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Review Paper

Pre-milling treatments and milling process of pulses: Current practices and innovations

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ABSTRACT

Pulses play an important role as a cheap protein source for people living in under developed and developing nations. Dehusking and splitting of whole pulses, to convert into dal, is the primary process before consumption. The process is referred to as pulse milling,with the primary objective to remove the outer husk (or hull) to improve cooking and culinary properties. Pre-milling treatments are given to loosen the seedcoat for efficient dehusking and minimizing losses in the form of broken and powder of cotyledons, and produce cleanly split dehulled cotyledons of pulse grains. The presence of gummy substances between the seedcoat and cotyledons is the main cause for the attachment of the seedcoat to the cotyledons. Based onthe quality and quantity of gums, pulses are considered easy or difficult kinds of pulses. Pigeonpea, blackgram and greengram are relatively difficult to mill in comparison to chickpea, lentil, and filedpea. Traditionally, pre-milling treatments are given to the whole grains to reduce the attachment of the seedcoat for ease of husk removal and splitting into two halves.Pulse milling in India is a process adopted at the domestic scale of milling. Modern commercial milling is the upscaling of the traditional pulse milling process. Water soaking and roasting were common traditional pre-milling treatments for small-scale milling. Commercial pulse mills use oil smearing or thermal treatment processes to loosen the seedcoat. This review paper has compiled work done by various researchers about traditional and innovative approaches, pre-milling treatments adopted for various pulses and their influence on the dehulling process.

***Key words**: Dal mill, Dal recovery, Milling methods, Pre-milling treatments, Pulses*

INTRODUCTION

Pulses belong to the Leguminosae family, which produces edible grains consumed by both humans and animals. They serve as a major nutritional source for billions worldwide. The terms "legumes" and "pulses" are often used as synonyms, but not all legumes qualify as pulses, whereas all pulses fall under the category of legumes. To increase worldwide awareness of the nutritional benefits and contribution of pulses to sustainable food production, the Food and Agriculture Organisation (FAO) of the United Nations proclaimed 2016 to be the International Year of Pulses. Pulses are grown on 96 million hectares globally, with a yield of around 97.4 million metric tonnes (Shahbandeh 2024, Anonymous 2024). This expansion is essential as it is anticipated that there will be 10 billion people on the planet by 2050 which will increase demand for wholesome and sustainable food supplies (Fernando 2021). In India, pulses cover around 29 million hectares (ha), yielding around 26 million tonnes annually, with an average productivity of 902 kg/ha againsta global average of 1015 kg/ha (Anonymous 2024). A large vegetarian population relies on pulses to meet their protein requirements and eats them as a staple food in combination with cereals. Pulses are a rich source of proteins (18-30%) and carbohydrates (50-65%), and are low in fat and calories. Mature grain of pulses comprises three major components, viz., seedcoat (5-15%), embryonic axis (1-2%) and cotyledons (80-90%) (Chibbar *et al*. 2010). Lysine-rich pulses,when consumed in combination with methionine-rich cereals, complement each other, making themthe best source of proteins to combat malnutrition (Singh 2017).

Pulses are consumed in various forms, viz., whole grains or split grains with husk, dehulled and split cotyledons, and ground powder (flour), to cater to diverse usage and consumer preferences. Pulses contain comparable amounts of total carbohydrates, fat, niacin, riboflavin, thiamine, and pyridoxine to cereal grains, but they have greater amounts of protein, folate, iron, magnesium, potassium and zinc. Several species of pulses are widely cultivated and consumed globally. It includes common beans, chickpeas, peas, cowpeas, lentils, faba beans and pigeonpeas, among others. They are an important part of the Indian dietary system, providing significant nutritional value and containing approximately 20 to 25% protein and offering a well-balanced profile of essential amino acids, making them a valuable food source (Gurusamy *et al.* 2022). Additionally, pulses are low-input crops, requiring fewer resources for cultivation than many other crops, which increases their economic importance. Their role in crop diversification is also noteworthy, as they serve as an alternative to staple crops, promoting agricultural sustainability. Research by Pathak *et al.* (2016) highlights their significance, particularly in resource-limited regions. Pulses are an essential for global security for food and nutrition as well as for the sustainability of agriculture, in addition to being a staple food. Dal (dehulled split seed) accounts for around 80% of the pulses consumed in India, including pigeonpea, lentil, chickpea, blackgram, greengram, and fieldpea. Dal does not need to be soaked before cooking. It gets cookedmore quickly and is easyto digest, which is why dal is liked by the people (Venkidasamy *et al.* 2019). The process of seedcoat removal and splitting of cotyledons is known as pulse milling. Milling not only reduces cooking time but also eliminates antinutritional factors, making pulses more palatable and enhancing their nutritional value, protein digestibility, and texture (Yadav *et al.* 2021).

Recent research has been extensively examined to study the influence of various pre-milling treatments on improving the dehulling efficiency of pulses. These treatments play a crucial role in loosening the seedcoat, enhancing separation and minimizing breakage and powdering of cotyledons, thereby increasing milling yield and quality. Among the most extensively researched approaches are wet milling procedures, which have been shown to improve dehulling performance (Kumar *et al*. 2023, Chavan *et al*. 2020, Choo 1993). Dry milling has also been thoroughly investigated, where pulses are processed without the use of water, relying on physical means such as abrasion or impact to remove the husk. This method is considered more energy-efficient and suitable for large-scale operations (Pulivarthi *et al*. 2021, Schmidt *et al*. 2022, Martin *et al*. 2022). Additionally, chemical pre-treatments using sodium bicarbonate or various acids have been employed to weaken the adhesion between seedcoat and cotyledons, resulting in improved dehulling efficiency (Haileslassie *et al.* 2019, Purschke *et al*. 2018). Enzymatic pre-treatment (Dabhi *et al*. 2019, Dabhi *et al*. 2018, Wood *et al*. 2022), and electromagnetic heat-assisted pre-treatments (Sunil *et al*. 2018, Pawar *et al*. 2021, Kumar *et al*. 2022, Solanki *et al*. 2022) have also been explored for improvement in the effectiveness of pre-milling treatments. Among these, wet milling has traditionally been used with promising results, whereas dry milling has become the preferred commercial method in India. Additionally, bioactive components found in pulses, such as phenolic compounds, phytates, and trypsin inhibitors, would be less prevalent in purer protein sources. Because these substances may block metabolism and decrease the digestibility of vital nutrients, they may be harmful, indigestible, or anti-nutritive to humans (Kumar *et al*. 2022). This review paper aims to examine systematically various pre-milling treatment methods adopted for pulses that help to retain nutritional value and quality attributes. Research in this field highlights several gaps, including the need for further studies on milling techniques for emerging crops, reducing energy consumption, and creating more sustainable processing methods. Overall, this review covers a broad spectrum of topics, focusing on advancements in pre-milling technologies to enhance efficiency, sustainability and product quality.

PULSES USE IN INDIA

In India, the majority of pulses are consumed in split or in the form of flour. Pigeonpea, chickpea, greengram, blackgram and lentil are major pulses of the continent, with greenpeas, cowbeans and Kabuli chickpeas as noteworthy outliers. Both whole and split pulses are commonly cooked into dal, a staple dish which is often enjoyed with cooked rice or traditional Indian flatbread (roti). Additionally, snack items like papads are frequently made using flour from black or green gram. Whether whole or split, pulses play a vital role in Indian cuisine. Cooked dal,when fried with a combination of onions, garlic, and other spices along with desi ghee, makes dal fry a staple dish available from road side Dhabas to high-end restaurants. Chickpea flour i.e., besan) is a key ingredient in many Indian dishes and snacks, while black and green gram flour are essential for making papads. Peas are enjoyed in various forms-cooked, fried, or roasted. These are commonly used as fillers in snacks like samosa or added to fried rice dishes. The widespread use of pulses (Figure 1) in the snack industry highlights their importance. As India's snack market continues to expand, the demand for pulses like desi chickpea, blackgram, greengram, and peas is steadily increasing (Didinger and Thompson 2021).

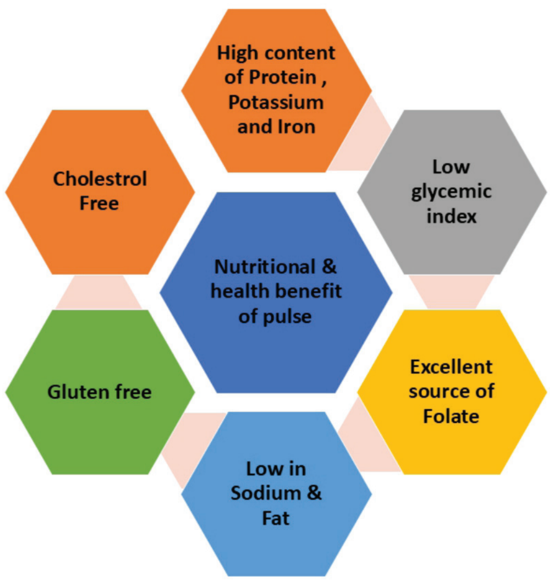

Fig. 1. Nutritional attributes of pulses

PULSES MILLING

Pulses, such as lentils, chickpea, peas, and beans, are an important source of protein, dietary fibre and various other micronutrients. In broader terms, milling is described as a method of size reduction by which materials are reduced from a larger size to a smaller size. But in the case of pulses, it is referred to as dehusking and splitting of cotyledons, to make it into a ready-to-use form. Thus pre-milling procedure is an essential process to loosen the seedcoat for ease of dehusking, which makes pulses more acceptable for ingestion and increasestheir food value. Dehulled or decorticated and split cotyledons may further be converted into flour (Wood and Malcolmson 2011). Different pre-milling methods have been developed and studied over the years to optimize the extraction of dal or flour from pulses while retaining nutritional quality, minimizing waste, and improving the functionality of the milled product for food applications. Pulses are frequently pre-treated to facilitate the separation of the cotyledon and seedcoat (Fernando 2021). Pre-treatment techniques are also used to increase the quality of the final products and lessen anti-nutritional elements present in whole pulse grains. This literature review provides an overview of the various pre-milling and milling methods adopted for pulses, their effects on product quality, energy consumption and nutritional content.

Milling for pulses is typically meant for removing the outer seedcoat. In regions like Asia and Africa, the two main steps involved in milling pulses are dehulling-removing the seedcoat to obtain polished grains and splitting, which involves separating the dehulled grain into two halves (Wood and Malcolmson 2011). Dehulling plays a key role in pulse processing, and the efficiency of this process is measured by the yield of dehulled grains, which is a critical trait for plant breeders, millers, processors and exporters a like (Wang 2005, Ross *et al*. 2010). The primary purpose of dehulling pulses is to enhance their cooking efficiency, shelf-life, taste and ease of digestion (Singh 1995, Narasimha *et al*. 2003). This process also plays a crucial role in reducing anti-nutritional factors, particularly polyphenols, chiefly present in the seedcoat, by as much as 80 to 90% (Singh 1993). The major goal of pulse milling is to completely remove the outer hull, with minimumlosses in the form of powder and broken grain cotyledons, or in some cases, even unwanted splits (Wang 2005, Asif *et al*. 2013). The process generally involves several steps, such as cleaning, grading, pitting, pre-treatment, drying, dehulling, and splitting. However, the specific steps may vary depending upon the type and variety of pulse, ease of processing, and the quality of the desired end product.

PRE-MILLING TREATMENT

It is necessary to work on the seed hull to weaken the link between it and the cotyledons and to use mechanical action to separate it. This procedure is known as pulse pre-treatment or pre-milling process. To release the seedcoat, pre-milling procedures are typically used (Singh 1995). Additionally, it aims to enhance the quality of the end product and decrease breakage. To dehull pulses, several pre-milling treatment techniques have been developed, including wetting, heating, hydrothermal treatment (Tiwari *et al*. 2010), applying edible oils, chemicals, enzymes and hydrothermal (Tiwari *et al*. 2010, Singh 1995, Joyner and Yadav 2015a).

Wet pre-milling treatment method

Wet milling is a process the pre-treatment involves soaking pulses in water or mixing with chemical solutions, tempering for a set duration, followed by sun or mechanical drying. In wet milling, the soaking process softens the seedcoat and facilitates a more efficient husk removal process. Recent studies have aimed to improve water usage and explore more efficient ways to integrate wet milling with other methods, such as enzymatic treatments, to enhance product quality (Patel *et al*. 2017). This process softens the grains to assist the separation of the seedcoat from the cotyledons. According to Zamindar *et al*. (2016), Iranian red kidney beans (Akhtar and Derakshan varieties) had softer kernels when their shear strength was reduced by employing acid/alkaline tempering solutions. A study conducted by Fernando *et al*. (2017) examined the effects of tempering on the milling efficiency of black beans by adjusting the moisture content between 10% and 50%. Their findings indicated that tempering resulted in a higher removal of the seedcoat compared to the traditional method of boiling followed by drying. The loosening of the seedcoat effectively facilitates the removal of husk from the cotyledons and enhancesthe overall dehulling process. The presence of increased moisture content in pulse grains has been shown to aid in dehulling while improving the functional properties of the milled product, making it more suitable for various food applications.

The research conducted by Ballido *et al*. (2006) and Pathiratne *et al.* (2015) suggested that moisture-based pre-treatments, such as tempering with water, salt, or acidic solutions, can reduce bean hardness and affect protein solubility, enhancing pulse processing efficiency. Ballido *et al.* (2006) found water alone was effective, while Pathiratne *et al*. (2015) showed that both temperature and moisture levels significantly influenced the functional properties of lentil flour. Additionally, Prayudani *et al.* (2023) reported that dehulling followed by 24-hour soaking improved the nutritional value and safety of velvet bean flour, reducing hydrogen cyanide to safe levels and yielding high protein, fiber and mineral content, making it suitable as a food ingredient.

Steam pre-treatment method

The application of steam pre-treatment to blackgram grains has been shown to improve their dehulling efficiency. This was explained by the disintegration of the chemical connections between gums and mucilage, which caused the seedcoat attachment of the seedcoat to the endosperm to weaken (Joyner and Yadav 2015a, 2015b).

Dry pre-treatment methods

Dry pre-treatment method for grains involves modifying the seed surface through physical processes such as abrasion, pitting, or scratching. These techniques help in enhancing the efficiency of dehulling by making the seedcoat easier to remove. According to research by Narasimha *et al*. (2003), the effectiveness of such methods largely depends on various seed characteristics, including toughness and shape. Additionally, key dehulling attributes such as pitting speed, roller gap settings, and processing time influence the overall efficiency of the treatment. One significant factor affecting the dehulling process is the moisture content of grains. Edible oil treatment is widely used in commercial milling across the nation for hard-to-mill types of pulses. Long-term soaking and drying during the wet treatment procedure cause the formation of cups in cotyledons (Verma *et al*. 2024). Dal discoloration after water soaking treatment lowers its marketability and consumer preference. Goyal *et al*. (2010) investigated the impact of different moisture levels, ranging from 6% to 14%, on the pitting and milling efficiency of pigeonpea. Their findings suggested that the most favourable moisture content for optimal dehulling performance was around 10%. Apart from mechanical abrasion, microwave treatment has also been explored as a method to enhance dehulling efficiency.

Edible oils pre-treatment method

Edible oils are also applied in pre-treatment techniques to improve the dehulling process. This is because oil penetrates the seedcoat and dissolves pulse gums, releasing the seedcoat (Fernando 2021, Tiwari *et al*. 2007). However, because pigeonpea has a stronger seedcoat adhesion to the cotyledon, this treatment is mostly limited to pre-treating for pigeonpea (Ghermezgoli *et al*. 2017) and other difficult-to-mill pulses like blackgram and greengram.

Now a days, pre-milling treatments using edible oils are widely used in commercial-scale pulse milling. Grains are pitted or scratched in emery rolls (at 10-12% moisture content), then edible oil is applied (0.1-1% w/w). After tempering, the grains are sun-dried in a thin layer for 2–5 days, the desired amount of water is added to increase the moisture content by 2-5%, the grains are tempered in heaped form for 12-18 hours, then grains are sun-dried to about 10-11% moisture content, and the grains are milled (Narasimha *et al*. 2003, Sokhansanj and Patil 2003, Tiwari *et al*. 2007). This method involves scratching 40–50% of the grains in a single (first) pass using an abrasive roller mill. After separating the dehulled lot, the unhulled or semi-dehulled material is treated once more with 0.1-0.3% edible oil and water (2-3%), and it is then allowed to dry in the sun. After many passes through the abrasive mill, the entire lot of the hard-to-mill pulses is typically dehulled (Narasimha *et al*. 2003). The oil loosens the cotyledons by penetrating the pitted shell (Deshpande *et al*. 2007). Dal made using this approach is supposed to cook more quickly than dal made using the wet method. This method's main drawback is the considerable dehulling losses brought on by breakage and powdering. The literature reports on pre-treating pulses with various edible oils to enhance dehulling. Pigeonpea pre-treatments with 1% coconut and sunflower oil (Perera 2001), 0.3% soybean oil (Deshpande *et al*. 2007), 0.4-0.8% palm, mustard, and sesame oils on blackgram (Tiwari *et al*. 2007, 2008), 0.3% mustard oil (Goyal *et al*. 2008, Hiregoudar *et al*. 2014), and 0.3% cottonseed oil (Goyal *et al*. 2009) are among these studies. According to Tiwari *et al*. (2007), oil is thought to either dissolve gums or aid in loosening the link between the cotyledon and seedcoat. Effect of oil treatment (2.4 to 4.0 g/kg) followed by tempering for 5-10 h was studied on milling of greengram, resulting in dal recovery of 70.01 to 74.93%. Application of oil at the rate of 3.17g/kg and tempering for 7.72 h were the optimum conditions for maximum dal recovery from greengram (Wani *et al*. 2011).

Thermal treatment

Hot air heating of grains has been observed to facilitate dehusking of pigeonpea and the process was standardised by CFTRI, Mysuru (Singh 1995). In the process, grains are heated using heated air at 120-180°C in LSU dryers and tempered for 6-8 hours in insulated concrete bins. The process is repeated before dehusking in abrasive rolls, yielding 81-86% dal recovery (Singh and Ilyas 1994). Alternate heating and tempering cause sweating of grains, resulting in loosening of the husk. The thermal process is most suited for difficult-to-mill pulses (pigeonpea). The process eliminatesthe use of water or oil and is weather weather-independent process, which saves time and human manpower involved in traditional milling. It also prevents the chances of development of microbial growth (water treatment) and rancidity (oil treatment) (Goyal *et al*. 2015). Sand roasting at 125^{0}C for 2.5 minutes resulted in maximum dehusking efficiency in the case of pigeonpea (Karsolia 1978). Roasting at 80 to 120^{0}C as thermal treatment for greengram before milling yielded dal recovery of 71.18 to 78.12%. Roasting at 99.24^{0}C for 2.86 min gave the maximum dal recovery at a moisture content of 10.25% (w.b.) Dal recovery of 61.19-65.64% was obtained from untreated greengram (Wani *et al*. 2011).

Hydrothermal pre-treatment method

The dehulling attributes of blackgram were significantly enhanced by the continuous hydrothermal treatment. The best results were obtained for samples with an initial moisture content (IMC) of 18% w.b. (wet basis) and steaming at an initial steam pressure (ISP) of 4 kg/cm^2 for 6 minutes, and reported change in colour value difference with only oil-treated dal. Using the Response Surface Method, the optimal hydrothermal treatment condition was calculated to be 13.1% (w.b.), ISP of 4 kg/cm^2, and Grain Residence Time (GRT) of 6 minutes. The yield achieved was comparable to the oil-pretreated samples and much higher than the untreated samples. The continuous hydrothermal treatment approach decreases overall processing time and eliminates the use of oil, preserving a non-renewable and limited natural resource. Furthermore, the moisture content of the blackgram frequently available on the market is around 13% (w.b.). As a result, these grains may be processed without any pre-conditioning requirements (Joyner *et al*. 2015). Usage of microwave heating was explored to study the dehulling properties of blackgram. Optimum microwave dose of 972 J/g gave the dehulling efficiency of 73.7% (Joyner and Yadav 2015a). Commercial exploitation of hydrothermal and microwave pre-treatment processes is still in an early stage.

Enzyme pre-treatment method

Enzymatic pre-treatment has emerged as a promising method to enhance the milling efficiency and quality of pulse-derived products. By targeting specific structural components of pulse grains, enzymes can facilitate dehulling, reduce cooking times, and improve nutritional profiles. Verma *et al*. (1993) explored the possibility of using cellulase enzyme for premilling treatment of pigeonpea and optimized process parameters using RSM and reported 87% dehulling efficiency when compared to the traditional oil-based pre-treatment process. Murumkar *et al*. (2016) evaluated enzyme treatment for improving pigeonpea milling. The optimal conditions were a 2:1:1 mix of xylanase, pectinase and cellulase at 45 mg/100 g dry matter, incubated at 45.64°C for 7.6 h. Under the recommended circumstances of enzyme treatment variables, the observed values of dehulling efficiency, dal recovery, protein content, and cooking time were 96.19%, 76.60%, 18.56%, and 23%, respectively, while the highest efficiency occurred at 45 mg/100 g, 45°C, and 8 hours. Dabhi *et al.* (2019) found that enzymatic pre-treatment of pigeonpea (var. BDN2) significantly improved dehulling efficiency with reduced cooking time, and enhanced protein content using xylanase, pectinase, and cellulose. Wood *et al*. (2022) reported the effect of enzyme pre-treatment on chickpea milling performance and dal quality. Enzymes such as endo-polygalacturonase, α-galactosidase, and cellulase were found to improve dehulling efficiency and splitting yield. However, the study also noted that some enzyme treatments resulted in negative effects, including tough seedcoats and undesirable changes in colour and texture, underscoring the importance of selecting appropriate enzymes for specific pulse varieties. Pre-treatments with xylanase and protease were employed to assess the dehulling capabilities of horse gram, pigeonpea, black gram, and green gram. Easy dehulling has been made possible by the breakdown of non-starch polysaccharides (NSP) by xylanase. Horsegram that had been pre-treated with xylanase produced 84.4% dehulled kernels, whereas green and blackgram generated 78.4% and 75.7% dehulled kernels, respectively. Green and black gram that were pre-treated with protease produced more dehulled kernels. Compared to protease, which produced a higher output of fines and undehulled kernels,xylanase pre-treatment significantly improved the dehulling qualities of horsegram. Xylanase pre-treatment was very effective in improving the dehulling properties of horsegram compared to protease, which resulted in the yield of more undehulled kernels and fines. Compared to xylanase, protease pretreatment resulted in more dehulled kernels in pigeonpea. It is also clear that the enzyme dehulling pre-treatments decreased the quantity of powder and fines created, in addition to increasing the dehulling efficiency (Sreerama *et al*. 2009). These studies highlighted the potential of enzymatic pretreatment in pulse processing, emphasizing the need for tailored approaches based on the specific characteristics of each pulse variety to optimize milling efficiency and product quality.

Chemical pre-treatment method

Researchers have observed the use of several aqueous chemical solutions, such as acetic acid, sodium hydroxide (NaOH), sodium bicarbonate ($NaHCO_3$), sodium carbonate (Na_2CO_3), and sodium chloride (NaCl) to help in weakening thelink between the hull and cotyledons in pigeonpea grains (Singh 1995). Among these, sodium bicarbonate proved particularly effective in enhancing dehulling efficiency, prompting further optimization of the process for pigeonpea (Hiregoudar *et al*. 2014, Srivastava *et al*. 1988). The method involved several steps: first, the grains were pitted, then mixed with a 5-6% (v/w) sodium bicarbonate solution, conditioned for four hours in the shade, dried to about 9.5% moisture, and finally dehulled using an abrasive mill. This approach achieved dehulling efficiencies ranging from 74.2% to 88.1%, along with a noticeable reduction in the cooking time of the resulting splits. The improved efficiency was attributed to the hydrolysis of pectin and gums in the seedcoat, which made the hull easier to remove (Srivastava *et al*. 1988). Despite these promising results, this technique has not been widely adopted on a commercial scale. Concerns have been raised about the potential leaching of valuable nutrients such as sugars, proteins, and electrolytes into the soaking solution. Additionally, discoloration of the dehulled grains and the presence of residual chemicals in the by-products (such as broken grains and hulls) make them unsuitable for use as animal feed, limiting the practicality of this method (Phirke and Bhole 2000, Lal and Verma 2007). Further, various other pre-treatment methods have been explored to enhance the dehulling efficiency and yield of pulses like pigeonpea and black gram. Singh (1995) observed that soaking pigeonpea in acetic acid significantly improved dal yield. Another study by Phirke and Bhole (1999) demonstrated that a sequence of pitting the pigeonpea, treating it with 8% urea solution at a 1:25 grain-to-solution ratio for five hours, followed by heating at 60°C for five minutes, drying to 8% moisture content, and then dehulling using an abrasive mill, led to a product recovery rate of 81%. This process was effective because the urea and heat helped weaken the bond between the seedcoat and the cotyledon (Phirke *et al*. 1995). Tiwari *et al*. (2008) soaked the grains of blackgram in 5%

aqueous solutions of sodium bicarbonate, sodium carbonate, sodium chloride, acetic acid, urea, and ethanol for one hour. Among these, ethanol yielded the highest percentage of dehulled grains at 59.6%. Interestingly, the same study found that treating black gram with just 1% groundnut oil resulted in an even higher yield (86.4%), suggesting that oil treatments could be more effective than chemicals for improving dehulling performance.

Novel and emerging pre-treatment method

Over the past few years, there has been a growing interest in exploring innovative milling techniques that could enhance the efficiency and sustainability of pulse milling. Some of the emerging methods include:

Ultrasound-assisted pre-treatment method

Ultrasound-based milling generates pressure waves that have the potential to reduce heat generation and nutrient loss during milling and preliminary research suggested it for improving the milling efficiency (Sharma *et al*. 2019). Sunil *et al*. (2018) reported the dehulling yield of nine ultrasonic treatments and exposure times. The dehulling time increased with increasing ultrasonic power and exposure time. The maximum dehulling yield (76.46%) was obtained with 450 W ultrasonic power and a 3.5-hour exposure time.

Gama irradiation and microwave-assisted pre-treatment method

Microwave energy has shown promise as a pre-treatment method for pulses, making them easier to process and reducing the energy needed for milling. This approach also helps lower the levels of certain anti-nutritional compounds like phytic acid and lectins, thereby enhancing the overall nutritional value of the final product (Mishra *et al*. 2015). In a study by Joyner and Yadav (2015a), microwave treatment of black gram grains led to better dehulling efficiency. Likewise, Solanki *et al*. (2021) found that treating chickpea with microwave energy, specifically at a power level of 90 watts for 2.5 minutes, resulted in improved yield and processing efficiency. Ballido *et al.* (2006) studied the effect of different pre-treatments (Water, saline, and acidic solution) on the Navy and Black beans and reported a change in the hardness of the beans. These studies emphasized the potential of microwave-assisted processing as an efficient way to enhance the dehulling performance of various pulse grains. Alongside microwave techniques, infrared (IR) heating has also been explored as a promising method to improve the dehulling process. For instance, Kumar *et al*. (2022) examined how IR heating affected hull attachment and the structural integrity of pigeonpea cotyledons. They observed a reduction in hull adherence after fine-tuning important elements such as voltage (203-237 V), heating duration (1.3-4.7 minutes), and seed moisture levels (8.6-15.4 g per 100 g). Their results indicate that the efficacy of IR therapy is primarily dependent on these processing parameters. Divekar *et al*. (2016) explored how microwave treatment could help reduce the cooking time of dehulled pulses such as red lentils, mung beans, and pinto beans. They found that the shortest cooking time was achieved when the pulses had a moisture content of 18% and were treated at 600W for 56 seconds for chickpea and pigeonpea, while red lentil had 14% moisture content with 600W, with a time duration of 56 seconds. Interestingly, at a lower moisture level of 10%, the microwave treatment had a more pronounced effect on red lentils and mung beans compared to pinto beans. In another study, Dronachari and Yadav (2015) highlighted various applications of microwave heating in pulse processing, including drying, cooking, extraction, and disinfestation. These applications not only improve quality but also extend shelflife. Moreover, microwave heating often consumes significantly less energy than conventional methods. While most pulse processing operations still rely on batch systems, there is growing interest in using continuous flow microwave heating as a pre-treatment to aid dehulling. In a separate investigation, Guldiken *et al.* (2022) studied the influence of infrared (IR) heating on the quality of milled flour from chickpea and navy beans, offering further insights into alternative thermal processing methods. This study was focused on evaluating how variations in seed moisture content (20% and 30%) and heating temperature (120°C and 140°C) influenced flour quality. Their research demonstrated that IR heating plays a crucial role in modifying seed properties, potentially improving the milling efficiency and overall quality of processed legumes. IR heating alone reduced the solubility, oil emulsification, and foaming ability of flours; however, adding moisture enhanced the functions. Sunil *et al.* (2018) used Response Surface Methodology (RSM) to fine-tune ultrasound treatment conditions for black gram grains, aiming to boost dehulling efficiency. Their study found that applying ultrasound at 513.4 watts for 2.12 hours led to a noticeable increase in dehulling yield while minimizing material loss. This improvement was linked to the cavitation effect created by the ultrasound, which disrupted the internal structure of grains and helped loosen the seedcoat, making the easy to removethe seedcoat during processing. Pawar *et al.* (2021) examined how gamma irradiation and microwave treatment influence the milling performance of pigeonpea across four moisture contents and irradiation doses ranging from 2.5 to 10.0 k Gy. The study found that gamma irradiation did not lead to any significant improvement in dehulling efficiency. In contrast, microwave treatment markedly enhanced both dehulling efficiency and the degree of dehulling, with the most notable increases of 18.04% and 21.65%, respectively, occurring at an energy input of 864 Joule/g and 10% moisture level. Table 1 provides an overview of the findings from various studies that employed different pre-milling treatments across multiple pulses.

METHODS OF MILLING

Traditional milling methods

Historically, pulses have been milled using manual techniques like hand grinding or stone grinding. These methods, although simple, are time-consuming and labour-intensive.This method is simple with minimal energy consumption, which makes it suitable for small-scale or household production. While the traditional method preserves the nutritional integrity of the pulses, like texture and consistency of the final product are not always optimal. In ancient mills, the average yield of dhal is claimed to be 65-74%, although contemporary mechanical processes may obtain 80-84% (Goyal *et al.* 2005). Additionally, the milling efficiency is much lower compared to modern mechanical methods in terms of yield and time. In some developing countries, traditional milling continues to be the dominant method, especially for small-scale and artisanal operations. However, these methods are becoming increasingly outdated due to advancements in milling technologies and the increasing demand for large-scale and efficient food production.

Hand pounding

Pulse milling had been a domestic-level process adopted at the household level**.** The use of a mortar and pestle was commonly used for dehusking and splitting (Figure 2). Whole grain mixed with a small quantity of water was allowed to soak and dry for a few hours. Thus, treated grains were dehusked due to the shearing action through hand pounding in a mortar and pestle. Husk, separated from the cotyledons, is removed by winnowing. The milled fractions are separated manually to obtain dehusked dal and whole. Whole grains are pounded again for complete dehusking.This method produces low dal recovery because of cotyledon rupture, yet it may be used for domestic pulse milling.

Table 1. Summary of pulses of different pre-milling treatments

Pulse type	Pre- milling treatment	Effect	References
Navy and black beans	Micronization of tempering solution with water, saline, and acid	Reduced bean hardness and solubility of protein Lower bean hardness and protein solubility	Ballido *et al.* (2006)
Black gram, green gram, pigeonpea and horsegram	Enzyme – assisted processing	Protease treatment was effective in promoting dehulling efficiency as compared to control	Sreerama *et al.* (2009)
Black gram	Irradiation by microwave	Dehulling efficiency peaked at 972 Joule/g at power level greater than 630 Watt (W)	Joyner and Yadav (2015a)
Black gram	Treatment by steam	improve dehulling efficiency	Joyner and Yadav (2015b)
Black gram	Ultrasound, exposure time	Maximum dehulling yield at 513.4 W and treatment duration of 2.14 hours	Sunil *et al.* (2018)
Pigeopea	Infrared heating, grain moisture, time	Reduced hull adherence, increased dehulling by infrared heating	Kumar *et al.* (2022)
Pigeonpea	Moisture, Pitting	Maximum dehulling efficiency at 10% moisture	Goyal *et al.* (2010)
Chickpea	Microwave	Maximum dehulling was achieved at 90 P.L. (Power Level) at 2.5 min	Solanki *et al.* (2021)
Chickpea	Enzyme treatment	Enhance milling yield, dehulling, color change darker color, maximum visual damage	Wood *et al.* (2022)
Chickpea and navy bean	Infrared heating, grain moisture, temperature	Reduced α-amylase, greater level of gelatinization, and elevatedhydrophobicity	Guldiken *et al.* (2022)

Fig. 2. AI-generated image of a hand pounding

Stone chakkies

Wooden or stone chakkies are commonly used for cottage-scale pulse milling, where relatively large quantities can be milled. These chakkies can also be used for domestic pulse milling (Figure 3). Grains are preconditioned either by applying water followed by tempering and drying, before milling in the chakkies. Roasting grains in a pan, with or without sand, can also be adopted as a preconditioning method in cottage-scale milling. The intensity and duration of treatment may vary according to grains. Burr mills and plate shellers can also be used in place of stone chakkies. In this method of dehusking, it is not possible to attain complete husk removal, which may lead to poor dal yield and high breakage.

Fig. 3. Traditionally used stone chakki for pulse milling

Commercial milling methods

To mill large volumes of pulses, large capacity commercial-scale mills are used. The milling techniques involve the up-scaled process of grain pre-treatment and milling. The dehusking techniques differ greatly with dal mills and regions, even though the fundamental milling processes are the same. Dal millers most often use the traditional method, which is conceptually quite like cottage-level treatment. For easy-to-mill kinds of pulses, moisture conditioning followed by sun drying is commonly adopted. Oil and thermal treatments are quite common for tough-to-mill pulses and are at commercial-scale pulse milling. Thermal treatment is weather weather-independent process. Milling in abrasive roller milling is one of the most widely used industrial methods for milling pulses. This method involves passing pulses through a series of abrasive rollers that scratch the grain surface to remove the outer husk cover. Depending upon the thickness of husk and attachment with cotyledons grit size of abrasive materials, such as emery or carborundum, is adopted for different pulses. Abrasive roller milling tends to remove the outer layers, which can lead to the loss of the protein-rich outer layer of cotyledons, dietary fiber, vitamins, and minerals. Cottage-scale pulse milling can be performed in mini dal mills, developed by ICAR-IIPR, Kanpur (Figure 4). The traditional method of dehulling pigeonpea is followed in various states of India, are presented in Figure 5. Research suggests that to preserve the nutritional content, adjusting the roller settings and introducing pre-conditioning steps before milling can improve yield and reduce nutrient loss. The status of dehulling of pulses and optimization of process and machine parameters are presented in Table 2.

Fig. 4. Commercial Mini dal mill (Developed by ICAR-IIPR, Kanpur)

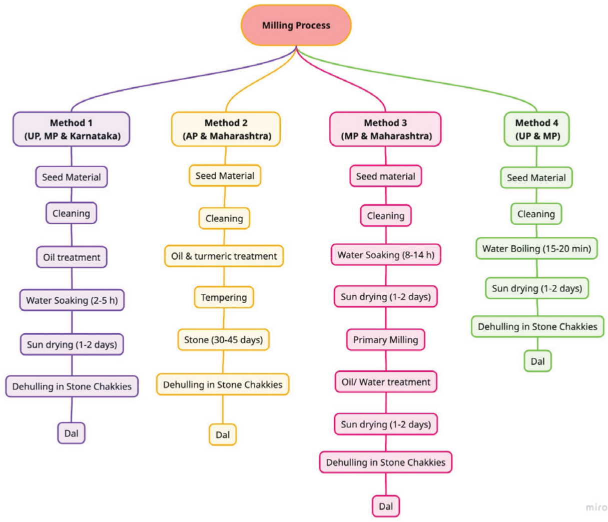

Fig. 5. Traditional method of dehulling Pigeonpea followed in various Indian States (Source: Lal and Verma 2007).

CHALLENGES AND FUTURE DIRECTIONS

Despite major break throughs in pulse milling, several obstacles remain, including increasing energy utilization in milling, enhancing bioactive chemical and nutrient retention, and resolving environmental concerns about milling waste. Future research thrust should beon the development of more sustainable pulse milling technologies, as well as techniques that retain the nutritional value of pulses while optimizing product quality. Furthermore, additional research is needed on the milling of non-traditional pulses, such as those having unique seed textures or compositions that necessitate specialised milling procedures. Advances in automation and precise milling are also required to accommodate the increasing demand for pulse-based products. As global demand for pulses continues to rise due to their nutritional benefits and role in sustainable agriculture, there is a growing need to refine existing milling techniques and explore new, energy-efficient, and environmentally responsible technologies. Future research should prioritize the development and optimization of these advanced milling systems, aiming to reduce energy consumption, minimize nutrient loss, and support large-scale, eco-friendly pulse processing to meet both consumer and industry needs.

Table 2. Status of dehulling of pulses and optimization of process and machine parameters

Crop	Type of pretreatment	Experimental design	Machine used for dehulling	Dehulling moisture content (%)	Optimum Condition	DE/DI	References
Pigeonpea	Enzyme pretreatment using Xylanase, pectinase and cellulase	RSM	Abrasive Polisher	10 d.b.	0.08%Enzyme concentration	88.7% DE	Verma *et al.* (1993)
Pigeonpea	Pitting, heat treatment after urea application	RSM	TADD	10 d.b.	12.6 m/s rotor speed	0.78 DI	Phirke and Bhole (2000)
Black gram	Pitting, palm oil treatment & drying 90	-	Abrasive Polisher	10 d.b.	0.4-0.8% oil	85.7% DE	Tiwari *et al.* (2007)
Chickpea	Oil treatment	-	IIPR dhal chakki	10 d.b.			Lal and Verma (2007)
Pigeonpea	$NaHCO_3$		IIPR dhal chakki	10 d.b.			Lal and Verma (2007)
Lentil	Storage duration	RSM	Abrasive Polisher	10.4-11.7% d.b.	10.4-11.7%	92.8-98.2% DE	Lucas *et al.* (2010)
Horsegram	Wet milling and tempering, dry milling with oil and tempering and enzyme		Abrasive Polisher (Satake grain testing mill)	10 ±0.5% w.b.	1:1:1 ratio of enzyme of cellulase, pectinase and xylanase	82.74% DE	Chandola *et al.* (2025)
Desi chickpea	Water soaking treatment with different six enzyme		Sheller component (attrition style) laboratory scale SK Engineering Mill		Endo-polygalacturonase treatment for 90 minutes	68.7% DE	Wood *et al.* (2022)
Green Gram	Oil and thermal treatment	RSM	Hand mill	8-12%	Oil application 3.17 g/kg and holding time 7.72 hours		
Black gram	Microwave (4560-810 W; exposure time 60-150 sec.)	RBD	Abrasive polisher	-	810 W for 120 sec.	73.7% DE	Joyner and Yadav (2015a)
Pigeonpea	Enzyme (Xylanase, pectinase, cellulase 2:1:1)	RSM	Abrasive polisher	10±0.5%	Enzyme conc. 37.8 mg/100g, incubation at 48°C for 8.7 min	88.12% DE	Sangani *et al.* (2014)

d.b.: Dry matter basis; RSM: Response Surface Methodology; TADD: Tangential Abrasive Dehulling Device; DE: dehulling efficiency; DI: dehullingindex

CONCLUSION

Pulses milling has been widely researched using a variety of techniques, each presenting its own set of benefits and drawbacks. Traditional milling methods, though still practiced in many regions due to their simplicity and low cost, often fall short in terms of efficiency, consistency, and product quality. In contrast, modern milling approaches such as pre-milling treatments and roller milling, have significant improvement in processing efficiency and quality of endproduct. These methods allow for better control over husk removal, reduced breakage, and wastages. In recent years, innovation like ultrasonic milling hasemerged as promising alternative. Ultrasonic milling, on the other hand, uses high-frequency sound waves to break down pulse grains, offering a cleaner and potentially more sustainable method of processing. Traditionally, soaking in water or oil mixing processes adopted at cottage and commercial scale pulse milling, though effective, but are weather dependent process. Weather independent thermal process adopted in modern commercial mills is cost and energy intensive process. Thus, there is need to explore low cost, energy efficient and weather independent pre-milling treatments for pulses to maximize dal recovery with minimum milling losses.

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