramath, Yenagi, & Orsat, 2015). Millets release sugars slowly and thus have a low glycemic index (GI) (Ballolli et al., 2014; Neelam et al., 2013). The proximate composition of the major nutrients present in millets are 60-70% carbohydrates, 7-11% proteins, 1.5-5% fat, 2-7% crude fibre, vitamins and minerals (Asharani et al., 2010; Hadimani & Malleshi, 1993; Mohamed et al., 2009; Shahidi & Chandrasekara, 2013). But these values vary between the different millet varieties (Table 2.3).

Finger millet, the most important of all the minor millet varieties, is found to be low in fat content (1.5-2%) compared to the other millet types (3.5-5%) and also it has the highest calcium content of about 330-350mg/100 g which makes it unique from other millets (Antony et al., 1996; Devi, Vijayabharathi, Sathyabama, Malleshi, & Priyadarisini, 2014; Shahidi & Chandrasekara, 2013). Furthermore, its lysine, valine and threonine contents are much higher than other millets (Saleh et al., 2013). Important to note though is that these millets also contain proanthocyanidins (also known as condensed tannins), which are capable of reducing the bioavailability of proteins and minerals and their nutritional value, if present in abundance (Devi et al., 2014).

In comparison with major cereal crops like rice and wheat, finger millets contain higher levels of crude fiber and minerals as well (Saleh et al., 2013). In addition to this, the finger millet seed coat, which goes as waste, has been reported to contain higher amounts (6.2%) of phenolic compounds than in the finger millet flour (0.8%) (Chethan & Malleshi, 2007b; Shahidi & Chandrasekara, 2013). However, this composition has been found to vary depending on the variety of finger millet.

Pearl millet, on the other hand, is found to have the highest protein content among all the millet varieties (El Hag, El Tinay, & Yousif, 2002) with higher concentration levels of threonine and tryptophan (Elyas, El Tinay, Yousif, & Elsheikh, 2002). However, these millets are deficient in lysine and low in leucine content compared to that of sorghum. Pearl millets are also an important source of anti-nutrients like phytic acid, polyphenols and tannins (Elyas et al., 2002). Apart from these, pearl millets are rich in dietary fibre (soluble and insoluble), minerals, antioxidants and resistant starch (Saleh et al., 2013).

Foxtail millet is composed of considerable amount of insoluble dietary fibre (Hadimani & Malleshi, 1993; Ushakumari, Latha, & Malleshi, 2004) which is said to increase the digestibility. The major portion of the dietary fibre includes polymers of hexoses, pentoses, cellulose and pectinaceous materials. It also contains significant antioxidant capacity (4.4 – 5.7 mM TE/g) which adds to its functional quality. The total carotenoid content (164 – 191 μg/100g) and total tocopherols content (1.2 mg/100g) in the foxtail millet adds to its antioxidant activity (Asharani et al., 2010). A protein concentrate from foxtail millet has been found to be a potential functional food ingredient and its essential amino acid profile suggests possible use as a supplementary protein source to most cereals, which is attributed to its high lysine content (Saleh et al., 2013).

Barnyard millet has significant amounts of fibre content and minerals like calcium and iron, which are comparatively higher than those of rice, wheat and other millet varieties (Wallace et al., 2015).

Other millet varieties, namely kodo millet and little millet have the highest amount of dietary fibre (37-38%) which is also the highest among the cereals (Hegde & Chandra, 2005). It has also been reported that kodo millet variety has the highest free radical quenching activity among all millets making it a good source of antioxidant (Hegde & Chandra, 2005). Little millet contains considerable amounts of antioxidants and phytochemicals (Mannuramath et al., 2015) like tannins, phytate, phenolic acid, etc., which have been found to increase upon roasting (Pradeep & Guha, 2011). These millets are also found to have a low glycaemic index, which is attributed to their high dietary fibre content (Mannuramath et al., 2015). Proso millet has been found to have the highest amount of carotenoid content (366 µg/100g) among all the millet varieties with the least being little millet (7 µg/100g) (Asharani et al., 2010). Table 2.4 presents the total phenolic acid content found in the most common millet varieties.

Table 2.3. Proximate composition of commonly grown millet varieties (per 100 g of edible portion; at 12% moisture content)

Millet variety	Protein (g)	Fat (g)	Ash (g)	Crude fibre (g)	Carbohydrates (g)	Energy (Kcal)	Calcium (mg)	Iron (mg)	Thiamin (mg)	Riboflavin (mg)	Niacin (mg)
Pearl millet	11.8	4.8	2.2	2.3	67.0	363	42	11.0	0.38	0.21	2.8
Finger millet	7.7	1.5	2.6	3.6	72.6	336	350	3.9	0.42	0.19	1.1
Foxtail millet	11.2	4.0	3.3	6.7	63.2	351	31	2.8	0.59	0.11	3.2
Proso millet	12.5	3.5	3.1	5.2	63.8	364	8	2.9	0.41	0.28	4.5
Little millet	9.7	5.2	5.4	7.6	60.9	329	17	9.3	0.30	0.09	3.2
Barnyard millet	11.0	3.9	4.5	13.6	55.0	300	22	18.6	0.33	0.10	4.2
Kodo millet	9.8	3.6	3.3	5.2	66.6	353	35	1.7	0.15	0.09	2.0

Adapted from: FAO (1995); Saleh et al. (2013); Shahidi and Chandrasekara (2013).

Table 2.4. Total phenolic acid content of millet grains; µg/g of defatted meal

Phenolic acid	Kodo	Finger	Foxtail	Proso	Little	Pearl
Gallic	1.8	5.0	4.5	6.2	2.1	5.4
Protocatechuic acid	70.5	119.8	11.8	72	48.8	1.6
p-Hydroxybenzoic	31.2	6.3	21.8	126	32.6	47.9
Vanillic	98.1	NA	118.7	168.6	162.4	16
Syringic	141.4	25.1	17.4	6.2	23.4	6.3
Chlorogenic	3.6	NA	NA	19	NA	NA
Gentisic	NA	NA	16.8	8.3	NA	NA
Caffeic	324.4	15.9	38.3	339.2	30.9	30.4
Cinnamic	37.4	NA	NA	NA	NA	NA
p-Coumaric	802	41.4	942.7	1235.2	1085.2	91.9
Sinapic	53.2	0.8	16.2	18.9	55.4	12.8
trans -Ferulic	2209.5	358.4	856.5	444.6	355.3	812.3

NA- not applicable. *Sources: Shahidi and Chandrasekara (2013)*

2.6 POTENTIAL HEALTH BENEFITS OF CONSUMING MILLETS

Even though millets are underutilized (Devi et al., 2014; Shahidi & Chandrasekara, 2013), these grains are considered to be much better at promoting overall health in humans than the other major cereal crops (Takhellambam et al., 2016). Millets are used as an alternative for rice, alongside wheat for diabetic patients (Takhellambam et al., 2016) and also for people suffering from atherosclerosis and celiac or gluten intolerance (Hejazi & Orsat, 2015). As part of healthy nutrition, millets, with their phytonutrients, can help in preventing certain types of cancer (Chandrasekara & Shahidi, 2011a), chronic diseases, in lowering LDL cholesterol levels and blood pressure, cardiovascular diseases, gastrointestinal problems, obesity, hyperlipidemia etc. (Saleh et al., 2013; Takhellambam et al., 2016). Many significant contributions have been made in discovering the health benefits and importance of consuming millets, both *in-vivo* (human and animal subjects) and *in-vitro* conditions. However, extensive studies to promote and incorporate millets as a part of the human diet are still in progress.

In accordance, finger millet offers many significant beneficial properties (Table 2.5) which are attributed to its polyphenol content (Chethan & Malleshi, 2007b; Saleh et al., 2013). These millets were found to be effective in reducing the risk of diabetes mellitus, blood glucose levels (Desai, Kulkarni, Sahoo, Ranveer, & Dandge, 2010) and gastrointestinal disorders. A study conducted by Kumari and Sumathi (2002) has demonstrated that finger millet based diets reduced the plasma glucose levels and also resulted in lower glycaemic response which can be attributed to the high fibre content and the presence of anti-nutritional factors (Saleh et al., 2013; Shahidi & Chandrasekara, 2013). In addition, in-vivo studies with rats held by Hegde, Anitha, and Chandra (2005) showed a protective effect of feeding finger and kodo millet meal against hypoglycaemic status and alloxan-induced oxidative stress. They also found that dermal wound healing in rats was quite effective by the application of a paste made from finger and kodo millet flour. Finger millet also increased the antioxidant status and controlled the glucose levels in diabetic animals fed for 4 weeks, hastening the dermal wound healing (Rajasekaran, Nithya, Rose, & Chandra, 2004). Furthermore, sprouted finger millet grains have been suggested for infants and elderly people, as germination improves digestibility (Bwai et al., 2014).

Finger millet and proso millet have the potential to prevent cardiovascular problems by reducing the plasma triglycerides, which has been reported in a research conducted by Lee, Chung, Cha, and Park (2010) on hyperlipidemic rats. Proso millet protein improved the glycemic response and insulin in obese type-2 diabetic mice under high-fat feeding conditions (Park, Ito, Nagasawa, Choi, & Nishizawa, 2008). In a study conducted by Chandrasekara and Shahidi (2012a), phenolic extracts from various millet varieties were evaluated for inhibitory effects on lipid peroxidation. All the varieties were found to be effective in inhibiting lipid peroxidation with kodo millet being the most superior among the millets. Hegde, Chandrakasan, and Chandra (2002), found that methanolic extracts from finger millet and kodo millet have the ability for glycation and cross-linking of collagen. Moreover, these millets have good antibacterial activity which is attributed to their polyphenol content (Sharma et al., 2017) and can be used in the formulation of health foods like nutraceuticals and functional foods.

Table 2.5. Beneficial properties of finger millet polyphenols

Properties	Functional role	References
Antimicrobial properties	• Seed coat phenolic extract—active against *Bacillus cereus, Aspergillus niger* • Fermented finger millet extract—suppress growth of *Salmonella sp., Escherichia coli* • Germinated and ungerminated millet phenol extract—against *Bacillus cereus, Staphylococcus aureus, Yersinia enterocolitica, Escherichia coli, Listeria monocytogenes, Streptococcus pyogenes, Pseudomonas aeruginosa, Serrtia marcescens, Klebsiella pneumonia*	(Viswanath, Urooj, & Malleshi, 2009) (Antony, George Moses, & Chandra, 1998) (Chethan & Malleshi, 2007a)
Antioxidant properties	• Whole flour methanol extract—Antioxidant activity through β-carotene—linoleic acid assay, DPPH radical, hydroxyl quenching action—27%, 94%, 77% respectively • Seed coat methanol extract—Antioxidant activity (β-carotene—linoleic acid assay)—86% • DPPH scavenging effect IC50 (μg/ml)—Crude phenolic extract—90.12; Gallic acid—26.9; Protocatechuic acid—77.63; p—Hydroxy benzoic acid—183.7; p-coumaric acid—112.01; Vanillic acid—176.5; Syringic acid—155.6; Ferulic acid—189.1; Trans-cinnamic acid 96.7; Quercetin—56.8	(Viswanath et al., 2009), (Sripriya, Chandrasekharan, Murty, & Chandra, 1996) (Viswanath et al., 2009) (Chethan, Dharmesh, & Malleshi, 2008)
Antidiabetic properties	In vitro studies • Millet phenolics inhibits—Malt amylase, α—glucosidase, pancreatic amylase—reduce postprandial hyperglycemia by partially inhibiting the enzymatic hydrolysis of complex carbohydrates • Inhibits—Aldose reductase—prevents the accumulation of sorbitol—reduce the risk of diabetes induced cataract diseases • Methanolic extract—prevents glycation and crosslinking of collagen—reduce complication of diabetes and aging due to presence of free radical scavengers In vivo studies • Whole grain millet meal flour protects against hyperglycemic and oxidative stress • Finger millet feeding controls blood glucose level, improve antioxidant status and hastens the dermal wound healing process in diabetic rats	(Shobana, Sreerama, & Malleshi, 2009), (Chethan et al., 2008) (Chethan et al., 2008) (Hegde et al., 2002) (Hegde, Rajasekaran, & Chandra, 2005) (Rajasekaran et al., 2004)

Sources: Devi et al. (2014)

Foxtail millet, on the other hand, was found to reduce type-2 diabetes, cardiovascular diseases and atherosclerosis (Choi et al., 2005). Feeding treated and untreated barnyard millet starch to rats resulted in lower blood glucose level, serum cholesterol and triglycerides in comparison with rice and other millet varieties (Kumari & Thayumanavan, 1997). These millets were also found to be beneficial in increasing the HDL (good cholesterol) levels, thereby controlling type- 2 diabetes in a study conducted by Ugare, Chimmad, Naik, Bharati, and Itagi (2014). Though millets have many important health promoting potentials, their use as food or as an ingredient in human diet is limited till date, except in isolated areas in a few developing countries within Africa and in India.

2.7 POST-PRODUCTION UNIT OPERATIONS OF MILLETS

Once harvested, plant based foods must be handled adequately until they are consumed in order to prevent losses and ensure food security (Chakraverty, Mujumdar, & Ramaswamy, 2003). The most common post-harvest processes include threshing, grading, drying and storage. Depending on the need and the type of food, there can be variations in the unit operations employed. As far as millets are concerned, transportation, threshing, grading, drying, storage, dehulling and milling into flour are the important post-harvest operations. Before the harvesting operation is done, field inspection is to be carried out to ensure the uniform ripening of the crops. If that is not the case, selective harvesting is done to pick only the matured head of the crops (FAO, 2001).

2.7.1 Field harvesting

Harvesting is the step, which involves the removal of the heads that contain the edible grains from the crop, once the maturation stage has been reached. Generally, millets are harvested by the traditional and age-old method of using sickle or small hand knives (FAO, 2001) to pluck the individual heads manually from the plant stalk. Proso millets are harvested by pulling out the entire crop once the grains are matured (FAO, 2001). Manual harvesting might result in improper handling thus damaging the grain quality. Furthermore, this method is time consuming and tiresome, hence there is a need for developing mechanized harvesting equipment for millets. Combined harvesters which are currently being used for wheat, barley, oats etc., can be used for millets, taking into consideration the millet crops, of a given variety/cultivar, are of uniform height (FAO, 2001).

2.7.2 Threshing

The harvested millet cobs must be threshed in order to remove the edible grains. The process of removal of the edible grains from the harvested inedible portion of the crops is called "*threshing*". Similar to harvesting, this method is also carried out by manual labor. The traditional method of threshing involves the beating of the harvested chaff containing the millet grains with sticks or clubs against the floor, canvas or mat, until all the grains are removed from the chaff (FAO, 2001). In order to ease the collection of the grains, the millet heads may be filled in bags prior to threshing. This practice is common in Tanzania, Kenya, Malawi, Mozambique, Zimbabwe, and Uganda (FAO, 2001). However, the application of beating as a method to thresh millets, may result in the contamination of the grains with unwanted foreign material like small stones. Developing mechanical and electrical threshers, especially for millets as per need, thus reducing labor, threshing time, can overcome the problem of contamination with stones and other debris.

2.7.3 Transportation

Once the grains are harvested and threshed, they are usually transported within the farm or to the place where the grains are dried, depending on the farmers' needs (FAO, 2001). Transporting is traditionally done in the villages, by the use of animals like donkeys or animal pulled carts, in which the harvested crops are covered by a cloth or the whole crop is tied around and loaded. Millets are generally transported from rural to urban areas by means of trucks (FAO, 2001).

2.7.4 Drying

Drying is the most important unit operation applied to any food material that helps in maintaining its keeping quality during storage. Especially, cereals must be dried prior to storage in order to avoid germination and mold growth (Brennan & Grandison, 2012). Adequate information regarding drying of millets is not available (FAO, 2001). Sun drying is the most common method employed in drying millets; however, mechanical dryers are also used for this purpose, which are quite expensive at the farm level. The millets are dried under the sun at the place where threshing is carried out. Depending on the season of harvest (to avoid rains), millets can be sun dried for several days to a maximum of up to two weeks (FAO, 2001).

2.7.5 Cleaning

During threshing and drying, the millets can get contaminated with unwanted foreign substances like stones, sand, metal pieces, chaff, etc. The primary reason behind this is that threshing and drying operations are commonly practiced at the farm level, with little means, where the millets are spread out on the ground. In order to subsequently store the millets for future processing, the contaminated millets must be cleaned to set them free of all the foreign materials. This is traditionally done by a method called "*winnowing*". In this process, the threshed and uncleaned grains are taken in a flat reed- or raffia- woven basket and winnowed in up and down strokes (FAO, 2001). This makes the unwanted and lightweight particles to separate from the millet grains. These materials are then separated by means of hand motion at the front of the basket and thrown away. This method is highly time consuming.

As an alternate method, uncleaned grains are taken in a basket and poured from a certain height to fall onto the ground which has been lined with a plastic sheet or canvas. This forms a heap of grains, throwing away the chaff by bouncing off in the air (FAO, 2001). This method is much quicker than winnowing but heavy materials like stone, metal pieces, etc., cannot be separated well.

"*Screening*" is another technique, which can efficiently remove particles like sand, metal contaminants, immature grains, stones, etc. It uses a set of sieves with different pore diameters. However, stones that are of the same size as millets cannot be separated by screening.

2.7.6 Grading

The cleaned grains are usually graded into different uniform size and quality of millets. This is generally done to categorize the grains depending on the size and shape of the millets. This also helps in removing the foreign materials like small stones, straw, metal pieces, etc. However, this process is not practiced in villages because the cost of the equipment used for grading is expensive.

2.7.7 Storage

Storage of grains is another important step in preserving and preventing any losses in terms of quality and quantity, until it reaches the consumer (Brennan & Grandison, 2012). The threshed, dried, cleaned and graded grains are packed in hessian/sisal bags for storage and transportation

(FAO, 2001). Millets must be stored under conditions, which prevent infestations from insects, rodents, molds and birds (Brennan & Grandison, 2012). However, much attention to the conditions for appropriate storage of millets has not been given because millets have been neglected and are considered as minor cereal crops (Padulosi et al., 2009). It can also be attributed to the fact that millets grow in dry, arid and semi-arid regions, hence can be stored for as long as 4-5 years with simple facilities like traditional storage containers, granaries, sealed storage drum, mud straw bins, earthenware pots and jars (FAO, 2001).

To maintain the keeping quality during storage of millets, there are three governing factors: temperature, humidity and moisture content that must be taken into consideration (FAO, 2001). Reducing the temperature, humidity and moisture content during storage helps in maintaining the quality of the millets. The most preferred range of relative humidity for storage is 60-65% (FAO, 2001).

2.8 TRADITIONAL MILLET PROCESSING TECHNOLOGIES

2.8.1 Germination/ Malting

Germination/ Malting is a traditional age-old method of processing grains, which is known to increase the nutritional quality of the grains with some biochemical modifications, promoting them to be used in various recipes. Studies have shown that germination of millets has positive effects in improving their digestibility.

Germination of finger and pearl millet was found to increase the bio-accessibility of minerals (iron and calcium) and their *in-vitro* extractability, while their phytic acid content was decreased during germination (Suma & Urooj, 2014a). Furthermore, germination of pearl millet doubled the solubility of iron *in-vitro*, while finger millet germination for 48 h at 30˚C improved the *in-vitro* protein digestibility by 17% (Eyzaguirre, Nienaltowska, De Jong, Hasenack, & Nout, 2006). A significant decrease in the anti-nutrient factors was generally observed with phytic acid (45%), tannins (46%) and oxalate (29%) contents (Hejazi & Orsat, 2016).

Germinating the millet grains also has some negative impact on the grain quality. For example, germinated foxtail millets are reported to have decreased crude protein and fat content, which may be due to the loss of low molecular weight nitrogenous compounds and hydrolysis of lipids and oxidation of fatty acids during germination (Choudhury, Das, & Baroova, 2011). However, germinating foxtail millets for three days and milling them to flour increased significantly their amylase activity, DPPH scavenging activity and mineral concentration (Coulibaly & Chen, 2011).

Germination in combination with other traditional methods like fermentation, soaking, etc. was also reported to have some further beneficial effect on the millets' nutritional content. It has been reported that germination of pearl millet followed by fermentation increased the nutritional value with significant changes in its chemical composition (Samia, AbdelRahaman, & Elfadil, 2005). It further led to the elimination of anti-nutritional factors. Similarly, Inyang and Zakari (2008) conducted a study on instant *fura* – Nigerian cereal food, to evaluate the effect of germination and fermentation of pearl millet. Germinating the grains improved the nutrient and energy densities of the food. In combination with fermentation, it reduced the phytic acid content significantly. Germination of pearl millet based food blends followed by fermentation with probiotic organisms resulted in improved contents of thiamine, niacin, total lysine, protein fractions, sugars, soluble dietary fiber, and *in vitro* availability of calcium, iron and zinc (Arora, Jood, & Khetarpaul, 2011).

There are various studies on the effect of malting with sorghum and millets, which reported a decrease in phenolic content (Table 2.6). This decrease was attributed to two mechanisms – leaching of phenolic content and the imbibition of the same along with water into the endosperm during steeping or germination (Taylor & Duodu, 2015). Malting of pearl millet, when compared to malting of sorghum, was reported to be advantageous due to its higher amylase activity and higher free α- amino nitrogen (Pelembe, Dewar, & Taylor, 2004). Furthermore, malted pearl millet (72 h) resulted in a significant increase in the *in-vitro* protein digestibility (14-26%) which was attributed to the degradation of the storage proteins (Sehgal & Kawatra, 2001) and an increase in starch digestibility (86-112%) when compared to blanched and malted pearl millet (48 h).

Malted finger millet, on the other hand, showed a significant increase in the bioaccessibility and content of minerals like calcium, zinc and iron by 20, 29 and 65 g/100 g respectively, with a decrease in the inhibitory factors like phytic acid (84 g/100 g), polyphenols (78 g/100 g) and dietary fibre (81 g/100 g) (Krishnan, Dharmaraj, & Malleshi, 2012).

2.8.2 Fermentation

Fermentation is one of the oldest and most common traditional method of processing foods after germination, which is also used to enhance their nutrient quality and shelf life. In Africa, where availability of modern technology is limited (Amadou et al., 2013; Amadou et al., 2014; Saleh et al., 2013), due to their economic conditions, fermentation is widely used to ensure food safety in particular for infants and young children health. Fermentation has been found to reduce the anti-nutrient content with substantial increase in the nutritional composition of many cereal grains. Furthermore, it tends to induce desirable physical and chemical changes in the resulting food product (Amadou et al., 2014). In addition, fermentation helps in increasing the protein and starch digestibility in many foods (Dhankher & Chauhan, 1987; Eltayeb et al., 2016; Osman, 2011).

Several research findings have proven that fermentation can reduce the anti-nutrient content of millets to a significant level without affecting negatively the nutritional quality (Dhankher & Chauhan, 1987; Elyas et al., 2002; Osman, 2011; Usha & Chandra, 1998). Sorghum and millets, being the major staple food in most African countries, are fermented by introducing microflora like lactic acid bacteria (LAB) or by a combination of lactic acid bacteria and yeasts, in the form of sourdoughs and traditional beer fermentation (Taylor & Duodu, 2015). Like germination, fermentation is also used in combination with other processing technologies to enhance the nutrient availabilities furthermore than when it is used as a single process. Eltayeb et al. (2016) reported that processing (grinding, soaking, autoclaving, debranning and germination) of pearl millets followed by fermentation for 12 h and 24 h minimized the composition of anti-nutritional factors, like phytic acid, polyphenols and tannins significantly. Table 2.6 shows the effect of fermentation on pearl and finger millets (Taylor & Duodu, 2015).

Table 2.6. Effect of malting and fermentation on the phenolic content of a few millet varieties

Grain type	Processing method	Effect of processing
	Malting	
Pearl millet	Steeping overnight and germination for 48 h.	Soaking reduced total phenolics by 15% and germination decreased total phenolics by a further 73%.
Finger millet	Steeping for 24 h and germination for 96 h.	Decrease in the major bound phenolic acids caffeic acid, coumaric acid and ferulic acid by 45, 42 and 48% respectively.
Finger millet	Steeping and germination at 25˚C.	Reduction in total phenolics, catechols and resorcinols, with 79, 54 and 68% retention respectively.
Finger millet	Steeping for 24 h and germination for up to 120 h.	Loss of polyphenols by 44% after the first 24 h of germination and by another 40% over the next 48 h.
	Fermentation	
Pearl millet	Natural fermentation at 30˚C for 14 h.	Reduction in total polyphenols by 60 and 31%.
Finger millet	Natural fermentation at 37˚C for 48 h.	Reduction in total phenolics by 26–29% and tannins by 44–52%.

Adapted from: Taylor and Duodu (2015).

A study was conducted to evaluate the protein and starch digestibility of *Rabadi* – a pearl millet fermented food. The pearl millet mixture used for making Rabadi, was allowed to ferment for different fermentation time (3, 6 & 9 h) and temperatures (35°, 40°, 45° & 50°C). The mixture that was fermented for 9 h at 45°C showed significant increase in protein (51%) and starch (58%) digestibility (Dhankher & Chauhan, 1987). In another study with Rabadi, fermentation for 16 h was reported to increase the crude protein and flavonoids, while it decreased the crude fibre and fat content (Gupta & Nagar, 2010). Similarly, *Uji*- a traditional African fermented food made from maize-finger millet, was evaluated for chemical changes and digestibility (Onyango, Noetzold, Bley, & Henle, 2004). The results observed showed a potential increase in the amino acid availability (aspartic acid, glycine, cysteine, methionine, tyrosine and lysine) of the product during fermentation. Another African fermented product, *ogi* was found to have increased availability of starch and protein for digestion when compared to unprocessed grain. It also had increased amounts of lysine, tryptophan, vitamin B2, with a decrease in the net quantity of vitamin A, flavonoids and paste viscosity (Akingbala, Uzo-Peters, Jaiyeoba, & Baccus-Taylor, 2002).

Varied microbial cultures have also been employed in fermenting millets and their products (Saleh et al., 2013). Antony et al. (1996) studied the changes in the primary nutrients present in finger millet during fermentation using endogenous microflora at 30°C. Fermentation decreased the starch and long chain fatty acid contents of the finger millet. Foxtail millets also showed increased nutrient value on fermentation. Fermentation of these millets with *Lactobacillus paracasei* Fn032 and heat moisture treatments resulted in increased protein content (12.02–20.54%), total starch (15.78–51.01%) and starch fractions (Amadou et al., 2014). Cultures like *Saccharomyces diastaticus, Saccharomyces cerevisiae, Lactobacillus brevis,* and *Lactobacillus fermentum* have also been used in pearl millet fermentation (Saleh et al., 2013).

Fermentation of pearl millet slurries with lactic acid resulted in decrease in the phytate content and α- galacto- oligosaccharides (Songré-Ouattara et al., 2008). In addition to these changes in the composition, microbial flora has also been used successfully to develop fermented millet beverages. In accordance, a study by Mugocha, Taylor, and Bester (2000) came to a conclusion that yoghurt type bacterial cultures are suitable to produce composite fermented beverage using finger millet and skim milk.

2.9 VALUE ADDITION OF MILLETS

Ever since the domestication of millets, they have been utilized as feed for animals and birds, incorporated as a part of the human diet as a food ingredient. However, the use of millets as staple foods has reduced with the increase in popularity of rice, corn and wheat (Ballolli et al., 2014) even in these developing nations. Because of its lower popularity as a food crop, value addition has been employed to encourage consumption of millets in diversified forms. There has been a lot of millet based food products developed till today in countries like Africa, India, China and Russia.

Millets have been used in Africa for making non-alcoholic beverages like '*togwa*', (Kitabatake et al., 2003) and porridges like '*ogi'* (Akingbala et al., 2002), '*ugali'* (FAO, 2001) and '*ugi'* (FAO, 2001; Onyango et al., 2004). In India, millets have been consumed traditionally in various food products like '*porridges'* (FAO, 2001)*, 'breads', 'roti'* (Mannuramath et al., 2015) and *dosa (pan cakes)* and they are also cooked and consumed as rice in most regions of India. As a food ingredient however, millet flour cannot be readily used in the bakery industry, as pure-millet products cannot be prepared due to their lack of gluten (Saleh et al., 2013). Hence in many food systems, millet can be incorporated only as a fraction along with other cereal ingredients such as rice or wheat.

Biscuits made from millet flour and pigeon pea flour blend (100:0, 75:25, 65:35 and 50:50) resulted in higher protein and digestible carbohydrate (Eneche, 1999). The sensory characteristics like flavor, texture, appearance, etc. have been evaluated and it was found that flour blends with 65% millet and 35% pigeon pea resulted in highest sensory score. Similarly, biscuits prepared with 60:40 (w/w) ratio of finger millet and wheat was reported to have the best biscuit quality and dough characteristics compared with other finger millet-wheat blends (Saha et al., 2011). Anju and Sarita (2010) developed millet biscuits incorporating barnyard millet and foxtail millet flours. The glycemic index for the biscuits developed using foxtail millet flour was significantly lower when compared to the refined wheat flour and barnyard millet flour and it was also found that the overall acceptability of the biscuits made using the foxtail millet flour was better than that of the biscuits made with either wheat or barnyard millet flour.

Millet incorporated breads have been formulated using a composition of barnyard millet and wheat flours. These breads were prepared by mixing 61.8 g/100 g barnyard millet, 31.4 g/100 g wheat, and 6.8 g/100 g gluten. The overall acceptability of these millet incorporated breads was the same as normal wheat breads (Singh et al., 2012). Mannuramath et al. (2015) also formulated wheat breads replaced with little millet flour (at 10, 30 and 50%) in the view of enriching the breads with fibre. The little millet incorporated breads were evaluated for physical, sensory and nutritional attributes. The breads incorporated with 30% little millet flour had increased amounts of micronutrients (iron, zinc, copper, phosphorous and fibre) and it was concluded to be considered as a functional food.

Apart from breads and biscuits, millets have also been used in the preparation of noodles for their low glycemic index. Noodles were prepared using 30% and 50% finger millet flour along with refined wheat flour composite (Shukla & Srivastava, 2014). The glycemic response of the finger millet incorporated noodles was evaluated in comparison with the control. It was found that finger millet incorporated noodles had a lower glycemic response than the control noodles, making them suitable for diabetic patients. In a study conducted by Ferriola and Stone (1998), white proso and foxtail millets have been used in the formulation of a flaked whole grain ready-to eat breakfast cereal. The results showed that use of 100% millet in ready-to-eat breakfast cereals seems feasible. Millets have also been used in the preparation of weaning foods because of their various health benefits (Hejazi & Orsat, 2017).

Besides utilization of millets in making bakery products and other ready-to-eat/ready-to-cook products, the millet husks/hulls generated as a waste while processing have been used in the production of bioethanol (Oyeleke & Jibrin, 2009; Rabah, Oyeleke, Manga, & Hassan, 2011), biofilms (Rathore, Singh, & Kumar, 2016), polyphenols extraction (Chandrasekara & Shahidi, 2011b, 2011c; Hegde & Chandra, 2005) and in the production of enzymes like *cellulase* and *tannase* (Khokhar, Haider, Mushtaq, & Mukhtar, 2012; Milala, Shugaba, Gidado, Ene, & Wafar, 2005; Paranthaman, Vidyalakshmi, & Singaravadivel, 2009; Salihu, Abbas, Sallau, & Alam, 2015).

2.10 CONCLUSION

This literature review provides an overview of millets from its emergence as a cereal crop, to its current role in the food industry including its applications, health benefits and nutritional composition. Millets have been proven to have excellent potential in promoting human health, from infants to the elderly people, if consumed on a daily basis. Especially patients suffering from diabetic diseases, atherosclerosis and gluten sensitivity can benefit from including millets as a part of their diet. However, there is still a lack of knowledge about millets' health benefits in the developed nations, while mechanical processing methods have not been properly implemented in the developing nations, where drudgery in processing has reduced millet consumption. Hence, there is a necessity for researchers to explore and innovate new ways to process millets, in view of eliminating drudgery, in the developing nations and to promote the consumption of millets by value addition worldwide.

CONNECTING STATEMENT

In Chapter II, we discussed the role of millets from ancient agriculture, their health promoting potential as a food crop, value addition to millets and the various unit operations involved in millet processing. Traditional methods of millet processing cause drudgery among the millet processors, who are generally women. This processing drudgery decreases the overall cultivation and consumption of millets in the developing world. The next chapter reviews the complications faced during millet processing using traditional methods and various modern technologies implemented to reduce drudgery.

CHAPTER III

IMPLEMENTATION OF MECHANIZED POST-HARVEST PROCESSING TECHNOLOGIES FOR MILLETS: A REVIEW

3.1 ABSTRACT

Millets are considered one of the oldest known cereal crops with interesting combinations of nutrients when compared to other commonly consumed cereal crops like rice, wheat, rye, etc. Despite this, millets are regarded as a valuable food crop only among some limited rural communities. Even in places where millet cultivation is quite common, there is a steady decline in production and consumption of these grains. This decrease can be attributed to many reasons, the major one of which is the drudgery involved in processing these grains using traditional methods due to insufficient adapted post-harvest technologies, to facilitate human consumption. Processing by mechanical means can significantly reduce drudgery and processing time, thereby encouraging farmers to increase production, consumption and commercialization of millets and millet-based food products. This review focuses on the application of mechanical aids for processing millets in rural areas of both developed and developing countries, thereby creating a pathway to devise promising technologies in a manner that causes less or no adverse effects on the nutritional attributes of millets during processing.

KEYWORDS: Millets, drudgery, mechanization, traditional handling methods, post-harvest technologies, nutritional value.

3.2 INTRODUCTION

Ever since the advent of agriculture, cereal grains have been the main source of energy for humans, along with other food groups like meat, fruits and vegetables, etc. Cereals play a significant role in the human diet, hence occupy the base of the food pyramid with food groups like bread, rice and pasta (Chandrasekara & Shahidi, 2011c; USDA, 1992). Consumption of cereal grains account for over 50% of the world's daily calorific intake (Sarwar, Sarwar, Sarwar, Qadri, & Moghal, 2013). Cereal grains are grown for human consumption and as animal feed in different forms, depending on the geographical location and are available as different varieties like wheat, rice, barley, millets, rye, oats, etc. Each type of cereal grain has its own significance in terms of its nutritional benefits and market value in both developed and developing countries. Cereals are generally consumed in their natural form or processed into ready-to-eat products. For human consumption, in general, cereal grains must be processed in one way or another to remove the inedible portion (hull or husk) from the edible endosperm.

Millets are cereal crops that are classified as a group of small seeded annual forage grasses belonging to the family *Graminae/Poaceae* (FAO, 2001; Michaelraj & Shanmugam, 2013; Shahidi & Chandrasekara, 2013). The word millet comes from the French word "*mille*", meaning thousand, implying that a handful of millets can contain thousands of grains (Shahidi & Chandrasekara, 2013; Taylor & Emmambux, 2008). These crops, which are known to be resilient, can be used as an alternative crop when the major cereal crops fail during harsh weather conditions and are harvested within a shorter period of time than many other cereals. Millets are extremely drought tolerant, which makes them a well-suited crop for cultivation in the arid and semi-arid regions of the world (Bagdi et al., 2011; Devi et al., 2014; Hejazi & Orsat, 2016). Adding to these advantages, millets are considered highly nutritious, comparable and sometimes even superior

(Neelam et al., 2013; Shrestha & Srivastava, 2017; Thilagavathi et al., 2015) to other cereal grains like rice and wheat (Amadou et al., 2013; King, 2016; Obilana, 2003; Sehgal, Kawatra, & Singh, 2003; Suma & Urooj, 2014b), with respect to their proximate constituents. They are good sources of protein, dietary fibre, antioxidants, phytochemicals, micronutrients (Saleh et al., 2013) and phenols (Shahidi & Chandrasekara, 2013); free of gluten, hence can be used as an excellent alternative to wheat based foods for people having 'gluten sensitivity' or 'celiac diseases' (Hejazi & Orsat, 2015). According to FAO/ICRISAT (1996), *pearl, finger, foxtail, kodo, proso, barnyard, little, fonio* and *teff millets* are the different millet varieties, with the first six being the most important. Pearl millet falls under a separate category, known as *'major millet'*, while the other varieties are termed as *'minor millets'* or *'small millets'* (FAO, 1995; FAO/ICRISAT, 1996; Obilana & Manyasa, 2002). Sorghum grains are often compared with pearl millet since they are similar in structure and development (FAO, 2001). Furthermore, these grains are referred to as the *'great millet'* in Africa (FAO, 1995), where they are believed to have been originated. However, sorghum grains are not classified as millet grains.

3.3 MILLETS' STATUS AS A FOOD CROP

World millet production has been estimated to be about 28 million tonnes in 2014 (Fig. 3.1), with India being the leading producer with a production of 11.4 million tonnes (FAOSTAT online database). Despite the notable production of millets and its general availability, consumption of millets has traditionally been restricted to the lower socioeconomic population of the world (Sehgal et al., 2003). Its utilization as a staple food has started to decline even in regions like Asia and Africa, where they are traditionally consumed on a large scale by the low income members of the society due to the increased production and consumption of cash crops like rice and wheat at an affordable price and the lack of availability of millet-based ready-to-eat food products (Devkota, 2014; King, 2016; Padulosi et al., 2009; Pradeep & Sreerama, 2015; Yenagi, Handigol, Bala Ravi, Mal, & Padulosi, 2010). There is also increased demand for the mechanization of millet processing to reduce drudgery involved in processing and to overcome the nutrient losses that occur during traditional processing, although machines designed for other cereals like maize could be used (Stanford & Bourdillon, 2001). For these reasons, millets have been increasingly neglected as a food crop. In the past 15 years, millet research has led to the formulation of a variety of novel ready-to-eat/ready-to-use products (Mannuramath et al., 2015; Ushakumari et al., 2004) with desirable taste and increased consumer acceptability, especially in the bakery industry, which could stimulate increased consumption.

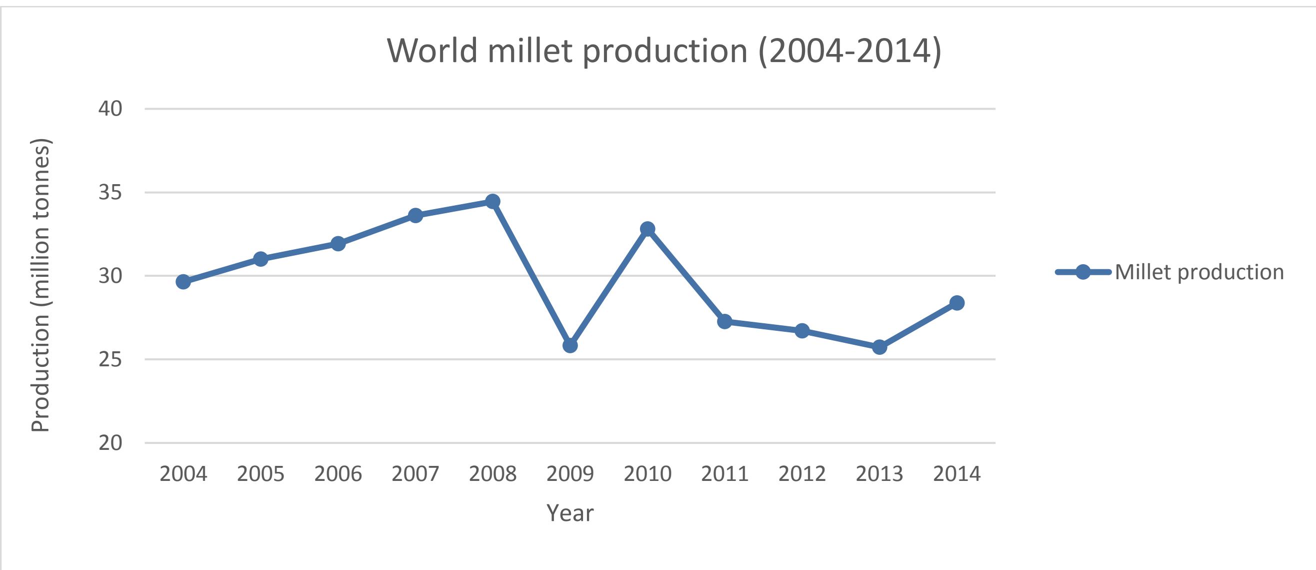


Fig. 3.1 World millet production (in million tonnes)

Sources: FAOSTAT online database.

3.3.1 Millets in developing nations

For a large group of people, especially the poor living in the arid and semi-arid regions of the developing nations, millets has been the main food crop included in their daily diet providing energy and food security (Ravindra, Vijayakumari, Sharan, Raghuprasad, & Kavaloor, 2008). Cultivation of these cereal grains is quite common in African, Asian and few ex-Soviet countries (Amadou et al., 2013; FAO, 2001; Geervani & Eggum, 1989; Padulosi et al., 2015; Shahidi & Chandrasekara, 2013) with Africa (43.7%) and Asia (52.3%) being the most substantial contributors in the production as of 2014 (FAOSTAT online database). However, not all varieties are grown with equal importance in these regions. For instance, pearl millet is the predominant millet variety grown in Africa, whereas foxtail millet is not grown to any extent in Africa outside of the eastern highlands (FAO/ICRISAT, 1996).

Millets are generally consumed either in the form of whole grains or by grinding them into a flour. Millets have been traditionally consumed by making porridges (*pap, sadza, ugali, ugi, ogi, tô, fura; ambali*), alcoholic beverages (*talla or pito, opaque beers like Ndlovo, tella and spirits like katikalla; chhang or jnard/jaanr*), non-alcoholic beverages (*togwa, oskikundu, kunun zaki*), fermented (*injera and kisra*) and unfermented (*roti/chapatti; kitta*) flatbreads, dumplings (*mudde*) and snack foods (popped millets) (Inyang & Zakari, 2008; Kitabatake et al., 2003; Onyango et al., 2004; Taylor & Emmambux, 2008). However, due to a lack of sufficient processing machinery and technologies at the household and village levels, these nutritious grains have recently been neglected.

3.3.2 Millets in developed nations

Unlike the other major cereal varieties, millet cultivation is not prevalent in developed countries like the United States of America and Canada. Only 1.1% of the world's total millet production is contributed by the Americas and a very little quantity of this percentage is being used in human diet (FAOSTAT online database). This situation prevails due to the unavailability of millets in the form of ready-to-eat/ready-to-use products and the little knowledge and awareness about these crops as valuable food grains for their wholesomeness (Ushakumari et al., 2004). In the American continent, proso millet varieties are the main cultivated millet crop (Bagdi et al., 2011), especially in the Prairies and Ontario regions of Canada and in parts of Colorado, Nebraska and the Dakotas of the United States (Small, 2013). However, proso millet is grown mainly as an ingredient of bird seed mixes, poultry and animal feed and as a pasture crop (Bagdi et al., 2011; Bookwalter et al., 1987; Shahidi & Chandrasekara, 2013). While most other varieties are generally regarded as weeds.

3.4 NEED FOR MECHANIZATION

Once harvested, millets have to undergo a series of post-harvest operations like threshing, drying, storage, etc., (FAO, 2001) before further processing for human consumption. This is done to ensure the keeping quality and to prevent the grains from being infested with insects and rodents until reaching the processing facility, where the edible endosperm is separated from the bran and the husk. It is important to remove the outer husk as it contains anti-nutritional and organoleptically unacceptable compounds (Bassey & Mbengue, 1993), which make the grains undesirable for consumption. The separation of the inedible outer husk and bran is the most tedious process in millet processing because of its smaller grain size compared to many other cereals (Saleh et al., 2013; Taylor & Duodu, 2015; Verma, Singh, & Shahi, 2014). This step, which is time consuming and requires immense human effort, is carried out in the traditional way using mortar and pestle in the rural areas among the developing nations. Hence, there is a great need for developing processing machineries affordable, at the village scale, which could ease millet processing, eventually leading to the production of high quality millet food products at the commercial scale that could be distributed for the consumption of urban populations (Saleh et al., 2013).

Taking into consideration the significance of machinery in rural areas and the need for further research to ease millet processing, this review paper emphasizes the availability of various machines like threshers, mechanical mills, dehullers, etc., to process millets and their impact on millet grain quality.

3.5 CHALLENGES FACED DURING PROCESSING

Proper post-harvest operations are crucial in any cereal grain processing as they are prone to infestation (Rajendran, 2003). Preliminary post-harvest processing involves threshing, decorticating and pulverizing of the millet grains to flour as shown in Fig. 3.2. Historically, millets have been processed manually in most scenarios by women and children (Schmidt, 1992). Women, especially, play a crucial role in the on-farm and off-farm processing of millets, from harvesting to flour production and also in value addition (Anonymous, 2013; Devkota, 2014; FAO, 2001; King, 2016; Stanford & Bourdillon, 2001).

Usually, millets are threshed by beating the stalks containing the grains against the floor (FAO, 2001) or beaten with sticks (Singh, Poddar, Agrawal, Hota, & Singh, 2015) and trodden underfoot by humans (women, in most cases) or animals like bullocks (Gbabo, Gana, & Amoto, 2013; Gull, Ahmad, Prasad, & Kumar, 2016; Parmanand & Verma, 2015; Singh et al., 2015). The problem with the traditional way of threshing is the accumulation of dust, small stones and foreign impurities, which not only reduce the grain quality but also increase processing time by the need to have a preparation or cleaning step (Parmanand & Verma, 2015).

Majority of the millet producers/consumers face the challenge of manual dehulling and pulverizing before preparing their millet meal (Schmidt, 1992). Except for pearl millet, which can be consumed as both whole and dehulled grain products, all minor millets have to be dehulled prior to cooking (Pushpamma, 1986). Dehulling and milling is carried out by crushing the grains between two stones or by pounding the whole seeds using mortar and pestle (FAO, 2001; Sehgal et al., 2003; Taylor & Emmambux, 2008). This practice, however, varies from place to place. For example, in Africa, millets are threshed, decorticated and ground into a flour using wooden mortar and pestle (FAO, 2001; ICRISAT, 1988). In other cases, dehulling of millets can be done by wetting the grains with water to help in the removal of the bran by winnowing or sieving, thereby reducing/preventing endosperm damage (Balasubramanian, Viswanathan, & Sharma, 2007; Bassey & Mbengue, 1993; Taylor & Emmambux, 2008; Verma et al., 2014). However, in some countries, millets are dehulled without addition of water, which is then winnowed and ground into a flour using emery stones (Balasubramanian et al., 2007; FAO, 2001). Even though it is time consuming and a cause of drudgery, these operations are still in practice among the rural farmers and people who consume millets on a daily basis because of the unavailability of adaptable processing machinery.

To overcome the challenges faced during the traditional millet processing and eventually satisfy the demand for processing machinery in the developing world, organizations like the International Development Research Centre (IDRC), Canadian International Development Agency (CIDA), International Crops Research Institute for the Semi-Arid Tropics (ICRISAT), Development of Human Action (DHAN) foundation, etc., and several other research institutions have focused research and development efforts on revitalizing millet cultivation by designing efficient processing machineries for millets and formulating novel millet based foods.

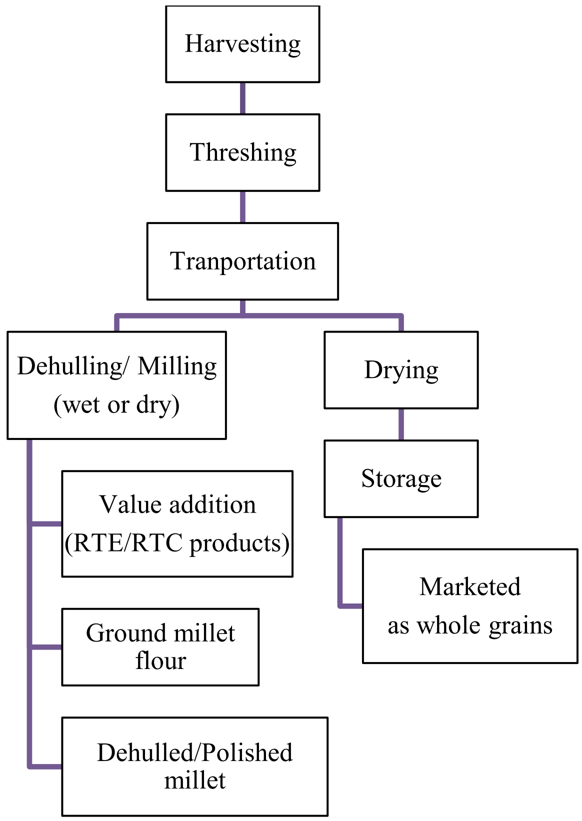
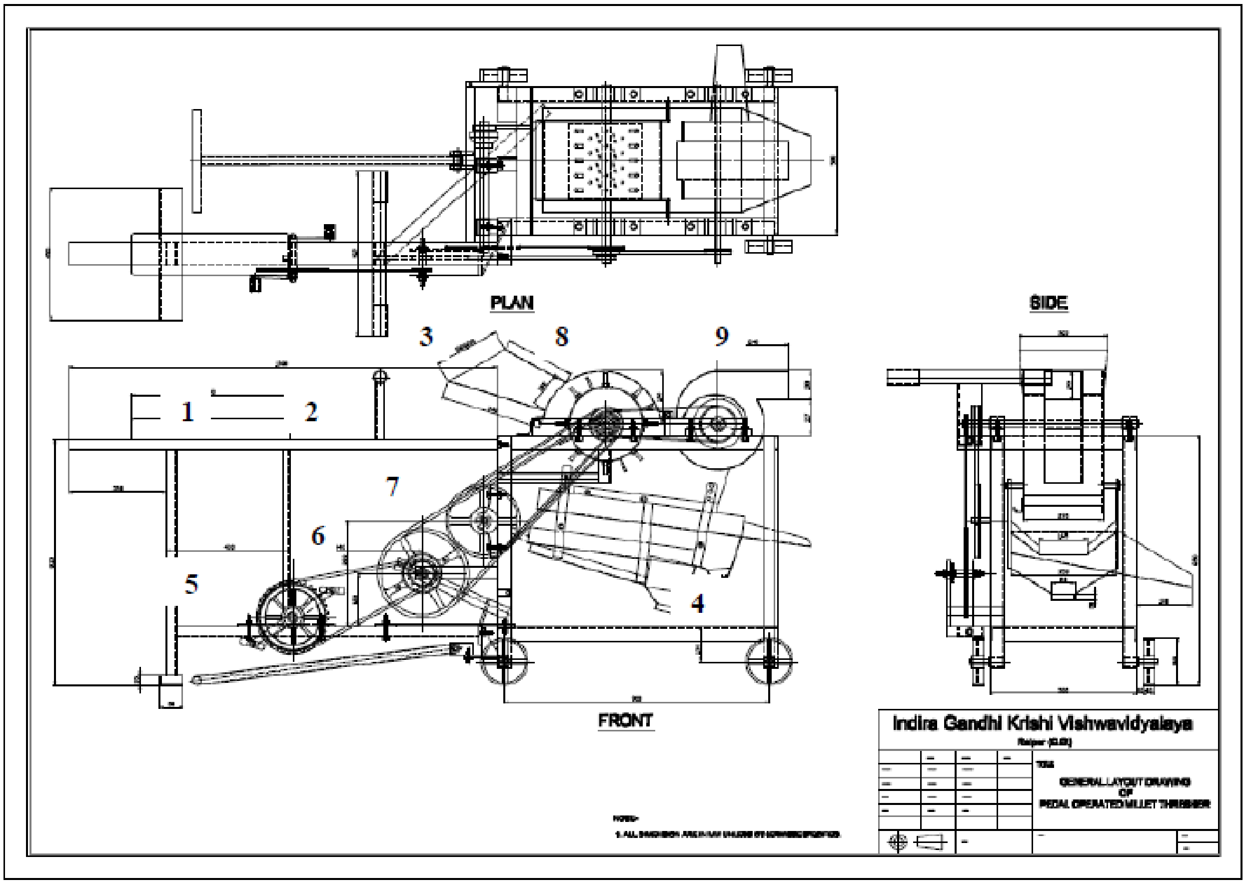


Fig. 3.2 Flow diagram of millet processing

3.6 MECHANICAL THRESHERS

Traditional methods of threshing carried out manually by thrashing/beating the grain stalks against the ground, is disadvantageous in many perspectives. It is largely labor intensive, uneconomical, contaminates the millets with foreign materials and is time consuming (Singh et al., 2015). When it comes to energy demand, manual threshing by beating is considered as “moderately heavy” work, which was categorized based on the maximal oxygen intake or aerobic capacity of the person doing the operation (Nag & Dutt, 1980; Nag & Nag, 2004). Nag and Dutt (1980) assessed and recorded the cardio-respiratory performance of agricultural workers during two of the important agricultural practices - threshing and planting of germinated seedlings. The energy requirement for manual threshing of crops by beating was estimated to be about 19 KJ/min (approx.) during the study. Manual threshing method can be replaced with mechanical means, to reduce the aforementioned undesirable factors. Researchers have developed many efficient mechanical cereal grain threshers that are available on the market (Parmanand & Verma, 2015). However, threshers and threshing studies in the case of millets are scanty (Singh et al., 2015).

The basic design of a millet thresher consists of a feed hopper, a threshing unit/threshing drum housing a cylinder fitted with beaters and a concave, and a separation/cleaning mechanism, just like other mechanical grain threshers (e.g. paddy and wheat crops) with slight modifications to account for the physical grain characteristics. In general, grain threshers are designed to work based on striking (impact), rubbing (shear) and squeezing or a combination of these principles (Simonyan, 2009; Simonyan & Dunmade, 2010; Singh et al., 2015) to efficiently separate the grains from the stalk. Recently, it has been noticed that the application of impact and shear forces simultaneously on millet stalks resulted in increased threshing efficiency (Singh et al., 2015). Depending on location and power availability, threshers are fabricated to operate manually (by hand or leg) and electrically to meet the demand. For example, a pedal operated thresher developed by Parmanand and Verma (2015) utilizes human power in the most efficient manner eliminating the use of electricity. The schematic design of this thresher is shown in Fig. 3.3. It had a maximum efficiency of 68% (drum peripheral velocity of 11.18 m/s or 850 rev/min; concave clearance – 7 mm) for finger millet at 11% moisture.



1 – saddle; 2 – handle; 3 – feeding chute; 4 – sieve mechanism; 5 – chain wheel; 6 – main pulley; 7 – sieve shaker pulley; 8 – threshing unit; 9 – blower unit

Fig. 3.3 Schematic design of pedal operated millet thresher. Reprinted from "*Development and testing of pedal operated thresher for finger millet*" by Parmanand and Verma (2015), International Journal of Agricultural Science and Research, 5 (3). Adapted with permission.

3.6.1 Importance of threshing cylinders

The threshing cylinder forms the most important component, where the grains are detached from the stalk/panicle. Threshing cylinders come in different categories depending on the threshing principle involved – spike-tooth (striking action) and rasp bar (friction/rubbing action) types (Simonyan, 2009). Swinging hammer cylinders is another category of threshing cylinder, which however consumes more power than the other two types. Furthermore, spike-tooth and rasp bar cylinders are considered safer (Simonyan, 2009; Simonyan & Dunmade, 2010) for farmers during feeding of the grains manually into threshers at the village level. Threshers having these type of threshing cylinders are also reported to have high threshing efficiency (Simonyan, 2009). Studies also reveal that increasing threshing cylinder speed increases threshing efficiency (Hanumantharaju, Vikas, & Kumar, 2017; Ige, 1978). Apart from the threshing cylinder speed, threshing efficiency depends on several grain characteristics and machine parameters (Gbabo et al., 2013; Simonyan & Dunmade, 2010) like moisture content of the millets, clearance of concave, grain feeding rate, etc.

Gbabo et al. (2013) fabricated and tested a millet thresher in Nigeria to determine percentage loss and efficiencies in threshing and cleaning. The maximum threshing efficiency was found to be 63.2% (threshing speed -800 rpm) when the grains (pearl millet) were at 13% moisture and the least efficiency (40.68%) was observed at 17% moisture, with a threshing speed of 600 rpm. The increased threshing efficiency was influenced by the dryness of the millet stalk as well as the low grain moisture content and high threshing drum speed which was in accordance with earlier studies made on threshing efficiencies (Gbabo et al., 2013).

3.6.2 Millet threshing with other grain threshers

Over the last few decades, threshing mechanisms have been developed for millets by modifying and redesigning the existing ones available for other cereal grains (Table 3.1). In a study conducted for constructing a millet thresher prototype, a commercially available soybean thresher (2.2 KW) was used as the main body to determine the design parameters like drum rotation speed, air velocity and screen opening size (Chung, Jung, Kang, Cho, & Park, 2012). Using these parameters, the prototype thresher was built to thresh selected grains (sorghum, proso and foxtail millets) and its performance was evaluated for grain loss ratios and percentage of pure grain output through the grain discharge outlet. Grain loss ratios for sorghum, proso and foxtail millets were reported as 5.6%, 6.47% and 2.18% of the total grain weight respectively. Some researchers (Naveen Kumar, Kumar, Arun Kumar, Sandeep, & Sudhadevi, 2013; Prasannakumar & Naveenkumar, 2012) studied the performance of rasp bar thresher in threshing two varieties of finger millet (MR1 and HR911) against traditional methods. Two threshing drum speeds (960, 1200 rpm) and three concave clearances (5, 7, 11 mm) were evaluated during the study to obtain the best threshing results for millet grains at different moisture levels. For the MR1 variety, the highest and the lowest threshing efficiencies were observed to be 79.6% (1200 rpm and 5 mm) at 9.8% grain moisture content and 63.2% (960 rpm and 11 mm) at 18.2% grain moisture content respectively, with a grain output of 140.5 kg/h. Whereas for HR911 variety, the highest and lowest threshing efficiencies were 76.38% (1200 rpm and 5 mm) at 10.1% moisture content and 63.2% (960 rpm and 11 mm) at 18.9% moisture content respectively, with a grain output of 130.3 kg/h. However, the initial cost for adopting mechanical means was much higher when compared to that of the traditional threshing methods.

Table 3.1. Studies conducted on the development and evaluation of various millet grain threshers

Studies conducted	Grains tested	Reference
Optimization of machine parameters of finger millet thresher-cum-pearler	Finger millet	(Singh, Saha, & Mishra, 2010b)
Development of a Thresher for Small Grain Cereal Crops	Proso millet & foxtail millet	(Chung et al., 2012)
Design, fabrication and testing of a millet thresher	Pearl millet	(Gbabo et al., 2013)
Efficiency of mechanical thresher over traditional method of threshing finger millet	Finger millet	(Naveen Kumar et al., 2013)
Development and evaluation of multi millet thresher	All millet varieties	(Singh et al., 2015)
Development and testing of pedal operated thresher for finger millet	Finger millet	(Parmanand & Verma, 2015)
Ergonomic evaluation of developed pedal operated millet thresher for threshing of finger millet	Finger millet	(Parmanand, Verma, & Guru, 2015)
Comparison study of prototype thresher with different methods of threshing whole crop finger millet.	Finger millet	(Hanumantharaju et al., 2017)

3.6.3 'Vivek' millet thresher

In the hilly region of Uttarakhand, India, an efficient machine capable of threshing and pearling (debranning/polishing) was fabricated at Vivekananda Institute of Hill Agriculture (ICAR-VPKAS) in Almora. It was specifically developed for finger millet (*Mandua*) and barnyard millet (*Madira*), therefore named as 'Vivek Mandua/Madhira thresher' or 'Vivek millet thresher cum pearler' (ICAR-VPKAS, 2016; Joshi, Chandra, & Jethi, 2014; Joshi et al., 2016; Singh et al., 2015; Singh, Saha, & Mishra, 2010a; Singh et al., 2010b). This machine can also thresh and pearl other minor millet varieties like proso and foxtail millets. Table 3.2 shows the characteristic features of the Vivek thresher model. In case of finger millet, threshing and pearling activities are done simultaneously, while for the other grains, the two activities are carried out separately (Joshi et al., 2016).

In comparison to the manual method of threshing practiced in Uttarakhand, the machine was found to be ergonomically safe for the local farmers to operate (Joshi et al., 2016). In an attempt to improve the capacity of the machine and its performance, the threshing drum of the Vivek thresher was modified at the Indian Institute of Technology, Kharagpur, India (Singh et al., 2015; Singh et al., 2010b). The Vivek thresher was later modified to work as a dehuller with a dehulling capacity of 18-20 kg hulled kernel per hour (Singh et al., 2010a).

Table 3.2. Salient features of Vivek Millet thresher-cum-pearler

Salient features of the machine	Details
Weight of the machine	45 kg without prime mover; 46.4 kg with prime mover
Type of threshing cylinder/drum	Rasp bar type
Threshing capacity	30-35 kg grains/h; 98%
Pearling capacity	Finger millet – 40 to 45 kg grains/h
	Barnyard millet - 2.5 to 3 kg grains/h
Efficiencies	Threshing – 98%; Pearling – 90%
Initial investment & operating cost	17,000 INR* (Electric motor operated); 31,000 INR (Engine operated)

*- Indian National Rupees.

Adapted from: ICAR-VPKAS (2016); Joshi et al. (2016); Singh et al. (2010b)

3.6.4 Multi-millet thresher

Based on impact and shearing principle, Singh et al. (2015) designed a millet thresher at the Central Institute of Agricultural Engineering (CIAE), Bhopal, India, which can efficiently thresh all the millet varieties, and optimized the operating parameters with little millet crop for maximum threshing efficiency using response surface methodology (RSM). The parameters under consideration were moisture content of the millet (7.79%), feed rate (105.31 kg/h), cylinder speed (626.9 rpm) and threshing sieve size (6 mm). Testing of the thresher resulted in maximum threshing (99.5%) and cleaning efficiencies (88.5%).

3.7 DEHULLING/ MILLING DEVICES

Dehulling or dehusking is a crucial step in the post-harvest processing of millet crops since it removes the inedible outer layer (pericarp and testa) of the grains, thus making the grains available for milling and consumption (Bassey & Mbengue, 1993; Reichert, 1982). Dehulling increases the digestibility (Singh et al., 2010a; Verma et al., 2014) of the grains by removing the pericarp (bran) and the testa, which are rich in fibre and anti-nutritional factors (Bassey & Mbengue, 1993). Once the millet grains are dehulled, they are immediately ground into flour by milling, hence facilitating the preparation of millet-based products. Millets are sometimes subjected to milling without dehusking/dehulling to a certain degree where the outer hulls are loosened and separated from the edible grain after which the mixture is sifted, winnowed and ground to prepare a whole meal (FAO, 2001). Like threshing, dehulling and milling the grains are also done manually by hand pounding and pulverizing grains using wooden/stone mortar and wooden/stone pestle (Bassey & Mbengue, 1993; Mukuru, 1992). It has been reported that, it takes one hour to dehull 2-2.5 kg of barnyard millet by the traditional pounding method (Singh et al., 2010a). Similarly, for dehulling 1-2 kg of fonio millet it takes nearly an hour by traditional hand pounding (Marouzé et al., 2008). However, dehulling methods may vary depending on the millet variety and the hardness of the hull. For example, foxtail millet is dehulled by an abrasive method using a big boulder like stone which is rolled from one side to the other (Pushpamma, 1986). For more effective dehusking, some millet grains especially the small millet varieties, require some level of preconditioning/pretreatment such as soaking (Ravindra et al., 2008). Presently, hammer mills are being used in Africa for milling millets, while in India, millstones called *'chakki'* are generally used (Taylor & Emmambux, 2008).

Even though there are already several grain milling units employed for the processing of millets, they were originally designed for other types of grains, thus dehullers/ mills exclusively designed for millets are being developed to increase millet supply. Another major reason for fabricating millet-processing machinery is the relatively lower dehulling efficiencies and grain damage that occur when processed using modern cereal grain machinery. For instance, rice mills have been adopted for dehulling specific millet varieties like proso millet (Pushpamma, 1986) since the availability of dehullers is limited to only a few varieties of millets. However, rice milling equipment has been found to be less efficient for grinding millet grains (Bassey & Mbengue, 1993). Recently dehullers have been made available for few common millet varieties like barnyard millet (Singh et al., 2010a) and finger millet (Verma et al., 2014), whose machine parameters were optimized for enhanced performance. Furthermore, few studies were conducted for establishing the dehusking and milling efficiencies of existing grains dehullers fabricated for other cereal types and their impact on millets (Lochte-Watson, Weller, & Jackson, 2000; Ravindra et al., 2008; Reichert, 1982). In one such study, two mills, namely the provender mill and a rubber roll sheller/ grain polisher were tested on little millet with pretreatments, to reduce milling losses and improve the quality of the millet. For 100% dehulling of little millet, parboiling-drying treatment was suggested as an essential pretreatment before milling (Ravindra et al., 2008).

3.7.1 Principles of operation

Dehulling of cereal grains is achieved by the application of various principles like abrasion, attrition (or shear forces) and impact (Bassey & Mbengue, 1993; Malathi, Varadharaju, & Gurumeenakshi, 2014; Reichert & Youngs, 1976; Singh et al., 2010a). Attrition type dehullers/mills are used for dehulling grains whose hulls are loosely attached, while abrasive types are preferred for grains with firmly attached hulls (Reichert, Oomah, & Youngs, 1984). Dehullers which function based on abrasion have been investigated in many studies, whereas the other two types have received comparatively less attention (Reichert & Youngs, 1976). The abrasive method of dehulling grains are found to cause high dehulling losses by crushing the seeds (Lazaro, Benjamin, & Mpanduji, 2014; Singh et al., 2010a). Moreover, the grains get polished during abrasion leading to the loss of nutrients by the removal of the bran layers, which is not the case with impact hullers (Malathi et al., 2014).

3.7.2 Abrasive dehulling/milling

Abrasive dehulling or decorticating of millets is a common practice in Africa and India, where the endosperm is separated from the outer hulls (Lochte-Watson et al., 2000). This method of dehulling is also used to simulate industrial or traditional dehulling at the laboratory scale (Hama et al., 2011; Hama et al., 2012). Such laboratory scale models include Udy cyclone sample mill, Kett Husk Pearler and the Tangential abrasive disk dehuller (TADD) among which the TADD is popular for sorghum and millet dehulling (Hama et al., 2011; Lochte-Watson et al., 2000). Abrasive type dehullers consist of rotating abrasive surfaces that removes the outer hull layer, and are made available in different forms depending on the dehulling needs and technical skills available in the country where the dehuller is used (Bassey & Mbengue, 1993). The commonly used means for creating abrasive action in dehullers are either carborundum stones or resinoid disks mounted on a rotating shaft driven by a motor (Bassey & Mbengue, 1993). It was reported in a study that dehullers with fine grit carborundum stones or resinoid disks are more efficient than the coarse grit stones for the selective removal of outer layers of cereal grain kernels (Oomah, Reichert, & Youngs, 1981).

Bassey and Mbengue (1993) discussed the performance of several abrasive disk dehullers developed by various institutes in Canada and Africa for cereal grains. Table 3.3 shows the different types of abrasive dehullers available and their place of manufacture. Dehullers with large capacities (e.g. PRL, NUHULL and RIIC) have an aspirating system for bran removal and their mode of operation is continuous or batch type, whereas mini dehullers have lower dehulling capacities and operate only in batch mode (Bassey & Mbengue, 1993).

Table 3.3. Regional abrasive type dehullers and their place of origin

Dehuller type	Place of Manufacture
PRL	Prairie Research Lab. (NRCC), Canada
Mini PRL	Prairie Research Lab. (NRCC), Canada
RIIC	Rural Industries Innovation Centre, Botswana
NUHULL	Nutana Machine Ltd, Canada
Mini-CRS	Catholic Relief Services, Gambia
Mini-SISMAR/ISRA I	Centre Nationale de Recherches Agronomiques/ Institut Sénégalais de recherches agricoles (ISRA) and SISMAR, Senegal
Mini-SISMAR/ISRA II	Centre Nationale de Recherches Agronomiques/ / Institut Sénégalais de recherches agricoles (ISRA) and SISMAR, Senegal
Mini-ENDA	Environment Development Activities (ENDA), Zimbabwe

Sources: Bassey and Mbengue (1993); Schmidt (1992)

3.7.3 Prairie Research Lab (PRL) Dehuller

The Prairie Research Lab dehuller (PRL) was the first successful model designed by modifying an existing barley threshing equipment (George Hill Grain thresher) under the support of IDRC (Reichert, 1982; Schmidt, 1992). Among the many abrasive dehullers, the PRL dehuller was the most popular for mechanical dehulling of sorghum in Africa (Taylor, 2003). In this dehuller, milling is done subsequently using hammer mills to produce meal or flour (Taylor, 2003; Taylor & Emmambux, 2008). These dehullers are designed for dehulling millets, sorghum and maize (Marouzé et al., 2008). In Maiduguri, Nigeria, the PRL dehuller was tested during 1974-76 and found effective in dehulling millets, sorghum and cowpeas (Schmidt, 1992). Later, the National Agronomic Research Centre (CRNA) of Senegal also started using these dehullers for sorghum and millet dehulling in 1979 (Ajayi & Olasunkanmi, 2013) . These dehullers played a significant role in Southern Africa for promoting food security and eliminating drudgery especially in Botswana, Zimbabwe and South Africa, where these dehullers were commercially manufactured, and over 200 are currently in use. In industrial milling, however, these dehullers have few drawbacks, which is mainly because of the high milling losses (up to 30%) and smaller batch size (Taylor, 2003). As a solution to this problem, small roller mills (2-3 pairs of rollers) with a capacity of 500 kg/h were developed for milling coarse grains in South Africa. However, use of this machine requires preconditioning of grains to 16% moisture to achieve good milling performance (Taylor, 2003).

3.7.4 'Palyi' compact milling system

A more efficient and compact attrition-type milling system, the *'Palyi'* (Reichert & Youngs, 1976; Sahay, 1990), was developed for dehulling a variety of cereal grains like sorghum and millets. It contains three dehulling units each consisting of a dehuller and a cyclone for husk separation (deMan, Banigo, Rasper, Gade, & Slinger, 1973). The dehulling action was achieved by passing the grains between the clearances of the attrition plates, which are fitted with saw tooth blades, fixed inside the dehuller. Subsequently, the grains undergo abrasive action by a drum rotating in a cylindrical screen. The grains leaving the plates, enter the cylindrical head where the drum rubs the grains against the cylindrical screen, producing abrasion, and the hulls get removed by the cyclone separator (Reichert & Youngs, 1976). The percentage yield of *Palyi* milling system dehulled millet and sorghum procured from US (77% and 85%), Senegal (77% and 78%) and

Niger (77% and 80%) was evaluated by deMan et al. (1973) and their proximate constituents were also determined. For dehulling millets and sorghum using this system, tempering or moisture adjustment was found to be unnecessary. In addition, its low cost and ease of operation makes it suitable for use in developing countries (deMan et al., 1973).

Reichert and Youngs (1976) compared the *Palyi* milling system with two other mills which work on abrasion namely, the Strong-Scott barley pearler (laboratory scale) and a lab modified version of a George O. Hill grain thresher. This work was carried out in concurrence with the village scale milling operation in Maiduguri, Nigeria. In this study, millets were found to be much harder than sorghum grains to crack open using abrasive carborundum stones or attrition plates. It was concluded that abrasive type mills favor the dehulling of sorghum and millets over attrition type mills in village level milling operations.

3.7.5 Fonio mill

Fonio millet is a variety of minor millet which is a very important indigenous crop in many African countries. Known by several other names like *acha*, *fundi* or *hungry rice*, this crop is said to be the oldest West African cereal not grown outside Africa (FAO, 2001; Obilana & Manyasa, 2002). Similar to other millet crop varieties, fonio seeds are also difficult to dehull/dehusk. They require four to five consecutive poundings with winnowing after each and every pounding (Marouzé et al., 2008). This level of laborious and time-consuming challenge faced by African women during processing calls in for adopting grain dehulling technologies to ease the processing. The task of developing a suitable mill for fonio millets was undertaken in a regional project to reduce drudgery and enhance grain quality to improve commercialization. Marouzé et al. (2008) chose four grain mills or dehullers working on different milling principles to study their effectiveness on fonio millet. The four mills analyzed included PRL dehuller, DMS 500 dehuller, Sanoussi friction mill and Engelberg-type rice mill. For fonio milling/dehulling, the Engelberg type rice mill was chosen due to suitability of the principle involved in milling, favorable results, equipment availability and no requirement of special imported parts like millstones, disks, etc. (Marouzé et al., 2008). The friction-shearing principle employed in this kind of dehuller detaches the hulls by creating friction among the grains as it passes between the rotor and the stator of the dehulling device as described by Hama et al. (2011) and Marouzé et al. (2008).

A replica of the Engelberg rice mill model was designed by fitting a large diameter rotor, thereby reducing the volume of the milling chamber to increase the friction and shearing of the grains. Evaluation of this replica gave acceptable results while milling the grains in two successive passes (first pass – husking; second pass - whitening), and was found to be satisfactory, leading to the development of the fonio mill prototype. The developed fonio mill/dehuller showed a milling rate of over 99% with more than 70% milling yield in two successive passes, which was better than milling in a single pass (milling rate: 93-98% and milling yield: 65-72%). In addition, the results obtained with the fonio dehuller prototype were almost similar to the Engelberg rice mill replica (Marouzé et al., 2008).

3.8 IDRC'S CONTRIBUTION TOWARDS PROMOTING POST-HARVEST MECHANIZATION

The International Development Research Centre, which was created in 1970, was involved in much regional research and development to benefit developing nations in Africa and Asia by formulating strategies to tackle food insecurity. Early achievements included the development of the effective PRL dehuller, which was tested in Nigeria, Senegal and Botswana (Schmidt, 1992). The PRL dehuller was later modified across Africa adapting to different grain processing needs (Table 3.3).

Until 2010, IDRCs contribution has been negligible in Asian countries, where production and consumption of indigenous food crops, especially small millets, is declining at a faster rate. This decrease is mainly due to the insufficient availability of processing technologies, increased drudgery and demand for women labor. Hence, to eliminate these issues in millet processing and encourage farmers of Asian countries (India, Nepal and Sri Lanka) to revive millet consumption, IDRC-CIDA in collaboration with a few other research institutions and organizations developed appropriate processing technologies under the project entitled *Revalorizing Small Millets in Rain fed Regions of South Asia (REMISA)*, 2011-2014 and field tested those technologies for efficiency (IDRC, 2014). The project evaluated many existing threshers for their suitability to thresh millets. A 'Four walker multi-crop thresher' was tested and found to be suitable for threshing finger millet crops in India, whereas in Sri Lanka, a panicle thresher model was found satisfactory among the farmers in threshing the same. The latter reduced the threshing time significantly by 35%.

The REMISA project also prototyped different dehullers for reducing drudgery among the rural farmers of South Asia (Table 3.4). A centrifugal dehuller was initially built with a single chamber by Tamil Nadu Agricultural University (TNAU) for dehulling little and foxtail millets, which reduced the traditional dehulling time by 50-70% during field trials (Devkota, 2014; IDRC, 2014). This was later modified into a double chambered dehuller to include kodo and barnyard millet dehulling with increased head rice recovery and versatility (Devkota, 2014). Central Food Technology Research Institute (CFTRI) and Central Institute of Agricultural Engineering (CIAE) developed the rubber roll dehullers (100 kg/h) and the abrasive type dehuller (50 kg/h) respectively for village use. A mini-rubber roll dehuller (5 kg/h) was developed by McGill University for household purposes and was later tested in Kolli hills, India, by the M.S. Swaminathan Research Foundation (MSSRF) (King, 2016). The rubber roll dehuller proved to be more advantageous than the local prototype - based mill in terms of hull separation and amount of broken grains with a significant reduction in the processing time. However, there was also a significant difference observed in the recovery of full grains when the dehuller was tested in the field and the laboratory (Table 3.5) showing that there is a need for further research in dehulling technology (King, 2016).

Table 3.4. IDRC studies and field testing of processing technologies in South Asian Countries

Technology	Field tested prototypes
Threshing	Four walker multi-crop thresher
	Manual operated finger millet threshers
	Panicle thresher model
Dehulling/Dehusking	TNAU- Centrifugal dehuller (single & double chamber)
	CFTRI- Rubber roll dehuller
	CIAE-Millet mill (abrasive type)
	McGill- Mini rubber roll dehuller

Sources: IDRC (2014)

Table 3.5. Test results obtained in Kolli hills with McGill mini rubber roller dehuller

Attributes observed	Results
Full grain recovery	90% - Laboratory trials; 82-85% - Field trials
Capacity	6 kg/h – Household level; 5 kg/2.30 h – Field trials
Hull/Husk separation	100%

Sources: King (2016)

3.9 CONCLUSION

It is crucial to resume the cultivation and consumption of millets in a large scale especially in the semiarid and arid regions of developing nations, where production of major crops like rice and wheat is difficult due to adverse climatic conditions. Millet production and consumption will contribute to ensuring food security in the long term. However, it is clear from the literature that availability of promising efficient machinery to process millets are limited compared to other cereal crops even though millets are highly nutritious. Thus, it is essential to develop ergonomically safe machinery with better performance and simple mechanisms so that it is affordable, easy to operate at farm and households in rural communities. As a result, innovation of such machinery could eliminate the drudgery involved in conventional processing and provide quality product. Awareness must also be created among the developed nations, where these grains are not considered for human consumption, by formulating novel, millet incorporated food products (ready-to-eat/ ready-to-cook).

CONNECTING STATEMENT

The previous chapter dealt with the application of mechanical processing aids to ease millet processing. Adopting and developing suitable, efficient machinery for processing millets could eliminate drudgery. This may eventually encourage the farmers, who rely on millet cultivation for their livelihood, to increase production. To reduce drudgery at the household level, a simple hand operated dehuller was fabricated with rubber rollers to dehull a variety of millets. Structural development of this dehuller and its dehulling ability is being discussed in Chapter IV.

CHAPTER IV

DEVELOPMENT AND PERFORMANCE EVALUATION OF A HAND OPERATED MILLET DEHULLER

4.1 ABSTRACT

A simple hand operated rubber-roll millet dehuller was designed, developed and tested for its effectiveness on dehulling different millet varieties namely foxtail, kodo and barnyard millets. The main components of the dehuller included 1) the feeding unit, 2) rubber roll assembly, 3) blower assembly and 4) mechanical power transmission system. A complete description of the individual components, with the operating principle of the dehuller is included. The dehuller was designed to accommodate a hand operated blower that functions simultaneously, to facilitate husk removal from dehulled grains. By altering the machine parameters like roller spacing and number of consecutive passes, the machine efficiency in terms of dehulling and hull separation was studied. On testing the dehuller, it was possible to achieve a dehulling efficiency of up to 99% in 3 – passes for foxtail and barnyard millets at a roller spacing of 0.20 mm and 0.25 mm. While for kodo millet the maximum efficiency was 77% at 0.25 mm spacing after 3 – passes.

KEYWORDS: Dehuller, hand operated, millets, rubber rolls, roller spacing.

4.2 INTRODUCTION

Millets are among the highly nutritious cereal grains that come under the family *Graminae/Poaceae* (FAO, 2001; Nazni & Bhuvaneswari, 2015). Owing to their rapid growing period and drought tolerant characteristics, millets are often grown in adverse environmental conditions where major cereal crops cannot thrive. For these reasons, millet cultivation is quite common in arid and semi-arid regions of the world, which include many African and Asian countries (Amadou et al., 2013; FAOSTAT online database). It is even believed that millet varieties have been domesticated first in parts of Asia and Africa (Hunt et al., 2008; Lu et al., 2009; Manning et al., 2011). Millets are being consumed on a daily basis by the lower economic strata of traditional consumers and by people who are aware of millets' health benefits in these regions (Yenagi et al., 2010). However, the food basket of the most urban populations does not include millet for the most part, due to a lack of millet-based food products, quick availability of other major cereal grains and a lack of knowledge about millets' nutritional value (Padulosi et al., 2009; Ushakumari et al., 2004). Although, inclusion of a neglected and underutilized crop like millets, in the global food basket, could contribute in formulating a solution for combatting food insecurity and malnutrition.

Almost 96% of the world's millet production comes from Africa and Asia as of 2014 (FAOSTAT online database). India remains the largest producer of many varieties of millets in the world. However, millets' share in total grain production has fallen severely (Agrawal, 2017). Finger (*Elusine coracana*), barnyard (*Echinochola colona*), proso (*Panicum miliaceum*), kodo (*Paspalum scrobiculatum*), foxtail (*Setaria italica*) and little millets (Panicum sumatrense) are the common small millet varieties that are grown in many states of India starting from Uttarakhand in the North to Tamil Nadu in the South (AICRPSM, n.d.; Padulosi et al., 2009). Finger millet is regarded as the most important and popular among the small millets, considering the area under cultivation and its production throughout the country. Despite its popularity, cultivation of finger millet has steadily declined over the years. In fact, cultivation and production of other small millets has dropped simultaneously (Padulosi et al., 2009). In India, millets are mostly being grown for localized human consumption, rather than as feed for animals. However, consumption has decreased over the past few decades. It has been noted that, millet intake has greatly diminished in India since the Green Revolution in the 1960s which firmly established wheat and rice (FAOSTAT online database). A steady decline in consumption of finger millet (47%) and other small millet varieties (83%) has been recorded between 1961-2009 (PTI, 2014). The major contributing factor for this situation to prevail was the adequate supply of wheat and rice at subsidized prices during that time period (Padulosi et al., 2015). On the other hand, the difficulties faced by women in traditionally processing millets, reduced cultivation and consumption of small millets even further to marginal levels. With a little support from the policymakers and the government, research and development on different aspects of small millets could potentially overcome these issues and eventually promote millets from the status of underutilized crops to '*nutria-millets*' or '*nutria-cereals*' throughout India (Lahangir, 2012; Passi & Jain, 2014).

Dehulling is crucial in millet processing as it removes the inedible hulls from the edible grains. Despite the availability of large scale cereal grain processing equipment like rice mills and other mills, the rural women prefer the traditional methods for processing millets, since large scale mills are mostly inefficient in hull removal and result in more broken grains. As traditional millet dehulling involves beating and hand pounding using *chakki* (Indian stone mill) or mortar and pestle, it creates a great amount of physical stress on women and is time consuming because of the smaller grain size and hard outer shell (FAO, 2001). These adverse effects on the processing side of small millets urge for more efficient, compact and most importantly affordable dehulling technologies to ease millet processing in farm and household levels, thus promoting cultivation and consumption.

In the recent years, several research groups and institutions have come forward to boost millet production and consumption in India (Agrawal, 2017). Among those organizations, Development of Humane Action (DHAN) foundation is a significant contributor which is working on bringing back millets, teaming up with few research institutions under the support of the Canadian International Food Security Research Fund (CIFSRF). Since 2011, the team has already promoted millets through value addition and developing processing technologies during the first phase of the project (DHAN Foundation, 2011). The current / second phase of the project (2016-2018) is also focused on reducing drudgery in processing millets through scaling up of post-harvest processing technologies. Under this project, it was decided to develop an appropriate small scale, table top, hand operated dehuller for dehulling lower capacities of millets at households and farm levels, and this paper deals with its design, fabrication and performance on dehulling millets as its main objective.

4.3 MATERIALS AND METHODS

4.3.1 Collection of millet samples

Three different millet varieties namely, foxtail (*Setaria italica L.*), barnyard (*Echinochloa spp.*) and kodo millets (*Paspalum scrobiculatum L.*) were procured as whole grains from the local markets of Coimbatore, Tamil Nadu, India.

4.3.2 Determination of moisture content

The initial moisture content of each millet variety was determined according to the method used by Obi, Ezeoha, and Egwu (2016) and Ramappa, Batagurki, Karegoudar, and Shranakumar (2011) with slight modifications. Triplicates of 5-gram samples of each variety were dried at a temperature of 105±2°C in a hot air oven until constant weights of the samples were recorded using a weighing balance. The dried samples' weight represents the weight of dry matter present in the grains. The initial moisture content of the samples was calculated using Eqn. 4.1 and is expressed in percentage wet basis (% wb).

$$\text{Moisture Content, MC (\% wb)} = \frac{W_i - W_f}{W_i} \times 100 \tag{4.1}$$

where W_i is the initial weight of the sample and W_f is the final weight or dry weight of the sample.

4.3.3 Determination of grain size and shape

The grain size of different millet varieties was determined by randomly selecting 50 whole grains from each variety and measuring their three linear dimensions (length, width and thickness) using a vernier caliper having least count of 0.02 mm. With those measured dimensions the geometric mean diameter and degree of sphericity of the millet grains were calculated using Eqns. 4.2 and 4.3 respectively (Mohsenin, 1970).

$$\text{Geometric mean diameter, } D_g = (L \times W \times T)^{\frac{1}{3}} \tag{4.2}$$

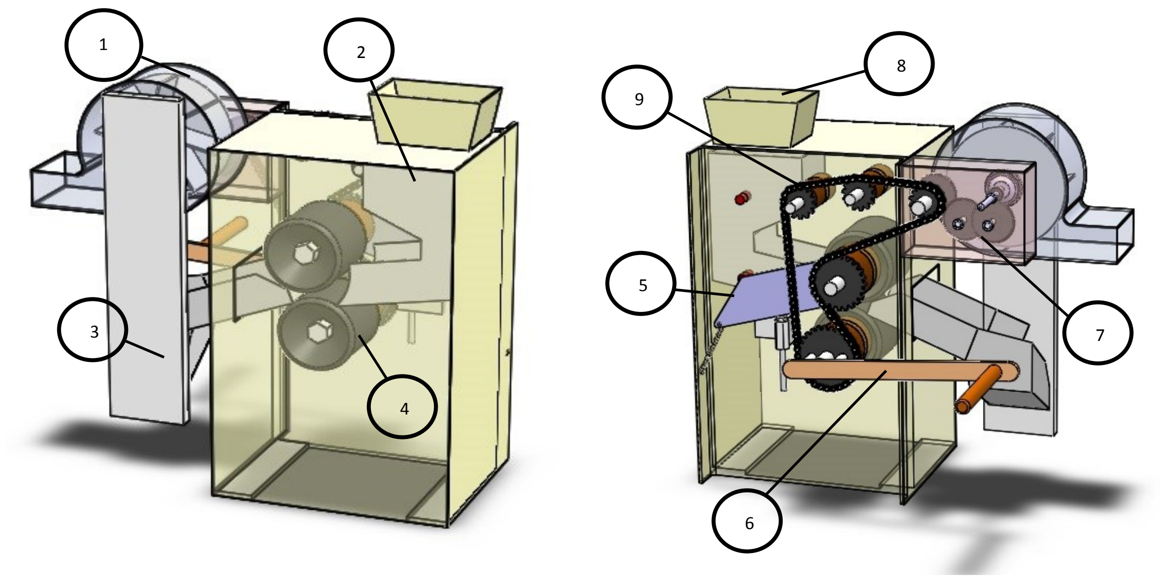
$$\text{Sphericity}, \phi = \frac{(L \times W \times T)^{\frac{1}{3}}}{L} \text{ or } \frac{D_g}{L}$$

(4.3)

where L is the grain length, W is the grain width and T is the grain thickness.

4.3.4 Design and principle of operation

The hand operated dehuller was thought of a simple design to comprise 1) a feed hopper, 2) a set of rubber rolls and 3) a centrifugal blower connected to a vertical channel. The basic idea targets to dehull the grains by allowing them to pass between two rubber rolls, which create enough stress/strain on the grains due to friction and shear. The shear stress thus applied on the grains removes the outer husk without rendering much damage to the edible portion. The shearing principle was adopted from the motor-operated rubber roll dehuller fabricated during 2011-2014, which showed promising results in dehulling millets (Chin, Matlashewski, & Swan, 2012; IDRC, 2014). The current 3-D design of the dehuller is presented in Fig. 4.1 and its components are explained in detail as follows.



a) b)

1- blower; 2 – feeding chute; 3 – vertical channel; 4 – rubber roll; 5 – lever for spacing adjustment; 6 – crank handle; 7 – gear box; 8 – hopper; 9 – chain-sprocket arrangement

Fig. 4.1 a) & b) Schematic design of hand operated millet dehuller.

4.3.4.1 Feed hopper design

Since vertical feeding of the grains creates bouncing (Chin et al., 2012), the feed hopper was designed in a way that the grains flow almost horizontally through the set of rollers. The hopper design consisted of two separate parts, the feeding area at the top of the dehuller and the chute that aids in the movement of the grains. The chute was inclined at 10°, since keeping the chute completely horizontal will stop the movement of the grains. Whereas a higher angle of inclination will result in bouncing of grains when they come in contact with the rubber rollers. Singulation of grains is a crucial factor that is to be considered while designing the feeding assembly as singulation ensures shearing of every grain that passes through the rollers. Hence, to achieve singulation, the chute was vibrated by making it to slide over the surface of the bottom roller when the dehuller was operated.

4.3.4.2 Rubber roller assembly

The two rubber rollers were mounted in a specific fashion shown in Fig. 4.2 so as to accommodate the passage of grains. In order to adjust the spacing between the rollers, the top roller was kept movable while the bottom roller was kept immovable. A hole for the top roller bearing was bored in the cylindrical bearing holder and it was offset by $3/16^{th}$ of an inch. This makes the top roller shaft movable. The bearing cage was welded with a lever for adjusting the roller spacing and can be lifted up and down using a nut and bolt arrangement as shown in the Fig. 4.1. The tension required to hold the lever in its position is provided by the use of an extension spring.

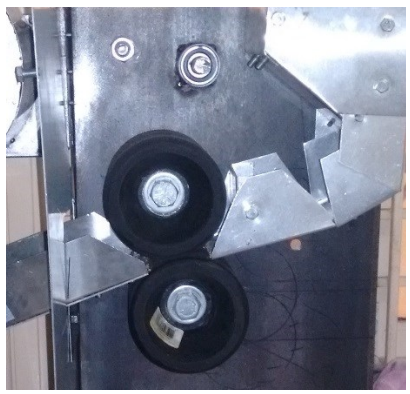


Fig. 4.2 Front view showing the roller assembly

The rollers that were used for our prototype were 4 inch by 4 inch with a bore diameter of $3/4^{th}$ of an inch and were readily available in the market. They also had a satisfactory rubber hardness in the range of 85-90 durometer. To ensure the shearing action, the rotational speed of one of the rollers was kept higher than the other by mounting sprockets on the roller shafts with different number of teeth (1: 1.2), and in opposing directions towards each other.

4.3.4.3 Centrifugal blower - Design and fabrication

Initially, tests were conducted with a commercially available blower to evaluate its suitability in our prototype to aspirate the millet hulls. Since the dehuller works on human power, the commercial blower was not efficient in separating the hull from the grains with minimum energy utilization. Hence it was decided to design and fabricate a centrifugal blower especially for aspirating the hulls. The blower was designed to house a centrifugal impeller with 8 forward inclined blades supported by a back plate, since this design was found to be optimal in removing lighter particles like dust and husk (Chin et al., 2012). To fabricate the blower, terminal velocity of the grains and millet hulls was essential. So terminal velocity was calculated experimentally since aerodynamic properties like drag coefficient, Reynolds number, etc. have not been established for millets. On the other hand, Gorial and O'Callaghan (1990) measured the terminal velocities of various grains including millets, but the millet varieties that were used in their study was not stated.

The terminal velocity was measured using a hand-held anemometer, by passing a mixture of hull-less grains and hulls in a vertical column of air stream supplied by a blower with air velocity control. The terminal velocities for the hulls of three varieties were in the range of 1.5-2.3 m/s, while the hull-less grains were in the range of 4.03-5.21 m/s. Thus, air velocity required to aspirate the hulls was found to be between 1.5-4 m/s. The power required to achieve the aforementioned air velocity was supplied by using a compound gear train mechanism. The suction end of the blower is connected to a vertical channel through which the dehulled grains and the hull mixture passes through, while at the blowing end the hulls from the mixture get discharged. The column of air stream created by the blower aspirates the hulls, allowing the dehulled grains to flow down the vertical channel.

4.3.4.4 Mechanical power transmission system

The energy required to dehull the whole millet grains and aspirate the hulls was supplied using a two-stage power transmission. The first stage included the chain-sprocket mechanism which helps in dehulling the grains, while the second stage being the compound gear train assembly helps in the functioning of the blower.

4.3.4.4(A) Chain-Sprocket arrangement

The major reasons for opting for the chain-sprocket mechanism in the first place instead of a belt drive was that wearing can be avoided and occurrence of slip is zero. In addition, maintenance requirement of chain drives is also low compared to that of belt drives. The number 35 single stranded roller chain was used to rotate a total of five sprockets with different number of teeth. Among the five sprockets two were used for the rubber rollers, one to transfer power to the blower arrangement and the remaining two as idlers to provide tensions to the chain drive. The driving sprocket, mounted on the bottom roller shaft, and driven sprocket was in the ratio of 1:2. The crank handle was provided at the bottom roller shaft for operating the dehuller.

4.3.4.4(B) Gear train mechanism

A compound gear train assembly was installed that includes a series of spur gears in mesh. The purpose of the gear train was simply to multiply the rotational speed of the centrifugal impeller manifolds and reduce the input torque at the same time. The chain-sprocket mechanism was not sufficient to rotate the impeller at the required speed. Hence adding a gear train to the dehuller would solve this problem. The gear train had input (driver) and output (driven) gears, and two compound gears to increase the resulting gear ratio. The input gear was mounted on the shaft mounted with the driven sprocket so that both the rubber rolls and the blower can be operated simultaneously as a complete system. With this arrangement, we were able to achieve an overall gear ratio of 12.8:1 (input: output) calculated from Eqn. 4.4 (Gear trains, n.d.). A gear ratio of 12.8:1 means that for every single turn of the input gear, the output gear turns 12.8 times.

$$\text{Gear ratio (GR)} = \frac{\text{Number of teeth on the driven (output)}}{\text{Number of teeth on the driver (input)}}$$

Hence for a compound gear train with six spur gears,

$$GR = \left(\frac{N_2}{N_1}\right)\left(\frac{N_4}{N_3}\right)\left(\frac{N_6}{N_5}\right) \tag{4.4}$$

where N_1, N_2, N_3, N_4, N_5 and N_6 are the number of teeth on gears 1 to 6 respectively.

4.3.5 Testing procedure

The fabricated dehuller was analyzed for its ability to decorticate the hulls. Before testing the prototype, the millet varieties were cleaned to get rid of unwanted impurities like small stones. Twenty grams of the cleaned whole millet grains were randomly selected for each trial conducted, from the three varieties (foxtail, kodo and barnyard). Four roller spacing (0.35 mm, 0.30 mm, 0.25 mm and 0.20 mm) were chosen to determine the optimum spacing for each variety, and the spacing between the rollers was measured and adjusted using a Feeler gauge. The criteria for selection of the roller spacing was based on the experiments conducted with little millet using previous motor operated model (Chin et al., 2012). In each trial, millet grains were passed thrice consecutively and the dehulling efficiency after each pass was calculated using Eqn. 4.5. Along with the efficiency, percentage broken grains and head rice recovery were also determined (Eqn. 4.6 & Eqn. 4.7).

$$\text{Dehulling efficiency (\%)} = \left[\frac{\text{Weight of dehulled grains including brokens}}{\text{(Initial weight of grains} - \text{Weight of hulls)}}\right] \times 100$$

(4.5)

$$\text{Broken grains (\%)} = \left(\frac{\text{Weight of broken grains}}{\text{Initial weight of grains}}\right) \times 100$$

(4.6)

$$\text{Head rice recovery (\%)} = \left(\frac{\text{Weight of dehulled grains} - \text{Weight of broken grains}}{\text{Initial weight of grains}}\right) \times 100$$

(4.7)

4.4 RESULTS AND DISCUSSION

4.4.1 Properties of the tested millet varieties

Physical properties of any food material are important to be considered while building a processing machinery, since these attributes help in designing efficient machinery (Baryeh, 2002). The physical attributes of the three millet varieties that were used for testing the performance of the dehuller are given in Table 4.1.

Table 4.1. Physical properties of millet varieties

Variety	Moisture content (% *wb*)	Geometric mean diameter D_g (mm)	Sphericity ϕ
Foxtail millet	9.31 ± 0.01	1.645 ± 0.06	0.666 ± 0.06
Kodo millet	9.5 ± 0.03	2.303 ± 0.06	0.724 ± 0.02
Barnyard millet	11.07 ± 0.08	1.738 ± 0.06	0.686 ± 0.05

Values are means ± SD of triplicate determinations.

4.4.2 Assessment of dehuller performance

The performance of the dehuller was analyzed based on its efficiency to dehull the three millet varieties – *foxtail*, *barnyard* and *kodo* millets. Tables 4.2, 4.3 and 4.4 presents the dehulling performance of the hand operated dehuller for each millet variety. From the results, it was clear that the roller spacing and number of consecutive passes per trial played a crucial role in increasing/decreasing the dehulling efficiency. With the hand operated prototype, it was possible to achieve maximum dehulling efficiency of over 99% with 3 – passes for both foxtail and barnyard millet varieties. Whereas, for kodo millet the highest efficiency was recorded as 76.8% after 3 – passes. This difference in dehulling efficiency in comparison with the other two varieties can be attributed to the hard outer hull layers of kodo millets (Sharma et al., 2017). Fig 4.3 a), b) and c) presents the dehulling efficiencies for the three millet varieties at different roller spacing and after each respective pass. Increasing the number of passes per trial would likely increase the dehulling efficiency for kodo millet, while this may also result in increased amount of broken grains and reduce the grain quality by polishing and removing the bran. Because it is a hand operated model, the rotational speed (rpm) at which the machine is operated is significantly low and it lies from 30-40 rpm on an average. Since the degree of dehulling depended on the various physical attributes (e.g., size, hull hardness, etc.) of the millet grains and the number of consecutive passes, the throughput capacity of the dehuller varied for each variety tested. Owing to their smaller size and lower hull hardness, the capacity of the machine for processing foxtail and barnyard millets ranged between 300-350 g/h, after three passes. Similarly, a capacity of 180-200 g/h was achieved for processing the kodo millet variety, due to its high hull hardness.

4.4.3 Effect of changing roller spacing and number of passes

Testing the machine at different roller spacing showed that changing the gap between the two rollers had an impact on its dehulling ability. Highest efficiencies for dehulling the different millet varieties were observed at roller spacing of 0.25 mm, which was also found to result in the highest amount of broken grains compared to efficiencies obtained at other spacing. Results obtained at 0.25 mm and 0.20 mm roller spacing were almost comparable for all the varieties. The percentage of broken grains at 0.25 mm was less than 2% in each trial due to influence of the rubber hardness. During 2 – pass and 3 – pass of some trials, it was observed visually that the broken grains from the respective previous pass were milled into flour. However, the milled fraction, when taken into consideration, did not increase the percentage of broken grains above 2%.

4.4.4 Assessment of blower performance

The centrifugal blower which was made to operate along with the dehuller was also evaluated for its capacity to aspirate the hulls from the dehulled grain outlet. Experimentation showed that, for foxtail millet the blower was able to aspirate over 90% of the hulls from the output after 3 consecutive passes. However, for the remaining two varieties, complete hull separation could not be achieved. This is more likely due to the fact that barnyard and kodo millet grains have multiple layers of hulls that stick onto the kernels, which was evident through visual observation. Another factor that may result in insufficient aspiration is the rotational speed (rpm) at which the centrifugal fan rotates. However, this issue can be sorted out by replacing the existing blower with a more powerful blower by simply multiplying the gear ratios. Changing the roller spacing had no influence on the aspirating capacity of the blower.

Table 4.2. Machine performance on dehulling foxtail millet variety

No. of passes	Roller spacing (in mm)											
	0.20			0.25			0.30			0.35		
	Dehulling efficiency	Broken grains (%)	Rice recovery (%)	Dehulling efficiency	Broken grains (%)	Rice recovery (%)	Dehulling efficiency	Broken grains (%)	Rice recovery (%)	Dehulling efficiency	Broken grains (%)	Rice recovery (%)
1	54.46±4.97	0.15±0.02	48.95±2.07	61.3±2.3	0.25±0.06	55.35±2.21	49.33±1.8	0.1±0.02	44.2±2.3	61.1±1.46	0.05±0.001	54.95±2.1
2	92.6±3.21	0.16±0.01	85.25±2.4	95.73±0.88	0.39±0.02	88.64±2.2	92.14±2.17	0.17±0.02	85.3±2.74	87.5±2.5	0.06±0.01	77.72±2.22
3	99.4±0.1	0.30±0.06	97.96±0.3	99.4±0.12	0.83±0.07	98.10±0.14	98.84±0.13	0.36±0.04	97.24±0.2	98.06±0.29	0.125±0.02	94.88±0.84

Values are means ± SD of triplicate determinations.

Table 4.3. Machine performance on dehulling kodo millet variety

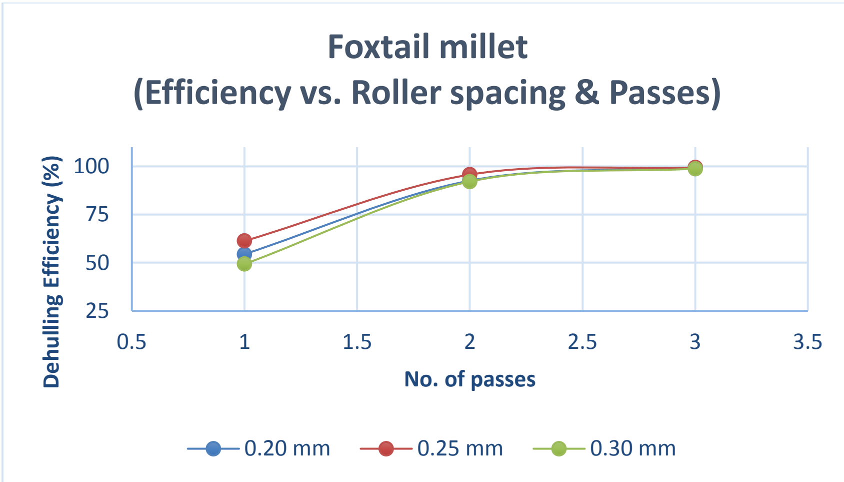
No. of passes	Roller spacing											
	0.20			0.25			0.30			0.35		
	Dehulling efficiency	Broken grains (%)	Rice recovery (%)	Dehulling efficiency	Broken grains (%)	Rice recovery (%)	Dehulling efficiency	Broken grains (%)	Rice recovery (%)	Dehulling efficiency	Broken grains (%)	Rice recovery (%)
1	16.13±0.1	0.1±0.02	14.95±2.01	17.04±1.75	0.1±0.02	15.55±1.42	10.91±2.21	0.04±0.004	10.31±0.77	3.83±0.65	0	3.75±0.45
2	46.09±1.9	0.32±0.02	40.14±1.9	48.3±3.12	0.16±0.01	42.19±1.4	37.46±3.51	0.06±0.003	33.89±2.43	20.04±2.75	0.03±0.004	18.69±0.5
3	72.3±1.32	0.36±0.01	65.26±1.8	76.83±0.67	0.19±0.01	68.96±1.94	64.8±1.63	0.08±0.004	59.03±2.46	41.15±1.84	0.03±0.003	37.82±3.06

Values are means ± SD of triplicate determinations.

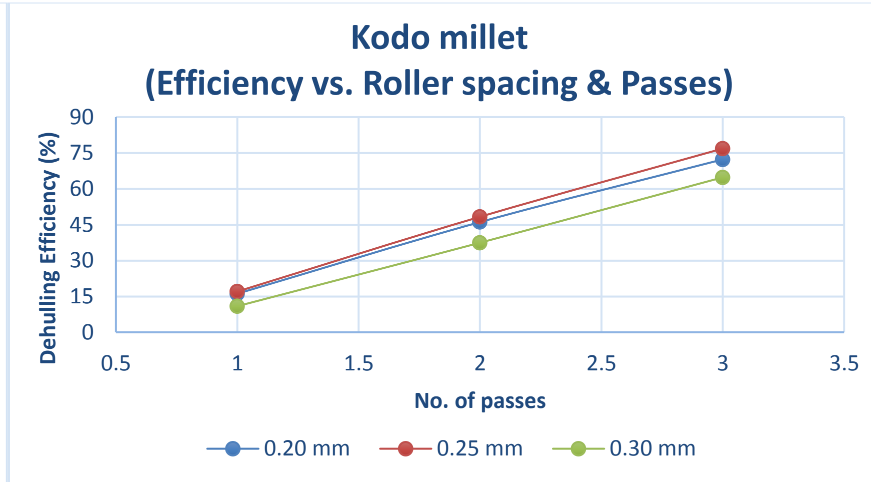
Table 4.4. Machine performance on dehulling barnyard millet variety

No. of passes	Roller spacing (in mm)											
	0.20			0.25			0.30			0.35		
	Dehulling efficiency	Broken grains (%)	Rice recovery (%)	Dehulling efficiency	Broken grains (%)	Rice recovery (%)	Dehulling efficiency	Broken grains (%)	Rice recovery (%)	Dehulling efficiency	Broken grains (%)	Rice recovery (%)
1	46.82±4.79	0.15±0.01	39.3±0.36	54.14±2.56	0.2±0.03	45.2±1.71	37.21±2.12	0.1±0.02	31.85±2.23	35.11±3.62	0	30.9±2.01
2	90.23±1.9	0.12±0.02	79.25±2.07	92.68±2.04	0.36±0.03	81.22±1.73	77.17±4.9	0.17±0.004	69.71±4.19	74.37±1.6	0.06±0.002	55±2.92
3	99.01±0.51	0.47±0.05	94.27±0.29	99.44±0.05	1.22±0.09	94.17±1.26	94.99±0.51	0.32±0.04	90.03±1.9	93.06±0.97	0.08±0.005	87.49±2.19

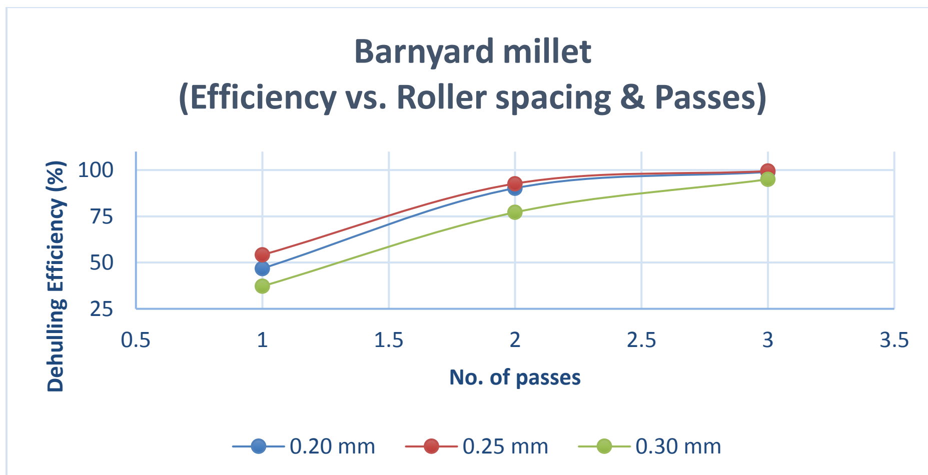
Values are means ± SD of triplicate determinations.



a)



b)



c)

Fig. 4.3 a), b) & c) Effect of changing roller spacing and number of passes on dehulling efficiencies for *foxtail*, *kodo* and *barnyard* millets

4.5 CONCLUSION

A table top hand operated dehuller was designed and fabricated which was tested for its performance on dehulling three millet varieties. The dehuller was able to dehull foxtail and barnyard millets in 2 to 3 – passes with an efficiency of over 90% with a throughput capacity of 300 g/h. For the kodo millet variety the dehulling efficiency on 3 – passes was comparatively low with a maximum of 77%. Adjusting the rubber roller spacing played a significant role in changing the dehulling efficiency. Roller spacing in the range of 0.20 mm and 0.25 mm was found to be the optimum level for rubber hardness ranging from 85-90 durometers. This study could serve as a pathway to stimulate the development of commercial hand operated dehullers to function at household levels where millets are consumed regularly.

CONNECTING STATEMENT

According to the literature, millets are an excellent source of phenolic compounds which have the potential to act as food antioxidants. These organic groups can be located in considerable proportions in millet hulls. However, utilization of millet hulls for extracting phenolic compounds is limited. Only a few researchers have studied millet hulls' phenolic compounds through various extraction methods and their possible health benefits. Chapter V discusses the application of microwave energy for extracting the phenolic antioxidants from millet hulls under different extraction conditions, thus leading to its optimization using a specific millet variety.

CHAPTER V

OPTIMIZATION OF MICROWAVE-ASSISTED EXTRACTION (MAE) OF PHENOLIC ANTIOXIDANTS FROM KODO MILLET HULLS (*PASPALUM SCROBICULATUM*) AND EVALUATION OF ITS ANTIOXIDANT ACTIVITY *'IN VITRO'*

5.1 ABSTRACT

Kodo millet (*Paspalum scrobiculatum*) belongs to the minor millet class, and exhibits high antioxidant potential, especially with the many phenolic compounds contained in its hulls. Phenolic antioxidants were extracted from kodo millet hulls in a microwave system operating at a constant frequency (2.45 GHz) and the extraction was further optimized using response surface methodology. The effectiveness of solvent concentration (30%, 60% and 90% *v/v* ethanol), extraction temperature (60°C, 80°C and 100°C), holding time (2, 4 and 6 min) and their interactions were determined in terms of the resulting extracts' total phenol content (ferulic acid equivalents) and antioxidant activities (2,2'-diphenyl-1-picrylhydrazyl **(**DPPH) radical scavenging activity, 2,2′-azino-bis (3-ethylbenzothiazoline-6-sulfonic acid) diammonium salt (ABTS) radical scavenging activity and total antioxidant capacity). Based on results, the overall optimum conditions for microwave-assisted extraction of kodo mill hulls were predicted as: holding time, t = 5.48 min; extraction temperature, T = 100°C and solvent concentration, C = 49.27% *v/v*. The predicted values at these conditions were: total phenol content - 175.11 µmol ferulic acid equivalents /g defatted hull; DPPH radical scavenging activity - 91.67 % inhibition; ABTS radical scavenging activity - 96.37% inhibition; total antioxidant capacity - 69.2 µmol ascorbic acid equivalents /g defatted hull.

KEYWORDS: Microwave extraction, millet hulls, response surface methodology, antioxidant activity.

5.2 INTRODUCTION

Polyphenolic compounds (phenolic acids, flavonoids, etc.) are a major group of phytochemicals that can be found in plants, produced to serve as plant pigments that form their defense mechanisms, thus helping in the plants' growth and development (Ballard, Mallikarjunan, Zhou, & O'Keefe, 2010; Karakaya, 2001; Li et al., 2012). These compounds are noted for their remarkable antioxidative potential (Karakaya, 2001) and are the most abundantly found antioxidants in the human diet with other reducing agents like Vitamin E, Vitamin C and carotenoids (Hayat et al., 2009; Manach, Scalbert, Morand, Rémésy, & Jiménez, 2004). In general, an '*antioxidant*' refers to any substance that significantly interrupts, delays or prevents the oxidation of an oxidizable substrate, when present in lower concentrations than the latter (Halliwell, Aeschbach, Löliger, & Aruoma, 1995; Sies, 1997). Free radicals and other reactive oxygen species (ROS), collectively known as '*pro-oxidants*', attack biological molecules like lipids, proteins, DNA and cell membrane when the body's antioxidant system is overwhelmed by the free radicals and ROS, resulting in cell damage and several age related diseases (Apak et al., 2013). Perhaps it is the '*oxidative stress*' (a state of imbalance in the pro-oxidants and the antioxidants in favor of the former) induced on the biological molecules that can be attributed to the health related issues (Sies, 1997). Predominant sources of phenolic compounds include fruits, vegetables, cereal grains and few plant-derived beverages like tea and red wine (Scalbert, Johnson, & Saltmarsh, 2005; Vattem, Ghaedian, & Shetty, 2005). However, the beneficial effects of these compounds on the human body depend on the amount being consumed and their bioavailability (Manach et al., 2004). So far, thousands of polyphenols have been identified and studied in plant based foods, and consumption of these foods has been found to contribute in the reduction of health risks linked to oxidative stress.

In recent years, plant-derived natural phenolic antioxidants have become the subject of interest for researchers and scientists in food and pharmaceutical/nutraceutical industries, due to their potential health promoting properties and therapeutic values. Use of synthetic antioxidants in the food industry, in limited concentrations, have reduced oxidation in foods to a considerable level. However, elevating concerns over the potential long term carcinogenic effects that synthetic antioxidants can induce on human health has created an urge to replace synthetic antioxidants like *butylated hydroxyanisole* (BHA), *butylated hydroxytoluene* (BHT), *propyl gallate* (PG) and *tert-butylhydroquinone* (TBHQ), with natural antioxidants (Jayaprakasha, Selvi, & Sakariah, 2003; Rakholiya, Kaneria, Nagani, Patel, & Chanda, 2015; Shahidi, 2000). Hence, phenolic compounds from various natural sources have been studied and recovered through extraction for industrial/commercial applications. Several procedures have been established and standardized for extraction of phenolic compounds, employing advanced technologies like pressurized fluid extraction, supercritical extraction, ultrasonic assisted extraction, microwave assisted extraction in addition to conventional solvent extraction techniques (Routray & Orsat, 2012; Terigar et al., 2010). Owing to its advantages (reduced solvent requirement, less time consuming, higher extraction yield and environmental-friendly) over other extraction techniques, Microwave Assisted Extraction (MAE) has gained a great deal of attention over the past twenty-five years (Nkhili et al., 2009).

MAE involves the application of microwave energy to organic matrices within solvent medium, to cause dipole rotation within the matrices, producing heat sufficient enough to rapidly migrate the target substances into the solvent system used (Zhong, Lin, Wang, & Zhou, 2012). It has been observed and reported in several previous studies that the influence of microwave energy on the extraction yield depends on the extraction time, microwave power, extraction temperature and contact surface area. Hence it is critical to choose the optimum operating levels for extracting the particular compound of interest (Routray & Orsat, 2012). MAE has been employed for many plant systems like peanuts (Ballard et al., 2010; Zhang et al., 2013), tomatoes (Li et al., 2012), mandarin peels (Hayat et al., 2009), rosemary leaves (Rodríguez-Rojo, Visentin, Maestri, & Cocero, 2012), tea products (Nkhili et al., 2009; Spigno & De Faveri, 2009; Sultana et al., 2008), potato peels (Singh et al., 2011), grape seeds (Krishnaswamy, Orsat, Gariépy, & Thangavel, 2013), apple (Wang et al., 2007), pumpkin seeds (Jiao et al., 2014), flax seeds (Nemes & Orsat, 2011), soy flour (Terigar et al., 2010), mung bean hulls (Zhong et al., 2012), rice (Duvernay, Assad, Sabliov, Lima, & Xu, 2005; Setyaningsih, Palma, & Barroso, 2012; Setyaningsih, Saputro, Palma, & Barroso, 2015; Zigoneanu, Williams, Xu, & Sabliov, 2008), etc., to efficiently extract and recover the desired functional compounds.

Cereal grains constitute the main staple foods for humans, and consumption of cereals alone accounts for more than one half of the world's calorific intake, since they can provide all the required basic nutrients for human growth in significant quantities (Sarwar et al., 2013). In cereals, phenolic compounds exist in free, soluble conjugated and insoluble bound forms with the latter being predominant in cereals (Arranz & Calixto, 2010; Chandrasekara & Shahidi, 2011b). It is important to consider the hull fractions of cereals for phenolic antioxidant extraction, since the hulls of cereals also comprise phenolic compounds, besides those contained in the edible grain. For instance, wheat grain polyphenols are mainly concentrated in the aleurone layer and seed coat (Scalbert & Williamson, 2000). Majority of polyphenols present in cereal grains are phenolic acids and tannins with little amounts of flavonoids. Phenolic acids, especially ferulic acid and diferulate are reported to be significant in grains (Manach et al., 2004; Sreeramulu, Reddy, & Raghunath, 2009). Millets are small seeded cereal grains having a strong phenolic profile, besides other proximate constituents. Their ability to act as antioxidants has been studied by researchers over the past few years (Asharani et al., 2010; Chandrasekara & Shahidi, 2010, 2011c, 2012a, 2012b; Chethan & Malleshi, 2007b; Hejazi & Orsat, 2015; Pradeep & Sreerama, 2015; Sreeramulu et al., 2009; Suma & Urooj, 2012; Viswanath et al., 2009). It has been reported that, among the several millet varieties, kodo millet has higher antioxidant potential in both hull fractions and the starchy endosperm(Chandrasekara & Shahidi, 2011b; Hegde & Chandra, 2005). To the best of our knowledge, optimization studies have never been conducted on the extraction of phenolic compounds from kodo millet hulls. Hence in our study, it was decided to employ Microwave Assisted Extraction to efficiently extract the phenolic antioxidants from kodo millet hulls and further optimize the extraction parameters through response surface methodology.

5.3 MATERIALS AND METHODS

5.3.1 Chemicals and Sample collection

Kodo millet (*Paspalum scrobiculatum*) was procured from the local markets of Coimbatore, Tamil Nadu, India. Gallic acid, ferulic acid, ascorbic acid, 2,2-diphenyl-1-picrylhydrazyl (DPPH), Folin-Ciocalteu's phenol reagent, ammonium molybdate, sulfuric acid and sodium phosphate were purchased from Sigma-Aldrich Co (St. Louis, MO, US). Potassium persulphate, hexane and sodium carbonate were purchased from Fisher Scientific Co (Hampton, NH, US). Ethanol was purchased from Commercial Alcohols Inc. (Brampton, ON, Canada) and 2,2′-azino-bis (3-ethylbenzothiazoline-6-sulfonic acid) (ABTS) was purchased from MP Biomedicals Inc. (Santa Ana, CA, US)

5.3.2 Sample preparation

Kodo millet hulls (KMH) were obtained from the whole millet grains by decorticating/dehulling them in a prototype dehuller with subsequent winnowing. The collected hulls were pulverized mechanically using a blender (Magic Bullet Single shot, Homeland Housewares, LLC.) into a fine powder and allowed to pass through a 250µm sieve (Mesh No. 60, US Standard Sieve Series) to ensure uniformity in particle size. The ground millet hulls were then defatted with hexane (1:5 w/v) to remove the low polar constituents that would interfere with phenolic compounds extraction. Defatting was carried out for 90 min at ambient temperature, under constant stirring using a magnetic stirrer (Thermolyne Cimarec 2 Hotplate stirrer) and the defatted samples were used for extraction.

5.3.3 Microwave-Assisted Extraction

MAE of KMH was performed using a microwave digester, Mini-WAVE Digestion Module (SCP Science, Canada) powered by a 1000 W central magnetron source. This system was operated at a microwave frequency of 2.45 GHz. With this digester, the operating time and temperature can be controlled during extraction. The defatted hull samples were used for MAE under different extraction conditions namely holding time (2, 4 and 6 minutes), solvent concentration (30%, 60% and 90% v/v) and extraction temperature (60°C, 80°C and 100°C). To reach the desired extraction temperature from room temperature, a constant time of 5 min was set as the come-up time for each extraction to maintain uniformity. The extraction solvent used in our study was aqueous ethanol at different ethanol concentrations. Each defatted sample (1±0.005 g) was taken in a 75mL quartz reactor vessel, to which 50mL of various concentrations of aqueous ethanol was added and closed with Teflon caps. The extractions were carried following different operating condition combinations using response surface methodology (Tables 5.1 and 5.2). The obtained ethanolic extracts were centrifuged at 10000 rpm for 15 min (Sorvall™ Legend™ X1R Centrifuge Series, Thermo Scientific). The resulting clear, supernatant liquid was used for antioxidant analysis within one week of extraction.

5.3.4 Experimental design & Statistical analysis

Response surface methodology (RSM) is a set of various mathematical and statistical techniques employed as a tool to design the experiments and optimize the response based on the obtained experimental results (Ren, Heo, Kim, & Cheong, 2013). In this study, JMP statistical software (SAS Institute Inc.) was used to perform the RSM driven experimental design. The effects of three independent variables (holding time, temperature and extraction solvent concentration) on the response variables (total phenol content, DPPH scavenging activity, ABTS scavenging activity and total antioxidant capacity) were investigated using a face-centered central composite design (CCD), which reduces the number of experimental runs required to optimize the responses (Equbal, Sood, Ansari, & Equbal, 2017). Table 5.1 shows the chosen factors at different levels with the corresponding codes for optimization using CCD.

Table 5.1. Process variables involved in extraction and optimization, including their coded levels

Coded levels	Process variables		
	Holding time, min (t)	Extraction temperature, °C (T)	Solvent Concentration, % *v/v* (C)
-1	2	60	30
0	4	80	60
1	6	100	90

The CCD is very useful in establishing a relationship between the various factors at various levels and the response variables by generating a second order polynomial model, with a lower number of experimental runs. In this study, the CCD included three center points, six axial points and eight factorial points, which totals 17 experimental runs (Table 5.2). The second order full quadratic model created by CCD for each response variable is given in Eqn. 5.1.

$$Y = \beta_0 + \sum_{i=1}^{3} \beta_i X_i + \sum_{i<j=1}^{3} \sum \beta_{ij} X_{ij} + \sum_{i=1}^{3} \beta_{ii} X_i^2 \tag{5.1}$$

Where Y is the predicted response, β_0, β_i, β_{ij} and β_{ii} are the regression coefficients of the intercept, linear effect, quadratic effect and interaction respectively, and X_i and X_j are the independent variables. Each experiment was conducted in triplicate and the results were expressed as a mean value of the triplicates. The adequacy of the JMP software generated model was determined by evaluating the lack of fit, analysis of variance (ANOVA) and the coefficient of determination (R^2). The statistical significance of the quadratic model was determined at 5% probability level (p<0.05). The optimization of MAE of phenolic antioxidants from KMH was done based on modelling and desirability function to derive the best extraction conditions.

Table 5.2. Randomized Central Composite Design with coded and real levels

Experimental run	Holding time, min (t)	Extraction temperature, °C (T)	Solvent Concentration, EtOH % *v/v* (C)
R_1	4 (0)	100 (1)	60 (0)
R_2	2 (-1)	80 (0)	60 (0)
R_3	2 (-1)	100 (1)	30 (-1)
R_4	6 (1)	80 (0)	60 (0)
R_5	2 (-1)	100 (1)	90 (1)
R_6	2 (-1)	60 (-1)	30 (-1)
R_7	6 (1)	100 (1)	90 (1)
R_8	4 (0)	60 (-1)	60 (0)
R_9	6 (1)	60 (-1)	30 (-1)
R_{10}	4 (0)	80 (0)	90 (1)
R_{11}	6 (1)	60 (-1)	90 (1)
R_{12}	4 (0)	80 (0)	60 (0)
R_{13}	6 (1)	100 (1)	30 (-1)
R_{14}	2 (-1)	60 (-1)	90 (1)
R_{15}	4 (0)	80 (0)	60 (0)
R_{16}	4 (0)	80 (0)	30 (-1)
R_{17}	4 (0)	80 (0)	60 (0)

5.3.5 Determination of total phenol content

The total phenol content (TPC) of the ethanolic KMH extracts was determined using Folin-Ciocalteu's reagent method. The method followed by Singh et al. (2011) and Krishnaswamy et al. (2013) was adopted with slight modifications. Briefly 1 mL of the extract or standard (ferulic acid) was taken in 15 mL centrifuge tubes, to which 7.5 mL deionized water and 0.5 mL Folin-Ciocalteu's phenol reagent were added. Then 1 mL of 7.5% sodium carbonate solution was added within 1-8 min and the reaction mixture was vortexed thoroughly (Corning® LSE™ Vortex mixer). The absorbance was measured at 765 nm using a UV/Vis spectrophotometer (Ultrospec 2100 pro, Biochrom Ltd., Cambridge, England) against a blank sample, after incubating the mixture in the dark at ambient temperature for 30 minutes. The concentration of total phenolic compounds in the extracts was determined by plotting calibration curves using different concentrations (0-750 μg/ml) of the standards and was expressed in terms of ferulic acid equivalents (FAE) in micromoles per gram of defatted KMH.

5.3.6 Determination of antioxidant potential

The antioxidant activity of the ethanolic extracts was determined using several assays namely DPPH radical scavenging activity, ABTS radical scavenging activity and total antioxidant capacity.

5.3.6.1 DPPH radical scavenging activity

The ability of an antioxidant to quench the DPPH radical can be analyzed by performing DPPH radical scavenging activity assay (RSA). In this study, the method used by Nair et al. (2007) was followed with some modifications. Briefly 1.5mL of freshly prepared 2,2-diphenyl-1-picrylhydrazyl **(**DPPH) solution (3.94mg/ 100mL ethanol) was taken in Eppendorf tubes to which an aliquot (30µL) of the ethanolic kodo millet hull extracts was added and mixed thoroughly. Discoloration of the purple color of the DPPH solution was due to the pairing of the free electron in the DPPH radical in the presence of an antioxidant. The reaction mixture was incubated in the dark for 20 min and the absorbance was measured at 517nm using UV/Vis spectrophotometer (Ultrospec 2100 pro, Biochrom Ltd., Cambridge, England). The lower the absorbance, the higher the scavenging potential of the extracts. The radical scavenging activity of the extracts was expressed as percentage (%) inhibition and calculated using Eqn 5.2.

$$\text{DPPH RSA (\%)} = \left(1 - \frac{\text{Abs sample}_{\ 517\text{nm}}}{\text{Abs control}_{\ 517\text{nm}}}\right) \times 100 \qquad (5.2)$$

where, Abs sample – absorbance of the KMH extract and Abs control – absorbance of the blank sample (DPPH radical + ethanol).

5.3.6.2 ABTS radical scavenging activity

An improved method as developed by Re et al. (1999), to assess the antioxidant activity of both aqueous and lipophilic systems, was followed with few modifications. Initially, stock solutions of ABTS (7mM) and potassium persulphate (2.45mM) were prepared separately in water. The two stock solutions were then mixed in equal volumes and incubated in the dark at room temperature for 12-16 h to produce the green ABTS radical cation ($ABTS^{\bullet +}$) prior to use. This working solution mixture was diluted with ethanol to a final absorbance of 0.7±0.02 measured at 734nm using a UV/Vis spectrophotometer (Ultrospec 2100 pro, Biochrom Ltd., Cambridge, England). To evaluate the scavenging activity, an aliquot of 10µL of individual extracts was added to 1mL of the $ABTS^{\bullet +}$ working solution taken in Eppendorf tubes. Discoloration of the green color was observed due to the presence of the antioxidant compounds. The reaction mixture was incubated at room temperature for 6 min and the absorbance was measured at 734nm against blank using the spectrophotometer. The $ABTS^{\bullet+}$ scavenging activity of the hull extracts was expressed as percentage (%) inhibition calculated using Eqn 5.3.

$$\text{ABTS}^{\bullet+}\ \text{RSA}\ (\%) = \left(1 - \frac{\text{Abs sample}_{734\text{nm}}}{\text{Abs control}_{734\text{nm}}}\right) \times 100 \qquad (5.3)$$

where Abs sample is the absorbance of the KMH extract and Abs control is the absorbance of the blank sample ($ABTS^{\bullet+}$ + ethanol).

5.3.6.3 Total antioxidant capacity (Phosphomolybdenum method)

The total antioxidant capacity/ Phosphomolybdenum method is used to study the antioxidant capacity of food extracts by the formation of a green phosphate/molybdenum complex. The method developed by Prieto, Pineda, and Aguilar (1999) was adopted without any modifications. Briefly, an aliquot of 0.1mL of the hull extracts and different concentrations of ascorbic acid were added to 1mL of the reagent solution containing 0.6 M Sulfuric acid, 28 mM sodium phosphate and 4 mM ammonium molybdate. The extract-reagent mixture was vortexed and incubated at 95°C for 90 min. The absorbance was measured after the reaction mixture had cooled to room temperature at 695 nm using UV/Vis spectrophotometer (Ultrospec 2100 pro, Biochrom Ltd., Cambridge, England). A blank was prepared by reacting an aliquot of 0.1mL ethanol with the same reagent (1mL) under same incubating conditions. The antioxidant capacities of the hull extracts were determined by plotting the calibration curve (Eqn. 5.4; R^2= 0.9989) obtained from the absorbance of various concentrations (0-300 µg/ml) of ascorbic acid and expressed in terms of ascorbic acid equivalents (AAE) in micromoles per gram of defatted kodo millet hull.

$$\text{Absorbance of KMH extract (695 nm)} = 0.004 \times \text{Concentration of KMH extract} + 0.0504 \qquad (5.4)$$

5.3.7 Measurement of extract color

The color of the extracts was determined with the use of a colorimeter (Chroma Meter, Konica Minolta CR Series) equipped with 8mm measuring head. The extract color was measured in CIE L*a*b* system, which represents lightness/darkness as L*, red/green value as a* and yellow/blue value as b*. Positive and negative a* (a+/a-) values represents the intensity of red and green light respectively in the extracts. Similarly, positive and negative b* (b+/b-) values represents the intensity of yellow and blue light. The colorimeter was calibrated with the standard white calibration plate given by the manufacturer before measuring the color of the different extracts. 25 ml of the extracts was taken in a round container having 8 cm wide opening and L*, a* and b* values were recorded by placing the measuring head perpendicular to the container. With the measured L*, a* and b* values, the total change in color of the extracts was calculated according to Eqn 5.5.

$$\Delta E = \sqrt{(L_0 - L*)^2 + (a_0 - a*)^2 + (b_0 - b*)^2} \tag{5.5}$$

where L_0, a_0 and b_0 denote the color values of aqueous ethanol at 30%, 60% and 90% *v/v* used as reference values to compare the color change of the ethanolic extracts.

5.4 RESULTS AND DISCUSSION

5.4.1 Extraction & model fitting

In this study, phenolic antioxidants were extracted from KMH by the application of microwave energy (MAE) and optimized using RSM. Various factors affect the extraction efficiency of phenolic compounds, among which holding time (t), extraction temperature (T) and solvent concentration (% *v/v*) were selected as the study parameters. The response surface analysis was used to fit the data obtained from the 17 experimental runs presented in Table 5.2.

5.4.2 Effect of process variables on Total Phenol Content (TPC)

The impact of the process variables on the TPC of the extracts was analyzed using response surface regression analysis. The least squares regression model used for fitting the independent variables was significant with a low *p*-value (<0.0001) and higher R^2, closer to 1 (0.9739). Further, a non-significant lack of fit ($p > 0.05$) confirms the validity of the model (Pavlović, Buntić, Šiler-Marinković, & Dimitrijević-Branković, 2013), suggesting that it can be used to predict the TPC of the kodo millet hull extracts. The actual values of TPC obtained through experimentation were very similar to the predicted values as evidenced in Fig.5.1. The ANOVA of the model for TPC is shown in Table 5.3.

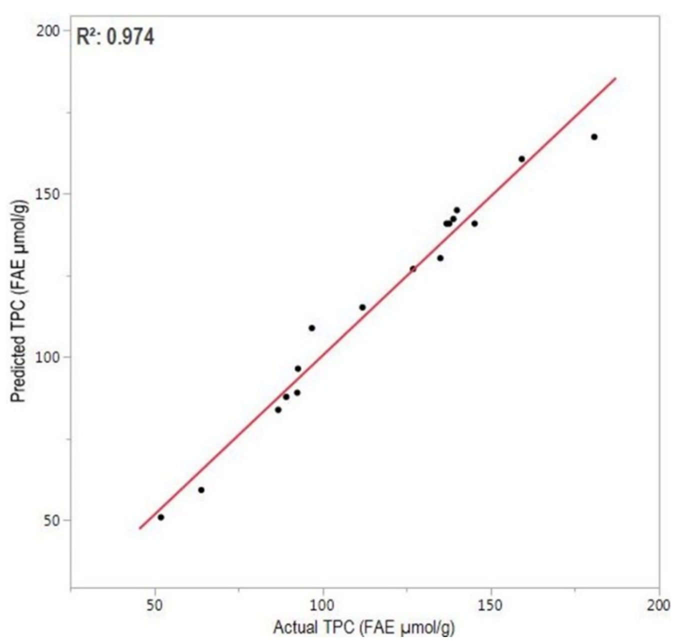


Fig. 5.1 Predicted vs Actual plot for total phenol content of the extracts

Table 5.3. Estimated regression coefficients for the full quadratic model and analysis of variance (ANOVA) for the effect of process variables on TPC

Source	*df*	SS	MS	*F*-value	*p*-value
Model	9	18741.940	2082.44	29.1049	<0.0001[a]
LOF	5	458.51932	91.7039	4.3332	0.1981
Term	Estimate	Std Error	*t*-ratio	*F*-value	*p*-value
Intercept	140.84295	3.619473	38.91		<0.0001[a]
t	6.0021807	2.674871	2.24	5.0351	0.0597
T	29.2428	2.674871	10.93	119.5177	<0.0001[a]
C	-19.56437	2.674871	-7.31	53.4966	0.0002[a]
$t \times T$	2.601035	2.990597	0.87	0.7564	0.4133
$t \times C$	0.780301	2.990597	0.26	0.0681	0.8017
$T \times C$	-3.900363	2.990597	-1.30	1.7010	0.2334
t^2	-4.583408	5.167692	-0.89	0.7867	0.4046
T^2	-2.737174	5.167692	-0.53	0.2806	0.6127
C^2	-33.4731	5.167692	-6.48	41.9564	0.0003[a]
R^2	0.973972				
Adjusted R^2	0.940508				

[a] Significant; *LOF*- Lack of fit

Fig 5.2 presents the response surface plot for TPC of the extracts. Two of the linear effects of the quadratic model namely, extraction temperature (T) and solvent concentration (*C*) effects, and the quadratic effect of the solvent concentration (C^2) were significant ($p < 0.05$), while the other factors (e.g., t, t × T, t × C, etc.) in the model were insignificant ($p > 0.05$). Hence, neglecting those insignificant factors from the full model, the final predictive regression model was obtained as follows (Eqn. 5.6).

$$Y_{TPC} = 138.7513 + 1.4621\,(T) - 0.6521\,(C) - 0.0413\,(C^2) \tag{5.6}$$

The experimental values of TPC of different extracts expressed in μmol FAE/g of defatted KMH are presented in Table 5.4. The TPC of the kodo millet hull extracts varied from 51.96 to 180.77 μmol FAE/g, influenced by the various combinations of the process variables. The highest TPC of 180.77 μmol FAE/g was observed at the following extraction conditions: *t* - 4 min, *T* -

100°C and *C* - 60% *v/v*, and the lowest TPC of 51.96 µmol FAE/g was observed at: *t* - 2 min, *T*- 60°C and *C* - 90% *v/v*. Experimental and visual observations clearly indicated an increase in TPC of the extracts with the increase in extraction temperature (Order $_{TPC}$ = 100°C > 80°C > 60°C). The increase in TPC of the hull extracts may be due to the increased extractability of the insoluble bound phenolics by MAE. Several authors also concluded that thermal processing increases the TPC, which is linked to the release of bound phenolics from the breakdown of cellular constituents (Boateng, Verghese, Walker, & Ogutu, 2008; Dar & Sharma, 2011; Dewanto, Wu, & Liu, 2002; Omwamba & Hu, 2010; Oufnac et al., 2007; Pradeep & Guha, 2011; Siroha & Sandhu, 2017). It was also evident that increasing the solvent concentration from 30% to 60% increased the TPC. However, further increase in concentration from 60% to 90% drastically reduced the TPC of the extracts. This trend was also observed in TPC of barley extracts, when an ethanol-water solvent system (water, 50% ethanol and 100% ethanol) was used (Omwamba & Hu, 2010). Unlike for extraction temperature and solvent concentration, the effect of holding time on TPC was not significant. An increase in TPC was observed when the holding time was increased from 2 min to 4 min, but decreased with further increase in time to 6 mins. Previous works employing a different extraction technique showed similar results on the TPC of KMH (Chandrasekara, Naczk, & Shahidi, 2012; Chandrasekara & Shahidi, 2011b).

Table 5.4. Experimental responses for total phenol content from MAE of KMH.

Experimental run	Coded variables			Total Phenol Content, FAE (µmol/g of defatted KMH)
	t, min	T, °C	C, %*v/v*	
R_1	0	1	0	180.77 ± 1.04
R_2	-1	0	0	135.01 ± 2.75
R_3	-1	1	-1	139.93 ± 4.11
R_4	1	0	0	138.90 ± 5.14
R_5	-1	1	1	92.70 ± 2.24
R_6	-1	-1	-1	86.83 ± 0.65
R_7	1	1	1	111.88 ± 2.77
R_8	0	-1	0	96.83 ± 2.15
R_9	1	-1	-1	92.48 ± 1.84
R_{10}	0	0	1	89.21 ± 3.41
R_{11}	1	-1	1	63.97 ± 1.53
R_{12}	0	0	0	136.86 ± 2.9
R_{13}	1	1	-1	159.22 ± 5.29
R_{14}	-1	-1	1	51.97 ± 0.83
R_{15}	0	0	0	137.67 ± 4.21
R_{16}	0	0	-1	126.92 ± 4.79
R_{17}	0	0	0	145.21 ± 3.05

Actual values are means ± SD of triplicate determinations. *KMH* – Kodo millet hull; *FAE* - ferulic acid equivalents.

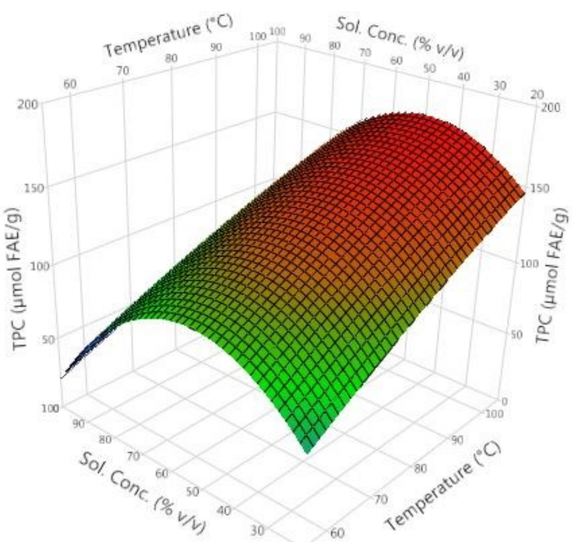


Fig. 5.2 Response surface plot for the total phenol contents of kodo millet hull extracts

5.4.3 Effect of process variables on the antioxidant activity

The antioxidant potential of the KMH extracts was studied using several antioxidant assays (DPPH, ABTS and total antioxidant capacity). The experimental results obtained for various combinations of the process variables on the antioxidant activity are given in Table 5.5.

Table 5.5. Experimental responses for antioxidant activity from MAE of KMH.

Experimental run	Coded variables			Antioxidant activity		
	t, min	T, °C	C, %*v*/*v*	DPPH RSA (%)	ABTS•$^{+}$ RSA (%)	Total Antioxidant Capacity, AAE (μmol/g defatted KMH)
R_1	0	1	0	89.48 ± 0.91	95.03 ± 0.43	75.98 ± 6.22
R_2	-1	0	0	80.02 ± 1.13	73.59 ± 2.67	54.16 ± 0.99
R_3	-1	1	-1	80.20 ± 1.04	80.09 ± 0.42	53.19 ± 1.26
R_4	1	0	0	77.42 ± 1.96	79.07 ± 2.93	53.62 ± 1.25
R_5	-1	1	1	44.89 ± 1.03	48.63 ± 2.65	34.52 ± 1.3
R_6	-1	-1	-1	48.10 ± 0.09	61.15 ± 0.98	39.51 ± 2.24
R_7	1	1	1	58.52 ± 2.74	62.90 ± 3.11	42.36 ± 1.43
R_8	0	-1	0	55.35 ± 0.47	61.28 ± 1.07	40.79 ± 2.98
R_9	1	-1	-1	54.89 ± 0.23	62.59 ± 2.45	46.25 ± 0.47
R_{10}	0	0	1	44.67 ± 0.47	50.14 ± 0.14	39.14 ± 0.49
R_{11}	1	-1	1	33.39 ± 0.68	37.61 ± 4.37	25.70 ± 0.82
R_{12}	0	0	0	74.05 ± 0.66	75.32 ± 6.9	58.91 ± 2.15
R_{13}	1	1	-1	84.92 ± 0.49	91.34 ± 1.33	63.15 ± 1.31
R_{14}	-1	-1	1	23.85 ± 0.65	37.38 ± 1.07	23.20 ± 2.87
R_{15}	0	0	0	70.84 ± 1.63	78.41 ± 0.71	51.76 ± 1.47
R_{16}	0	0	-1	72.15 ± 0.4	80.46 ± 0.99	52.51 ± 2.21
R_{17}	0	0	0	79.56 ± 0.65	87.64 ± 1.97	54.91 ± 1.88

Actual values are means ± SD of triplicate determinations

5.4.3.1 DPPH radical scavenging activity

Among the various assays used to study the antioxidant potential of substances, DPPH scavenging assay is the most common, cheap and simplest method. This technique determines the extent to which an antioxidant can quench the DPPH radical spectrophotometrically. The antioxidant potential of the KMH extracts was confirmed by the discoloration of the purple colored radical. Based on the results obtained from DPPH (2,2-diphenyl-1-picrylhydrazyl**)** radical scavenging assay, the regression model was fitted to the independent process variables. The coefficient of determination of the model (R^2) was 0.9785, as can be seen in Fig 5.3 and the corresponding adjusted R^2 was 0.9508.

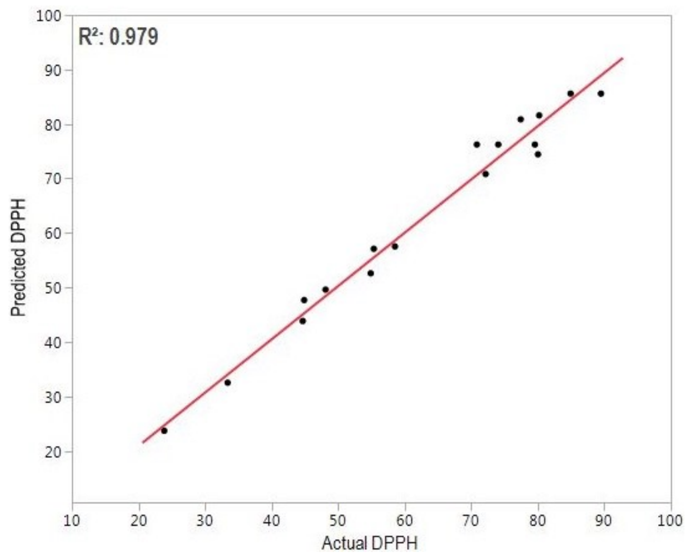


Fig. 5.3 Predicted vs Actual plot for DPPH radical scavenging activity

The significance in *p*-value of the model ($p < 0.0001$) and the non-significant lack of fit ($p > 0.05$) implies the reproducibility of the model in predicting the antioxidant activity in terms of DPPH scavenging activity. The independent process variables considered for microwave-assisted extraction represented as the linear effects of the quadratic model, their interactions with each other and the quadratic effects affected the antioxidant activity of the extracts. Holding time (t), temperature (T), solvent concentration (C) and its quadratic term (C^2) were the only effects that significantly influenced the DPPH scavenging activity. Excluding the insignificant factors, the final predictive regression model for DPPH radical scavenging activity was obtained as shown in Eqn. 5.7.

$$Y_{DPPH} = 75.2496 + 1.6039\ (t) + 0.7121\ (T) - 0.4498\ (C) - 0.0229\ (C^2) \tag{5.7}$$

The % inhibition of DPPH radical ranged from 33% to 89% for the different KMH extracts. The TPC and DPPH scavenging activity of the extracts significantly correlated with each other ($r = 0.9771$), suggesting that higher TPC of the extracts contributes in higher DPPH inhibition. Pradeep and Guha (2011) also reported higher DPPH inhibition (95.5%) for roasted little millet whole grains and concluded that higher TPC may result in higher DPPH quenching. Furthermore, formation of Maillard products like melanoids can also increase DPPH quenching capacity (Pradeep & Guha, 2011; Siroha & Sandhu, 2017). Fig 5.4 presents the surface plot generated for DPPH inhibition by the extracts. Effect of temperature and solvent concentration on the antioxidant activity in terms of DPPH inhibition were similar to that of TPC, however, an anomaly was observed in holding time (Order_{DPPH} = 2 min > 6 min > 4 min). The decrease in DPPH inhibition, observed when time was increased from 2 min to 4 min, maybe attributed to the binding of phenolic compounds to other molecules, thus reducing the extractability (Chandrasekara et al., 2012). However, at 6 min holding time the trend was opposite. i.e., percentage of inhibition increased.

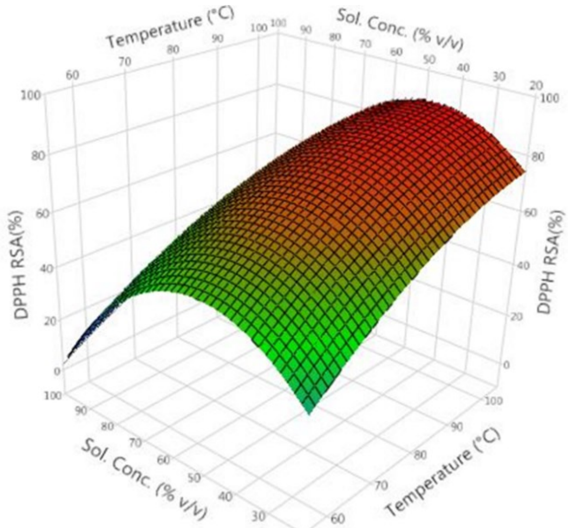


Fig. 5.4 Response surface plot for DPPH radical scavenging activity

5.4.3.2 ABTS radical scavenging activity

ABTS•$^{+}$ scavenging is also a discoloration assay like DPPH and is extensively used in studying the antioxidant properties of foods. Observations made from ABTS assay depicted a linear correlation (Fig 5.5) between the experimental values and the values predicted using the JMP generated model, with a high coefficient of determination ($R^2 = 0.9690$). The regression model was highly significant with a *p*-value of 0.0002 and lack of fit, which explains how well the model is fitted with the response variables, was not significant ($p > 0.05$). The final predictive regression model for ABTS•$^{+}$ scavenging is shown in Eqn. 5.8.

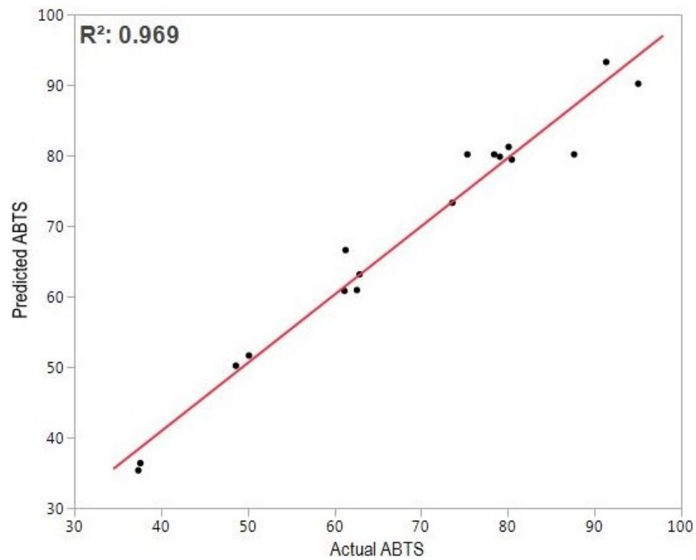


Fig. 5.5 Predicted vs Actual plot for ABTS radical scavenging activity

ABTS assay was significantly affected by the linear effects of extraction temperature ($p < 0.0001$), solvent concentration ($p < 0.0001$), and the quadratic effect of the solvent concentration ($p = 0.0014$). ABTS assay was well correlated with TPC ($r = 0.9644$) and unlike DPPH scavenging, effect of process variables on ABTS assay followed the same trend (increase/decrease) as TPC. The maximum value of 95% was observed at extraction conditions: $t = 4$ min, $T = 100$°C and $C = 60\%$ *v/v*, while the minimum inhibition percentage (37%) was observed at: $t = 2$ min, $T = 60$°C and $C = 90\%$ *v/v*. The response surface plot for ABTS$\bullet^+$ scavenging is shown in Fig 5.6.

$$Y_{ABTS} = 78.6249331214286 + 0.589873\ T - 0.46324\ C - 0.01932\ C^2 \tag{5.8}$$

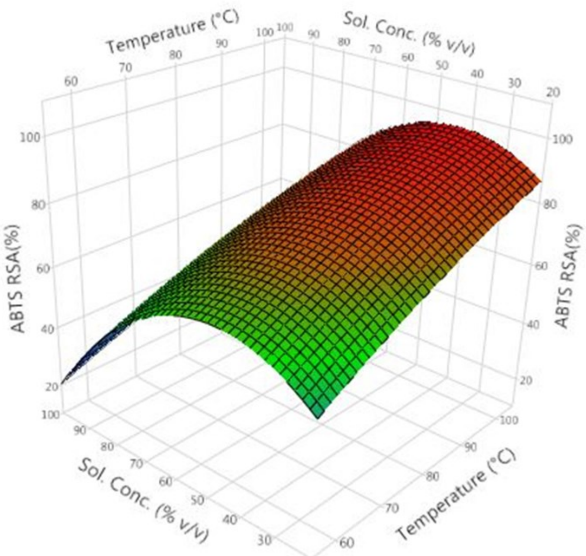


Fig. 5.6 Response surface plot for ABTS radical scavenging activity

5.4.3.3 Total antioxidant capacity (Phosphomolybdenum method)

The total antioxidant capacity (TAC) or the Phosphomolybdenum method is based on the formation of a green colored complex of phosphate and molybdenum due to the reduction of Mo (VI) to Mo (V) by phenolic extracts. This green complex is measured spectrophotometrically and expressed in ascorbic acid equivalents (AAE). TAC method of evaluating the antioxidant activity of the extracts was influenced by the same effects (T, C and C^2) which positively influenced the ABTS assay. This was evidenced through the full quadratic model fitted using response variables, and it was further used to predict the antioxidant activity after removing the insignificant parameters, as shown in Eqn. 5.9.

$$Y_{TAC} = 55.7356 + 0.4688 (T) - 0.2989 (C) - 0.0153 (C^2) \tag{5.9}$$

Fig. 5.7 shows the agreement between the actual experimental results and the predicted values of TAC, and Fig. 5.8 presents the surface plot for TAC of the extracts. Based on the *p*-values ($p < 0.05$) of individual terms of the quadratic model, the order of influence can be described as temperature ($p = 0.0015$) > solvent concentration ($p = 0.0020$) > solvent concentration * solvent concentration ($p = 0.0126$). However, the other terms included in the model showed no significant consequence ($p > 0.05$) on the total antioxidant capacity of the extracts. A non-significant lack of fit ($p > 0.05$), a significance in the p-value of the model ($p = 0.0055$) and a relatively high R^2 (0.9137) confirms the adequacy of the model. TAC and TPC of the extracts were significantly correlated ($r = 0.9676$), and similarities in effect of process variables on TAC and TPC were observed. The analysis of variance (ANOVA) for the antioxidant activity determined through DPPH, ABTS and TAC assays are presented in Table 5.6.

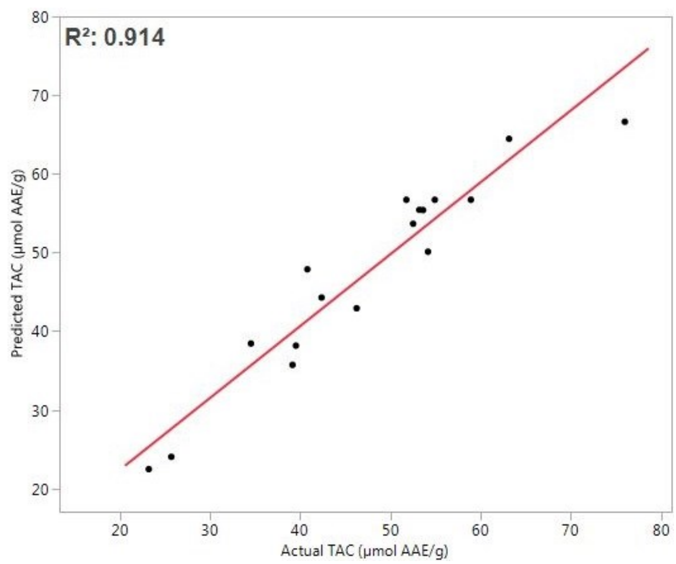


Fig. 5.7 Predicted vs Actual plot for total antioxidant capacity of the extracts

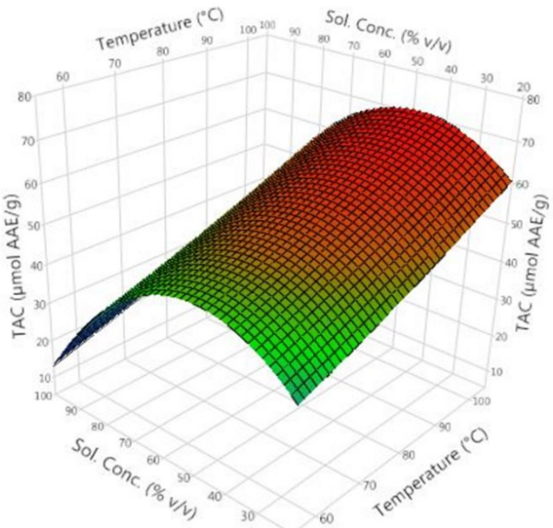


Fig. 5.8 Response surface plot for total antioxidant capacity of the extracts.

5.4.4 Effect of process variables on extract color

Consumer acceptability of any food product depends on several factors, among which the first noticeable attribute is its color. The color measurements and the total color change (*ΔE*), determined colorimetrically, for the various KMH extracts are presented in Table 5.7. Through statistical analysis and visual observation of the extracts, it was evident that solvent concentration had a significant impact on the extract color. It was found that, the lightness of color (L*) increased with increase in solvent concentration from 30% to 90%. Holding time, on the other hand, clearly reduced the lightness of the extract color as time was raised from 2 min to 6 min. The greenness (a*) of the extracts was directly influenced by solvent concentration and holding time. While yellowness (b*) reduced with increase in solvent concentration and temperature.

Table 5.6. Estimated regression coefficients for the full quadratic model and analysis of variance (ANOVA) for the effect of process variables on antioxidant activity of KMH extracts

	DPPH RSA (%)					ABTS RSA (%)					TAC (µmol AAE/g)				
Source	*df*	SS	MS	*F*-value	*p*-value	*df*	SS	MS	*F*-value	*p*-value	*df*	SS	MS	*F*-value	*p*-value
Model	9	5828.36	647.596	35.4071	<0.0001[a]	9	4824.276	536.031	24.3490	0.0002[a]	9	2594.2179	288.246	8.2415	0.0055[a]
LOF	5	89.1394	17.827	0.9168	0.5955	5	72.0308	14.406	0.3511	0.8506	5	219.0998	43.820	3.4067	0.2424
Term	Estimate	Std Error	*t*-ratio	*F*-value	*p*-value	Estimate	Std Error	*t*-ratio	*F*-value	*p*-value	Estimate	Std Error	*t*-ratio	*F*-value	*p*-value
Intercept	76.2439	1.8299	41.66		<0.0001[a]	80.1594	2.0076	39.93		<0.0001[a]	56.7120	2.5305	22.41		<0.0001[a]
t	3.2079	1.3524	2.37	5.6264	0.0495[a]	3.2663	1.4837	2.20	4.8464	0.0636	2.6482	1.8701	1.42	2.0053	0.1997
T	14.2434	1.3524	10.53	110.9218	<0.0001[a]	11.7974	1.4837	7.95	63.2221	<0.0001[a]	9.3761	1.8701	5.01	25.1356	0.0015[a]
C	-13.4928	1.3524	-9.98	99.5384	<0.0001[a]	-13.8972	1.4837	-9.37	87.7296	<0.0001[a]	-8.9688	1.8701	-4.80	22.9995	0.0020[a]
$t \times T$	0.2543	1.5120	0.17	0.0283	0.8712	2.9806	1.6588	1.80	3.2284	0.1154	1.0710	2.0909	0.51	0.2624	0.6242
$t \times C$	1.4591	1.5120	0.97	0.9313	0.3667	0.2269	1.6588	0.14	0.0187	0.8950	-0.7944	2.0909	-0.38	0.1444	0.7152
$T \times C$	-1.9963	1.5120	-1.32	1.7431	0.2283	-1.3937	1.6588	-0.84	0.7060	0.4286	-0.3236	2.0909	-0.15	0.0240	0.8813
t^2	1.4138	2.6127	0.54	0.2928	0.6052	-3.5982	2.8664	-1.26	1.5758	0.2497	-3.9569	3.6130	-1.10	1.1994	0.3097
T^2	-4.8940	2.6127	-1.87	3.5087	0.1032	-1.7724	2.8664	-0.62	0.3823	0.5559	0.5392	3.6130	0.15	0.0223	0.8856
C^2	-18.8983	2.6127	-7.23	52.3172	0.0002[a]	-14.6304	2.8664	-5.10	26.0506	0.0014[a]	-12.0195	3.6130	-3.33	11.0670	0.0126[a]
R^2	0.978505					0.969046					0.913765				
Adj. R^2	0.95087					0.929248					0.802891				

[a] Significant

Table 5.7 *L*a*b** values and total color change of KMH extracts

Experimental run	Coded variables			Color measurement			
	t, min	T, °C	C, %*v/v*	*L**	*a**	*b**	*ΔE*
R_1	0	1	0	21.418 ± 0.14	-0.906 ± 0.2	+6.806 ± 0.32	7.687
R_2	-1	0	0	21.9 ± 0.19	-1.108 ± 0.13	+6.126 ± 0.21	6.865
R_3	-1	1	-1	20.576 ± 0.19	-1.202 ± 0.31	+5.242 ± 0.31	5.873
R_4	1	0	0	20.294 ± 0.27	-1.612 ± 0.21	+5.586 ± 0.31	7.089
R_5	-1	1	1	22.346 ± 0.09	-1.782 ± 0.21	+3.73 ± 0.26	5.348
R_6	-1	-1	-1	21.782 ± 0.3	-1.128 ± 0.21	+5.048 ± 0.23	5.071
R_7	1	1	1	21.9 ± 0.47	-1.532 ± 0.32	+4.232 ± 0.33	5.946
R_8	0	-1	0	21.676 ± 0.17	-1.144 ± 0.14	+4.91 ± 0.1	6.037
R_9	1	-1	-1	20.968 ± 0.04	-0.842 ± 0.19	+5.162 ± 0.18	5.566
R_{10}	0	0	1	22.53 ± 0.06	-1.508 ± 0.22	+3.292 ± 0.21	4.873
R_{11}	1	-1	1	23.372 ± 0.46	-1.812 ± 0.05	+2.78 ± 0.12	4.020
R_{12}	0	0	0	22.266 ± 0.2	-0.946 ± 0.14	+6.126 ± 0.18	6.663
R_{13}	1	1	-1	20.706 ± 0.22	-0.438 ± 0.23	+6.796 ± 0.36	7.112
R_{14}	-1	-1	1	22.464 ± 0.3	-1.578 ± 0.13	+2.552 ± 0.16	4.532
R_{15}	0	0	0	21.234 ± 0.07	-1.36 ± 0.05	+5.76 ± 0.11	6.987
R_{16}	0	0	-1	21.208 ± 0.1	-0.728 ± 0.22	+6.378 ± 0.3	6.504
R_{17}	0	0	0	21.978 ± 0.19	-1.242 ± 0.29	+6.594 ± 0.32	7.231

L, a** and *b** values are means of five replicates. *ΔE*- total change in color of the extracts

ΔE values correspond to the visual color change and for kodo millet hull extracts the *ΔE* values ranged from 4 to 7.69. The change in color during microwave extraction is likely due to the degradation of color pigments like carotenoids and the Maillard reaction that may occur due to the presence of reducing sugars and amino acids in the hulls (Barreiro, Milano, & Sandoval, 1997; Chethan & Malleshi, 2007b; Hayakawa & Timbers, 1977; Krishnaswamy et al., 2013; Odjo, Malumba, Dossou, Janas, & Béra, 2012). Few studies have been reported on the potential of finger millet fractions to act as antioxidants and their corresponding color change during extraction have also been recorded (Chethan & Malleshi, 2007b; Viswanath et al., 2009), however there is no information regarding the color change of KMH subjected to microwave processing or any other form of thermal processing. Hence, further research is essential in this field so as to determine the compounds responsible for the significant color change during microwave extraction of antioxidants.

5.4.5 Optimization of process variables for maximum extraction

For optimizing multiple responses simultaneously in a response surface design, the desirability function approach proposed by Derringer and Suich (1980) is a very useful method (as cited in Ferreira et al., 2007). In our study, to optimize the extraction conditions based on single response as well as multiple responses, the desirability function tool of the JMP statistical software was used. The best extraction condition for TPC of KMH extracts from MAE is t = 5.81 min, T = 100°C and C = 49.8 % *v/v*, with a maximum desirability of 0.82 and the corresponding value is 175.24 µmol FAE/g defatted KMH. Likewise, the optimal conditions for antioxidant activities in terms of DPPH is t = 6 min, T = 100°C and C = 48.86 % *v/v*, with a maximum desirability of 0.99, which showed a maximum inhibition of 93.07%, ABTS is t = 5.7 min, T = 100°C and C = 44.52 % *v/v*, with a maximum desirability of 0.93 and a maximum inhibition of 96.78%, and TAC is t = 5.02 min, T = 100°C and C = 47.89 % *v/v*, with a maximum desirability of 0.81 and the corresponding value is 69.45 µmol AAE/g defatted KMH. The overall optimal conditions for the antioxidant extraction from KMH as predicted by the desirability function were: t = 5.48 min, T = 100°C and C = 49.27 % *v/v*, with a maximum desirability of 0.88. The predicted value for TPC at the optimal conditions is 175.11 µmol FAE/g defatted KMH and the values for antioxidant activity in terms of the DPPH assay is 91.67 % RSA, ABTS assay is 96.37% RSA and TAC is 69.2 µmol AAE/g KMH.

5.5 CONCLUSION

This study optimized the extraction of phenolic compounds from kodo millet hulls using microwave energy. The impact of various process parameters was analyzed based on total phenol content and antioxidant activities of the extracts. Response surface methodology was helpful in creating the experimental design with minimal runs and also in optimizing the extraction conditions. The study revealed that kodo millet hulls can be used as a reliable source of antioxidant compounds for the production of quality extracts, thus adding value to millet hulls as by-products of millet processing. As a concluding remark, extended studies on the characterization of kodo millet hull specific phenolic compounds, as extracted under microwave conditions could yield more information on their particular potential applications.

CHAPTER VI

SUMMARY AND CONCLUSION

In modern era, millets have been pushed into the category of underutilized crops, despite their high nutritive value. It has been the primary source of energy among the poor and small farming communities of arid and semi-arid regions. Due to commercialization of other crops and their quick availability and affordability, millets' utilization as a food crop has dropped severely in places where it has been consumed on a regular basis. Moreover, the processing aspect of millets has to be strengthened, since existence of proper processing equipment for millets is minimal. Hence, it is important to understand the necessity to devise appropriate post-harvest technology for millets. As a result of which millet processing can be enhanced by reducing drudgery, giving a boost to its cultivation. Developing and adopting processing equipment can also increase the accessibility of millets and its food products in urban markets.

The literature review part of this thesis discusses the various types of millets, their contribution in ancient agriculture, potential health benefits to humans on consumption and the post-harvest unit operations applied to make millets edible. Processing plays a huge role in maintaining the grain quality, thus preventing any post-harvest losses. The review also highlights the threshing and dehulling practices around the world since dehulling is quite crucial in millet processing and it is the most tedious process step. These operations involve human labor or domestic animals for the most part because of the absence of millet processing technologies. However, since past few decades several millet processing machineries have been developed to process millets in places where millets are the primary staple crop. Development and application of those machinery has also been emphasized in the review.

The first part of this study was aimed at developing a working prototype dehuller for millets that operates primarily based on human power. It was successfully fabricated with a crank handle to transmit power using a chain and sprocket arrangement to operate the dehuller. In addition, the developed prototype was analyzed for its dehulling efficiency on different millet varieties (foxtail, kodo and barnyard millets) with respect to change in roller spacing (0.20, 0.25, 0.30 and 0.35 mm) and number of consecutive passes. A centrifugal blower was also fabricated to suit the purpose of aspirating the hulls from the dehulled outlet so as to obtain clean dehulled grains. Dehulling efficiency was found to be affected by the roller spacing and number of passes.

The last part of this thesis concentrated on exploring the applicability of microwave energy to extract antioxidants from millet hulls (Kodo variety). Microwave assisted extraction technique was effectively employed at 2.45 GHz for extracting polyphenols. Three parameters (microwave holding time, extraction temperature and solvent concentration) at different levels were chosen for extraction. Furthermore, the effect of each parameter on kodo millet hulls was studied to better understand the extractability under different microwave conditions. This method of antioxidant extraction was optimized for maximum yield using response surface methodology and central composite design (3 center points). The desirability function was used in this study to further derive the optimal extraction conditions for single and multiple responses. This study showed that millet hulls have the potential to serve as a good source of antioxidants and other polyphenols, and can be utilized as an ingredient in the nutraceutical industry.

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