A comparative evaluation of processing of yellow peas (*Pisum sativum* L.*)* with hot air and superheated steam

by

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Abstract

The present study was undertaken to evaluate the effect of hot air (HA) and superheated steam (SS) processing methods on the functional and nutritional properties of yellow peas. Moisture content, drying characteristics, hydration capacity, cooking characteristics, dehulling efficiency, protein content, peak starch gelatinization temperature and microstructure of peas affected by SS and HA were investigated. Three temperatures (120, 135, and 150°C) for 10 minutes processing at one velocity of 1 m/s for both HA and SS were used. The processing conditions significantly affected ($p<0.05$) all measured properties of processed peas except starch. Moisture content was observed to decrease from 20% to 8.4% and 6.3% for HA and SS, respectively at 150°C. Hydration capacity of peas after SS and HA processing ranged from 12.6-27.7% and 5.8-12.3% at 120 to150°C, respectively. Peas processed with HA resulted in decrease in protein content by 1.20, 2.16, and 2.38% than the peas processed with SS, in which protein content was decreased by 0.38, 0.44 and 0.75% at 120, 135, and 150°C, respectively. An increase of 19.1, 20.0, and 35.0% in porosity was observed in SS processed peas in comparison to HA at 120, 135, and 150°C, respectively. Dehulling efficiency of HA processed peas ranged from 83.5-88.2% whereas for SS it ranged between 85.4-89.9% at 120-150°C. In regard to cooking characteristics, SS processed peas needed less extrusion force than HA for all cooking times tested (5, 10, and 15 minutes).

Additional experiments were conducted for SS processing of high initial moisture content (26, 40, and 54%) yellow peas at varying temperature (120, 135, and 150°C) and time. The soaking step was eliminated before cooking peas for 5, 10, and 15 minutes. Decrease in the extrusion force of peas was observed from 1012.2 N (at 26% initial moisture content) to 587.5 N (at 54% initial moisture content) after 15 minutes of cooking. Superheated steam processing of peas at 135°C, 54% initial moisture content and 5 minutes cooking was deemed as the optimum processing condition. This study demonstrated that SS is an effective processing method that decreases overall cooking time without compromising functional and nutritional properties of yellow peas.

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Symbol	**Meaning**
HA	Hot air
SS	Superheated steam
EF	Extrusion force
w.b.	Wet basis
ρ	Density
ε	Porosity
DSC	Differential scanning colorimetry
T_p	Peak temperature
T_o	Onset temperature
T_c	Offset temperature
ΔH	Enthalpy
μCT	Micro-computed tomography
HC	Hydration capacity
T	Temperature
MC	Moisture content

1. INTRODUCTION

1.1 Background

Global production of dry peas, *Pisum sativum*, occurs mainly in three regions - Canada, France and the Russian Federation. In 2015, Canada and the United States were the worldwide leaders in production of whole yellow peas and were also primary global exporters. In 2016, Canadian pulse production broke a record of 8.4 million tonnes (Pulse Canada 2019). In 2017, Canada, China and Russia were producing 29, 16 and 14% respectively, of the global dry pea supply. Canada emerged as the biggest producer of yellow peas in the world in 2017 with the production of 4.6 million tons (FAOSTAT 2017). As for provincial production, Saskatchewan accounted for approximately 54% of the cultivated dry pea area, followed by Alberta at 42%, with the remainder seeded across Canada in 2019 (Agriculture and Agri-Food Canada 2019).

Peas, much like other pulse crops, are nutrient rich and contain considerable amount of minerals, vitamins, fibre, carbohydrates, and protein (Frias et al. 2011). Peas possess a potential to boost nutritional profile of snack foods and this has enhanced their recognition in market. Consequently, their healthful effects prevent certain non-communicable diseases, including type II diabetes, cardiovascular diseases and early onset of cancers (Campos-Vega et al. 2010; Singh and Basu 2012). Owing to their ability to substitute soy protein (listed as Health Canada's number one of 11 allergens) and having an excellent nutritional profile, peas are attracting a lot of attention from the nutraceutical and food processing industries. The versatility of peas combined with their nutritional benefits make them a commodity of choice for healthy foods, snacks, meal replacements, etc.

In order to prevent post-harvest agricultural losses and promote long storage and shelf life, drying is an important post-harvest process for most agricultural products, including peas. Drying also helps in further processing of these protein rich peas into consumer level convenient products such as split, dehulled and milled products. The common methods of drying are oven drying, hot air (HA), microwave and infrared drying (Kumar et al. 2005, Grewal et al. 2013). Most of these technologies have many disadvantages including nutrient loss, degradation of color and non-uniform quality of the product (Sehrawat et al. 2016, 2018a); longer drying time (Kumar et al. 2005; Leeratanarak et al. 2006) etc. Infra-red and microwave drying techniques reduce the drying time and are more efficient in maintaining quality but only when used in conjunction with vacuum, which adds an additional expense (Kumar et al. 2005). A novel technique for drying, that is superheated steam (SS) drying is proposed in this study for processing of yellow peas. Although the potential to use of SS has existed for quite some time, it is only in recent years that the technique has emerged as a viable means for food processing. Superheated steam drying (which is referred to as 'SS processing' throughout this thesis) has gained attention over the last decade because of its high energy efficiency over conventional drying (Jangam and Mujumdar 2015).

Although SS technology has been tested successfully to dry products such as oat groats (Head et al. 2011), Asian noodles (Pronyk et al. 2008), potatoes (Tang and Cenkowski 2000), (Uengkimbuan et al. 2006), rice (Taechapairoj et al. 2006), soybean (Prachayawarakorn et al. 2006), brewers spent grain and distillers' spent grains (Kittiworrawatt and Devahastin 2009), carrots, cauliflower (Van Deventer and Heijmans 2001), a comprehensive study to unravel the changes it brings about in the functional and nutritional properties of yellow peas is yet to be done.

Hence, this study focuses on evaluating the potential of SS processing of yellow peas and compare it with its most popular counterpart i.e. HA. In order to evaluate the efficiency of these processing methods (HA and SS), various physical, functional and nutrition properties of yellow peas post processing need thorough examination. These properties include moisture content, density, micro-porosity, hydration capacity, cooking characteristics, dehulling efficiency, protein denaturation and starch gelatinization.

To succeed in global market, yellow peas should possess acceptable dehulling efficiency, cooking quality and textural properties. High quality Canadian yellow peas are consumed as soups and stews (Drake and Muehlbauer 1985). Yellow peas are typically consumed after cooking in the form of whole seed as well as decorticated splits in different types of food. Therefore, the cooking quality is an essential parameter that must take into consideration to ensure a high-quality end product. The prolonged cooking times of pulses is a primary constraint for wider applications and can diminish their nutritive value (Wang et al. 2010; Chandrashaker et al. 1981).

In order to minimize the overall time that is required to incorporate peas into food formulations, experiments were also performed to eliminate soaking by tempering peas to high moisture content before SS processing. However, there is little information on cooking quality of Canadian yellow peas after processing them with different processing media is available. Hence, this research focuses on proposing an efficient processing method and optimizing it for processing yellow peas with a goal of minimizing the cooking time while retaining its nutritional qualities, to ensure the utilization of this abundantly available plant-based protein.

1.2 Objectives

The main objective of this study was to evaluate processing of yellow peas (*Pisum sativum* L.*)* with convective HA and SS methods. The specific objectives were:

- To compare the effect of SS and HA processing on (CASE 1):
    - Functional properties of yellow peas such as moisture content, drying characteristics, hydration capacity, dehulling efficiency, cooking characteristics, and microstructure of pea post processing.
    - Nutritional properties of yellow peas such as protein denaturation and starch gelatinization.
- To optimize the SS processing parameters and initial moisture content of peas before processing in order to reduce the cooking time and eliminate soaking (CASE 2).

2. Literature Review

2.1 Peas

The field peas (*Pisum sativum*) are a member of the cool season legume crops group (Leguminosae) widely known as pulses. Globally, five major types of peas are grown, namely: green peas, maple peas, Australian winter peas, marrowfat peas and yellow peas. (Roy et al. 2010). However, owing to pea size and hull thickness, a distinction in nutrient content is not witnessed between yellow and green peas (Pulse Canada 2019). A slight variation is evidently seen among few types – e.g., maple peas have smaller seed size in comparison to yellow, green and marrowfat peas. A dramatic increase in the production of yellow or dry peas has been witnessed in western Canada. More than 80% of the Canadian dry pea produce is exported to about 20 countries in Europe, South America and Asia. Canada grown peas have an average 23% of crude protein with high amount of essential amino acid lysine, at 1.67% (Pulse Canada 2018).

2.1.1 Health and nutritional properties of peas

The health and nutritional properties of pulses is a matter of growing interest. Field pea is a high protein crop, with rich dietary fibre and mineral content, and is a good cereal grain complement. It has been demonstrated by numerous studies that pulses possess protective compounds against certain cancers such as those of the breast, colon and rectum (Campos-vega et al. 2010). Frequent intake of pulses also prevents diabetes and reduces the risk of cardiovascular diseases (Flight and Clifton 2006).

The amount of protein, starch, fibre, vitamins, minerals, and phytochemical components have been recommended as primary factors influencing the health impacts with respect to physiological attributes of each fraction (Dahl et al. 2012). Epidemiological, in vitro, and interventional studies have determined that peas and pea ingredients could affect glycemic response and insulin resistance, gastrointestinal and cardiovascular health, and weight management. The appetite-suppressing impacts of peas can be associated with high levels of protein and dietary fibre which may detain gastric emptying, attenuate the absorption and concentration of glucose, and induce the appetite-regulating hormones release (Nadathur et al. 2016).

2.1.2 Adaptation

Pea plant is a durable crop in regard to the climatic limitation imposed by some regions. Due to lower sensitivity and a tolerance for low temperatures, the germination and growth remain unaffected in colder climates. According to records, peas are one of the world’s oldest crops and was grown approximately 9000 years ago in the Middle East (Miller et al. 2002).

Peas have a relatively shallow root system. Moist dark-brown and black soil zones are most favorably adapted for the crop. However, its aversion to drought makes it suitable for, and productive in, brown soil zones (Oelke et al. 1991). The Canadian prairies have suitable soil and climatic conditions for growing pulse crops (STAT Canada 2016). Although historically wheat has been regarded as the main crop in Canada, recent findings identify a variety of non-cereal grains as beneficial to the country's economic policy, resulting in increased pulse production. Pulses are now included in Canada's top five agricultural commodities after wheat, barley, canola, and corn (Campbell et al. 2002).

2.2 Yellow peas

2.2.1 History

Yellow Pea (*Pisum sativum* L.) is a pulse crop and a member of the Leguminosae family. It was first grown in the Fertile Crescent, close the Tigris and Euphrates. In present-day it is located in southern Turkey and northern Syria and was domesticated in approximately 9,000 BC. It has also been harvested for thousands of years in Europe (Roy 2010).

2.2.2 Composition

Yellow peas are composed of a blend of various nutritional elements. They are rich in protein and complex carbohydrates and contain plenty of nutrients such as vitamins and minerals, to meet the needs of health-conscious consumers. Composing products of peas such as flour protein, starch, and fibre fractions can be useful in different food products (Han et al. 2010; Wang et al. 2012a).

Yellow peas have less amount of sodium, high amount of protein and are an exceptional source of both soluble and insoluble fibre, B vitamins, complex carbohydrates, and minerals such as calcium, iron and potassium. Table 1 provides the mineral and chemical composition of yellow peas (Wang 2018).

Table 2. 1. Quality of western Canadian peas 2018.

Quality Parameters	**Amount**
Chemical compositions	*% dry basis*
Moisture content	10.6
Protein content	23.4
Starch content	47.6
Total dietary fibre	15.0
Ash content	2.6
Minerals	*(mg/100 g dry basis)*
Calcium (Ca)	89.2
Copper (Cu)	0.86
Iron (Fe)	5.1
Potassium (K)	940.7
Magnesium (Mg)	132.6
Manganese (Mn)	1.1
Phosphorus (P)	323.7
Zinc (Zn)	3.6

2.2.3 Demand and production of yellow peas

Increasing demand for plant protein affects the production and trade flow of whole yellow peas, globally. Direct consumption, feed ingredients and starch are described as the primary applications of yellow peas, although pea protein concentrate is high in demand and is witnessing rapid growth in China, North America and Western Europe.

The matter stands as such: dry pea protein ingredients are not the main driver of production of yellow pea. The peas possess the highest value as a food product in the form of flour and starch, rather than in forms for direct consumption. In North America, which dominates production and exports (Canada), demand for processed pea protein is reaching a peak. Demand across the rest of the globe (for instance, China) is also witnessing a rise in development; such countries are importing a substantial quantity of whole yellow peas. The top 10 producers of yellow peas are shown in Fig. 2.1.

Encountering the substantially growing demand for pea protein, food ingredient and protein companies seek to utilize the high yellow pea production of North America by widening processing in the United States and Canada. Expectations are that European food businesses seek collaboration with processing firms to maintain cost competitiveness, or will build international operations in the United States, Canada and China (Wood 2015).

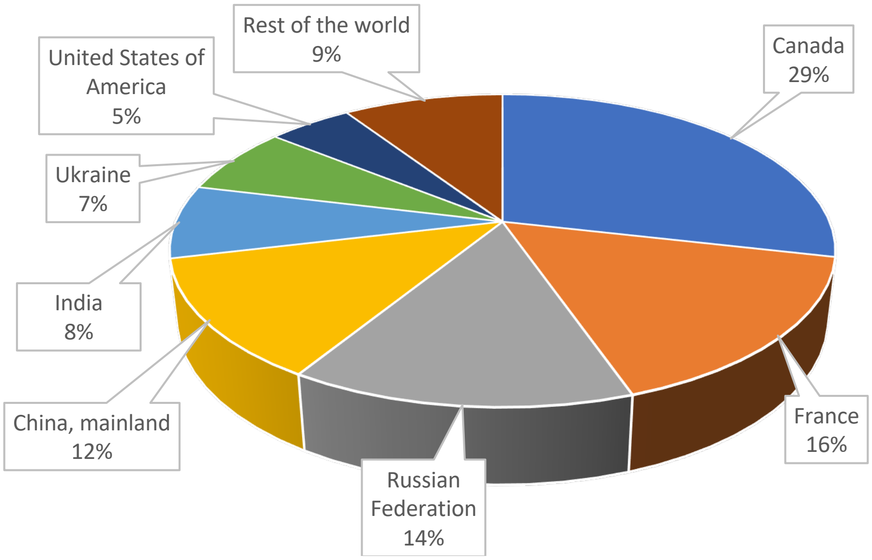


Fig. 2.1. Top 10 producers of yellow peas in 2017 (FOASTAT 2017)

2.2.4 Processing of yellow peas

In Canada, yellow peas are used for making soups which are marketed as processed soup in cans. Peas are also marketed in whole or split form in packages. Consumable forms of dry peas include canning, split, and whole dry markets, as well as products such as starch, flour, and fibre. Pea fibre has been in great demand for use in high fibre bread or pasta. Yellow peas offer good potential as a raw ingredient for the brewing industry, with historical writings approving that it has been strongly used by this industry for more than four decades (Cornell 2012). As a food product, peas are excellent in soups, can be roasted to produce a crunchy nut-like snack and pea purees can be added to food product formulations. These products are also used in baked goods, baking mixes, soup mixes, breakfast cereals, processed meats, healthy foods, pastas and purees (Han et al. 2010; Wang et al. 2012a). Typically, yellow peas are consumed after cooking and cooking time and texture of cooked peas are essential qualities (Moscoso et al. 1984). Given economic feasibility yellow peas are used as a feed ingredient and can be used as replacement for corn and soybean meal imported in western Canada. Purification of pea starch and protein, production of fine and coarse pea hull fibre, and consumer-packaged products such as pea soups, are all processing dimensions in Manitoba. Regarded as a gluten free vegetable protein source, yellow pea flour is also an exceptional source of the B vitamin folate. Its utilization in the food industry is elevating due to distinctive functional properties. Also, it is undeniable that throughout the world, peas are an approved element of the human diet. The viscosity of slurried pea flours renders them effective in aqueous food systems. (Manitoba 2018a, b).

Subjecting legumes to heat for different periods of time, namely via toasting and roasting, is extensively practised as an approach of food processing (Koksel et al. 1998). Although there are several methods available for processing yellow peas, there is no data available on the processing of yellow peas with SS.

2.3 Processing methods

2.3.1 Hot air

The conventional and the most common method to dry food products is HA drying. Heat conduction effect allows the transfer of HA to the wet material. As the wet material absorbs heat, two diffusions take place. The first is internal diffusion of moisture from inside of the material to its surface because the moisture content on the surface is lower than the internal moisture (Liu and

Zhou 2008). The moisture gradient will move water through the substance to the outer layer where the low vapour pressure results in a phase change to replenish the boundary layer of moisture-saturated air. The second is external diffusion, or the diffusion of the moisture from a material's surface to the dry medium. A wet substrate's moisture is removed from the saturated boundary layer due to the forced action air with low relative humidity. The thickness of the boundary layer for a drying substance is not a steady state but rather a function of air movement, temperature gradient, moisture content, and thermal conduction properties of the substrate. Once the moisture at the outer layer is dried, the moisture diffusion rate of the substance facilitates the rate of drying. These two diffusions proceed continuously until the moisture in the material descends to a certain degree and the purpose of drying is realized (Niu et al. 2008).

2.3.2 Superheated steam

The SS drying process can be divided into three different periods. The first period commences when there is a direct contact between the SS and the product to be dried. The temperature of the product rises to its boiling point at the processing pressure due to the portion of the sensible heat of SS given to the product to be dried. During this period, condensation is likely to happen in the 'drying chamber' or on the product owing to a lack of sensible heat in SS. The second period is defined as the constant rate period, in which the internal resistance to diffusion of moisture is lower than the external resistance to water vapour removal from the surface of the substance. The third period is the falling rate period, where drying continues until all moisture is removed.

Hundreds of SS drying systems are being used by the industries around the world. Numerous universities and research institutions have performed detailed analyses to study SS and its applications in detail (Shibata and Mujumdar 1994). Superheated steam can be used for simultaneous processing and drying of food products. Pronyk et al. (2008, 2010) conducted experiments on drying Asian noodles made from wheat flour and reported simultaneous gelatinization of starch while drying. According to Iyota et al. (2001a) and Jensen (1995), an effect of sterilization is witnessed as materials dried using SS heated up quickly. Several outcomes during processing of food, such as blanching, pasteurization and deodorization of foodstuff, can result secondary to the SS drying process (Pimpaporn et al. 2007; Devahastin and Suvarnakuta 2004; Pronyk et al. 2004; Kudra and Mujumdar 2000; van Deventer and Heijmans 2001).

2.3.3 Differences between Superheated Steam and Hot Air drying

- The heat transfer coefficient is greater for SS, and evaporation of water into SS is greater than into HA, other than when the temperature of SS approaches the saturation temperature (Chu et al. 1953).
- Superheated steam drying is done under oxygen free conditions whereas HA drying is done in the presence of oxygen (Pronyk et al. 2008; Mujumdar and Huang 2007; Pronyk et al. 2004; Iyota et al. 2001a; Iyota et al. 2001b; Tang and Cenkowski 2000).
- A period of condensation and a restoration period are observed during SS drying. Such periods are absent in HA drying (Iyota et al. 2001b).
- The HA dryer are simple in construction and in action in comparison to the SS system. However, SS drying yields better product with minimum risk of explosion, and also consumes less energy (Pronyk et al. 2010).
- As a faster drying method, SS drying requires less space than HA drying, enabling smaller size of drying systems. Thus, 50 to 80% savings in term of energy consumption and smaller equipment setups can be achieved (Pronyk et al. 2004).

- The closed-circuit system of SS machines aids to maintain an environmentally friendly condition by preventing the emission of odor, dust or other hazardous components. For instance, a 90% reduction in dust emissions during coal drying was observed in SS compared to traditional HA dryers due to very restricted ventilation gas flow (Woods et al. 1994).
- Superheated steam drying systems are substantially more efficient as compared to HA drying systems. Using SS drying at temperatures above the inversion temperature (The inversion temperature has most commonly been described as the gas temperature at which the evaporation rates into completely dry air and pure superheated steam are equal.) can contribute to shortened overall drying time in comparison to HA drying, increasing the efficiency of a drying system (Iyota et al. 2001b; Woods et al. 1994).

Yoshida and Hyodo (1963) in Osaka, studied the quality of synthetic fibres spun in a SS dryer. It was found that SS yields stronger and finer fibre. Yoshida and Hyodo (1966) also examined the drying of potato slices. Results showed that there was less oxidation, greater porosity, and a higher drying rate in SS compared to HA. List of some other food stuffs processed with HA and SS is provided in table 2.2. The merits of SS over HA encouraged research and supported reviewal methods to study SS as the drying medium rather than HA drying.

Table 2. 2. List of products used for comparison of properties after dried/processed with SS and HA by various researchers.

Product	Drying conditions	Main findings	References
Sugar beet fibre	HA- 40, 58, 78, 105°C SS-130, 140, 150 °C flow rate is 0.7 m/s	The white colour of fibre was preserved with HA drying whereas fibre turned yellow with SS.	Bernardo et al. 1990
Tortilla chips	115, 130,145 ºC	Higher drying rates, starch gelatinization and convective heat transfer coefficients were observed for SS than HA.	Li et al. 1999
Potato	125, 145, and 165°C 0.35 ± 0.01 m/s Atmospheric pressure	Drying medium temperature had a higher effect on rate of drying, overall moisture diffusivity, and therefore dehydration time for SS was lower than HA dehydration.	Tang and Cenkowski 2000
Pork	130, 140, 150°C velocity 2.1 m/s.	The color of the product from SS was relatively more intense brown than HA with lower L∗ value and higher a∗ value.	Moreira 2001
Slices raw potato	170 and 240°C	In HA drying, starch gelatinization occurs slowly than SS. Samples were more reddish when dried with SS.	Iyota et al. 2001a
Potato chips and tortilla chips	115, 130, and 145°C 100 and 160 W/m^2 °C	Drying was faster (above 130 °C) while using SS compared to HA. The SS dried chips had less color deterioration and less nutritional losses (Vitamin-C).	Moreira 2001
Processed potato chips	115, 130, 145 ºC	Superheated steam processed chips had higher shrinkage, higher bulk density, lower porosity, and lighter color than HA. Chips retained more vitamin C and texture was closer to commercial chips.	Caixeta et al. 2002

Popped Amaranth seeds	170, 200, 230, 260, 290ºC and 1.64 m/s	Heating by SS decreased the volume slightly.	Konishi et al. 2004
Paddy drying	150 °C Paddy bed depth -10 cm Superficial velocity of $1.3U_{\mathrm{mf}}$, and $1.5U_{\mathrm{mf}}$	Initial condensation assists starch gelatinization making head rice yield of paddy dried by SS more than HA. The value of whiteness of paddy dried by SS was lower than samples dried with HA.	Rordprapat et al. 2005
Soybean	120, 135 and 150°C Drying times of 2, 5, 7, 10 and 15 min Velocity 3.2 m/s	Superheated steam dried soybean had faster enzymatic inactivation was than HA. Protein solubility and lysine content maintained in typical range, between 135-150°C for HA and could be decrease to lesser than 135°C by SS.	Prachayawarakorn et al. 2006
Wet porous material	160, 200, 240, 280 °C 1m/s	Under all wet-bulb conditions, the time needed to reduce the moisture content below the critical moisture content was nearly the same at the same constant drying rate, irrespective of steam condensation.	Inoue et al. 2010
Distillers spent grain	150°C 0.5 m/s 4 Pa above atmospheric pressure.	Among the analyzed samples, the DSG (distillers spent grains) samples dried with SS had higher phenolic content. SS drying may be an appropriate method for drying DSG without an unfavorable effect on protein and phenolic content.	Cenkowski et al. 2012
Victorian brown coal	100, 130, 170, 200 °C Flow rate - 800 mL/min Steam flow rate - 6×10^{-4} m^3/s	Superheated steam drying revealed only minimal changes in the organic structure of the coal as the aromatic carbon content was kept relatively unchanged and aliphatic structures were negligibly reduced.	Tahmasebi, Arash et al. 2013

Paddy drying	130, 150, 170°C velocity of 20 m/s impinging distance 0.05m Pressure -20 kPa	Paddy dried with SS was redder and more yellowish than the HA. Also, SS drying aided in enhancing the starch gelatinization level as compare to HA at same drying temperatures	Swasdisevi 2013
Waxy rice	130, 150 ° C, bed height - 10 cm superficial air velocity - 3.5 m/s	Due to complete starch gelatinization, SS drying caused a significant change in the textural properties of both varieties of paddy.	Chungcharoen 2015
Mango cubes	60, 70, 80°C Pressure-10 kPa	High moisture diffusivity and low activation energy was attained in cubes dried by vacuum drying followed by low-pressure SS and HA drying.	Sehrawat et al. 2018b
Milk	110°C	The surface of SS dried milk particles had higher wettability than air dried. The presence of hydrophilic components was also promoted with SS drying.	Lum et al. 2018
Single lignite particle	117 °C velocity of 1 m/s	Minimal time was needed to heat the lignite sample with SS compared to HA.	Celen and Erdem 2018
Distillers spent grains	120,150 and 180 1m/s	Pallet expansion ranging from 90-133% was noticed when dried with SS. Also, the drying time was decreased by 81%, when processed with SS as compare to HA.	Erkinbaev et al. 2019

2.4 Protein

Similar to other legume seeds, yellow peas are rich in proteins (18–30%). Globulins are present in considerable amounts (80% of total protein) in pea protein along with a small fraction of albumins. Legumin, vicilin and convicilin formulate globulins and are storage of protein located in cotyledons (Pate 1977; Boulter 1983). The vicilin-legumin ratio is equivalent to 1:2, ranging from 1:1.3 to 1:4.2. (Gueguen 1983). The remaining 13-14% of the total proteins are albumins, cytoplasmic proteins composed of different kind of subunits. Albumins hold more sulfur amino acid residues than the globulins (Mosse and Pernollet 1983; Pate 1977; Grant et al. 1976). The concentrate and isolate of pea protein have excellent nutritional quality (i.e. protein efficiency ratio, essential amino acid content) and potential as a dietary protein fortifier (Linder 1985). Pea proteins are low in fat and are cholesterol-free (Swanson 1990). The amino acid profile of pea protein is stable, and the protein is rich in lysine (Schneider and Lacampagne 2000).

Throughout their development, pulse seeds accumulate protein, so mature pulse seeds are usually high in protein. Chickpea, lentil and dry pea contain about 22, 28.6 and 23.3% protein, respectively (Sotelo and Adsule 1996). However, based on plant species, variety, maturity and growing conditions, percentage of protein can vary slightly (Roy et al. 2010). Yellow pea production and trade flow is being affected by increasing demand of plant protein.

A recent study conducted by the University of Toronto, Canada, states that blood glucose response curve decreased by pea protein more than the pea fibre fraction (Mollard et al. 2014). According to Smith et al. (2011) recorded that short-term energy intake and postprandial glycemia get suppressed in young healthy males because of pea protein isolate and it also lower the pre- and post-meal blood glucose. Pea protein was used in sausage as a meat extender and as a protein fortifier for bread (Delaquis 1983; Grant 1983). Compared to the price of whey protein isolate ($13.5 to $27/Kg), soy protein isolate ($3 to $3.8/Kg) and corn zein ($23 to $35/Kg), pea protein concentrate ($2.5 to $2.8/Kg) provides a great potential for pea protein to be used in food and other industries (Krochta and De Mulder-Johnston 1997).

2.4.1 Protein denaturation

Processing techniques such as pasteurization and sterilisation are applied on protein-stabilized emulsions considering the practical applications depending on end use (McClements 2004). Denaturation is the deliberate processing activity to alter the secondary, tertiary, and quaternary structure of a protein molecule. Functionality and applicability of food proteins as well as plant protein is also expected to be affected due to denaturation. Wu and Inglett (1974) studied the effects of denaturation on plant proteins due to heat, acid, alkali, organic solvent, detergents, urea and guanidine hydrochloride. Heat treatment higher than denaturation temperature typically results in partial unfolding and subsequent protein aggregation (Wang et al. 2012b). The heat damage to protein was also noticed by Cromwell et al. (1993). They observed that during heating of DSG, drying of solubles occured, which in turn reduces the efficiency of protein utilization by animals.

2.5 Starch

Two major components of yellow peas are protein and starch. Present as discrete granules in the leaf, stem (pith, root/tuber), seed, fruit and pollen, starch is the major storage form of carbohydrates in all higher plants (Lineback 1984). Botanical origin determines the shape and size of the starch granules (Badenhuizen 1965). The total starch content of yellow peas ranges between 34 and 42.7% of dry matter (Wang et al. 2011).

Cotyledon, the largest part of the field peas, have starch granules (53%) which are tightly embedded in a matrix with protein bodies (22%) (de Almeida Costa 2006; Boye 2010). Negative correlation exists between protein content and starch content in field peas (Shen et al. 2016). According to Gujska et al. (1996) total starch content of field peas is approximately 43 and 50% for whole seed and dehulled flour, respectively. This suggests that after wet extraction and purification, the starch content is 30-35%, which is lower than the actual starch content (Ratnayake et al. 2001). China is well-positioned as the leading consumer of pea starch, process-wise, to meet pea protein demand while increasing the production of yellow pea **(**Wood 2015). Textural quality of freshly baked products and shelf life of the product is highly influenced by starch gelatinization (BeMiller and Whistler 2009).

Poor functional properties of pea starch restricted its food application; however, it is exclusively utilized for industrial application. Not only is starch utilized in industrial application, and to a much lesser extent in the food sector, but it can also be processed into nanocomposites (Ma et al. 2008; Yu et al. 2009). Availability of pea starch is majorly as by-product of protein extraction. Thus, as compared to corn, wheat and potato starches, peas are relatively economical.

2.5.1 Starch gelatinization

The word “gelatinization” of starch usually defines as irreversible change in structure noticeable in all products scales varying from micro to macro level. Hydration and radial swelling of starch granules, loss of optical birefringence, heat uptake, loss of crystalline order, diffusion of water into the granule, water uptake by amorphous background region, uncoiling and dissociation of double helices (in the crystalline regions) and amylose leaching are associated with starch gelatinization (Hoover and Hadziyev 1981; Donovan 1979; Jenkin 1994). This activity promotes thickening of the starch Gelatinization for various kinds of starch happens at distinct temperatures. As a general rule of thumb, lower temperature facilitates thickening of root-based starches (e.g. potato and arrowroot) though they break down at a fast pace. On the other hand, cereal-based starches (e.g. corn and wheat) thicken at higher temperatures but break down more slowly. Depending upon the species, sample preparation (flour or isolated starch) and methodology parameters used, the temperature range for starch gelatinization is 60 and 95°C, but this occurs only when the cotyledon moisture content is high enough (Chung et al. 2008; Hoover et al. 2010; Hood-Niefer et al. 2012).

2.5.2 Method to determine starch gelatinization

Flory-Huggins theory recommended that starch gelatinization may indeed be treated like a melting transition of a semi-crystalline synthetic polymer. Glass transition in food ingredients can be measured by numerous methods. Classification of these methods can be done into thermal (differential scanning calorimetry (DSC)), mechanical (thermo-mechanical analysis, dynamic mechanical analysis), spectroscopic (electron spin resonance, nuclear magnetic resonance) and electrical (dielectric measurements) methods (Seyler 1994). Mechanical and dielectric approaches calculate change in motion of molecules during glass transition. Determination of glass transition based on information on chemical bonding and molecular mobility is done by spectroscopic techniques (Roos 2010). DSC is one of the most common methods to measure starch gelatinization as it is easy to perform, rapid and reliable. With DSC, change in heat capacity between the glassy and rubbery states determines the glass transition temperature.

Differential scanning calorimetry is a thermal analysis technique for measuring changes in thermal and chemical properties of materials as a function of temperature (Gill et al. 2010). The change of the state of a substance is accompanied by a change in the energy level. Energy changes can be demonstrated by heat absorption (endothermal response) and heat liberation (exothermal reaction). Kinetic and thermodynamic data including protein denaturation temperature and enthalpy related to transition can be obtained by DSC (Privaloy et al. 1974; Jood et al. 1985; Hermansson1979; Murray et al. 1981). It has been stated that the peak temperature (T_p) and enthalpy (ΔH) of gelatinization values of smooth pea starch are from 60–67.5°C, and 14.1–22.6 J g^{-1} respectively (Davydova et al. 1995; Ratnayake et al. 2001). The temperature region has a strong endothermic peak between 54 and 73°C for different starches and this was described as the gelatinization temperature (Yu and Christie 2001).

2.6 Dehulling

Structurally, whole kernel consists of the seed coat (hull), embryo and the cotyledons. The process of removing outer hull (fibrous seed coat or testa) is known as dehulling. The hull is firmly attached with cotyledons usually via a thin layer of gum and mucilage along with uronic acids in the form of calcium pectate. Conversion of whole seeds of pulses to dhal for easy consumption is achieved via the dehulling process, also known as primary processing. Dehulling is an imperative operation performed during post-harvest handling of pulses, and therefore brings an ease in processing and utilization (Singh 1995). A decrease in tannin content and improvement in digestibility was observed by Deshpande et al. (1982), after dehulling.

Seed coat removal of pulses is considered as an inevitable step prior to cooking for making soups or other processing operations. In addition to improving appearance, texture and palatability of pulses, this step brings reduction in fibre content (Sokhansanj and Patil 2003). The seed coat is made up of cellulose, hemicellulose, lignin, pectin and calcium, and is poor in nutrients except for calcium (Kadam et al. 1989). Therefore, removing it does not have a large effect on the overall food value (Stanley el al. 1989).

Revolution in the industrial sector has brought mechanical methods of dehulling. First step of pulse dehulling involves pre-milling treatment (to loosen the bond between husk and cotyledon), followed by dehulling and at last splitting, however there are several differences in these steps (Sokhansanj and Patil 2003). Dehulling is an important means of improving the utilization of pulses and other legumes. Phillips and McWatters (1991) and Uzogara and Ofuya (1992) found that it brings improvement in the digestibility of protein through the reduction of anti-nutritional compounds such as tannins, found in the seed coat. It also leads to faster cooking times and removes a large proportion of oligosaccharides, which cause flatulence, especially in children.

2.6.1 Factors effecting dehulling efficiency

Machinery and methods affect the dehulling efficiency (yield of “splits”), while some factors such as environment, agronomic practices, grain characteristics and pre-treatments (method to loosen the hulls) are known to influence the dehulling process in various pulses (Ramakrishnaiah and Kurien 1983; Singh 1995). Dehulling efficiency is affected by the way of handling and storing pulses. Intrinsic seed characteristics, seed handling parameters and the dehulling process itself effects the outcome or yield of dehulling operations. These 3 factors are briefly discussed below:

⇒ **Intrinsic Seed characteristics**

- Pulse dehulling properties are influenced by the nature of the seed coat. A higher content of seed coat will consequently lead to lower cotyledon yield (Singh 1995).
- Dehulling efficiency of yellow peas also depends upon structure of seed coat. Sefa-Dedeh and Stanley (1979) suggested that dehulling of thin and rough seed coats is less satisfactory as compared to smooth seed coats.
- Binding of the seed coat to the cotyledon is a vital factor effecting dehulling efficiency. Ehiwe and Reichert (1987) considered that loose binding of seed coat is a main factor responsible for good dehulling quality.
- Seed size has a key role to play in the dehulling behaviour (Singh et al. 1992). Erskine et al. (1991) found that dehulling efficiency of large seeds is low due to the increased broken and powder fractions. Ehiwe and Reichert (1987) studied the 23 genotypes of yellow pea and concluded that seed size is usually the key factor that affects dehulling.
- Dehulling properties of pulses are influenced by the change in variety, growing conditions and environment. (Wang 2008; Erskine et al. 1985; Williams and Singh 1987).

⇒ **Seed handling parameters**

- Dehulling efficiency of pulses reduces due to high seed moisture content. (Mazza and Campbell 1985; Wang 2005).
- Storage temperature of pulses is also a principal factor. Area of research on effect of temperature on dehulling efficiency have not been explored much. Mazza and Campbell (1985) stated that temperature has no effect on dehulling efficiency of buckwheat.

- The pre-conditioning treatment before dehulling has been extensively studied as a factor effecting dehulling efficiency. Black et al. (1998a, b), Tiwari et al. (2008) and Goyal et al. (2008) used some pre-treatments such as moisture conditioning and soaking in chemical solutions or vegetable oils to loosen the seed coats and observe their effects on dehulling yields.

According to Komey (1999), cowpea seeds showed an increase in cotyledon hardness after steaming, which could account for the improved dehulling efficiency exhibited by steamed seeds as compared to non-steamed seeds. The most efficient dehulling method was drying at high humidity and high temperature. Dehulling efficiency was also enhanced by increasing drying temperature irrespective of steaming time or drying humidity.

⇒ **Dehulling process**

Eventually, method of dehulling and involved parameters influence the dehulling efficiency.

- Operating conditions such as type of mill, speed and dehulling time (Wang 2005; Reichert and Youngs 1976) affect the dehulling efficiency. Generally, dehulling efficiency is improved by increasing dehulling time and speed of motor (Wang 2005).
- Dehulling time is a key parameter affecting dehulling efficiency and dehulling loss. (Kharchenko et al. 2018).

2.6.2 Dehulling methods

Pulse dehulling is preferably accomplished by subjecting the grains to an abrasive force. There are mainly two type of dehullers – attrition-type and abrasive-type. With attrition-type dehullers, dehulling can be accomplished mechanically (DeMan et al. 1973). Grains pass through a cylindrical head where they are rubbed against a cylindrical metal screen by a drum (Reichert and Youngs 1976). Abrasive-type dehullers are also used to dehull pulses (Kurien and Parpia 1968), particularly ones that adhere more strongly to seed coats (Kurien 1984). This form of dehuller utilizes a carborundum or emery layer to gradually separate the seed coat from the cotyledon (Reichert et al. 1984). In a constant operation, grains are thoroughly fed into the machine by a hopper positioned at one end and released through an overflow outlet after the action of the stones (Reichert and Youngs 1976).

Considering the abrasive type dehullers, Satake type mill is commonly used for scientific studies. Black et al. (1998b) observed that a Satake testing mill was ideal for dehulling field peas with excellent reproducibility. They utilized it for research on the impacts of preconditioning and varieties on the dehulling efficiency of field peas. This test mill operates with an abrasive stone rotating at variable speeds. The stone, encircled by a screen, crushes the peas, causing the hulls to break and the seeds to split. This mill was also used for red lentils (Wang 2008), pigeon-peas (Goyal et al. 2008; 2009), and black gram (Tiwari et al. 2008). Both decortication and splitting of yellow peas could be performed in a very short time by Satake mill. Many pulse studies show that decortication becomes easier while preconditioning the seeds before processing (Swamy et al. 1991; Sachan et al. 1993), but little appears to have been reported on preconditioning of yellow peas.

Prairie Regional Laboratory (PRL) of the National Research Council of Canada in Saskatoon developed another abrasive type dehuller which is called the tangential abrasive dehulling device

(TADD) (Sokhansanj and Patil 2003). Pulse Processing Laboratory from the Central Institute of Agricultural Engineering, Bhopal, India include other designs as well (Sahay and Bisht 1988).

2.7 Hydration capacity

The hydration capacity is described as the degree to which cotyledon and cell contents such as starch, protein and cell wall components, become completely saturated with water. It helps to approximate the reactive time of cooking. Labuza and Busk (1979), stated that the terms ‘Water Hydration Capacity’, ‘Water Holding Capacity’ or ‘Water Binding Capacity’ are interchangeable for determination of water holding ability of food and its components. While investigating the Canadian field peas from different locations, An et al. (2010) found that hydration capacity of different verities of peas ranged from 57-127%.

2.7 Cooking quality

The cooking time required by the beans to attain a cooked texture acceptable for consumers is known as the cooking quality (Moscoso et al. 1984). Cultivar, seed composition, growing location and climate, along with many other factors can influence the cooking quality of yellow peas (Gubbels and Ali-Khan 1991; Wang et al. 2010). In addition to physical parameters such as seed size, weight, seed coat and cotyledon properties also bring respective alteration to the quality of cooking (Sefa-Dedeh and Stanley 1979).

The market value of peas is influenced by cooking quality, particularly those destined for processing into soup. There is consistent requirement of good-cooking peas in soup processing to ensure top quality product. Normal colour, flavour and texture could change in the final product, if a larger proportion of pea seeds are hard-to-cook (Gubbeles et al.1985).

Cooking is required to render peas edible and to ensure acceptable sensory quality (Bourne 1982). During their preparation as an edible product, the seeds undergo several physicochemical changes such as gelatinization of starch, denaturation of protein, solubilization of polysaccharides, softening of structure, physical and chemical change etc., which leads to palatable texture (Aguilera and Stanley 1985, Vindiola et al.1986). Cooking inactivates the level of antinutrients such as trypsin inhibitors and flatulence causing oligosaccharides and soften the seeds, thus improving nutritional quality, in addition to softening the seed (Jood et al. 1985). Inactivation of antinutritional factors including digestive enzyme inhibitors and hemagglutinins, leaching of polyphenolics, and gelatinization of starch from cooking leads to increase palatability and digestibility (Tharanathan and Mahadevamma 2003; Muzquiz and Wood 2007; Wood and Grusak 2007).

2.7.1 Soaking

Soaking is an essential step before the cooking of pulses and beans in order to reduce their cooking time. Whereas, soaking refers to immersing peas in excess media, tempering refers to adding a specific amount of media so that at the end of the pre-treatment period the seeds reach a specific level of moisture (Arntfield et al. 1997; Scanlon et al. 1998). In some studies, water alone was used as pre-treatment (Sefa-Dedeh et al. 1978; Anzaldula-Morales et al. 1996), whereas in other studies, various solutions were used. Beans are recognized for their gas producing effects. They contain compounds that are hard to digest for humans. Before cooking, pulses should be rinsed and soaked to decrease their cooking time and their gas-producing effects.

Bishnoi and Khetarpaul (1993) stated that there is a negative correlation between higher hydration capacity and cooking time. Wang and Daun (2005), Sharma (1989) and Bhatty (1984) presented positive results for the effect of soaking on chickpeas, lentils, as well as both desi and kabuli chickpeas. Many authors have proved that cooking time for lentils is reduced after soaking (Abou-Samaha et al. 1985; Singh et al. 1988; and Bhatty 1990).

2.7.2 Methods to determine cooking time

Pulses are generally cooked before human consumption by a hydrothermal process such as boiling, pressure cooking, or canning. Yellow peas could be cooked as such in their dry state or can be cooked after soaking for required time. Cooking time could be measured from several reported methods but there is none universally accepted (Wang et al. 2003). Although the tactile method developed by Vindiola et al. (1986) does yield valuable information, the process is time-consuming and subjective. Pulse cooking can be done in numerous ways, some involving dry heat, whereas others involve wet heat, with or without the use of pressure. Some of the methods used to determine the cooking time are discussed below:

- **Sensory Analysis**

Bourne (1972) claimed that food texture can be detected through mouthfeel with greater sensitivity compared with instruments and objective methods, although this may not be accurate anymore due to advances in instrumentation.

- **Tactile (Forefinger and Thumb) Method**

This method was described by Vindiola et al. (1986) and is probably the earliest developed methodology to assess the cooking time of pulse seeds (Ritthausen 1872), which is still used by some laboratories today (Sethi et al. 2011; Tripathi et al. 2012; Kinyanjui et al. 2015; Wani et al. 2014). The seeds are boiled in excess water and after scooping out approximately 10 seeds, they are squashed between index finger and thumb to test the softness of seeds. To ensure a set percentage to seed are adequately soft, this is performed at regular time interval (as short as 1 minute). The time at which this happens is recorded as the cooking time.

- **Spread Area Ratio (SAR) Method**

Cooking time of mung bean (*Phaseolus aureus* L.), horse gram (*Macrotyloma uniflorum* L.), pigeon pea, and lentil, as well as rice grains can be detected through this method, but it is not applicable for pulse whole seeds (Sashikala and Narasimha 2010). The working principle is similar to tactile (glass slide) method but focuses on squashed dhal spread rather than perceived softness.

- **Mattson Bean Cooker Method**

This methodology was first recommended by Mattson (1946). It includes individual hollow plungers with lead shots, each of which rests on a single grain. Cooking time is measured after immersing this unit in boiling water. For leaching prevention, the method intended to cook the seeds in steam from the boiling water, consequently the level of boiling water is maintained at approximately 1 in. (2.54 cm) below the seeds (Mattson 1946). Optimum cooking time is considered when 80% of seeds are cooked (Wang et al. 2003).

- **Texture Analysis Methods**

Cooling quality of pulses is analysed by texture analysis methods. Compared with methods designed to measure the optimal cooking time, the development of such methods is easier. The latter mostly precedes the former, due to the fact that cooked quality is analyzed most often at optimum cooking time. If the optimum cooking time is unknown, then the samples are often cooked for an adequate cooking at a standardised time set by the author. Based on estimation of required cooking time, degree of softness could be ranked using these methods (Wood 2007). Different texture analysis methods include:

- Puncture method
- Cutting method
- Deformation method
- **Ottawa Texture Cell Method.** A larger number of samples could be tested at any one time with this method of analysis as compared to other texture analysis methods, leading to more reliable results without much replication. It is used for cooking analysis, in which resistance to compression of seed is measured. Major drawback is difficulty in cleaning and realignment between samples and is also time consuming. Also, the cell is not suitable for large size beans (Wood 2007).

2.8 X-ray micro-computed tomography

X-ray micro-computed tomography (μCT) is an extensively used technology to characterize a number of physiological as well as pathological processes. Computed tomography was developed by Hounsfield in 1972. The word ‘tomography’ is derived from two Greek words: ‘tomo’ meaning ‘slice’ or ‘section’, and ‘graphy’ meaning ‘to write’ or ‘to display’. The CT scan enables three-dimensional, non-destructive imaging of the internal structure of the object under analysis by measuring the attenuation of the radiation beam (Boerckel et al. 2014). It is also very sensitive, easy, quick, precise and non-invasive. It can precisely differentiate between ordinary and abnormal structures. The X-ray μCT can provide the density distribution and the internal structure of the object of interest (Kelkar et al. 2015).

2.8.1 Applications of X-ray μCT

Since 1980, CT scanning has been a common diagnostic instrument in medicine. X-ray μCT is typically used in three areas: scientific research, industry and medicine. It has been used to create enlarged pictures of molecular and atomic structures. The technology has been extremely beneficial in diagnosing illnesses such as cancer, tumours, haemorrhages, head injuries and bone fractures. The implementation of this technology in X-ray attenuation enables innovations in medical diagnostic capabilities and has been needful for medical profession witnessing a decrease in the exploratory surgery for examination of inner human body structures.

Soil fractures, the density of a soil sample and macropores in soil can be quantified thorough computer tomographic images (Anderson et al 1990; Hopmans et al. 1994). X-ray μCT is a leading approach to identify physical factors related to voids or structures, desiccation or undesirable fragments (pits) and other foreign materials such as rocks, soil or pieces of equipment (Tollner 1993). Objects of different densities could be differentiated through X-ray μCT. Geoscience and archaeology are using this method for assessment of texture, geometric depiction and to quantify the porosity and water distribution in rocks and soils (Adderley et al. 2001; Ketcham and Carlson 2001).

X-ray μCT scanning is increasingly being used in non-medical research applications. X-ray imaging is an emerging technology for detecting strongly attenuating materials and has been applied to numerous inspection applications in the agricultural and food industries. Food industries submillimeter resolution capable of investigating the intricacies of many processes occurring in food products. Air cells of chocolate bars and marshmallows were observed by Lim and Barigou (2004) using μCT. Microstructural properties of red lentils puffed snacks was studied by Luo et al. (2020).

3. Material and Methods

3.1 Raw material

Yellow peas (*Pisum Setivum* L.) used in this research were purchased in 2018 from AGT Food and Ingredients (St. Joseph, MB, Canada) and transported to the University of Manitoba (Winnipeg, MB, Canada) in plastic bags each weighing 2.6 kg. The AC Agassiz variety of peas used for the research (Fig. 3.1) was grown in Southern Manitoba during the crop year of 2017. Upon arrival, peas were stored for 1 week at 4°C in closed Pioneer® plastic containers. All research experiments started 10 days after the arrival the of peas in the laboratory. All experiments were performed in triplicate unless otherwise stated. The initial moisture content of the peas was 9±1% (w.b).

Fig. 3. 1. Raw yellow peas.

3.2 Comparison of properties of yellow peas processed with hot air and superheated steam – Case 1

3.2.1 Tempering

Twenty kilograms of peas of 9% (w.b.) initial moisture content were divided into batches of 500 g each, and a predetermined amount of distilled water was added to raise the moisture content to 20±1.5%. The peas were stored in low density polyethylene (LDPE) bags with a thickness of 2 gauge/0.1 mm and placed in closed Pioneer® plastic containers of 5.3 L capacity, at 4ºC (Rani et al. 2013). Uniform distribution of water within the sample was ensured by spraying water on the peas and tumbling the bag twice a day for 5 days (Jian et al. 2019). The amount of water needed was calculated using the following relationship (Scanlon et al. 1998):

$$Water\ needed = M_T\ (\frac{m_t - m_{in}}{100 - m_t}) \tag{3.1}$$

Where, M_T = Total mass of peas (g)

m_t = Target moisture content (percentage wet basis)

m_{in}= Initial moisture content (percentage wet basis)

3.2.2 Moisture content

Moisture content of peas was measured by a laboratory oven (Thermo Electron Corporation, Waltham, MA) using AACC International method 44-17.01. Briefly, small aluminum trays were used to dry the peas in the oven for 72 hours at 103°C. The Adventure™ Pro (OHAUS®) scale with error ± 0.002 g was used to weigh the samples and trays.

3.2.3 Processing methods

Two methods of processing peas – HA and SS – were chosen.

3.2.3.1 Hot air

Pea samples were processed in a convection hot air oven (Tenney Environmental TPS, White Deer, PA) for 10 minutes at three temperatures (120, 135 and 150ºC) and 1 m/s air velocity. Before starting the experiments, the drying chamber, with an empty tray, was pre-heated to the selected operating temperature (Erkinbaev et al. 2019). A vane anemometer (Testo 417, Lenzkirch, Germany) with an accuracy of 0.1 m/s measured HA velocity at the sample tray. For each sample the tray was carefully placed at the same location in the oven to ensure that all peas were subjected to same drying conditions at 1 m/s velocity.

3.2.3.2 Superheated steam

The SS drying unit was designed and fabricated at the Department of Biosystems Engineering, University of Manitoba, Canada. The system comprises a water tank, boiler, superheater, drying chamber, and heat exchanger (Fig. 3.3). The water reservoir in the system supplies water to an electric boiler. The boiler produces saturated steam (at approx. 2.75 bar pressure) which passes through a pressure reducing valve, creating SS, and is then transferred to a superheater, rising the temperature of the steam above 100°C. Cenkowski et al. (2007) and Zielinska et al. (2009) have explained the function of each component of the SS drying unit. A thin perforated sample holding tray was placed inside the SS drying chamber and the position of the tray was adjusted to keep it at the center of the drying chamber. The tray was made from an aluminum collar with a stainless-steel mesh bottom and a glass cylinder. The diameter of the bottom of the collar, where steam enters the sample, was 81.3 mm. The mesh was woven stainless steel with a square aperture width of 1 mm and a wire thickness of 0.35 mm. The glass tube extending above the aluminum tray had a height of 75 mm and an inside diameter of 85 mm (Fig. 3.2). Operating conditions (120,135 and 150 °C and 1m/s velocity) were the same as for the HA processing. Steam velocity for all selected temperatures was kept at 1 m/s using the flow control valve, pressure gauge and calibration chart provided with the SS dryer. Condensation of steam on the tray and the inner walls of the drying chamber was avoided by pre-heating both of these components to the required operating temperature (120, 135 or 150°C).

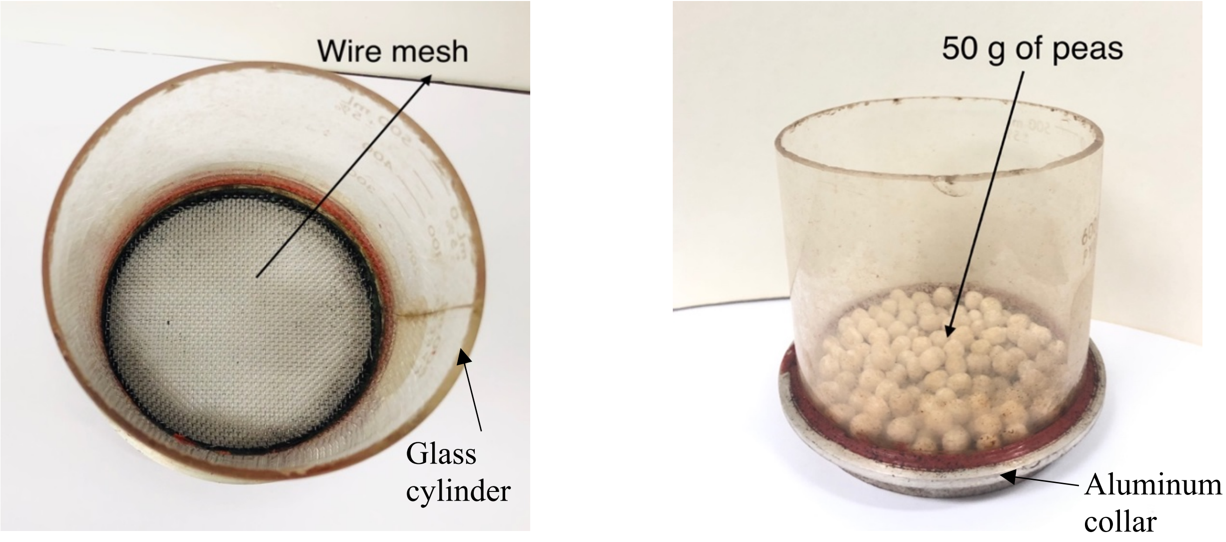


Fig. 3. 2. a) A sample holding tray b) tray holding 50 g of peas for SS processing.

Further, the glass door at the front of the drying chamber was opened and 50 g of peas were placed in a preheated holding tray. The glass door was held tightly with a silicon gasket of 3 mm thickness to prevent the leakage of steam (Ramachandran et al. 2017, 2018). Superheated steam was always diverted to the water tank before opening the drying chamber.

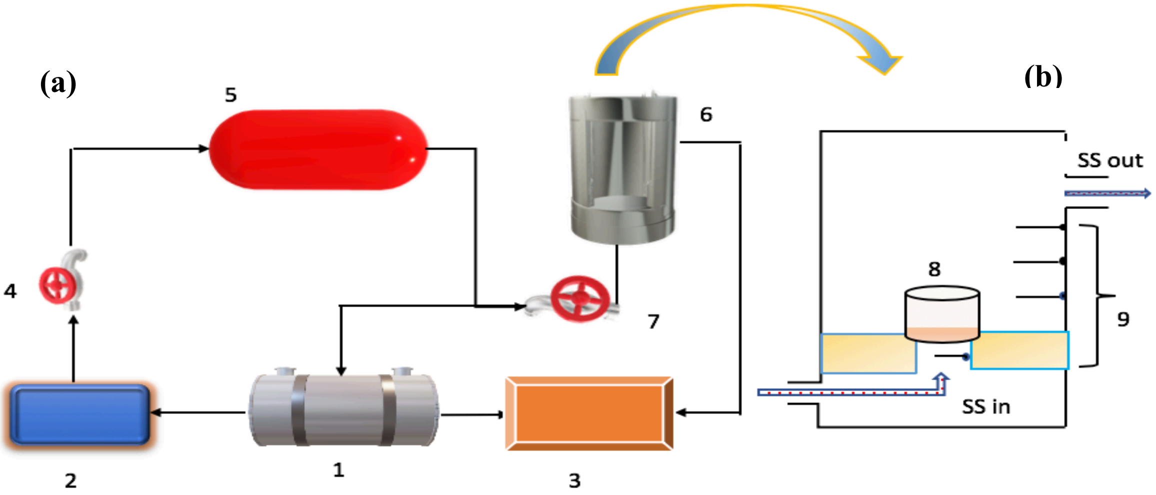


Fig. 3. 3 (a) Schematic diagram of SS drying system (1- water tank, 2- boiler, 3- heat exchanger, 4 and 7- flow control valve, 5- superheater, 6- drying chamber) (b) cross-sectional view of drying chamber (8- sample holding tray, 9- thermocouple assembly).

3.2.4 Hydration capacity

After processing of peas in HA and SS, distilled water in a ratio of 1:4 (sample mass:water mass), was added to the peas and placed at room temperature for 18 hours of soaking. After soaking, a 1410 µm sieve (14 mesh US Standard Sieve Series) was used to drain the peas for 5 minutes. The sieve was held at a 45° angle to ensure complete drainage. The mass of the drained and blotted dried peas was recorded as 'hydrated mass'. The drained water was collected in the plastic container and 2 mL of water was sampled from it. This collected water was deposited in an aluminum tray and evaporated at 100°C for 24 hours to calculate the amount of leached matter in the drained water. The leached solid mass was calculated by multiplying the amount of leachate in 2 mL of water with the total amount of water left behind. This is also called 'total leaching loss' (Bellido 2003) or 'soild loss'. The equation given below was used to express the 'corrected' water absorption capacity (%) (also expressed water absorption capacity (AACC Method 56-30.01) of yellow peas described by Jackson and Varriano-Marston (1981)):

$$\frac{Weight\ after\ soaking - Initial\ Weight + Solids\ Loss}{Initial\ Weight} \times 100 \qquad (3.2)$$

3.2.5 Cooking characteristics

3.2.5.1 Soaking

Soaking is a preferred pre-treatment for cooking of pulses. Glass jars (U-Line) of 473 mL capacity with plastic lids (Fig. 3.4) were used for soaking 55 g peas in 220 mL of distilled water for 18 h at room temperature (21±2°C). This ensures full penetration of water into the peas as reported in study on beans, wrinkled bean seed and legumes by Kon (1979), Buckle and Sambudi (1990), and Deshpande and Damodaran (1990), respectively.

Fig. 3. 4. Soaking process of yellow peas.

3.2.5.2 Cooking

Cooking of peas is a hydrothermal process involving gelatinization of starch, denaturation of protein and softening of structure. Cooking experiments were performed according to AACC International method 56-36-01 (2012). A glass beaker (Kimax®) of 1500 mL capacity was used for cooking. Figure 3.5 shows the cooking process of yellow peas. The peas were cooked for the predetermined time (5, 10, 15, 20 minutes) on a hot plate (Thermo Scientific ™, model No SP131325; Waltham, MA). After cooking the first batch for 20 minutes it was observed that the peas became overly cooked and mushy (Fig. 3.6). Therefore, 20 minutes cooking time was eliminated and only 5, 10 and 15 minute durations were chosen for cooking experiments.

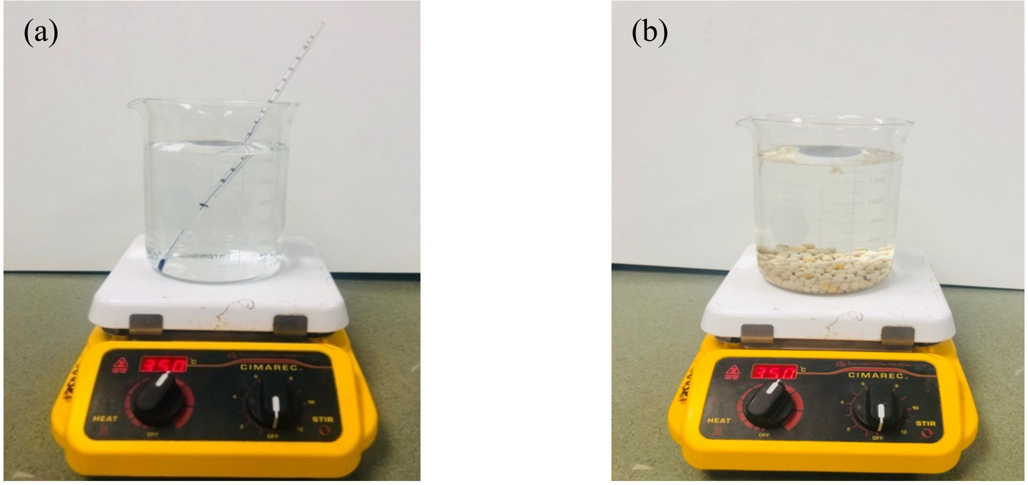


Fig. 3. 5. Cooking of yellow peas (a) preheating of water to 100°C (b) cooking of peas in preheated distilled water.

The amount of water used for cooking was in the ratio of 1:25 (soaked peas:distilled water). Peas were poured into the glass beaker only when the water temperature reached 100°C. After cooking for a predetermined amount of time, the cooked peas were drained for 15 s using a strainer. Next, the strainer was placed in the glass beaker of 1000 mL capacity, filled with 700 ml of distilled water (21± 2ºC) for 30 s. The peas were drained again and then immersed for 90 s together with the strainer in another glass beaker (Kimax®) of 700 mL capacity filled with distilled water at 21±2°C (Wang and Castonguay 2014).

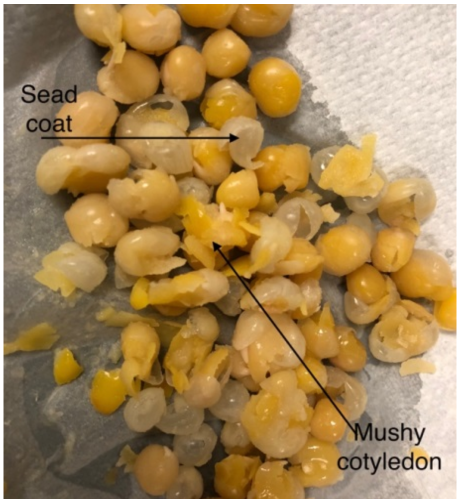


Fig. 3. 6. Peas cooked for 20 minutes.

3.2.5.3 Texture analysis

Texture of cooked peas was assessed using an Instron universal testing machine (model 3366, Instron, Norwood, MA) with a 2000 N load cell. The load cell was attached to Ottawa texture cell (model S4427 A) fitted with an extrusion insert (model S5404 A) consists of 52 holes, each 3 mm in diameter. Fifty-five grams of cooked peas were placed in the texture cell, and the sample was compressed to within 3 mm from the base of the cell with the help of a plunger set at a crosshead speed of 60 mm/min (Fig. 3.7).

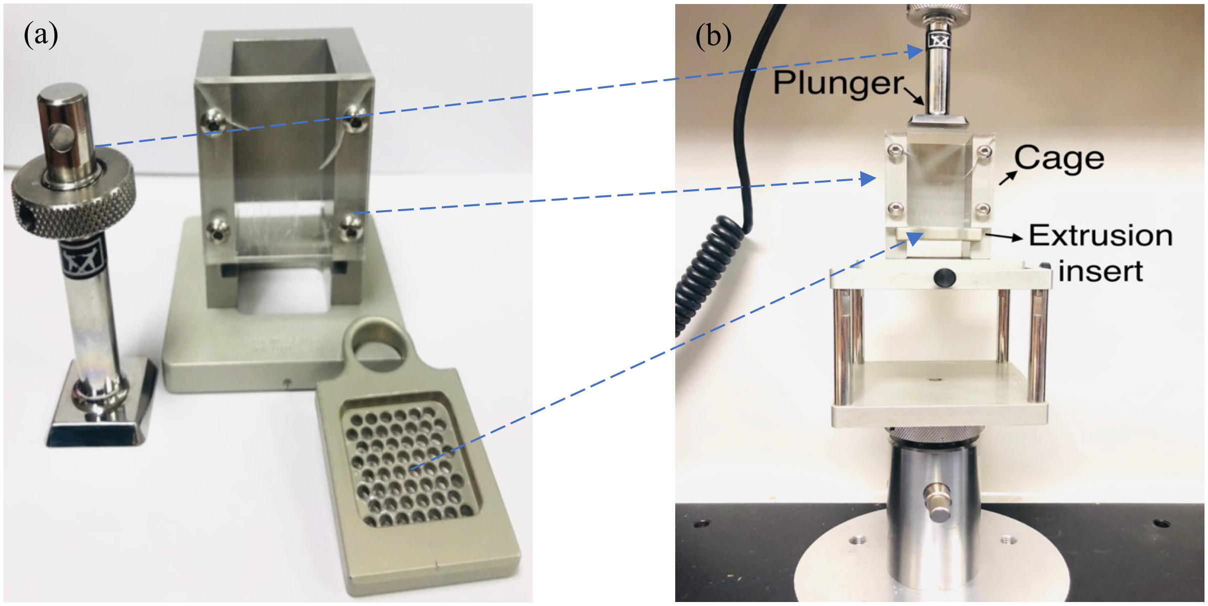


Fig. 3. 7 Ottawa textural cell (a) showing the plunger, cage and extrusion insert, and (b) experimental setup.

Instron Bluehill® Software (Instron, Norwood, MA) was used to collect the data. The test began when the compression force reached a load of 1 N; however, raw data was collected from the start of the plunger and thus data for deformation had to be normalized to 0 mm when the compressive load reached 1 N. Total crosshead travel was 29 mm. Raw data was analyzed for every replicate by visually identifying the inflection point as reported by Ross et al. (2009) and the following parameters were obtained: inflection force, inflection deformation, slope and extrusion force (EF). The inflection point was visually observed as the point where the curve at both coordinates (force and deformation) changes from concave upwards to concave downwards.

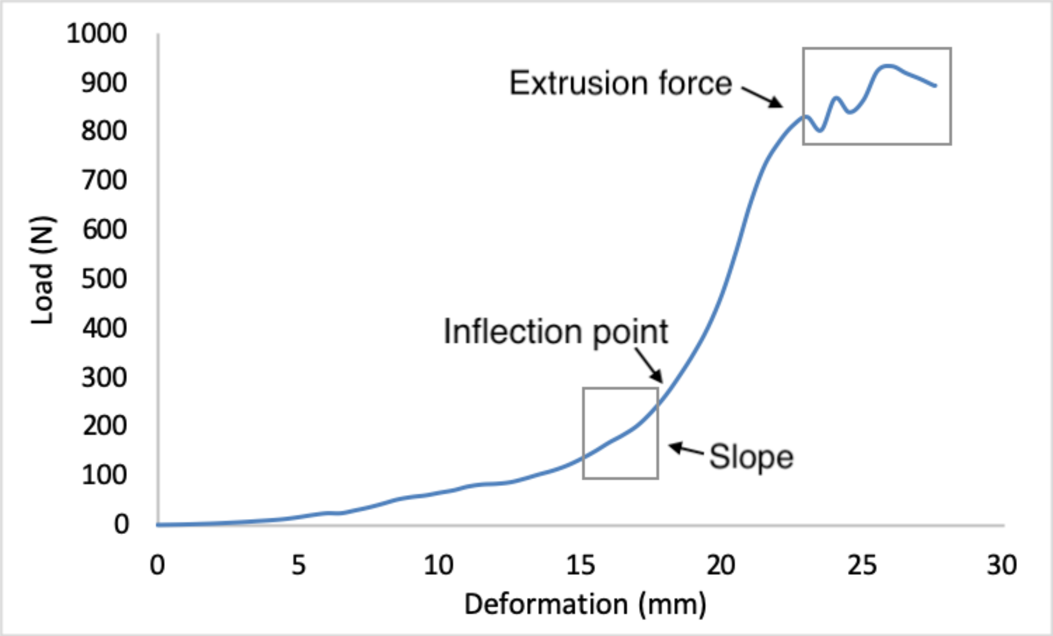


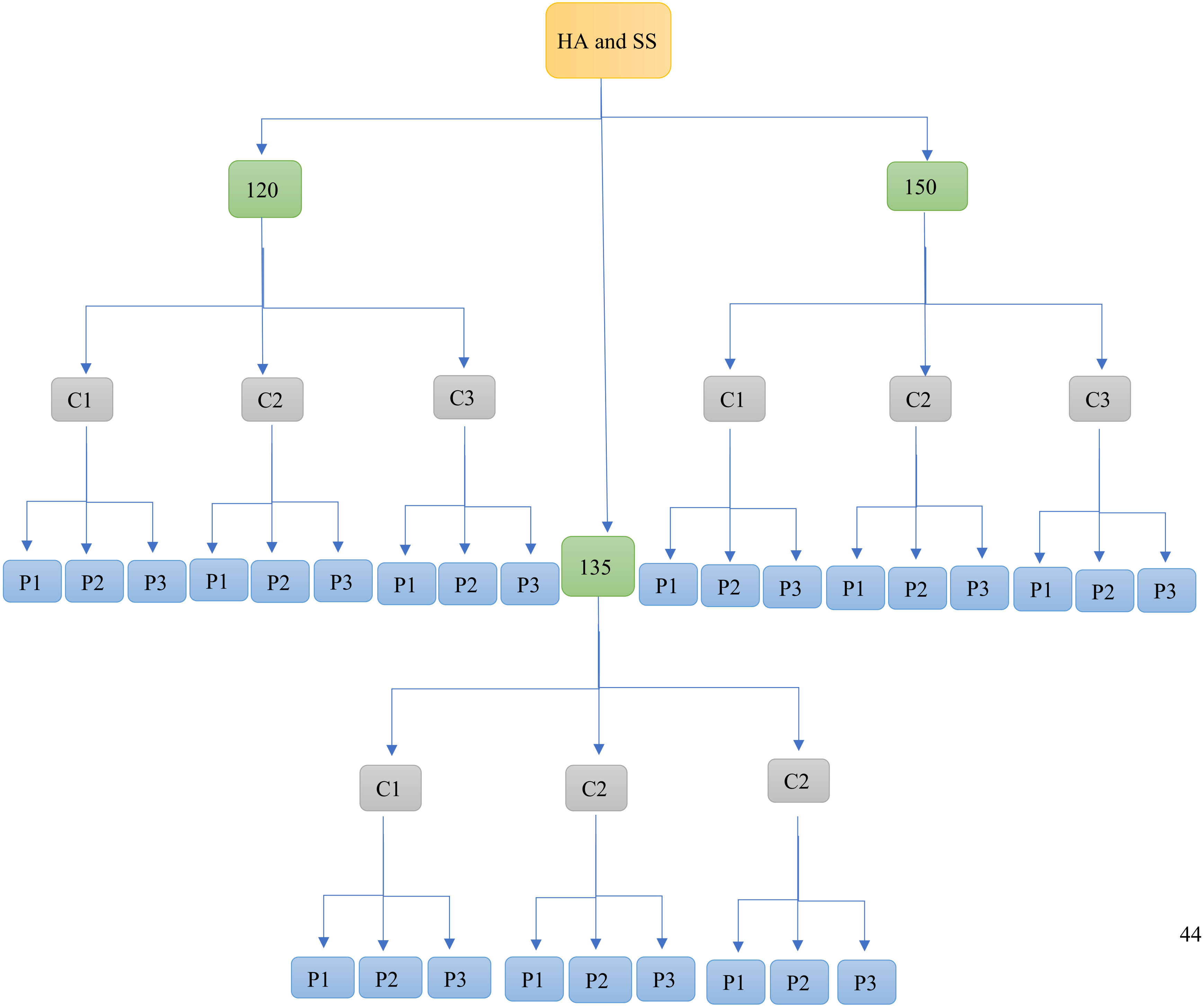
Fig. 3.8 Typical Force -Deformation curve for determining slope of cooked pulses.

Qualitative parameters such as EF, slope of force-deformation curve and force ratio at inflection are important while interpreting the force-deformation curves obtained during textural analysis. These parameters were used to examine whether a sample is undercooked or cooked to optimum. The EF was obtained visually and defined as the force value as the EF plateaus (the zigzag part of the graph) (Fig. 3.8) on the force-deformation curve (Arntfield et al. 2000).

Force ratio at inflection was the value obtained by dividing force at inflection by EF. Ross et al. (2009) stated that force ratio values above 0.5 defined undercooked samples while deformation ratios below 0.35 reflected a sample with overcooked texture. The slope of force-deformation curve was analysed from a point 1 mm prior to the inflection point (1 mm of deformation before the inflection point to the deformation at inflection).

3.2.5.4 Experimental design for cooking and texture analysis

Cooking characterises of processed yellow peas were studied by determining the qualitative parameters, such as EF, slope of force-deformation curve and force ratio at inflection. Three replicates of cooking and three replicates of compression were performed for all processing methods (HA and SS) and each processing level (120, 135, 150°C). The experiments of cooking and compression with an Ottawa textural cell with high standard deviation in EF, slope of force-deformation curve and force ratio, were repeated. In Fig. 3.9, C1, C2 and C3 depict the first, second and third replicate for cooking, respectively, and P1, P2 and P3 are the three replicates of compression/analysis of cooked peas in the Ottawa compression cage for each replicate of cooking (i.e. C1, C2, C3). The average of 9 values was taken as one representative value of parameters such as EF, slope and force ratio as shown in Fig. 3.9.


HA and SS
120
150
135
C1
C2
C3
C1
C2
C3
P1
P2
P3
P1
P2
P3
P1
P2
P3
P1
P2
P3
P1
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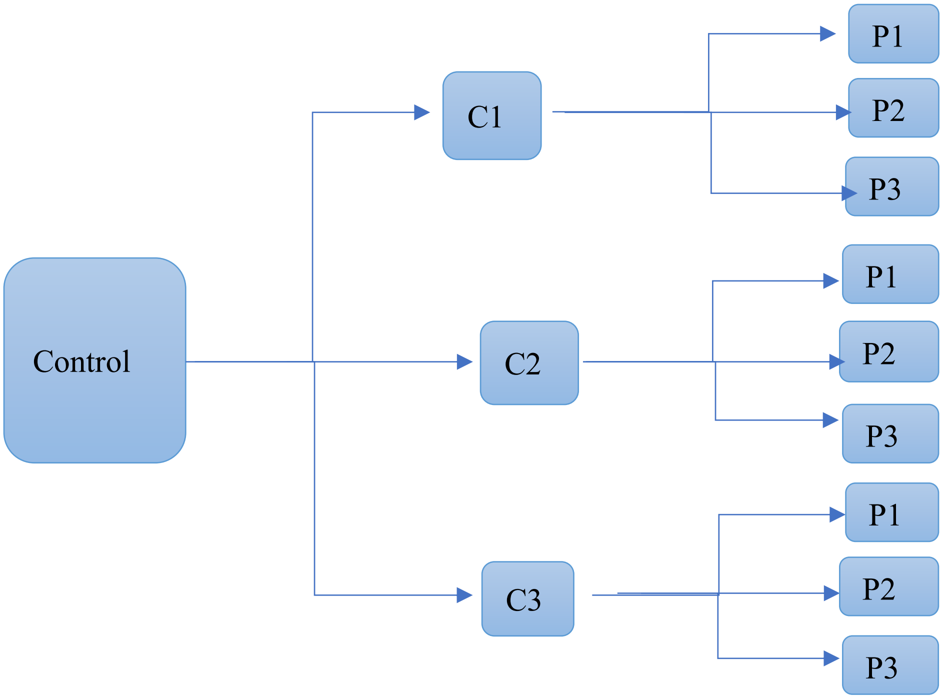


Fig. 3. 9 Experimental design for cooking and texture analysis of HA and SS processes peas, and Abbreviations: HA - hot air, SS - superheated steam, C1, C2 and C3 – cooking replicates 1, 2 and 3 respectively; P1, P2 and P3 are 1, 2 and 3 replicates of analysis of peas by compressing in Ottawa textural cell of Instron textual analyzer and 120, 135 and 150 shows the temperature of processing (120, 135 and 150 °C).

3.2.6 X-ray µCT scanning of single kernel of pea

Changes in two major microstructural properties, i.e. porosity and density were analysed using µCT technique. Qualitative and quantitative visual data along with morphometric parameters were acquired from images of a kernel to perform the evaluation (Herremans et al. 2013; Erkinbaev et al. 2014; Schoeman et al. 2016a).

Unprocessed and processed peas with SS and HA under various temperatures (120, 135, 150 ºC) at 1 m/s velocity for 10 minutes, were scanned using a Skyscan 1275 X-ray µCT instrument (Bruker Corp., Kontich, Belgium). The instrument configuration was designed with a 40kV source voltage and a 250 µA current. This soft energy level of the X-ray was adequate to penetrate the pea and produce 5 µm resolution images. For µCT, individual pea seeds were attached on a sample holder rod (3 mm diameter) and pasted with a thin layer of low-density wax to eliminate any vibrations while rotation of sample (Fig. 3.10). High resolution images were obtained while scanning the seeds at rotation angle of 0.2° over 180° (Erkinbaev et al. 2014; Herremans et al. 2013; Vicent et al. 2017). Each pea was scanned for 15 minutes and 4 averaged images of 1671×1382 pixels were acquired. To evaluate the morphometric parameters, the Bruker CTAn software was used for the visualization and image analysis (Erkinbaev et al. 2019).

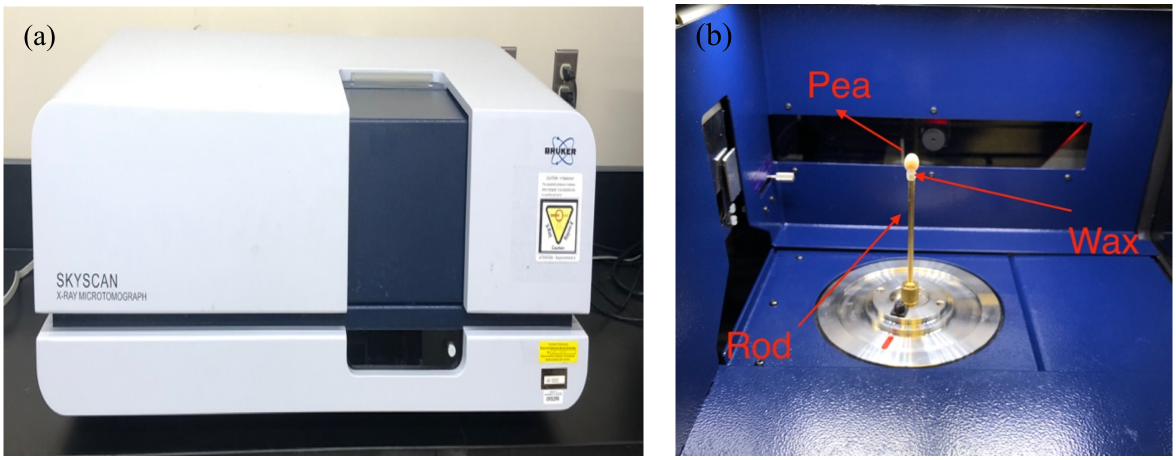


Fig. 3. 4. (a) Skyscan X-Ray microtomography (b) an individual pea was mounted on a sample holder rod and glued with a thin layer of low-density wax.

3.2.6.1 Image analysis

The 2D images obtained from the angular projections of a single pea kernel were reconstructed into a 3D hypercube using NRecon software (version 1.6.10.2, Bruker, Belgium), enabling further study of the sample's internal and external geometries. The correction of reconstructed images was performed to eliminate stretching or dark bands that may have been caused by the absorption of lower energy photons from the X-ray beam (including polychromatic energies) passing through the pea (Park et al. 2015). As the 3D stack of images required a high computation speed, a computer (Precision T7810, RAM 64 GB, 3.2 GHz, Dell corporation, US) with a graphics processing unit (GPU) was used for volume rendering and analysis. The whole pea was considered as region of interest (ROI) for describing major morphological parameters. A single slice was selected from the pea's middle hypercube to evaluate the grey level values for the pea's solid cells and air space (pore space). The grey threshold values have been set from 50-188 for effective discrimination of the pore spaces from solid cells. Quantitative parameters, like porosity, density and volume were then calculated from the image hypercubes (Erkinbaev et al. 2019). Three replicates were performed for each experiment, with repetitions done for samples with high standard deviations in porosity and density values.

3.2.6.2 Density

Density (ρ) was determined by dividing the mass of the sample by its volume. The volume (v) was obtained through x-ray μCT scanning results and the mass (m) of the single kernel of the pea was precisely weighed using an Adventure™ Pro (OHAUS®) scale with error ± 0.002 g. The mass of the unprocessed and processed (with HA and SS) peas was measured. The following formula was used to calculate the density of the single kernel of pea:

$$\rho = {}^{m}/_{v} \qquad (3.3)$$

Where, ρ is density (kg/m^3), m is mass (kg) and v is volume (m^3).

The ratio of mass to volume was calculated to compare the density of the pea before and after processing. The percentage deviation in density was compared for different processing methods (HA and SS) and processing temperatures (120, 135 and 150 ºC).

3.2.6.3 Porosity

Porosity (ε) is defined as the ratio of the volume occupied by the intergranular air to the total volume of the bulk sample and is expressed in percent (Jayas and Cenkowski 2010). The porosity of an individual pea seed was determined in terms of total porosity. Porosity analysis was initially conducted by thresholding the void spaces and by creating and extracting ROI (Kelkar et al. 2013; Schoeman et al. 2016b). On the basis of the ROI (Frisullo et al. 2010; Joardder et al. 2017), the total volume of air was calculated against the total volume of the sample giving the total porosity.

3.2.7 Protein analysis

Yellow peas were powdered in a Foss Cyclotec™ (1093 Sample Mill, Eden Prairie, MN) to a uniform particle size of 200 micrometer for analysis of protein using a LECO analyzer (FP-628, LECO Corporation, St. Joseph, MI) determined by the combustion method. The 0.25 ± 0.02 g of powdered samples were encapsulated in thin tin foils. The LECO machine took 2-4 minutes to produce the results of each sample. Input was given to the computer attached to the LECO in the form of mass of the sample and its moisture content. The percentage of crude protein was calculated as:

$$P = N \times C \tag{3.4}$$

where, N is the amount of nitrogen (in percentage)

P is the amount of protein (in percentage)

C is 5.7 for wheat, while it is 6.25 for all other crops (Asare et al. 2011).

In this study, the output in the form of percent of nitrogen was converted into the protein percentage by multiplying it by 6.25 (Jones's factor) (Mariotti et al. 2008).

3.2.8 Starch analysis

Thermal properties of gelatinized starch were analyzed using a differential scanning calorimeter (DSC Q200, TA Instruments, New Castle, DE) equipped with a refrigerated cooling system

(RCS90). During the experiments, nitrogen was used as a purging gas with a flow of 150 mL/min. The equilibration temperature was set at 40°C followed by a heating ramp of 40 to 180°C at a rate of 10 °C/min. Peas were powdered using laboratory grinder (IKA® A11BS1, Wilmington, NC). The sample was wetted by adding water (sample: water =1:2.5) in VWR® falcon tube of 45 mL capacity and mixed with a vortex mixer (VWR® Digital Vortex Mixture, Radnor, PA) for 30 s and the sample-water mixture was equilibrated at room temperature for 1 h. The starch sample and water mixture (13.5 to 15.5 mg) was precisely weighed using an electronic balance (Mettler AE 163, Mettler-Toledo Ltd, England, UK). The sample was weighed with an accuracy of 0.0001 g. A T zero aluminum hermetic pan (TA Instruments, New Castle, DE) was used in the experiments. The pan, with a known amount of mixture, was placed inside the DSC cell when temperature reached to 40°C. An empty pan was used as the reference standard. Enthalpy change (ΔH) and peak temperature (T_p) were measured using the TA Universal Analysis 2000 software on a graph between heat flow (mW) and temperature (°C) (Sivri et al. 1998). There were two peaks (Fig. 3.11) on the graph, one representing starch gelatinization and the other representing melting of protein. Five replicates were performed for each experiment.

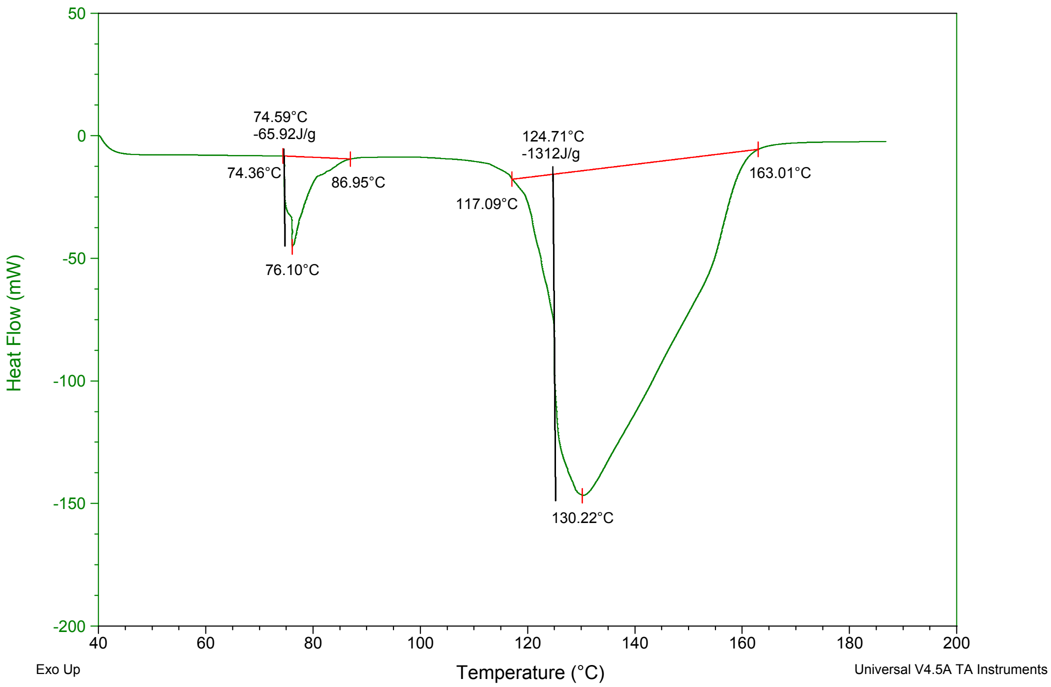


Fig. 3. 5. An example of the graph obtained from DSC Q200 indicating the gelatinization (first peak) of starch and melting (second peak) of protein in yellow pea powder processed with SS at 120 °C.

3.2.9 Dehulling

The Satake Grain Testing Mill TM05 (Satake Engineering Co. Ltd., Japan) fitted with an abrasive wheel mesh 40 with a clearance of 13.5 mm from the screen and operated at 830 rpm was used for dehulling of peas (Fig. 3.12). These conditions were suitable for processing field peas with 100 seed mass in the range 13-30 g. Thirty grams of peas processed with both SS and HA were dehulled in the Satake mill for 10 s. All the material from dehulling was recovered and five fractions - non-dehulled peas, splits, broken peas, powder and husk - were collected separately. These fractions were sieved to remove broken peas and powder followed by aspiration of husks from the splits to calculate the dehulling efficiency. The non-dehulled peas were removed manually and the leftover was sieved for 10 minutes using the US standard sieve set (ASTM E-11 USA) with a coarse sieve shaker (W.S. Tyler™ RX-812, Mentor, OH).

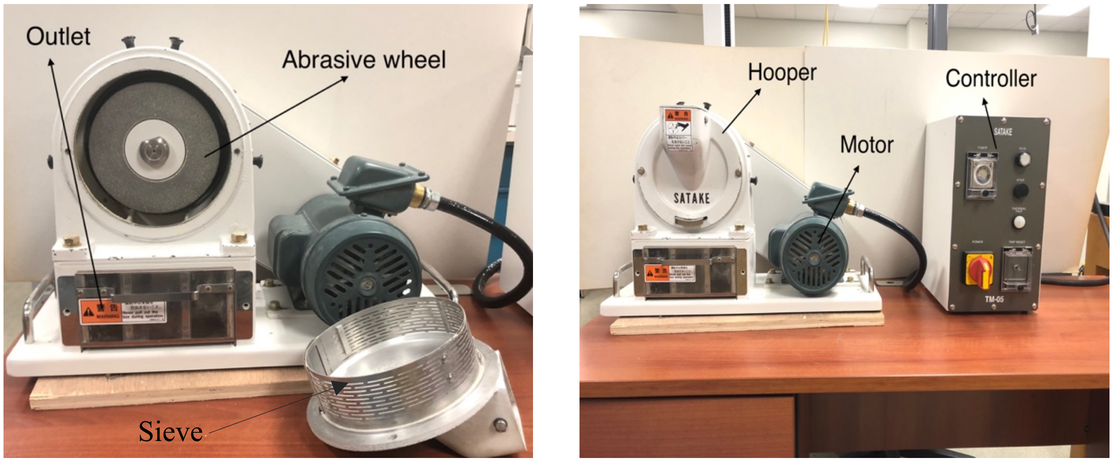


Fig. 3. 6. Satake grain test mill TM05C.

Broken peas retained on a 0.85 mm sieve and the powder that passed through the 0.85 mm sieve were also measured (Black et al. 1998b). Splits and husks were retained on a 1.70 mm sieve. To separate the husk from the splits, the husk and splits mixture was aspirated in a bates type laboratory aspirator (H.T.M© Gill, TX) (Fig. 3.13). The aspirating step was repeated until about 90% of the hulls had been removed. This usually required 4 runs through the feeding chute at air suction velocity of 7.16 m/s.

Dehulling efficiency is the estimate of the efficiency of producing the major product, splits, and was calculated as follows:

$$\text{Dehulling efficiency} = \frac{(W_1-(W_2+H+B+P))\times 100}{W_1} \qquad (3.4)$$

$$\%\ \text{Non-dehulled} = \frac{W_2 \times 100}{W_1} \qquad (3.5)$$

$$\%\ \text{Husk} = \frac{H \times 100}{(W_1 - W_2)} \qquad (3.6)$$

$$\%\ \text{Broken peas} = \frac{B \times 100}{W_1 - W_2} \qquad (3.7)$$

$$\%\ \text{Powder} = \frac{P \times 100}{(W_1 - W_2)} \qquad (3.8)$$

Where, W_1 is the initial mass of the sample, W_2 is the mass of undehulled seed, H is the mass of husks, B is the mass of broken peas and P is the mass of powder.

Note: the calculations for % husk, % broken and % powder are made relative to the seed that has been dehulled, thus the denominator is (W_1 - W_2).

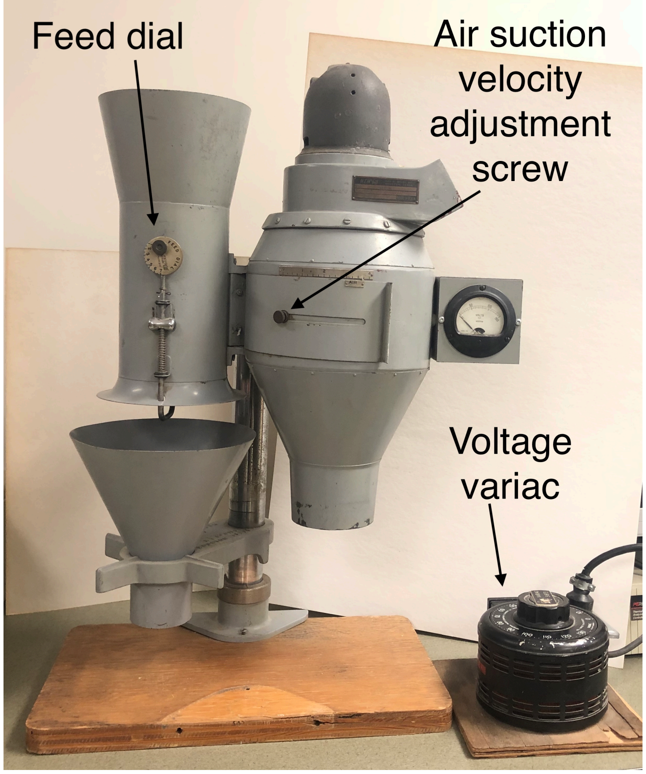


Fig. 3. 7. Aspirator used for collection of separated hulls from the splits.

3.3 Optimization of SS processing – Case 2

3.3.1 Tempering

The tempering method was the same as described in section 3.2.1 (case 1). The only difference was the amount of peas used for tempering. Only 50 g of peas were used in case 2, whereas amount of peas tempered was 150 g in case 1.

Soaking is the initial step before cooking. But soaking requires four times more water than the weight of the peas (AACC International Method 56-36.01). This extra water gets wasted in both industrial and home situations. Therefore, in case 2, peas were tempered to a high moisture content with the required amount of water to eliminate soaking before cooking. This high moisture content tempering could be helpful in eliminating the soaking step at the consumer end, as well as for industries.

In case 1, peas were tempered to moisture content of 20±1.5% (w.b.). But in case 2, three different levels of moisture content (26, 40 and 54%) were used. The maximum moisture content attained by peas after soaking overnight in 1:4 (peas:water) was 54.0±0.4% (w.b.). Therefore, the highest tempering level of 54% was chosen. Following Tyler and Karoutis (1993), 40% moisture content for peas was chosen, and 26% moisture content was selected in refence to Bellido (2003). The moisture content of peas was measured in a laboratory oven (Thermo Electron Corporation, Waltham, MA) using the AACC international method 44-17.01 as mentioned in section 3.2.2 of case 1.

3.3.2 Drying characteristics

Drying characteristics were evaluated by recording the change in moisture content during drying (Johnson et al. 2013). A glass tray with steel mesh at the bottom was used to hold a thin layer of 50 g of peas for SS processing. The holding tray and drying chamber were preheated for 10-15 minutes to remove condensation. The flow was diverted from the chamber using a diversion valve in the SS dryer. During the experiments, the sample's mass was measured at specific times (2, 5, 10, 15, 20, 30, 40, 50, 60, 70, 80, 90, 100, 110 and 120 minutes) (Kemp et al. 2001). An electronic balance (Model ENTRIS423-1S, Sartorius Lab Instruments GmbH & Co. KG, Gottingen, Germany) was used to measure changes in mass with an accuracy of 0.001 g.

The flow of SS was in a direction perpendicular to the sample tray. The collected experimental data was used to develop the drying characteristic curves of the peas. The experiments were repeated in triplicate for an initial moisture content of 26, 40 and 54% (w.b.), at three different temperatures (120, 135, 150°C) of SS and 1 m/s velocity inside the chamber. These experiments were performed to determine the time required by the peas to reach moisture content of 12% (w.b.).

3.3.3 SS processing

The temperatures of SS processing (120, 135, 150°C) were the same as in case 1 (section 3.2.3.2). In case 1, the SS processing time (10 min) for all temperatures was kept constant, whereas in case 2 the processing time was different for each temperature (i.e. 120, 135, 150°C) and moisture content level (i.e. 26, 40, 54%) as mentioned in table 4.6.

3.3.4 Cooking characteristics

3.3.4.1 Cooking (Case 2)

Cooking experiments of SS processed yellow peas with 12.0±1.6% moisture content (which were at 26, 40 and 54% before processing with SS at 120, 135 and 150°C) were conducted with the same procedure as described in case 1 (section 3.2.6.2). The same predetermined time was used for cooking (i.e. 5, 10 and 15 minutes). In order to optimize the SS processing operating conditions and to minimize the overall cooking time (soaking + cooking), processed peas were not soaked before cooking in case 2, as it was in case 1.

3.3.4.2 Textural analysis (Case 2)

Textural analysis of cooked peas was analyzed using the same method as mentioned in case 1 (section 3.2.6.3), with an Instron universal testing machine (model 3366, Instron, Norwood, MA). The experimental design and replication were the same as mentioned in Fig. 3.4 and section 3.2.4.3.

3.4 Statistical analysis

The effect of processing methods (SS and HA) and processing temperatures (120, 135 and 150 °C) on the functional (moisture content, drying characteristics, hydration capacity, dehulling efficiency, cooking characteristics, microstructure) and nutritional properties (protein content, starch gelatinization) of yellow peas was analyzed statistically using SAS (Version 9.4, SAS Institute Inc., Cary, NC). In order to test the significance of independent variables (processing method and processing temperature) on dependent variables, a factorial analysis of variance (ANOVA) and the least significant difference (LSD) analysis was performed with the data obtained from a full factorial experimental design.

4. Results and Discussion

4.1 Comparison between hot air (HA) and superheated steam (SS) – Case 1

4.1.1 Moisture content

Table 4.1 shows the moisture content of peas after processing for 10 minutes at 1m/s velocity using HA and SS, at temperatures of 120, 135 and 150°C, and unprocessed peas {initial moisture content of 20.73 ± 0.45% (w.b.)}.

Table 4. 1. Moisture content of peas processed in HA and SS at various temperatures for 10 minutes and 1m/s velocity of the medium.

Processing method	**Processing temperature (°C)**	**Moisture content (wet basis) % ± SD**
Unprocessed	22	20.73 ± 0.45^{a}
HA	120	15.77 ± 0.14^{b}
	135	14.65 ± 0.26^{c}
	150	12.96 ± 0.39^{d}
SS	120	13.68 ± 0.25^{c}
	135	11.98 ± 0.63^{e}
	150	$9.46 \pm 0.\ 53^{f}$

$^{a\text{-}f}$ Values with different superscripts are significantly different (LSD p < 0.05). Abbreviations for processing method: HA - hot air, SS - superheated steam.

Type of processing medium (HA and SS) used and processing temperature (120, 135, 135°C) have a significant effect (p<0.05) on moisture content of yellow peas (Table 4.1). The linear regression equation for final moisture content, as affected by the processing temperature for the selected range (120-150°C) of operating conditions of HA and SS, are given as follows:

$$MC_{HA} = -0.0936T + 27.093 \qquad \{R^2 = 0.95\} \qquad (4.1)$$

$$MC_{SS} = -0.1406T + 30.692 \qquad \{R^2 = 0.94\} \qquad (4.2)$$

Where, MC is the moisture content (% w.b.), T is the temperature (°C).

A decrease in moisture content with an increase in temperature of the processing medium (HA and SS) was noted. The decrease in moisture content of peas was higher when processed with SS as compared to HA. Moisture content decreased by 7.1, 8.8 and 11.3% for SS and 4.9, 6.1 and 7.8% for HA at 120, 135 and 150°C, respectively. Many authors (Yoshida et al. 1970; Bond et al. 1994; Nishimura et al. 1994) have shown that SS has a higher constant drying rate than HA, above a certain temperature. Iyota et al. (2001b) perceive that the greater the temperature of the SS, the shorter the drying time. Similar results were observed in the current study.

4.1.2 Hydration capacity

The hydration capacity of peas (18 hours of hydration time) processed with HA and SS, at temperatures of 120, 135, and 150°C for 10 minutes at 1m/s velocity are shown in Table 4.2. Hydration capacity of processed and unprocessed peas varied from 84.4 - 91.2%.

Table 4. 2. Hydration capacity of peas processed with HA and SS at various temperatures for 10 minutes and 1m/s velocity of the medium.

Processing method	**Processing temperature (°C)**	**Hydration capacity (% w.b.)**
Unprocessed	22	80.4 ± 0.14^{a}
HA	120	78.3 ± 0.79^{b}
	135	78.4 ± 0.48^{b}
	150	79.8 ± 0.33^{ab}
SS	120	80.7 ± 1.39^{a}
	135	85.9 ± 0.83^{c}
	150	91.2 ± 1.66^{d}

$^{a\text{-}d}$ Values with different superscripts are significantly different (LSD $p < 0.05$).
Abbreviations for processing methods: HA - hot air, SS - superheated steam.

The value of hydration capacity ranged from 78.3-79.8% for HA and 80.7-91.2% for SS when processed at 120, 135 and 150°C. Both temperature and processing methods have significant effect ($p < 0.05$) on the hydration capacity of yellow peas. The hydration capacity of SS processed peas was higher than peas processed with HA as well as unprocessed peas, which demonstrated that peas processed with SS can absorb more water in the cotyledon in comparison to others. As mentioned in section 4.1.5, with an increase in the processing temperature, the porosity of the SS processed peas increased, which in turn raised the hydration capacity of yellow peas in the present study.

The linear regression equations for the final hydration capacity, affected by the processing temperature for the selected range (120-150°C) of operating conditions of HA and SS, are as follows:

$$HC_{HA} = 0.0507T + 72.07 \qquad \{R^2 = 0.87\} \qquad (4.3)$$

$$HC_{SS} = 0.3511T + 38.53 \qquad \{R^2 = 0.85\} \qquad (4.4)$$

Where, HC is the hydration capacity (% w.b.), T is the temperature (°C)

Peas processed with SS have a higher hydration capacity than both HA and unprocessed peas (Table 4.2). Affrifah (2004) used SS to treat cowpeas at 121°C for 4 min and concluded that cowpeas had a lower hydration capacity than unprocessed peas. The reason for that, in their case, was that the temperature and time of steam processing were lower and shorter than the processing temperature and time used in this study.

Various researchers have studied the effect of heat treatment on the water absorption capacity in a variety of legumes. Narayana and Narasinga-Rao (1982), and Abbey and Ibeh (1988) have reported an increase in water absorption following heat treatment for winged beans and cowpeas, respectively.

4.1.3 Cooking quality

Slope of force-deformation curve and force ratio values for peas dried for 10 minutes at 1m/s velocity using two processing methods, HA and SS, at temperatures of 120, 135, and 150°C with respect to the reference sample, are given in Table 4.3.

Table 4. 3. Force ratio and slope of force-deformation curve value of peas processed with SS and HA at various temperatures and cooked for 5, 10 and 15 minutes (See Fig. 3.8 for definitions).

Processing methods	**Processing temperature (°C)**	**Cooking time (min)**	**Slope (N/mm)**	**Force ratio**
Unprocessed	20	5	135.4±1.0^{a}	0.62
		10	106.6±6.9^{b}	0.51
		15	93.0±8.4^{c}	0.50
HA	120	5	220.1±8.1^{d}	0.54
		10	200.9±3.7^{e}	0.54
		15	103.1±3.6^{fb}	0.45
	135	5	174.4±4.8^{g}	0.52
		10	162.6±8.6^{h}	0.54
		15	93.9±5.3^{fc}	0.43
	150	5	145.2±2.2^{gj}	0.51
		10	140.2±8.5^{ga}	0.53
		15	67.7±2.2^{i}	0.42
SS	120	5	163.7±3.1^{h}	0.53
		10	151.2±7.3^{j}	0.53
		15	92.5±6.3^{c}	0.42
	135	5	118.2±3.7^{k}	0.51
		10	93.4±4.7^{c}	0.41
		15	50.4±1.2^{l}	0.39
	150	5	86.2±5.3^{c}	0.50
		10	67.6±6.6^{j}	0.40
		15	42.1±6.9^{l}	0.37

[a-l] Values with different superscripts (column wise) are significantly different (LSD $p < 0.05$). Abbreviations for processing methods: HA - hot air, SS - superheated steam.

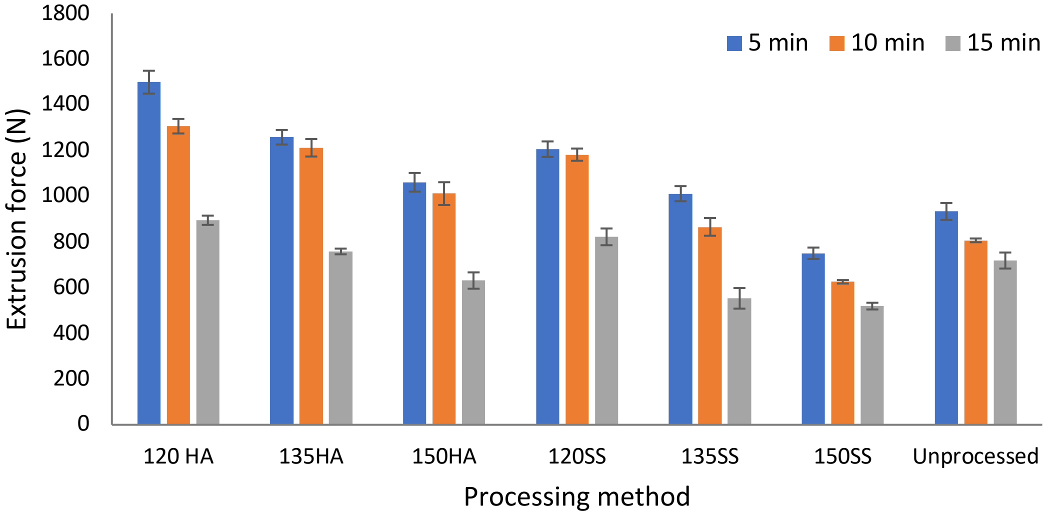


Fig. 4. 1. Extrusion force of yellow peas processed at different temperatures (120, 135, 150 °C) of SS and HA at 1m/s velocity and cooked for 5, 10 and 15 minutes.

An appropriate cooking time for whole peas (soaked) is 15-20 minutes, as suggested by the AACC international method 56-36.01. A high rate of water absorption and shorter cooking time are desired quality attributes for peas.

Figure 4.1 shows the effect of cooking time and processing temperature on the EF of cooked peas. The other factors for textural analysis (presented in the Table 4.3) are the slope of force-deformation curve and force ratio, which indicate if the product is cooked or uncooked. According to Ross et al. (2009), if the force ratio value is higher than 0.5, the sample is under-cooked, and if it is less than 0.5, it is considered to be cooked, whereas if force ratio at extrusion is less than 0.35, the sample represents an overcooked texture. Although these values were observed by Ross et al. (2009) for lentils, similar conditions were assumed for peas in this study. The repetitive curves for each value mentioned in Fig. 4.1 and Table 4.3 are provided in Fig. A1 in the appendix.

Superheated steam processed peas needed less EF to extrude through the Ottawa textural cell as compared to peas processed with HA. The EF of all the samples decreased with increasing cooking time and processing temperature, as shown in Fig. 4.1. The EF ranged from 631.0-1498.7 N and 519.1-1205.8 N, for HA and SS, respectively. A similar negative correlation between cowpea hardness and cooking time was found by Sefa-Dedeh et al. (1979a). According to them, softening of beans during cooking is accompanied by structural changes in the seed, primarily breakdown of the middle lamella, which leads to the easy separation of cells. Sefa-Dedeh et al. (1978) and Aguilera and Steinsapir (1985) reported that the initial softening of roasted beans occurred due to heat treatment. They suggested that during the roasting process, a combination of escaping moisture and the temperature gradient present in the beans softened the intercellular material and permitted easier separation of the cells.

The slope of force-deformation curve decreases in parallel with EF, with the increase in cooking time and processing temperature (Table 4.3). Therefore, the higher is the value of slope, the harder the peas are and the longer is their cooking time. Varoquaux et al. (1995) reported a decrease in the slope with an increase in cooking time of lentils. The value of the slope of force-deformation curve ranged from 67.65 2-20.13 and 42.07-163.75 N/mm for HA and SS, respectively. The values of EF and slope were smaller in case of SS as compared to HA processed peas at all processing temperatures (120, 135 and 150°C) and cooking times (5, 10 and 15 min).

According to the value of force ratios at extrusion, as presented in Table 4.3, peas cooked for 15 minutes in all processing methods demonstrated a cooked texture, with a value of force ratio less than 0.5. The peas processed with SS at 135 and 150°C yielded cooked texture (slope less than 0.5) at 10 minutes cooking time only. This scenario was not noted in HA. Peas cooked for 5 minutes at all processing temperatures (120, 135 and 150°C) with both processing methods (HA and SS), remained undercooked based on texture, except for peas processed at 150°C with SS.

4.1.4. X-ray Image analysis

To study the microstructure, micro-tomographic images of peas processed with HA and SS at all temperatures (120, 135 and 150°C) were evaluated as shown in Fig. 4.2. It was observed that porosity increased, and density decreased with an increase in processing temperature.

A comparative analysis of the porosity of peas processed with SS versus HA indicated that SS processing increased porosity in comparison to HA processing. Figure 4.2 (a) shows the porosity of peas processed with HA and SS relative to unprocessed peas. Both processing method and temperature had a significant effect ($p<0.05$) on the porosity of a single kernel. Processing with HA at 135°C and SS at 150°C were not significantly different from each other, whereas all other processing levels were significantly different from each other.

The linear regression equations for final porosity as affected by the processing temperature in the selected range (120-150°C) of operating conditions of HA and SS, respectively, are as follows:

$$\varepsilon_{HA} = 0.1296T + 11.524 \quad \{R^2 = 0.70\} \tag{4.5}$$

$$\varepsilon_{SS} = 0.2388T + 23.772 \quad \{R^2 = 0.85\} \tag{4.6}$$

Where ε is the porosity (% w.b.), T is the temperature (°C)

The porosity value of unprocessed peas was minimal (0.2%) as compared to SS and HA processed peas. The peas processed with SS at 150°C had the highest porosity (10.9%). The value of porosity increased with increasing processing temperature (120, 135, 150°C) for both HA and SS. Porosity of peas processed with HA ranged from 4.5-8.4%, whereas in the case of SS, porosity ranged from 4.9-10.9%.

Evaporation during drying process leads to the high porosity as water changes from liquid to vapour inside the kernel. The pea structure expanded as a result of water vapor pressure generated within cells, capillaries and pores. A study by Li et al. (1999) on microstructural analysis of tortilla chips also showed similar results, including an increase in pores and coarse appearance with increase in steam temperature.

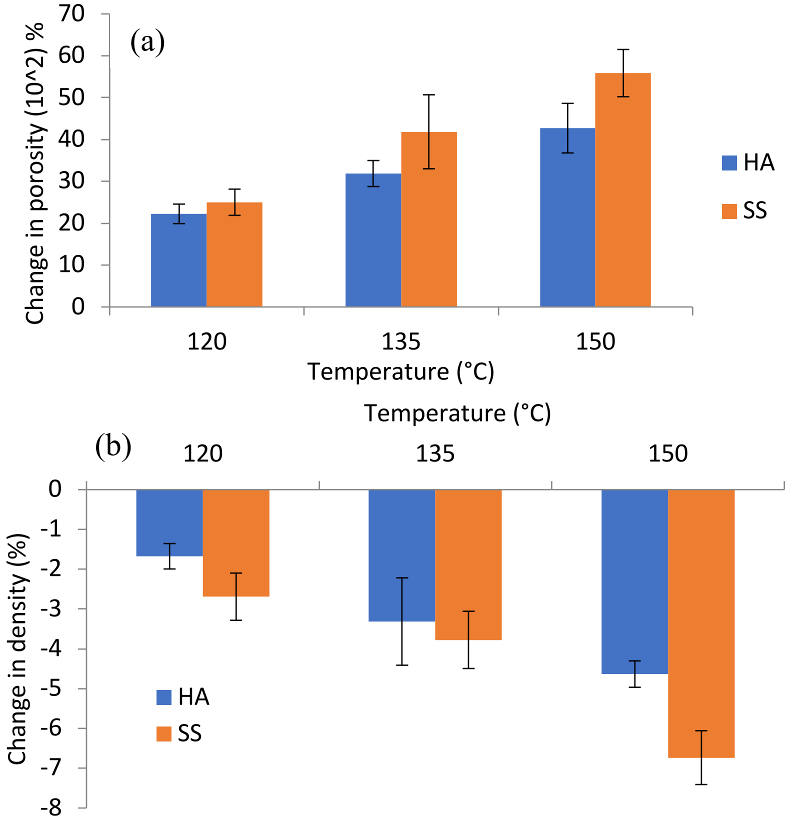


Fig. 4. 2. Change in (a) porosity and (b) density of peas processed in HA and SS at various temperatures (120, 135, 150 °C) for 10 minutes and 1m/s velocity of the medium. Abbreviations: HA – hot air, SS – superheated steam.

Both processing methods (HA and SS) had a significant effect ($p<0.05$) on the density of single kernels. Figure 4.2 (b) shows the density of peas processed with HA and SS relative to unprocessed peas. The absolute values of porosity and density of processed and unprocessed peas, with statistical analysis, are provided in (Table A2).

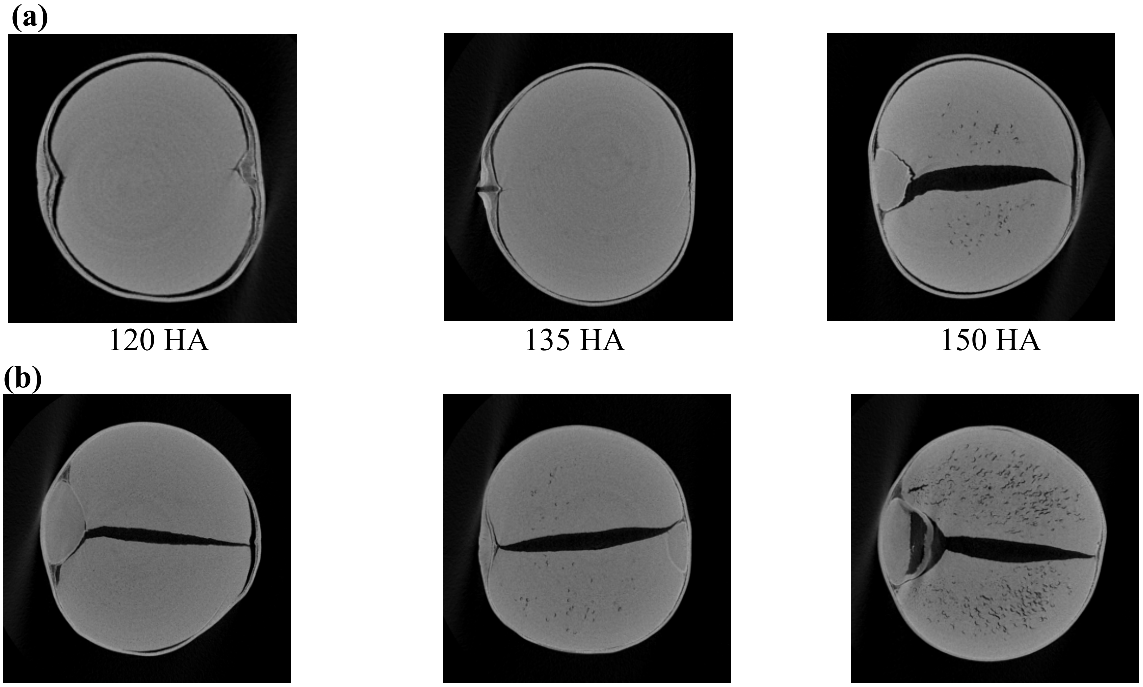
The linear regression equations for final density as affected by the processing temperature for the selected range (120-150°C) of operating conditions of HA and SS, respectively, are as follows:

$$\rho_{HA} = -1.3221T + 1475.2 \quad \{R^2 = 0.82\} \tag{4.7}$$

$$\rho_{SS} = -1.8053T + 1524.5 \quad \{R^2 = 0.85\} \tag{4.8}$$

Where, ρ is the density (% w.b.), T is the temperature (°C)

Unprocessed peas had a higher density (1339.72 kg/m^3) when compared to processed peas. Density decreased with the decrease in processing temperature (120, 135, 150°C). This decrease in density was higher for the peas processed with SS as compared to HA. Density of SS processed peas ranged from 1249.5-1303.67 kg/m^3, whereas for HA, density ranged from 1277.6-1317.9 kg/m^3. The increase in porosity and decrease in density is also noticed by Erkinbaev et al. (2019) in their comparative study of HA and SS on distillers spent grains.

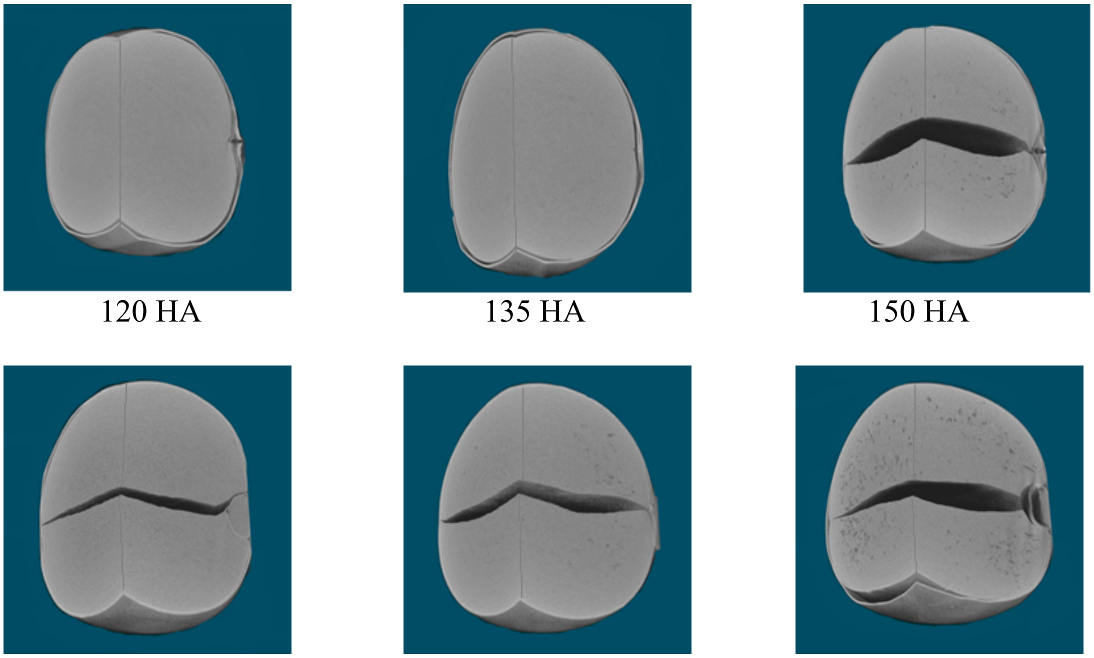

(a)

120 HA 135 HA 150 HA

(b)

120 SS 135 SS 150 SS

Fig. 4. 3 (a) 2D images of single kernel of pea processed with 120, 135, and 150°C hot air (HA). (b) 2D images of single kernel of pea processed with 120, 135, and 150°C superheated steam (SS).


120 HA 135 HA 150 HA

120 SS 135 SS 150 SS

Fig. 4. 4. (a) 3D images of single kernel of pea processed with 120, 135, and 150°C hot air (HA) (b) 3D images of single kernel of pea processed with 120, 135, and 150°C superheated steam (SS).

The 2D images of pores inside the pea are shown in Fig. 4.3 (a) and (b) as well as the 3D images of quarter sections of a pea kernel processed with HA and SS, are shown in Fig. 4.4 (a) and (b), respectively. Breakage of the middle lamella in steam processed peas at all levels of temperature (120, 135 and 150°C) and HA processing at 150°C was observed (Fig. 4.3 and 4.4). This breakage was also observed and explained by Affrifah and Chinnan (2006). According to them, a combination of steaming and subsequent drying leads to deformation of the mid lamella, causing cells to lose their integrity; as the processing temperature increased, damage of mid lamella also increased.

4.1.5. Protein

The change in protein content of peas after processing for 10 minutes at 1m/s velocity using two techniques, HA and SS, at temperatures of 120, 135, and 150°C is shown in table 4.4. The reference sample, marked as unprocessed, indicates the protein content before processing.

Table 4. 4. Protein content for processed (HA and SS) pea samples at various temperatures for 10 minutes and 1m/s velocity of the medium in comparison to unprocessed peas.

Processing methods	**Processing temperature (°C)**	**Protein (%)**
Unprocessed	22	25.7 ± 0.4^{a}
HA	120	24.5 ± 0.3^{b}
	135	23.6 ± 0.2^{c}
	150	23.3 ± 0.5^{2c}
SS	120	25.3 ± 0.2^{da}
	135	25.3 ± 0.3^{da}
	150	24.9 ± 0.1^{db}

$^{a\text{-}d}$ Values with different superscripts are significantly different (LSD $p < 0.05$).
Abbreviations for processing methods: HA - hot air, SS - superheated steam.

In this study, protein content of unprocessed peas was 25.7%. The protein content of HA processed peas differed significantly ($p<0.05$) from unprocessed peas, but SS processing showed an insignificant effect on the protein content (Table 4.4). In the current study, decline in protein content increased with an increase in processing temperature. Protein content was decreased by 1.2, 2.2 and 2.4% for HA and 0.3, 0.4 and 0.7% for SS at 120, 135 and 150°C, respectively. According to Hendrix and Dennis (1938), splitting of nitrogenous material from the molecule is the reason for lowering the amount of nitrogen in the sample, which in turn lowers the protein amount.

According to Wakabayashi et al. (1956), oxygen plays an important role in protein denaturation. Oxygen reacts with protein molecules activated by energy absorption, resulting in irreversible denaturation. Wakabayashi et al. (1956) found that protein denaturation does not occur in the absence of oxygen when protein solution was exposed to UV light. Because SS processing happens in the absence of oxygen, less protein was denatured while processing with SS as compared to HA.

4.1.6. Starch analysis

Differential scanning calorimetry (DSC) was used to measure the temperatures of the gelatinization transition: onset temperature (T_O), peak temperature (T_P) and offset temperature (T_C). Due to the varying interpretation of the onset and offset temperatures, the peak temperature was considered. The peak temperatures are displayed in table 4.5.

According to Shen et al. (2016), the peak temperature for different types of field peas varies from 66.7 to 79.8°C. In the current study, the peak starch gelatinization temperature of processed and unprocessed peas varied from 73.4 to 77.8°C. Neither of the processing methods (SS and HA) nor temperatures (120, 135 and 150°C) showed a significant effect (P<0.05) on starch gelatinization of yellow peas (Table 4.5).

The high standard deviation might be because of variation in moisture content (Wray 2000), although all samples were kept for equilibration in the same conditions. The peak temperature of processed samples was smaller than unprocessed samples. This is due to the heat that leads to breakage of intramolecular bond of starch molecules during processing, making it accessible at a lower temperature for gelatinization. Increasing processing temperature from 120 to 150°C resulted in a lower peak temperature.

Table 4. 5. Peak gelatinization temperature of pea-starch processed with HA and SS at various temperatures (120,135, 150 °C) for 10 minutes and 1m/s velocity of the medium.

Processing methods	**Processing temperature (°C)**	**Peak gelatinization temperature (°C)**
Unprocessed	22	77.8 ± 4.7^{a}
HA	120	77.1 ± 2.8^{a}
	135	76.7 ± 5.3^{a}
	150	74.7 ± 2.6^{a}
SS	120	76.0 ± 0.6^{a}
	135	75.5 ± 7.8^{a}
	150	73.4 ± 5.8^{a}

^{a} Values with same superscripts are insignificantly (LSD $p < 0.05$).
Abbreviations for processing methods: HA - hot air, SS - superheated steam.

The energy required to gelatinize starch for HA processed peas ranged from 0.05-0.27 J/g, whereas the energy values for SS processed peas ranged from 0.08-0.24 J/g. The unprocessed peas required 7.09 J/g of energy to gelatinize starch. These results demonstrated that the amount of energy required to gelatinize starch decreases after processing, but the type of processing method (HA or SS) and temperature (120, 135 and 150°C) does not exhibit any significant effect on the energy required to gelatinize starch.

4.1.7 Dehulling efficiency

Both processing methods (HA and SS) had a significant effect on the dehulling efficiency of yellow peas ($p<0.05$). Peas processed with SS at 150°C had the highest dehulling efficiency (89.9%). Dehulling efficiency was negatively corelated to the moisture content of peas. The moisture content decreased with an increase in processing temperature, whereas the dehulling efficiency increased with the increase in processing temperature. The experimental results for processed and unprocessed samples are presented in Fig. 4.5. The non-dehulled fraction in both processing methods (HA and SS) was zero.

The efficiency of unprocessed peas was lower than processed peas (which ranged from 9.5-15.8% w.b.) because of their higher moisture content (20.7% w.b.), as shown in Fig. 4.5. The hull was more adherent to the cotyledon when the moisture content of peas was high and was not removed by dehulling. The percent of non-dehulled grain was 21.7% which is negligible in peas processed with HA and SS (ranged from 0-0.3%). Hung et al. (1988) also noted that high temperature drying (50, 70, 90 and 110°C) was effective in promoting seed coat removal of akara seed. With an increase in processing temperature and decrease in moisture content, the seed coat became less firmly attached to the cotyledon; therefore, removal of hull/seed coat improved.

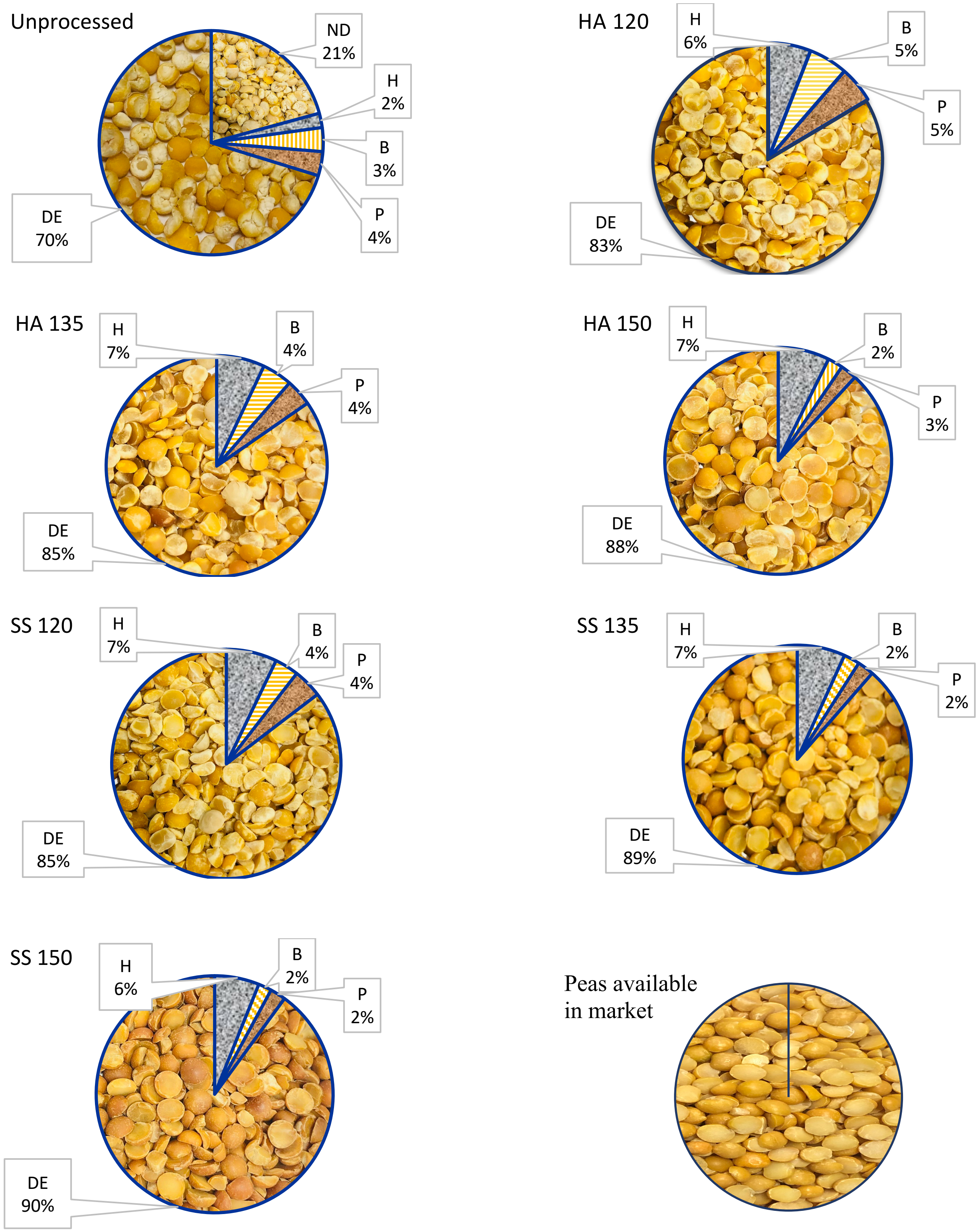


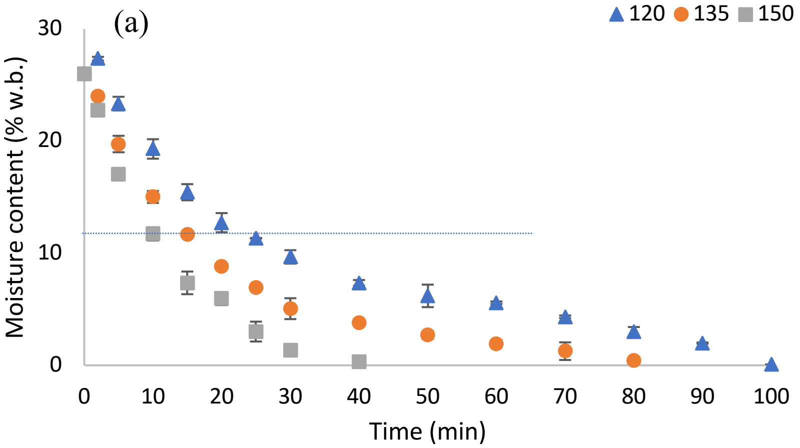
Fig. 4. 5. Dehulling quality characteristics of peas processed with HA and SS at various temperatures (120,135 and 150 °C) for 10 minutes and 1 m/s velocity of the medium. ND = non-dehulled, DE = dehulling efficiency, H = husk, B = broken, P = powder.

According to Black et al. (1998b), the theoretical yield of yellow peas is 90% if the hull is to be removed manually by soaking and using forceps. This yield is approximately equal to what could be achieved by processing peas in SS at 150°C.

4.2 Optimization of SS processing method – Case 2

4.2.1. Drying characteristics

Drying characteristics were used to evaluate the time for peas at initial moisture contents of 26, 40 and 56% to reach equilibrium at three SS temperatures (120, 135, and 150°C) (Fig. 4.8). Peas processed with a higher temperature (150°C) reached equilibrium faster than those processed with SS temperature at 120°C, irrespective of initial moisture content.



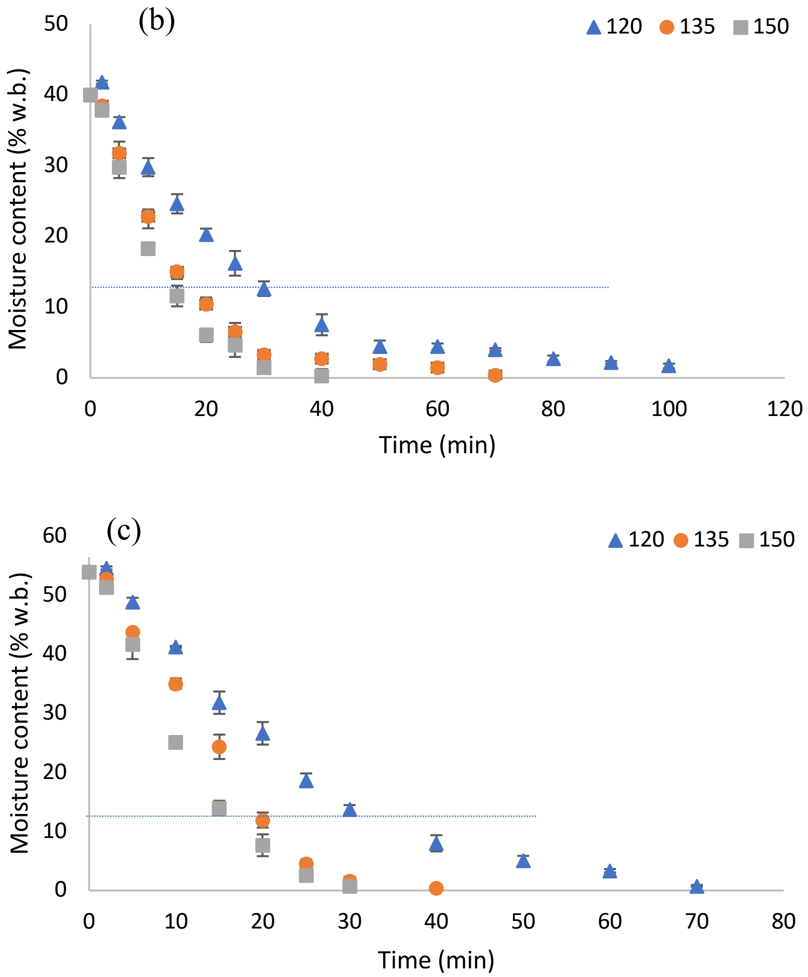


Fig. 4. 6. (a), (b) and (c) represent the drying characteristics of peas with initial moisture contents of 26, 40 and 54% processed with SS at 120, 135 and 150 °C, respectively. The dotted line indicates the 12% moisture content.

The first stage of drying in SS is referred to as a warm-up period during which the sample is heated to the saturation point. If the material is at a lower temperature than the saturation temperature of steam (100°C at atmospheric pressure), condensation occurs on the surface of the processed material. The quantity of condensation of water vapor during the warm-up period depends on the SS conditions (temperature and velocity) and the surface area of the sample.

The highest condensation was observed for peas dried at 120°C, whereas almost no condensation was observed at 150°C, at 1 m/s velocity. Condensation was observed in the initial 120 s of drying at 120°C. Similarly, Johnson et al. (2013) observed the condensation on spent grain pellets dried in SS at 120°C and 1 m/s velocity, but no measurable amount at 150°C. Conversely, when drying with HA, no condensation was observed on the surface of peas for the same operating conditions (120, 135 and 150°C; 1 m/s velocity). Similar findings were observed by Erkinbaev et al. (2019) while comparing the effects of HA and SS processing on properties of distillers spent grain.

As shown in Fig. 4.6 (dotted line) and Table 4.6, it was observed that peas with higher moisture content (54%) took more time to reach 12% moisture content as compared to peas with 26% initial moisture content. The trend could be because of the increased constant drying rate period found in peas with higher initial moisture content.

Table 4. 6. The processing times for peas to reach 12% moisture content when processed at various temperatures (120, 135, 150 °C) and initial moisture contents (26, 40, 54%).

Moisture content (%, wb)	**Temperature (°C)**	**Processing time (min)**
26	120	19
	135	13
	150	9
40	120	30
	135	16
	150	10
54	120	32
	135	19
	150	12

4.2.2. Cooking characteristics (Case 2)

Processing temperature and initial moisture content have a significant effect ($p<0.05$) on the EF (after eliminating the experiments which failed). During the compression test, it was noted that the maximum load capacity of the Ottawa compression cage is 2000 N (Fig. 4.7), hence the test was stopped when the maximum load for compression load reached 2000 N (Fig. A4).

As shown in Fig 4.9, an increase in cooking time resulted in decreased EF for all levels of selected initial moisture contents (26, 40 and 54% w.b.). Therefore, the initial moisture content of yellow peas had a significant contribution to changes in the textural parameters.

Fig. 4. 7. Extrusion insert and frame of Ottawa extrusion cell showing maximum load of 2000 N (2 KN).

The EF for peas at an initial moisture content of 26% at 120 and 135°C, processed with SS, exceeded 2000 N (Fig. 4.8). The processing temperature (120, 135 and 150°C) and time of cooking (5, 10 and 15 min) had a significant effect ($p<0.05$) on the EF and slope of the force-deformation curve. The EF of peas with an initial moisture content of 26% (w.b.), processed at 150°C with SS and cooked for 15 minutes, was similar to the EF for 5 minutes cooking of peas processed at 120°C when initial moisture content was 54%.

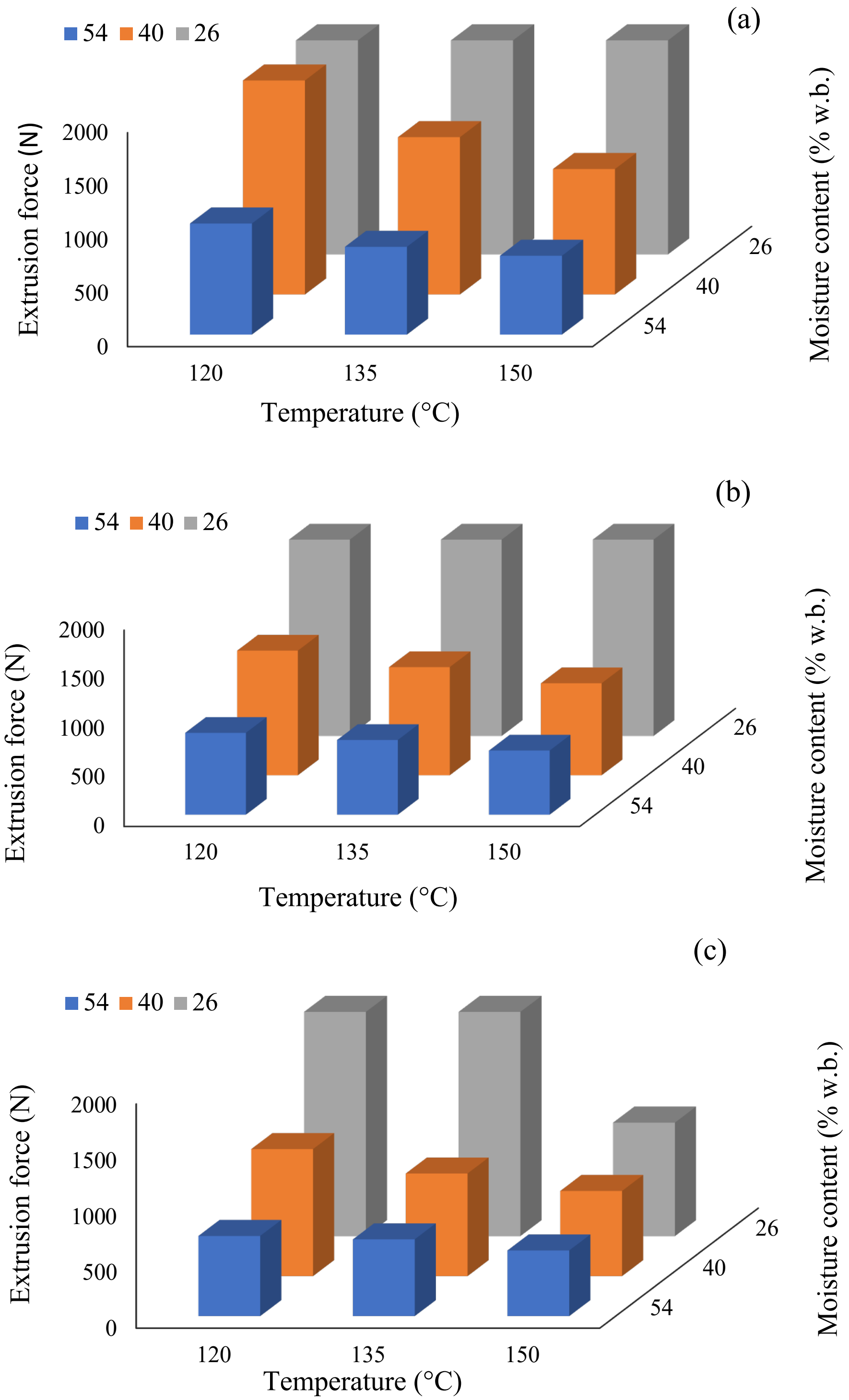


Fig. 4. 8. Extrusion force of yellow peas of the initial moisture content of 26, 40, 54% (w.b.) processed at different SS temperatures (120, 135, 150 °C) and at 1m/s SS velocity and cooked for (a) 5, (b) 10 and (c) 15 minutes.

As shown in Fig. 4.8 (a) and (b), all of the 5- and 10-minute cooking experiments with initial moisture content of 26% demonstrate an EF value of 2000 N (a value considered too high for the load cell). With an increase in processing temperature (120, 135 and 150°C) and time of cooking (5, 10, 15 min), the EF decreased (as mentioned in section 3.3). Figure 4.8 (c) shows the effect of initial moisture content (26, 40, 54%) and the SS processing temperature (120, 135, 150°C) on the EF for 15 minutes cooking time. It was postulated that a minimum force (585.7 N) was needed to compress peas processed with SS at 150°C at the initial moisture content of 54% (w.b.).

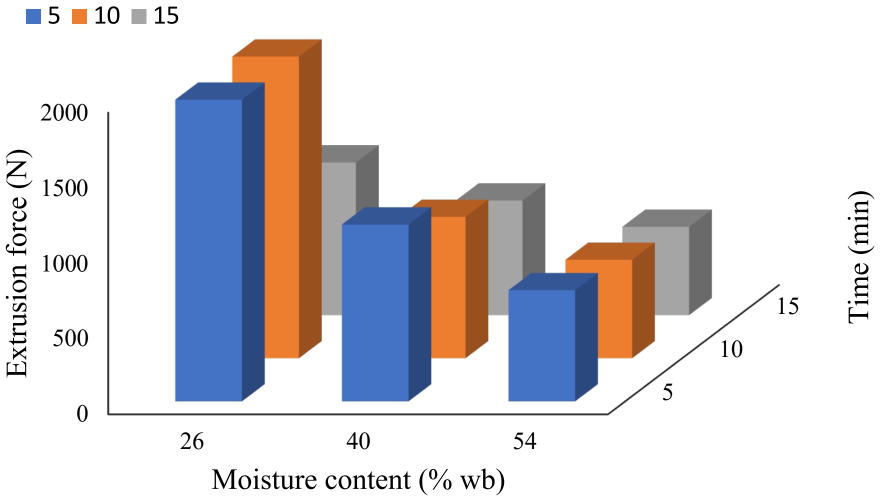


Fig. 4.9. Extrusion force of yellow peas processed at 150°C of SS and initial moisture content of 26, 40, 54% (w.b.) at 1 m/s velocity and cooked for 5, 10 and 15 minutes.

Figure 4.9 shows the effect of moisture content and cooking time on the EF for peas processed with SS at 150°C. As the value of initial moisture content increased, the EF decreased for all levels of cooking times for peas processed with SS at 120, 135 and 150°C. The repetitive curves for each value mentioned in Fig. 4.8 and table 4.7 are provided in Fig. A5.

As mentioned in case 1 (section 4.2), the EF value of peas (processed with SS) soaked before cooking ranged from 519.1-1205.8 N for the temperatures ranging from 120 to 150°C, whereas the EF value ranged from 585.7-1470.0 N for peas which were not soaked before cooking. The value of EF was higher for each of the cooking times (5, 10 and 15 min) and for all levels of processing temperatures (120, 135 and 150°C) for peas with an initial moisture content of 40%, than the EF mentioned in case 1 (Fig. 4.1), for SS processing. Superheated steam processed peas with initial moisture content of 54% showed a lower value of EF compared to peas soaked before cooking in case 1 (section 4.1.3), irrespective of the processing temperature (Fig. 4.8.).

Table 4. 7. Force ratio and slope for peas processed in SS at various temperatures, moisture contents and cooking durations of 5, 10 and 15 min.

Moisture content before processing (%)	Processing temperature (°C)	Cooking time (min)	Slope (N/mm)	Force ratio
26	120	5	F*	F
		10	F	F
		15	F	F
	135	5	F	F
		10	F	F
		15	F	F
	150	5	F	F
		10	F	F
		15	135.6±5.6^{a}	0.54
40	120	5	F	F
		10	189.6±8.3^{b}	0.55
		15	150.8±2.6^{c}	0.51
	135	5	214.1±11.8^{d}	0.51
		10	146.7±5.8^{c}	0.54
		15	118.8±8.3^{e}	0.48
	150	5	152.6±6.6^{c}	0.54
		10	132.1±3.7^{a}	0.48

		15	88.6±5.7^{fh}	0.47
54	120	5	106.7±3.7^{g}	0.47
		10	99.4±5.2^{h}	0.43
		15	75.3±2.9^{i}	0.41
	135	5	80.3±3.8^{fi}	0.43
		10	71.1±7.0^{ji}	0.40
		15	59.5±1.1^{k}	0.37
	150	5	64.1±1.7^{jk}	0.37
		10	58.5±4.8^{k}	0.39
		15	45.7±2.9^{l}	0.32

$^{a\text{-}l}$ Values with different superscripts (column wise) are significantly different (LSD $p < 0.05$).
*F represents the experiments which were considered as failure based the extrusion force (EF>2000N)

The slope of the force-deformation curve is another parameter that determines the cooking time of yellow peas. In this study, the force-deformation curves demonstrated a similar trend to EF. With an increase in the initial moisture content, processing temperature and cooking time, the slope of the force-deformation curve decreased, as shown in table 4.7. The force ratio, which is one of the other parameters obtained from the force-deformation curve, indicates whether the peas are cooked or uncooked. Peas which had an initial moisture content of 54% and were cooked for 15 minutes were overcooked, with a force ratio value of less than 0.35. Conversely, the peas with an initial moisture content of 26% were all undercooked.

The cooking time was decreased to 5 minutes from 15 minutes by increasing the initial moisture content of yellow peas from 26 to 54% in this study. Similarly, Piyawanitpong et al. (2018) reported a decrease in cooking time from 15 to 5-1 minutes by SS processing at 300 °C. The reason they employed to explain the decrease in cooking time was the change in structure from heat damage and the high degree of gelatinization before cooking.

5. Summary and Conclusions

The present study focuses on the effect of processing methods on the quality of yellow peas, which is divided into two cases. The first case covers the comparison between the effects of SS and HA (120,135 and 150°C at 1 m/s velocity and 10 minutes processing time) on functional and nutritional properties of yellow peas. In case 1, peas were tested for final moisture content after processing, drying characteristics, hydration capacity, cooking characteristics, protein content, starch gelatinization, dehulling efficiency and microstructural changes post processing. In the second case, only SS processing method was used for further experimentation on cooking characteristics, as SS performed better in preservation of functional and nutritional properties of yellow peas after the heat processing in case 1. An attempt was also made in case 2 to eliminate the soaking step before cooking as soaking can take up to 18 hours. Therefore, in the second case, the peas were conditioned to three moisture content levels (26, 40 and 56%) and cooked after SS processing without soaking. The conclusions drawn from these experiments (case 1 and 2) are given below:

Case 1

- Superheated steam processing performed better in removing the moisture content of yellow peas than HA. For selected operating conditions, decreases in moisture content of processed yellow peas was in the range of 7.1-11.3% and 4.9-7.8% for SS and HA, respectively.
- Hydration capacity was higher for the peas processed with SS as compared to HA. Hydration capacity ranged from 78.2-79.8% (w.b.) for HA and 80.4-91.1% (w.b.) for SS.
- Extrusion force and the slope of force-deformation curve of cooked yellow peas were higher when processed with HA as compared to SS. Both increase in cooking time (5,10

and 15 min) and increase in processing temperature (120,135 and 150°C) had a significant effect ($p<0.05$) on the reduction of EF and the slope of the force-deformation curve. The lowest EF obtained was 519.2 N at the highest cooking time of 15 minutes for peas processed with SS at 150°C (soaked before cooking). Hardness of cooked peas was in the range of 625.7-1498.7 N and was negatively correlated with hydration capacity.

- The increase in porosity of peas was higher when processed with SS by 19.1, 29.0, and 35.0% than when processed with HA at 120, 135 and 150°C, respectively.
- The highest density was noticed in unprocessed peas (1339.7 kg/m^3). The decrease in density was 1.6, 3.3 and 4.6% for HA whereas for SS the decrease was 2.6, 3.7, 6.7 for SS at 120, 135 and 150°C, respectively.
- An increase in temperature of processing resulted in increased dehulling efficiency. The peas with highest moisture content (unprocessed peas) showed the lowest dehulling efficiency (71.6%). The highest dehulling efficiency (89.9%) was noticed in peas processed with SS at 150°C. Dehulling efficiency of HA processed peas ranged from 83.5-88.2% and SS processed peas ranged from 85.4-89.9% at 120, 135 and 150°C.
- Superheated steam processing did not demonstrate a significant effect on starch gelatinization and protein denaturation. While HA processing had a significant effect on protein denaturation but not on starch gelatinization. The maximum amount of protein denatured was 2.38% for peas processed with HA whereas only 0.75% of protein was denatured with SS processing at 150°C.
- The softest cooked texture was obtained at a processing temperature of 150°C with SS for 15 minutes of cooking. The calculated EF for this combination was 519.1 N, which is

significantly lower than the EF of unprocessed peas (719.5 N) for the same cooking time. The value of force ratio (0.37) at this combination indicated the cooked texture.

- In light of the above conclusions, SS establishes itself as a suitable processing method for yellow peas to reduce the cooking time, as it requires less time to cook than the traditional HA method.

Case 2

- Peas with an initial moisture content of 26% processed with SS at 120, 135 and 150°C exhibit the average drying time of 19, 13, and 9 minutes, respectively. The average drying times for peas with initial moisture content of 40% were 30, 16 and 10 minutes when processed at 120, 135 and 150°C, respectively. Similarly, 32, 19 and 12 minutes were the average drying times for yellow peas processed with SS at 120, 135 and 150°C, respectively, with initial moisture content of 54% to reach to final moisture content of 12%.
- Peas with an initial moisture content of 26% processed with SS at 120, 135 and 150°C, remained undercooked, with the force ratio value lower than 0.5, irrespective of the cooking time (5, 10, 15 minutes).
- Peas with an initial moisture content of 40% resulted in cooked texture after cooking for 10 minutes when processed in 150°C SS. When processing at 120 and 135°C, a cooked texture was obtained after 15 minutes of cooking. Peas cooked for 5 min, with initial moisture content of 46% demonstrated under-cooked texture regardless of the processing temperature of SS (120, 135, 150°C). The value of EF ranged from 652.8-1498.7 N and the slope of force-deformation curve ranged from 88.6-189.6 N/mm.
- Peas processed at an initial moisture content of 54% (without soaking) demonstrated a cooked texture, with a slope value less than 0.5, for various combinations of processing

temperature (120, 135 and 150°C) and the cooking time (5,10 and 15 minutes). The value of EF ranged from 585.7 -736.8 N and the slope of the force-deformation curve ranged from 45.6 -106.7 N/mm.

- The softest cooked texture was obtained at SS processing temperature of 150°C, for 15 minutes cooking (without soaking) when initial moisture content before cooking was 54% (w.b.). The value of EF was 585.7 N, with a force ratio of 0.32, which is considered as overcooked texture (force ratio<0.35).

The present results lead to the conclusion that SS processing is advantageous over HA in terms of better functional and nutritional properties of yellow peas. A combination of tested processing parameters: processing temperature (120, 135 and 150°C) and cooking time (5, 10 and 15 min) without soaking showed smaller values of EF than unprocessed peas, except for peas cooked for 5 minutes after processing with SS at 120°C. The most suitable combination to obtain the lowest EF (652.8 N) and good cooked texture (force ratio>0.5) was 10 minutes of cooking after processing with SS at 150°C, with an initial moisture content of 54% (w.b.). The lowest cooking time obtained was 5 minutes with 135°C SS processing for peas with an initial moisture content of 54% (w.b.). This combination of moisture (54%) and temperature of SS processing (135°C) gave the cooked texture with a force ratio less than 0.5.

The study of the cooking characteristics of yellow peas at varying moisture contents (26, 40 and 56% w.b.) when processed with SS at different operating conditions (SS temperature 120, 135 and 150°C, and velocity of 1.0 m/s) showed that the EF and the slope of force-deformation curve decreased with SS temperature and cooking time (5, 10 and 15 min). Even though the SS processing at high temperature (150°C) reduced the EF and slope with an increase in cooking time, it is not recommended to increase temperature in excess of 135°C, as it leads to overcooking for

15 minutes of cooking time. Therefore, processing at 135°C is sufficient and increasing temperature beyond 135°C is not recommended because it affects the nutritional properties.

As processing is an inevitable unit operation for improving the shelf life of harvested yellow peas, SS can be used as a superior processing medium as an alternative to HA. The results of the present study could be used as a primary tool to determine the optimal processing conditions in SS drying units for pulses such as yellow peas.

6. FUTURE RECOMMNEDATIONS

The major findings of this research reveal that SS is a suitable medium for processing yellow peas. However, most food processing industries handle a variety of commodities in one facility; and in order for them to justify investment in SS processing equipment, it is worthwhile that research is done on a broader spectrum of crops and applications. Some other recommendations for further study on yellow peas and SS processing are as follows:

- Cooking time of yellow peas should be investigated after processing them with higher velocities of SS without compromising the nutritional properties – e.g. fluidized velocity.
- Use of different soaking solutions should be conducted to investigate the effect on cooking time of yellow peas before processing with SS.
- Studies could be further extended to investigate the effect of SS processing on the quality of processed food products made from yellow peas such as breads, pasta, purees, puffed products, etc.
- In order to make the technique industrially viable, it would be of great value to model the drying of yellow peas under various operating conditions of SS. Such models are an essential requirement for the design of industrial dryers.
- A study of the fundamental mechanical properties (e.g. modulus of elasticity, strength, toughness, bioyield point) of peas could be very useful for gaining a more comprehensive understanding of the consequences of the structural changes that peas undergo during processing. Other parameters, such as color and antinutritional factors could be determined after SS processing.

- The potential of SS generating air-bubbles in foods is one of the most important benefits of this innovative technique. Calculation of the water diffusivity coefficients of SS could be helpful in gaining a better understanding of the role of air-bubbles in soaking and cooking.
- Similar studies could be conducted on other pulses and beans like chickpeas, cowpeas, pigeon peas, blackeyed pes, soybean, kidney beans, lima beans etc.

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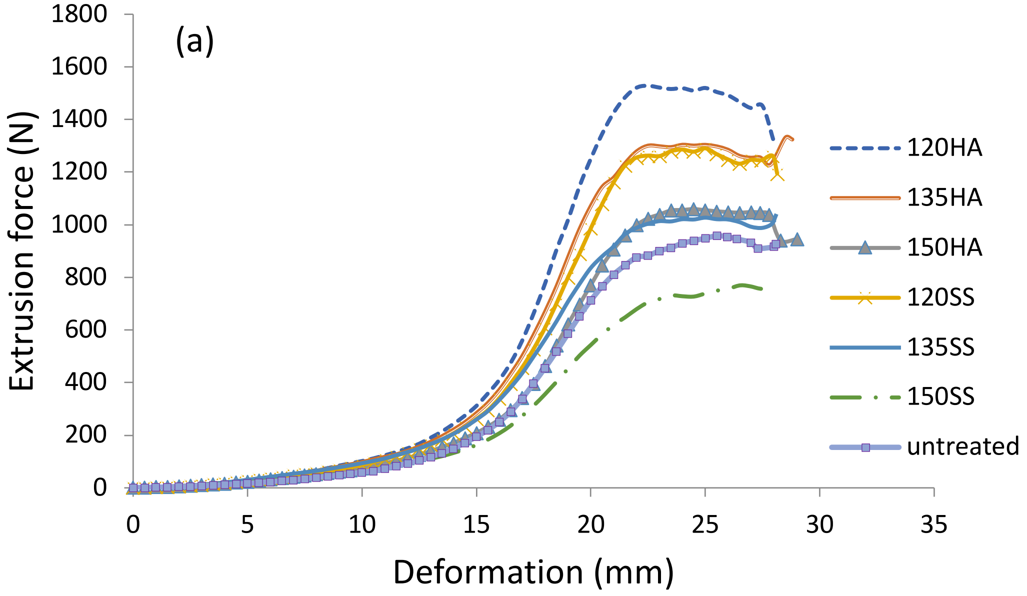
Appendix


(a)
Extrusion force (N)
1800
1600
1400
1200
1000
800
600
400
200
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15
20
25
30
35
Deformation (mm)
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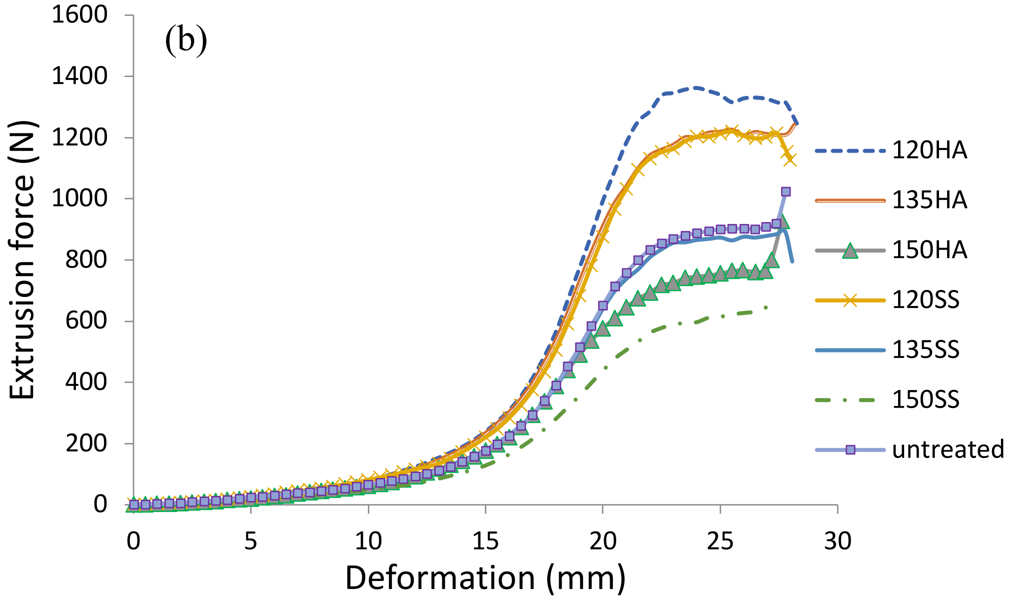
135HA
150HA
120SS
135SS
150SS
untreated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Extrusion force (N)
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Deformation (mm)
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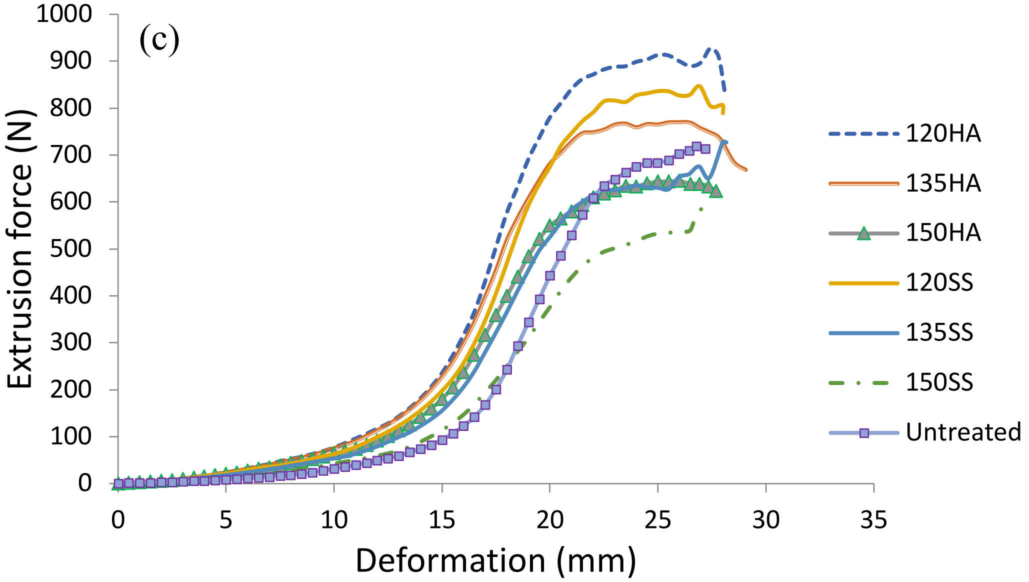


Fig. A. 1. Extrusion force of yellow peas treated at different temperatures (120, 135, 150 °C) of SS and HA at 1m/s velocity and cooked for (a) 5, (b) 10 and (c) 15 minutes. Abbreviations for processing methods: HA -hot air, SS-superheated steam.

Table A. 1. Porosity and density of peas processed in HA and SS at various temperatures (120,135 and 150° C) for 10 minutes and 1m/s velocity of the medium.

Processing method	**Processing temperature (°C)**	**Porosity (%)**	**Density (kg/cm^3)**
Untreated	20	0.19 ± 0.04^a	1339.72 ± 18.41^a
HA	120	4.08 ± 1.03^b	1317.29 ± 4.28^b
	135	5.89 ± 1.19^{bc}	1295.32 ± 14.71^{cd}
	150	7.97 ± 1.53^c	1277.63 ± 4.44^d
SS	120	5.00 ± 0.91^b	1303.68 ± 7.44^{cd}
	135	8.22 ± 2.40^c	1289.14 ± 9.63^{cd}
	150	12.16 ± 3.25^d	1249.52 ± 9.06^e

$^{a-e}$ Values with different superscripts are significantly different (LSD $p < 0.05$). Abbreviations for processing methods: HA - hot air, SS - superheated steam.

Table A. 2. Dehulling quality characteristics of peas processed in HA and SS at various temperatures (120,135,150 °C) for 10 minutes and 1m/s velocity of the medium.

Processing method	**Processing temperature (°C)**	**Weight of 100 seeds (g)**	**Undehulled (%)**	**Husk (%)**	**Broken (%)**	**Powder (%)**	**Dehulling efficiency (%)**
Untreated	20	24.62 ± 0.25	21.70 ± 0.23	2.10 ± 0.54	3.51 ±0.53	3.54 ±0.13	71.61 ± 0.78^{a}
HA	120	22.62 ± 0.29	0.00 ± 0.00	5.96 ± 0.77	5.44 ± 0.72	5.08 ± 1.09	83.53 ± 1.09^{b}
	135	22.02 ± 0.79	0.32 ± 0.00	7.01 ± 0.24	4.41 ± 0.36	3.90 ± 0.60	84.41 ± 1.13^{bd}
	150	21.41 ± 0.41	0.00 ± 0.00	7.33 ± 0.15	2.16 ± 0.21	2.34 ± 0.27	88.17 ± 0.41^{c}
SS	120	22.29 ± 0.60	0.00 ± 0.00	7.15 ± 0.63	3.38 ± 0.28	4.11 ± 0.50	85.36 ± 1.14^{d}
	135	21.51 ± 0.44	0.00 ± 0.00	6.80 ± 0.04	2.27 ± 0.09	2.35 ± 0.03	88.58 ± 0.09^{ce}
	150	20.51 ± 0.71	0.00 ± 0.00	6.09 ± 0.29	1.81 ± 0.31	2.13 ± 0.32	89.95 ± 0.33^{e}

$^{a-e}$ Values with different superscripts are significantly different (LSD $p < 0.05$). Abbreviations for processing methods: HA - hot air, SS - superheated steam.

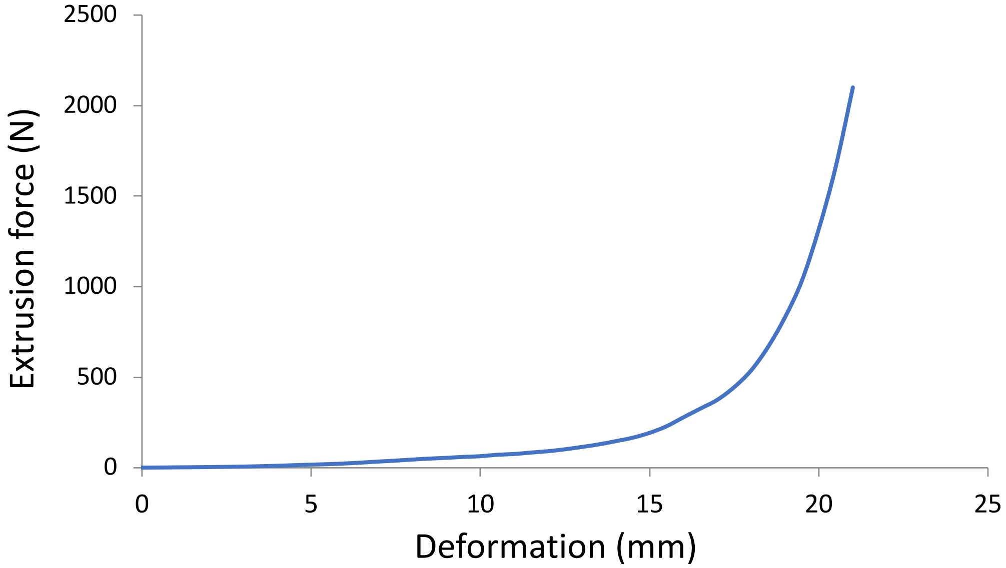
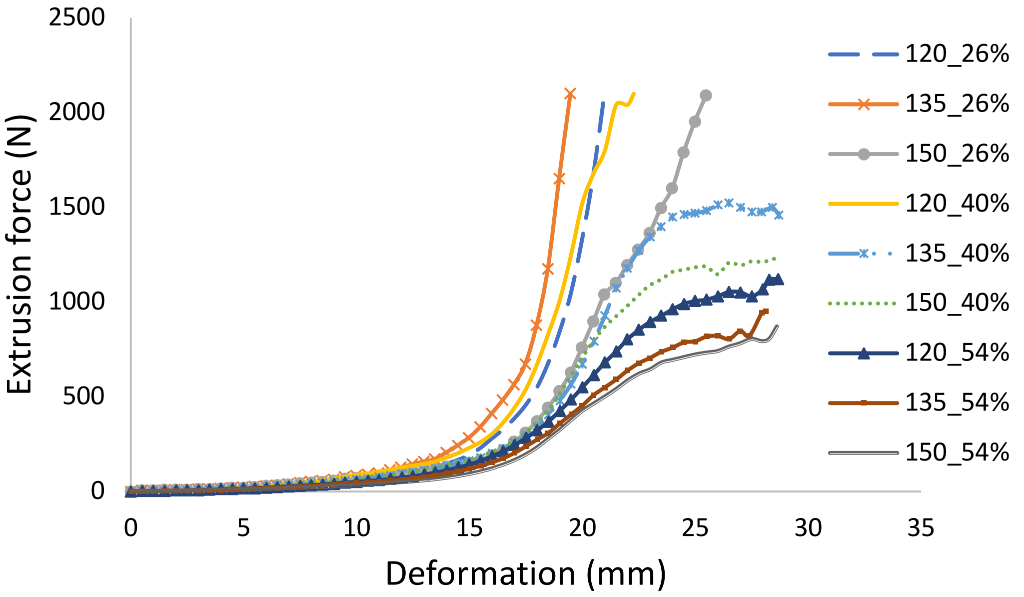


Fig. A. 2. The premature ending of curve shows the failure of experiment when extrusion force did not reach to 2000 N at 26% initial moisture content, 120°C SS temperature and 10 minutes cooking.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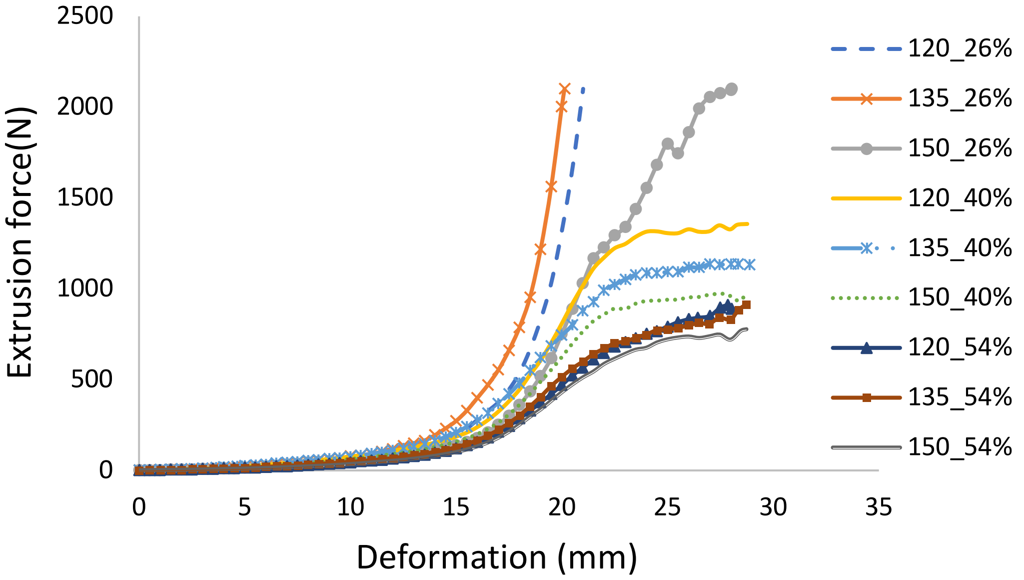
2000
1500
1000
500
0
Extrusion force (N)
0
5
10
15
20
25
30
35
Deformation (mm)
120_26%
135_26%
150_26%
120_40%
135_40%
150_40%
120_54%
135_54%
150_54%


2500
2000
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1000
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0
Extrusion force(N)
0
5
10
15
20
25
30
35
Deformation (mm)
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150_26%
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150_40%
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135_54%
150_54%

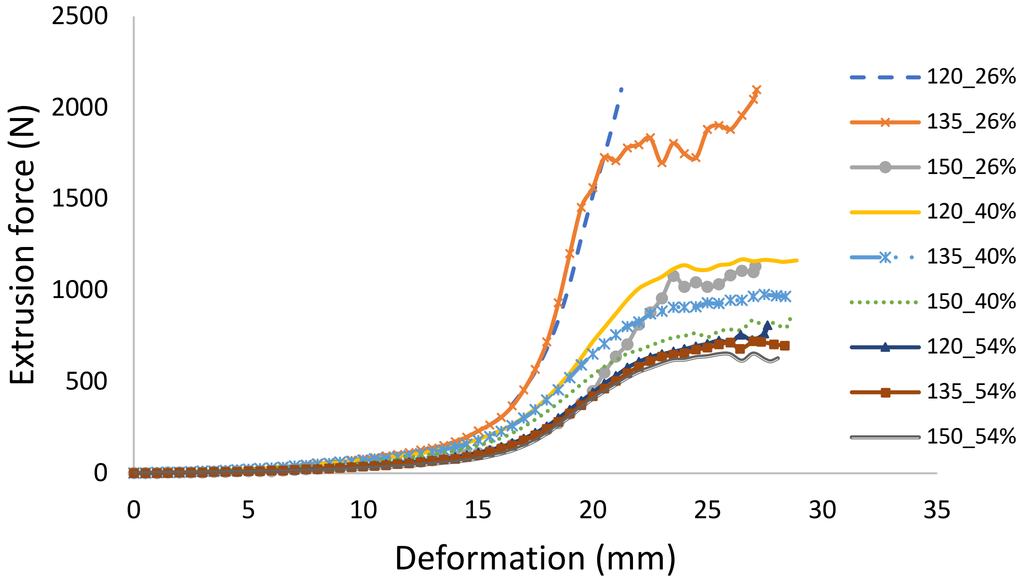

Fig. A. 3. Extrusion curves of yellow peas treated at different temperatures (120, 135, 150 °C) of SS and initial moisture content of 26, 40, 54% (w.b.) at 1m/s velocity and cooked for (a) 5, (b) 10 and (c) 15 minutes.