STORAGE PROPERTIES OF HIGH OIL CONTENT BULK CANOLA AND THEIR EFFECTS ON CANOLA STORAGE

A Thesis
Submitted to the Faculty of Graduate Studies
The University of Manitoba
in partial fulfilment of the requirements for the degree of

Doctor of Philosophy

by

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MECHANICAL AND CHEMICAL PROPERTIES OF HIGH OIL CONTENT BULK CANOLA AND THEIR EFFECTS ON CANOLA STORAGE

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KE SUN

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ABSTRACT

Bulk density, angles of repose and coefficients of friction against four structural surfaces of two varieties of high oil content canola (Invigor 5440; oil content 47.1% ± 0.27%; and Nex4 105; oil content 45.4% ± 0.35%) and mixtures of them (with ratios of 1:1, 1:2 and 2:1) at four moisture contents (8%, 10%, 12% and 14%, wet basis) were determined. The same physical properties of one high oil content canola (45H29; oil content 45.4% ± 0.12%) and one low oil content canola (5525 Clearfield; oil content 42.4% ± 0.07%) at three moisture contents (8%, 10% and 12%) were determined. The coefficient of friction was measured against four structural surfaces: galvanized steel, plywood, and wood-floated and steel-trowelled concrete. Seed major and minor axes (dimension) of 45H29 canola at moisture contents of 8%, 10% and 12%, and Nex4 105, Invigor 5440 and 5525 Clearfield canola at 10% moisture content were measured. Major and minor axes of 45H29 increased with increases in moisture content. The oil content did not affect axes of canola seeds. Bulk densities were significantly different between Invigor 5440 and Nex4 105 canola. Bulk densities of mixtures of Invigor 5440 and Nex4 105 were higher than that of Nex4 105 and lower than that of Invigor 5440. Bulk density decreased with an increase in oil content. Angles of repose depended more on canola types and surface properties than oil content. Coefficient of friction against structural surfaces was not significantly affected by moisture content but was affected by oil content. Bins used to store low oil content canola could be used to store high oil content canola.

Temperature and moisture content of stored crops affect safe storage time. The three high oil content canola varieties (45H29, Invigor 5440 and Nex4 105) and one low oil content canola variety (5525 Clearfield) with 8%, 10%, 12% and 14% initial moisture contents (wet basis) were stored at 10ºC, 20ºC, 30ºC and 40ºC for 20 wk. Moisture content, germination, fatty acid value (FAV) and visible and invisible mould of the canola seeds were determined every 2 or 4 wk. Increase of moisture content and temperature increased germination loss and mould infection. Fatty acid values of canola seeds at 10ºC, 20ºC and 30ºC increased with an increase of storage time; but at 40ºC, it increased at the beginning of storage, and then dramatically decreased. Storage fungi (*Penicillium* spp., *Aspergillus glaucus* group and *Aspergillus candidus* Link) were predominant throughout the study. Invisible mould and FAV were not suitable for predicting safe storage time of canola. Based on the 20% loss of initial germination, safe storage guidelines of high oil content canola were developed. To safely store high oil content canola, its moisture content should be lower than that of low oil content canola.

The variety (Nex4 105) with 10% initial moisture content was stored in three large bins (2.74 m diameter; 5.03 m high) at simulated Western Canadian storage conditions (from September to December in the year 2010), to verify the developed safe storage guidelines of high oil content canola. The developed safe storage guidelines worked well in the real situation, except that hot spots in the grain bulk

might cause dramatic increase of moisture content and temperature that can accelerate canola deterioration.

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ASABE	American Society of Agricultural and Biological Engineers
ATP	adenosine triphosphate
BD	bulk density (kg m^{-3})
CCC	Canola Council of Canada
CGC	Canadian Grain Commission
CWB	Canadian Wheat Board
DWT	seed dry weight
EEC	European Economic Community
EMC	equilibrium moisture content (%)
ERH	equilibrium relative humidity (%)
FAV	fatty acid value
FFA	free fatty acid
g	gravitational constant (9.81 m s^{-2})
G	germination (%) of canola seeds
GC	gas chromatography
h	height of material (m)
H-H	high oil content canola: 45H29 (oil content 45.4% ± 0.12%)
H-I	high oil content canola: Invigor 5440 (oil content 47.1% ± 0.27%)
HM	harvest maturity
$H\text{-}M_a$	H-I and H-N at the same moisture content were mixed with the mass

	ratios of 1:1
$H\text{-}M_b$	H-I and H-N at the same moisture content were mixed with the mass ratios of 1:2
$H\text{-}M_c$	H-I and H-N at the same moisture content were mixed with the mass ratios of 2:1
H-N	high oil content canola: Nex4 105 (oil content 45.4% ± 0.35%)
HPLC	high performance liquid chromatography
K	the ratio of lateral to vertical pressure
KOH	potassium hydroxide
L	length (major axis) of the seed (mm)
L1	sample collected at the grain depth of 0.25 m
L2	sample collected at the grain depth of 1.27 m
L3	sample collected at the grain depth of 2.29 m
L4	sample collected at the grain depth of 4 m
L-C	low oil content canola: 5525 Clearfield (oil content 42.4% ± 0.07%)
L-O	low oil content canola: Okapi (oil content not given in published paper)
L-S	low oil content canola: SLM (oil content not given in published paper)
MC	moisture content (%, wet mass basis)
P_d	the percentage pressure difference (%) between high and low oil

	content canola
$\Delta P_h/\Delta$factor	sensitive value of the factors
P_h	lateral bin wall pressure (kN m^{-2}) at depth h
P_H	the horizontal pressure produced by high oil content canola (kN m^{-2})
P_L	the horizontal pressure produced by low oil content canola (kN m^{-2})
PM	physiological maturity
q	the length of the torque arm (m)
R	hydraulic radius of storage structure (m)
R^2	coefficient of determination
RH	relative humidity
Sc	sample at the center of the bin (1.09 m to the bin wall)
Sw	sample close to the bin wall (0.13 m to the bin walls)
t	storage time (wk)
T	temperature of canola (ºC)
T_m	the measured torque (N.m)
TLC/FID	thin layer chromatography/flame ionization detection
w	specific weight of stored material (canola) (kN m^{-3})
w_r	the sample weight on the rotating surface (kg)
W	width of the seed (mm)
ρ	the bulk density (kg m^{-3}) of material (canola)
μ	the coefficient of friction

Φ	internal friction angle of a material (canola)

1. INTRODUCTION

Canola is one of the largest oilseed crops, and contributes around 13% of oilseeds in the world. Canola oil is extensively used in making salad and cooking oil, and margarine. It contains lower saturated fat than the other main vegetable oils, and is consumed in great quantities (Raymer, 2002). In Canada, 14.7 Mt (million tonnes) of canola (for the year 2012-13) is produced annually (CWB, 2014). New canola varieties are being developed to contain up to 50% oil from current levels closer to 40%. The increase of oil content changes chemical composition of canola seeds, which may affect physical and chemical properties of canola seeds.

Physical properties of bulk canola seeds are important parameters in designing and manufacturing of storage facilities and handling equipment. Bulk density is one of the significant properties, which affects loads on walls and foundations of structures holding stored canola. The coefficient of friction of canola seeds on different structural surfaces reflects the sliding capability of seeds against storage and handling structures, and is also used in calculating loads applied on walls of structures (Janssen, 1895; Airy, 1897; Lvin, 1970; Jenike et al., 1973; Walters, 1973; Rusinek and Molenda, 2007). Angles of repose reflect the internal friction within a grain bulk (Muir et al., 2000).

One of the most important applications of physical properties of grain is to estimate loads on walls of storage facilities. Grain overloading causes deformation or even collapse of storage bins. Estimation of pressures on walls is essential in designing and building storage structures. Many equations have been developed to predict lateral

pressures using physical properties of bulk materials (Janssen, 1895; Airy, 1897; Lvin, 1970; Jenike et al., 1973; Walters, 1973). Janssen's equation is frequently used because it is more practical (Singh (Jayas) and Moysey, 1985). Bulk densities, angles of repose and coefficients of friction of stored materials against structural surfaces are used in this equation. In grain elevators, different varieties of canola seeds are mixed. In order to obtain more accurate prediction of pressures of canola on wall structures, it is required to understand the physical property differences between single and mixed varieties of canola.

In Canada, quality control of canola is significant because the seed is frequently stored for prolonged periods before it is processed or exported. Deterioration of canola seed during storage may considerably reduce value of the oil, which is not acceptable (Paetkau and Lapp, 1972).

Fungal infection and mite infestation are major reasons to cause spoilage of canola (Brogan, 1986). Mites are not a problem until after the canola has already become mouldy because they prefer moist and mouldy grain (Sinha and Wallace, 1977). Increase of fungal infection causes the appearance of visible mould, odours and discolouration that are signs of seed deterioration. Loss of germination and increase of free fatty acid (FFA) levels occur in spoiled canola seeds (Tuma et al., 1989; White et al., 1999a). The changes of chemical properties of the spoiled canola reduce its processing quality, nutrient value and marketability (Tipples, 1995). High moisture content (MC, wet mass basis) and temperature accelerate grain deterioration

(Pomeranz, 1992). The duration of the intended storage period can influence the upper limit of moisture content of the grain for safe storage (Mills, 1996). Safe storage time of canola can be calculated using moisture content of the seed, storage period and CO_2 production (Pronyk et al., 2004). Regression equations to calculate CO_2 production using temperature, storage time and moisture content, and germination using CO_2 production rate, moisture content and temperature were developed (Pronyk et al., 2004). Sufficient information on deterioration rates of canola at different moisture contents and temperatures can help grain storage managers and farmers to decide the storage plan and maintain canola quality.

With the industry goal of increasing overall oil content of canola, research is needed to understand the physical and chemical properties of new high oil content canola seeds. The long-term objective of this research is to develop safe storage guidelines for high oil content canola cultivars. To safely store the new high oil content canola seeds, and to prevent seed deterioration, the temperature, RH and time effects on the quality and bulk physical and handling properties of these new cultivars should be obtained. Short-term objectives of this research are to:

1. Determine physical properties of high and low oil content canola seeds at different moisture contents.
2. Find the relationship between physical properties of pure and mixed high oil content canola seeds.

3. Compare the horizontal pressures on storage structure surfaces caused by high and low oil content canola seeds.
4. Set up both small and large scale controlled environment experiments to study storing high oil content canola with different initial moisture contents at different temperatures and different RH.
5. Observe seed germination, moisture contents, appearance of visible moulds, fatty acid value (FAV), and species of mould changes of the high and low oil content canola having different initial moisture contents.
6. Compare the quality changes during storage between high and low oil content canola seeds.

2. LITERATURE REVIEW

2.1. Canola

Canola is a modified form of rapeseed. The two rapeseed species, *Brassica napus* L. and *B. rapa* L., are the most common ones used to produce industrial vegetable oil in world commerce. Distinguished by vernalization requirement, there are spring and winter forms of *Brassica napus* L. and *B. rapa* L. Oil content of the rapeseed is generally 40% or more (Raymer, 2002). Oil of the rapeseed contains high concentrations of erucic acid. Erucic acid is a mono unsaturated fatty acid that leads to a sour flavour in oil. High quantities of erucic acids are toxic to humans. Glucosinolates will stay in the cake after oil extraction. They are subjected to enzymatic hydrolysis, which results in various toxic products (Savic, 2008) in animal guts. Through genetic manipulation and development of new plant varieties, the concentrations of these two toxic substances have been reduced to acceptable levels in canola. Thus, canola is physically similar to rapeseed, but is chemically different (Jayas et al., 1988).

In the modern market, canola oil is low in erucic acid and saturated fats. It is extensively used in making salad and cooking oil, and margarine. The low saturated fat content of canola oil makes it popular to health-conscious consumers (Raymer, 2002). Canada is one of the world's largest canola producers. It exports more than 50% canola seeds overseas each year. Weather patterns, crop rotation requirements and international commodity prices are the three main factors to control seed production

of canola. Both canola yield and seed quality are affected by the stage of seed development at harvest (Elias and Copeland, 2001). It is important to understand physiological maturity (PM) and harvest maturity (HM) of the seed in order to decide proper harvest time and prevent under- and over-ripe pods. Elias and Copeland (2001) identified PM and HM of six different canola varieties. They used seed and pod colour, seed dry weight (DWT) and seed moisture content (MC) as the identification markers. The seed quality was assessed using standard germination, accelerated aging and cold tests at several levels of PM and HM. They found that seed planting time affected HM. Their methods of testing quality of canola seed could be used to analyze the seed viability and vigour (Elias and Copeland, 1997). Seed viability was the germination ability of a seed under proper conditions. Seed vigour was the emerging ability of a seed under pressures (Bradbeer, 1988).

Many countries have established regulations of the standard of quality of oilseeds. These regulations grade oilseeds by different characteristics and help consumers to obtain the products with the specific qualities. Two kinds of grading systems for oilseeds are commonly used. One is to separate oilseeds by numerical grade, which is adopted in Canada, Sweden and the USA. This system allows each grade to contain a set of unique qualities. The other one is based on individual qualities. This system is used in Australia and the European Economic Community (EEC). Both of the above grading systems involve measurement of degrading factors (Daun and Burch, 1984). Daun and Burch (1984) fully described the grading system

of oilseeds in Canada, factors that can degrade oil quality, and the relationship between them. Quality of oilseeds is considered to be degraded when (a) oil (or protein) content of the seed is reduced, and (b) the oil content and meal of canola is difficult to process into desired products. Normally, the assessments of degrading factors are done using laboratory and visual assessment. Laboratory assessment usually includes oil content, chlorophyll and FAV determination. Immaturity, heated, broken and sprouted seeds, weathering and admixture are the main degrading factors (Daun and Burch, 1984). For industry, the main value of canola depends on the oil content. Although the value of the seed protein is useful for animal feed, it is less important. Therefore, the main purpose of the canola breeding industry is to increase oil content of the seed (Delourme et al., 2006). High oil content canola varieties have been developed and cultivated in Western Canada, and they contain up to 50% oil compared to previous levels closer to 40%. Current guidelines for safe storage of canola were developed based on the low oil content cultivars, which may not be suitable for the high oil content cultivars. There is a need for storage guidelines (based on temperature and moisture content during storage) for these new cultivars to reduce the storage quantity and quality losses.

2.2. Mechanical Properties of Bulks

2.2.1. Seed dimension

Size and shape are fundamental physical characteristics of grain kernels. They have important effects on pressures on storage structure surfaces, grain and air flow, and grain drying rate (Bakker-Arkema et. al., 1983; Cenkowski and Zhang, 1995).

2.2.1.1. Measurement of seed dimension Kernel dimensions of grain and oilseeds are irregular. In order to study these irregular dimensions, numbers of kernels are measured by researchers (Mohsenin, 1986; Nelson, 2002; Çahşır et al., 2005; Razavi et al., 2009). Mohsenin (1978) used a micrometer screw gauge (0.001 mm precision) to determine length, width and thickness of grain. Çahşır et al. (2005) measured major (lengths) and minor (widths) axes of 100 canola seeds with a micrometer (0.01 mm precision). Similarly, Razavi et al. (2009) randomly chose 30 canola seeds, and used a micrometer (0.0001 mm precision) to measure lengths and widths of them.

2.2.1.2. Factors affecting seed dimension Nelson (2002) randomly tested dimensions of 50 soybean kernels and found that length, width and thickness of soybean kernels increased 0.3, 0.1 and 0.2 mm, respectively, with increase in MC from 10.0% to 16.7%. Hindy et al. (2003) found that dimensions of soybean had a linear relationship with moisture content and this relationship was positive with moisture contents from 11.9% to 29.2% (dry basis). However, dimensions of grain kernels vary by varieties, can be affected by growing conditions and may be different at different moisture content. For example, lengths of soybean kernels were 7.52 to

9.11 mm from 7.1% to 43.7% MC for variety TGX 1871- 5E (Manuwa and Afuye, 2004) and were 8.3 to 10.4 mm from 9.9% to 39.6% MC for variety TGX 1448-2E (Manuwa, 2007); and widths of the kernels were 6.47 to 7.05 mm from 7.1% to 43.7% MC (Manuwa and Afuye, 2004) and 6.4 to 7.5 mm from 9.9% to 39.6% MC (Manuwa, 2007) for the same varieties.

Çahşır et al. (2005) indicated that length and width of rapeseeds increased with increase of moisture content from 4.7% to 24.0%. They found the relationship between length and width of the rapeseeds was as follows:

$$L = 1.125 \times W \quad (2.1)$$

where,

L = length of the seed (mm), and

W = width of the seed (mm).

This was somewhat different from the result of Razavi et al. (2009), who found that length of the canola seeds increased with increase of moisture content; but width of the seed decreased with increase in MC from around 5% to 15% and increased with increase in MC from around 15% to 23%.

2.2.2. Bulk density

Bulk density, ρ_b, is the total mass including intergranular air per unit volume, and the unit of it is kg m^{-3}. It is affected by the factors of grain type, variety, moisture content, and filling method. Bulk density (called test weight) is one of the main factors in the Canadian grading system (Muir et al., 2000).

2.2.2.1. Bulk density determination methods Measured bulk density is affected by several factors including size of the container, rate of the seed flow, vibration, falling height, and the way of removing overflow grain from the top of the container. There are several methods to determine the bulk density of grains. Canadian Grain Commission (CGC, 2010) used "a 0.5 L cup with an internal diameter of 9 cm and depth of 7.75 cm. Grain sufficient to over fill the cup is placed in a funnel with a bottom-opening, 3.81 cm in diameter. The funnel is placed with its bottom opening 4.41 cm above the top of the 0.5 L container. A slide gate at the bottom of the funnel is opened and grain flows into the cup to overflowing. A hardwood rod, 1.9 cm in diameter, is used to strike off the excess grain in the cup using three equal zig-zag movements at an angle of 45°. The mass of the grain in the level-filled cup is determined and converted to kilograms per cubic meter." The bulk density measured by this method is called standard bulk density. The bulk density could also be determined by dropping the grain slowly from the height of 1.6 m into a 0.5 L cup. Similar as the standard method, the mass of the grain in the cup is measured and calculated to kilograms per cubic meter. The bulk density measured by this method is called compacted bulk density (Muir et al., 2000). Irvine al. (1992) measured the bulk density "by dropping samples 1800 mm through a 76-mm diameter pipe from a conical container having a top diameter of 210 mm, a bottom diameter of 165 mm and a volume of 3785 mL into a 500 mL cup. The sample was then levelled and the mass

of the sample was measured." Densities from this test were designated as pail bulk density.

2.2.2.2. Factors affecting bulk density in grain storage Muir and Sinha (1988) tested both standard and compacted bulk densities of two canola varieties; Candle and Torch, with 8.1% moisture content. The standard and compacted bulk densities of Candle canola were 677 and 743 kg m^{-3}, and those of the Torch canola were 664 and 746 kg m^{-3}, respectively. Çahşır et al. (2005) used the method described by Jain and Bal (1997) to determine the bulk densities of rapeseed. "Bulk density of the grain was measured by means of a hectometer at storage moisture content of 4.7%, 13.1% and 24.0%. The vessel was filled with clean grain and gently tapped five times to cause the grain to settle. After initial settling the hectometer vessel was further filled with grains and again tapped twice. A sharp edge flat was used to remove excess grain to level the surface at the top of the vessel." The grains were not compacted any further. They found that at moisture contents from 4.7% to 24.0%, the bulk densities of rapeseed were from 612.1 to 585.1 kg m^{-3}. An equation was developed by them to express the relationship between bulk density (ρ) and moisture content (MC) as follows:

$$\rho = 616.74 - 1.4518MC \qquad (R^2 = 0.9264) \qquad (2.2)$$

where,

ρ = bulk density (kg m^{-3}),

MC = moisture content (%), and

R^2 = coefficient of determination.

From this equation, bulk density decreased with the increase of moisture content.

Irvine et al. (1992) measured both standard and pail bulk densities of flaxseed, lentils and fababeans. They found that both standard and pail bulk densities decreased with an increase in moisture content for all grains. Pail bulk density was always higher than the standard bulk density due to the increased drop height.

Jian et al. (2013) studied the bulk densities of high oil content canola (~45% oil content). They found that bulk density of high oil content canola followed a parabolic equation at temperatures from -20°C to 30°C and moisture content from 5% to 16%:

$$BD = y_0 + aT + bMC + dT^2 + fMC^2 \quad (2.3)$$

where,

BD = bulk density (kg m^{-3}),

T = temperature of canola (^{o}C),

MC = moisture content (%),

y_0 = 565.93±8.28,

a = -0.13±0.06,

b = 20.36±1.68,

d = (-0.29±0.32) × 10^{-2},

f = -1.11±0.08, and

y_0, a, b, d and f were coefficients in this equation.

Bulk density is affected more by moisture content than temperature (Jian et al., 2013).

2.2.3. Emptying and filling angles of repose

Angles of repose are used to measure the internal friction between kernels. The angle between the upper slope and the horizontal surface of a pile of grain formed when the grain freely flows out from the bottom-side of the bulk is the emptying angle of repose. The angle between the upper slope and the horizontal surface of a pile of grain formed when the grain flows onto the pile and its velocity is close to zero is the filling angle of repose (Muir et al., 2000).

2.2.3.1. Determination methods of emptying and filling angles of repose Irvine et al. (1992) studied the emptying angles of repose using a box (430 mm x 200 mm x 430 mm). A rectangular opening (50 mm high × 200 mm wide) was at the bottom of one side of the box. The researcher scooped the grain and hand-filled the box to an approximate depth of 350 mm for each replication, then opened the rectangular opening to allow the sample to freely flow out through the opening. They recorded the emptying angles with a depth gauge.

The filling angles of repose were measured in a large box (1220 mm × 100 mm × 760 mm) with one plexiglass side in their study. A wooden hopper with a "53 mm square opening was located midway along the box length and 800 mm above the bottom of the receiving box". The grain was filled through the opening of the hopper. The seed profile-depth at two points on both sides (left and right) of the cone was measured. The first point was about 100 mm away from the impact flattened apex. Filling slope angle was determined from the above measurements. White and Jayas

(2001) used the same method to determine the emptying angles of repose of canola and sunflower meal pellets. Their equipment for filling angles of repose had the same dimensions except that the hopper at the top was metal instead of wood, and distance from the centre of the hopper to the bottom of the receiving box was 1000 mm.

Fraser et al. (1978) determined the emptying angles of repose of fababeans. They used a cubic box with 450 mm of all three dimensions. A removable panel was mounted in the front of this box. The panel was removed rapidly after the beans were filled into the box. The beans were then allowed to flow freely to the natural slope. The perpendicular distance between the top front centre of the box and the exterior of the pile of fababeans were measured and used to calculate the angle of repose.

The filling angles of repose were determined by the following method. A cylinder (both top and bottom uncovered) with 30 cm diameter and 50 cm height was placed at the centre of a circular plate. It was filled with grain, and then gently uplifted in order to form a natural pile of grain. The measured height and diameter of the pile on a circular plate was used to calculate the angles of repose of the grain (Kaleemullah and Gunasekar, 2002; Taser et al., 2005).

2.2.3.2. Factors affecting emptying and filling angles of repose According to the study of Irvine et al. (1992), the emptying angle of repose for flaxseed increased with an increase in moisture content from 30.3º at 7.0% MC to 38.0º at 15.1%.MC. The filling angle of repose also tended to increase with an increase in moisture content. This behaviour might be due to increased cohesive properties of flaxseed at higher

moisture contents. An increase of foreign material also led to a slight increase in both emptying and filling angles of repose. However, foreign material, at levels used in their study, had less effect on the angles of repose than moisture content.

Razavi et al. (2009) studied filling and emptying angles of repose of canola seeds at different moisture contents. They found that except for the variety Hyola, emptying angle of repose of canola varieties (SLM, Okapi, and Orient) increased with increase of moisture content. This effect was more distinct when the moisture content of canola exceeded 13.6%. The reason might be that higher moisture content increased the stickiness of canola seeds. However, filling angle of repose dropped as moisture content of canola increased. They explained that the friction among kernels would reduce as the increased moisture content changed the characteristics of the seed skin. Izli et al. (2009) observed an increase in angle of repose of rapeseed with increasing moisture content.

Parde et al. (2003) experimented on three buckwheat cultivars (Koto, Koban, and Manisoba). The moisture contents of Koto and Koban were 15.8%, 16.6% and 17.9%, and Manisoba were 14.0%, 15.0%, 16.0% and 17.0%. Neither of the filling and emptying angles of the cultivars decreased with the increase of moisture content. The emptying angle for the Koban had a significant increase with increasing moisture content. This result also proved the conclusion of Irvine et al. (1992). Cohesiveness among the seeds increased with increase of moisture content, which led to increase of emptying angles. The filling angle for the Koban cultivar increased initially, and

stayed constant after the moisture content increased to 15.8%. The emptying angle for the Manisoba increased significantly until the moisture content increased to 15.0% and then stayed constant. The emptying and filling angles for Koto stayed constant all the time.

2.2.4. Coefficient of friction against structural surfaces

The coefficient of friction of the seed against the various surfaces needs to be known for designing of transportation and storage structures (Taser et al., 2005). Several factors might influence the coefficient of friction, including moisture content of the seeds, grain type, bulk density and surface condition of the wall structure (Mohsenin, 1978).

2.2.4.1. Determination methods of the coefficient of friction Irvine et al. (1992) tested the coefficient of friction of grains on six different structural surfaces by the following method. They attached the surfaces to a table that could be mechanically tilted. A frame made of 18 mm square wooden bars, was used to restrict an area (305 mm long ×255 mm wide) on top of the table. Initially, grain seeds were filled into the frame and leveled up. After that the frame was gently lifted up. The table was then manually tilted using a driven screw. The tilting was stopped when seeds started to slide. The angle between the table surface and the horizontal line was measured and used to calculate the coefficient of friction. White and Jayas (2001) used the same method to determine coefficients of sliding friction of canola and sunflower meal

pellets for the surfaces of galvanized steel, plywood, steel-trowelled and wood-floated concretes.

Çahşır et al. (2005) used a friction device that had three main components: (1) a stationary sample container with its support shaft; (2) a driving unit with a rotating disc; and (3) a data acquisition system. The sample was used to measure the coefficients of friction using the equation developed by Chung and Verma (1989) as follows:

$$\mu = T_m / (w_r \times q) \quad (2.4)$$

where,

μ = the coefficient of friction,

T_m = the measured torque (N.m),

q = the length of the torque arm (m), and

w_r = the sample weight on the rotating surface (kg).

2.2.4.2. Factors affecting coefficient of friction in grain storage Çahşır et al. (2005) used rapeseeds at 4.70%, 13.14% and 23.96% MC to test the coefficient of friction on an iron sheet, a galvanized sheet and plywood. They found an increase of the coefficients of friction against all three structural surfaces with increasing moisture content. Rusinek and Molenda (2007) found that coefficients of friction against a concrete surface increased by 0.9 when moisture contents of rapeseed increased from 6% to 15%.

Irvine et al. (1992) found that friction coefficients for flaxseed increased with

increases in moisture content on all six surfaces (galvanized steel, corrugated steel, parallel grain plywood, perpendicular grain plywood, smooth steel-trowelled concrete, and rough wood-floated concrete). The galvanized steel had the lowest coefficient of friction at low moisture contents (7%) but increased to the highest coefficient of friction at 15.1% moisture content with the exception of corrugated steel. This occurred because the flaxseed was somewhat sticky at 15.1% moisture content and the smooth galvanized steel offered the best surface for adhesion.

Taser et al. (2005) studied the coefficients of friction of Hungarian vetch (*Vicia pannonica* Crantz) and common vetch (*Vicia sativa* L.) at moisture contents of 11.57 and 10.3%, respectively. Friction surfaces: hard-wood sheet, galvanized steel, mild steel, chipboard, and rubber, were used in this study. The lowest coefficient of friction values were obtained against hard-wood sheet and galvanized steel surfaces and the highest values were against the rubber surface.

2.3. Chemical Properties of Seeds

2.3.1. Moisture content, equilibrium relative humidity (ERH) and temperature

Farm bins, silos, elevators, and bulks of grain are ecosystems. The interaction of physical and biological agents in these ecosystems reduces the quality and quantity of the grain (Sinha, 1973). The main factors that affect changes in these ecosystems are history, temperature, and initial moisture content of the grain. Moisture content and temperature of the canola seed are the first and second most important factors that influence the seed deterioration (Jayas and White, 2003). The mould infection spreads

and the grain deteriorates dramatically when the moisture content and temperature are over certain limits (Sinha, 1973; Wallace et al., 1983). Swathing of canola is carried out when the average seed moisture is 35-40%. Generally, moisture content of canola seeds reduces 1%-2% per day from the swathing moisture content (35%-40% MC). The swathed canola is threshed at 12% MC or slightly higher. The Canadian Grain Commission considers 8.5% MC to be the standard moisture content of canola seeds for extracting oil and 10% MC is considered dry. To store canola for long and safe periods, the seeds should not be higher than 8% MC (Mills, 1989).

The temperature, moisture and equilibrium relative humidity (ERH) for stored products are correlated to each other (Pixton and Warburton, 1971). The ERH is significantly important to the storage potential of grain. It shows the amount of water that can be used by micro-organisms, in order to indicate the biological activity of the grain (Ayerst, 1965; Jones, 1969).

2.3.1.1. Measurement of moisture content There are several techniques that can be used for measuring moisture content of grains. Oxley et al. (1960) measured the moisture content of the grain by drying samples in an oven equipped with mechanical ventilation for 4 h at 113ºC. Pixton (1967) mentioned three main methods of testing moisture contents in grain:

1. Oven dry method. It was similar to the method used by Oxley et al. (1960).

2. Electrical method. Electrical meters usually have two main categories. One group worked on the principle of measuring resistance. The grain (ground or whole

seed) was placed into the circuit. It produced resistance to the passage of an electrical current. This resistance was measured and converted to the value of moisture content. The resistance decreased with an increase in moisture content. The other group measured the dielectric constant. When the grain was filled in between two plates of a capacitor, the dielectric constant could be measured. This machine was suitable for testing moisture content of the whole grain. But this method usually caused large errors because the packing of grain varied in the capacitor. For obtaining more accurate results, the operator should maintain the filling consistently.

3. Chemical method. Two chemical methods were used for measuring the moisture content quickly. The principle of one method was the reaction between calcium carbide and the ground grain. The reaction produced acetylene gas. The release of acetylene gas caused the reduction of sample weight. This reduction part could be used to calculate or calibrate the moisture content. The moisture content was higher if the grain sample was finely ground. The second one was alcoholic extraction method. In this method the alcoholic extraction was titrated with Karl Fisher reagent to calculate the moisture content of the grain. Anderson and Alcock (1954) indicated that the Karl Fisher method might be the best method for water measurement, when no interference and side reactions existed. The results of the method dealing with biological material needed to be standardized. This method also required a trained operator and laboratory conditions, and was not commonly used in the grain industry (Pixton, 1967).

American Society of Agricultural and Biological Engineers (ASABE) (2010) had adopted the oven dry method as a standard for measuring moisture content of grain seeds. For example, for determining canola moisture content, 10 g of the representative sample (triplicate) should be oven dried at 130ºC for 4 h. The drying time and temperature varied depending on different grain species.

2.3.1.2. Measurement of ERH Pixton and Warburton (1971) described a method of determining ERH as follows. A sample was chosen from the sub-sample. Moisture content of approximately 20 g of the chosen sample (duplicate) was measured. A dew point device was used to test the sub-sample. Initially, a set temperature needed to be equilibrated in the device for approximately 24 h. The depression of the dew-point was then measured. Using this result, the RH could be matched in the tables of vapour pressure. Various temperatures were involved in this study. Another 24 h of equilibration was needed each time the temperature was changed. Control moisture content was decided by the mean of the four moisture content determinations.

Chen (2000) adopted the measuring technique of ERH that was used by Chen and Morey (1989). In his study, a plastic box was used. The box was tightly sealed after samples were put in it. The box was kept in a chamber that controlled a constant temperature of 53°C. When the equilibrium between the mass and thermal system inside the box was formed, the RH value was shown on the device and the temperature at this moment was also recorded. The temperature of the chamber was then changed to the other chosen level and the procedure was repeated. This method

is more rapid and accurate than the method described by Pixton and Warburton (1971).

2.3.1.3. Factors affecting moisture content, ERH and temperatures in grain storage White (1995) reported that moisture and temperature had primary effects on living and multiplication of biological pests in a grain bulk. When RH of the stored grain is above 75%, microflora multiplies rapidly. The multiplication produces more heat and accelerates germination loss and deterioration of grain. Generally, 70% RH is considered 'safe' in equilibrium with the moisture content of cereal grain and oilseed for maintaining their safe storage (Mills and Sinha, 1980). Distinct variance of temperature in the bulk grain can cause deterioration although initial moisture content of the seed is safe and consolidated. The temperature gradients in bulk grain cause convection currents and cause moisture at the warm area to move to the cooler area. The accumulated moisture at the cooler area supplies suitable conditions for deterioration. The air among the seeds is dynamic. The water vapour in the air can be condensed on the cold grain surface or walls of the storage structure when the temperature of the air dropped below the dew point (Pixton and Warburton, 1971).

Sorption characteristics reflect relationships between equilibrium moisture content (EMC) and ERH. These are used to optimize storing and processing of agricultural products, and to determine the extent that bulk grain dries or rewets during storage (Hulasare et al., 2001). Pixton and Henderson (1981) tested the relationship between EMC and ERH of Candle rapeseed. A small hysteresis

relationship, which was “the difference between the desorption and sorption EMCs at a given RH (Jayas, 2003)”, was shown between EMC and ERH of Candle. But no hysteresis was found on the EMC/ERH relationship of another low erucic acid and glucosinlate cultivar or high erucic acid cultivars (Pixton and Warburton, 1977). The modified Henderson equation and the Chung-Pfost equations are recommended as standards to represent the EMC-ERH data of cereals and oilseeds in the American Society of Agricultural and Biological Engineers Data (ASABE, 2010).

White and Sinha (1980) studied the effect of specific insect species on stored-wheat ecosystems, and found that in moist and warm grain insects, mites and fungi increased dramatically and produced moisture, heat and carbon dioxide due to respiration, which further led to deterioration of the grain bulk. Tipples (1995) reported that moisture content, water activity and RH affected the respiration rate of the stored grain and influenced the multiplication of moulds and insects. Pixton et al. (1975) studied the quality changes of bulk wheat during sixteen years of storage and found that dry wheat (11.9% MC) was not affected by any microorganisms even after more than 10 years of storage, which explained that high moisture content was the main factor to influence the deterioration of grain. In other words, higher moisture pockets inside the grain bulk can get spoiled and act as a locus for an infection by fungi and mites to multiply (Muir, 2001).

White et al. (1999a) stored oat and barley cultivars for one year to observe the grain deterioration. The oat and barley cultivars were: two hulled oat cultivars (Robert

and AC Marie), one hull-less oat cultivar (AC Belmont), one hulled barley cultivar (Bedford) and one hull-less barley cultivar (Condor). The storage conditions of these cultivars were from 10°C to 30°C and from 35% to 80% RH. They concluded that the deterioration rate of grain was higher at high temperature and moisture conditions than at cool and dry conditions having minimal deterioration. Zia-Ur-Rehman et al. (2002) observed significant changes in the pH value and titratable acidity values at higher temperatures, when they studied the temperature effects on nutritional changes of stored corn. During storage, the increase in acidity represented increase in free fatty acid values (FAV), which meant increase in grain deterioration. There was gradual decrease in moisture content of the stored grain if the temperature was kept higher. At high temperatures (25 and 45ºC) the corn lost a considerable amount of total soluble sugars and lysine. Significant protein and starch degradation were also observed. According to their study, the biochemical changes occurred to varied extents which mainly depended on the storage temperature and time.

White et al. (1999b) studied solin, high linolenic acid and standard flax seed for changes in quality during storage. Their results showed that oil content of the flax seed at high moisture content changed a little bit during 6 month storage. The FAV of samples rose with the increase of storage time, temperature, and moisture content. According to their research 8% moisture content of all cultivars could be kept well without any significant spoilage. Similar to results of White et al. (1999a), they found that rate of deterioration was higher in the grains at high temperature and high RH

than at low temperature and low RH. Moisture contents and temperatures of grain bulk have severe impact on grain quality changes during storage. When trying to develop safe storage guidelines of canola, storage temperatures and the initial moisture contents of the samples should be decided carefully based on previous studies and the physical and chemical properties of canola seeds.

2.3.2. Germination

Germination is a very significant factor for determining quality of cereal grains and oilseeds (Muir, 2001). Germination is the most important factor for determining grain quality (Pomeranz, 1992). Mould infection of the germ caused death of seed (Papavizas and Christensen, 1957).

2.3.2.1. Measurement of germination Karunakaran et al. (2001) measured the germination of wheat following the method of Wallace and Sinha (1962). "Twenty-five seeds were placed on Whatman no. 3 filter paper (90 mm diameter) saturated with 5.5 mL of distilled water. The plates were stacked, covered with a plastic bag and incubated at 10ºC for the first 3 d to begin germination. On the fourth day the cover was removed and the plates were incubated at 25ºC. Germination was assessed on the seventh day." This plating method is commonly used in the viability test of grain seeds.

White et al. (1982) reduced the 7 days of incubation to 1 day. Their method was similar to the one used by Wallace and Sinha (1962), except that 4.5 mL of sterile water was used to saturate the filter paper. They found that germination of wheat seed

at 17% MC or greater incubated for 7 d could be predicted by adding 12% to the germination of seeds incubated for 1 d. However, germination of wheat seed at less than 17% MC could not be predicted by this method.

2.3.2.2. Factors affecting germination in grain storage Wallace and Sinha (1962) indicated that germination was high with high infection of field fungi (newly harvested seed); and was low with high temperature and high infection of storage fungi (after prolonged storage). White et al. (1982) used moisture contents and temperatures of stored rapeseed to estimate storage time of rapeseed until a 5% germination drop. Karunakaran et al. (2001) studied the deterioration rates of a wheat cultivar (*Triticum aestivum* L. cv. AC `Barrie') with 15-19% initial moisture content stored at various temperature conditions. Germination of the seeds and respiration rates of the grain and microflora were used to measure the deterioration rates. They found that germination of wheat stored at 15% and 16% MC and 25ºC did not change for 70 d, but the germination of wheat stored at 17% to 19% MC and 25ºC decreased with the increase of storage time. The dry mass of seeds was lost approximately 0.05% followed with a decrease of germination of 98% to 92%-89%. When the dry mass lost approximately 0.1%, visible mould appeared on the seeds. They defined the time of 10% initial germination loss as the safe storage time.

Homdork et al. (2000) measured germination changes of wheat samples infected by *Fusarium culmorum* (Wm. G. Sm.) Sacc. at different levels and stored under different conditions during 36 weeks. They found that seed germination increased

slightly or remained nearly constant at 25ºC and 62% RH; kept high germination at 15ºC and 56% RH; but the grain could not be safely stored under warm and humid conditions.

Since grain with high moisture content is vulnerable by mould and mites, moisture content of the seeds should be lowered to prevent severe deterioration (Karunakaran et al., 2001). Grain storage managers should have sufficient information of relationship among moisture content, temperature, storage time and deterioration of grain, in order to take steps, such as changing the storage condition or drying the grain, to avoid receiving unmarketable products. A fast and convenient method to measure the storability and the quality of grain would also help them to monitor grain bulks efficiently, and find and solve problems without large economical loss. Germination loss can occur before visible mould is observed. Germination test is considered to be one of the best and most sensitive methods to decide the stored grain quality. Determination of germination is a simple but slow measurement, which can easily be adopted by a farmer, and can be applied to various kinds of grains. Although some other methods, such as microfloral infection, FFA and mycotoxin measurement, can detect the deterioration of grain, more time and expensive training and buying equipment.

2.3.3. Fungi

Fungi absorb their food, spread through their surroundings in the form of tip-growing hyphae, and produce clouds of spores in air and in water (Money, 1998).

Fungi establish parasitic symbioses with plants and animals (Sternberg, 1994; Plattner and Hall, 1995). Fungi commonly have two classifications: "field fungi" and "storage fungi". Field fungi, such as *Alternaria, Cladosporium* and *Hormodendrum,* are very common on or in freshly harvested seed. Storage fungi, such as *Penicillium* spp., *Aspergillus* spp. and *Absidia* spp., are usually found more on the relatively dry seeds (Wallace and Sinha, 1962). One of the primary biotic agents to cause grain spoilage is seed borne fungi (Tuma et al., 1989).

2.3.3.1. Measurement of fungi Wallace and Sinha (1962) used the traditional plating method to determine fungal infection. “Twenty-five seeds of each sample were placed on Whatman no. 3 filter paper saturated with 5.5 mL of 7.5% aqueous sodium chloride solution. The plates were incubated at ambient temperature for 7 days and the organisms were identified using a dissecting microscope.” Traditionally, the plating method is predominant in studying various fungal infections on grain seeds (Lacey et al., 1980; King et al., 1986). This method is usually time consuming and only practical to test cultivable fungi.

Besides the traditional method, researchers have developed several other methods: detection of fungal enzymes, biochemical tests, electrochemical methods, detection of fungal volatiles and immunofluorescence methods (Hornok and Jagicza, 1973; Warnock, 1973; Donald and Mirocha, 1977; Abramson et al., 1980; Kaspersson, 1986; Swain et al., 1989; Tuma et al., 1989; Jain et al., 1991; Marfleet et al., 1991; Tothill et al., 1992; Magan, 1993). Enzyme detection can be achieved quickly (in 1-2

h), but the reliability of this method has not been proven. Further experiments should be done to characterize enzyme quantities of the infected grain to that of dry grain. Biochemical methods measure biochemical compositions, such as adenosine triphosphate (ATP), chitin and ergosterol, in stored products to detect fungal invasion. Adenosine triphosphate extraction has failed to detect internal fungi; and detection of chitin that is also a main cuticle composition of insects and bacteria in stored bulk grain. Electrochemical methods can quickly detect fungi, but suitable media for measurement are hard to choose. Odour volatile detection in stored grain could possibly be an effective method to find storage fungi and to predict grain deterioration. However, there are no sufficiently measured variables to conclude the cause-effect relationships with the microflora present. Immunofluorescence method is appropriate for studying individual grains, but not for counting percent of fungal infection and for analyzing fungi in large samples (Magan, 1993).

The traditional incubation method was used to accurately count invisible mould infection in this study.

2.3.3.2. Factors affecting fungal detection in grain storage Fungi are one of the most significant factors to cause stored grain deterioration in hot spots and the surrounding areas. Loss of germination and increase of FFA levels are found on spoiled stored products. The spoilage causes odours and visible mould (Tuma et al., 1989). Christensen and Kaufmann (1969) found that most cereal grains and oilseeds at higher moisture content were more vulnerable to fungi. Similar results were also

concluded by Sathya et al. (2009a), who described that three storage conditions: temperature, moisture content, and time had significant effects on germination of canola seed.

The deterioration caused by fungi can be characterized by heating, mustiness, decrease of germinability and processing quality, germ-damage and discolouration. Pronyk et al. (2004) considered first showing of visible mould as a signal of canola deterioration, and concluded that first appearance of visible mould might not happen before a 5% germination drop. Pronyk et al. (2004) stored and studied freshly harvested canola seeds. The canola seeds were initially highly infected by field fungi (*Alternaria alternata* (Fr.) Keissler and *Cladosporium* sp.), but only a few storage fungi (*Aspergillus glaucus* group, *Aspergillus candidus* Link, and *Penicillium* spp.) were found. Infection of field fungi decreased while storage fungi increased during storage; and at the end of the storage, storage fungi were predominant. They also found that growth of *A. glaucus* group required less water activity than *A. candidus* and *Penicillium* spp., which was similar as the result found by Sauer et al. (1992).

Commonly initial moisture content of the grain affects the rate and extent of deterioration by fungi (Wallace and Sinha, 1962). Wallace and Sinha (1962) studied and reported on the role of fungi in the initial development and decline of hot spots in stored grain. Samples from normal and heated grains in 13 granaries were collected and analyzed. They found that hot spots and loss of germinability could occur anywhere in a bin. Field fungi, such as *Alternaria*, were common in viable seed, but

negligible in heated grain. However, storage fungi were predominant in hot spots, in which *Penicillium* spp. were the most abundant, even in relatively dry grain at the 1.83 m depth. Other species, *Aspergillus* spp. especially *A. flavus* Link, *A. fumigatus* Fresenius, A. *versicolor* (Vuillemin) Tiraboschi and *Absidia* spp., were also common. This study tested samples of a wide range of grains and gained sound information on grain fungi associated with hot spots. The results can all be good references for future work.

Effective management of storage and the prevention of loss in grain quality require sufficient and precise information of fungal activity in bulk grain (Magan, 1993). Kreyger (1972) considered the appearance of visible mould to be the criterion for estimating how long the grain could be safely stored. He indicated that quality change of grain could be ignored if dry mass loss was less than 2%. Seitz *et al.* (1982) found a contradictory result. According to their study, when dry mass loss was more than 0.5% or visible mould appeared on the seeds the deterioration of bulk maize was unacceptable. Visible mould appeared on wheat kernels when loss of dry mass was 0.15% (Hamer *et al.*, 1991 and 1992). Attributing to the controversy, methods should be chosen properly and used to accurately study fungal activity. On the basis of the fungal study, remedial measure should be done earlier than the appearance of visible mould.

2.3.4. Free fatty acid value determination

There are polar or nonpolar compositions in grain lipids. Different compositions

classified different lipids that are soluble or insoluble in different solutions. Fatty acids are the main composition of the lipids. They sometimes exist in the form of binding with other cellular compositions. The unbounded fatty acids are usually called free fatty acids and are present in smaller amounts. Hydrolysis and metabolic accumulations of the original composition produce the FFA (Becker, 2008). Release of FFA initially occurred when the lipids of cereal grains are degradated. This procedure is followed by oxidative degradation. Chemical saponification or lipases is the substance to cause the release of fatty acids. The oxidative reaction or fungal infection usually causes discolouration of grain seeds (Pomeranz, 1992). Activation of the methylene groups is the major reason to cause fatty acid oxidation. The increase in the quantity of adjoining double bonds observed in polyunsaturated fatty acids increase the oxidation rate (Becker, 2008). Handling quality and marketable value of bulk grains are lowered because of the aging and deterioration of grain. The qualities that are affected by chemical changes during grain deterioration include baking effects and loss of nutritional quality and yield of flour (Tipples, 1995). Lipids and lipid-associated factors are main compositions that affect canola quality and market value.

2.3.4.1. Determination methods of FAV Traditionally, the FAV shows how many mg of KOH can neutralize the total free fatty acid in 100 g of moisture-free seeds. The alkaline titration method is used for FAV determination. This method is considered to be simple and inexpensive, thus is widely used by many investigators

(Nishiba et al., 2000; Xiao and Yang, 2002; Zhou and Ackman, 1996). This method also has some drawbacks: (1) the result may be inaccurate because different operators have different judgement of the endpoint in titration by his/her naked eye, and (2) low sensitivity of this method requires adequate sampling and a disciplined operator especially when the lipid of the grain is low (Nishiba et al., 2000).

Berezin et al. (1996) developed a rapid way of analyzing FFA. They compared two sets of reagents in extracting FFA from oilseeds. Reagent A contained triethanolamine in a mixture of water, isopropanol, and heptanes, and allowed the carrying out of rapid (1-2 min) solid-liquid extraction of the FFA and some other acids from oilseeds. Reagent B contained a strong acid and inorganic salt in water, and provided the separation of the FFA only into the heptane phase (5 min), which can be used directly for the free fatty acid determination. The new experimental reagents required short extraction time (up to 10 min) while maintaining the uncertainty of the FAV determination at an acceptable level. There was no significant difference between precision of results obtained by traditional and their developed techniques. The reagents expense of the proposed techniques was higher than that of the traditional technique. Moreover, during FFA extraction with these two sets of reagents, pH value of the solution should be monitored and controlled all the time to obtain accurate results.

Nishiba et al. (2000) tried to use semiautomatic thin layer chromatography/flame ionization detection (TLC/FID) system to analyze the FFA content of rice during

storage. The ionized flame detection combined with the TLC operation is the principle of this method. “The sample mixture is spotted on the edge of a quartz rod coated with silica gel and developed with a solvent system that is similar to the conventional planar TLC.” Different compositions of the mixture are then separated. They travel through a rod to a hydrogen flame and are detected by FID. More than one rod can be developed at the same time and multiple analyses are carried out. The TLC/FID method has advantages in simplicity and rapidity compared to other chromatographic methods such as high performance liquid chromatography (HPLC) or gas chromatography (GC) (Rao et al., 1985; Zeman et al., 1986). Before the study of Nishiba et al. (2000) the TLC/FID method was hardly used in grain storage research. They found the method to be more sensitive and accurate than the traditional technique. It required only a small amount of sample; showed more detailed information such as the overall state of grain lipid degradation; and required inexpensive reagents or toxic substance (only H_2 gas and the organic solvents). However, this method has to be performed at constant temperature and humidity. The changes in humidity and temperature have large effect on the TLC reproducibility. Moreover, the experimental environment should be clear. Large differentiation of the result is formed when the rods are contaminated. The TLC/FID method is delicate but convenient for studying the degradation of lipids in stored cereal grain, especially when the grain sample is relatively small.

2.3.4.2. Factors affecting FAV in grain storage During grain deterioration, microflora consumes the seed and enzymatically secretes on them, which causes lipid hydrolysis and produces more FFA. Both the characteristic odours and the flavours of the fatty acids show the evidence of deterioration. Physical breakage of the seed, poor storage conditions or long storage periods can also cause the degraded lipids to be discharged into the seed. The lipase reaction degradates the lipid to FFA (Aibara et al., 1986; Takano, 1989; Ohta et al., 1990). It is considered that the poor qualities of stored rice, such as aged flavours and dark colours, are produced by the discharged lipids (Yasumatsu et al., 1966a, b; Shibuya et al., 1974). Measuring the FAV is one of the most common methods to indicate deterioration in grain storage. White and Jayas (1991) used 1.5-fold increase in initial FAV as criteria of flaxseed deterioration. They found that safe storage time of flaxseed decreased in dry seeds from 10^{o} C to 50^{o} C; and it also decreased at the same temperature when moisture content of seeds increased.

Usually, FAV of cereal grain and oilseed increases with the increase of storage period and moisture content (Clayton and Morrison, 1972; Schweizer et al., 1974; Frey and Hammond, 1975; Welch, 1977; Sahasrabudhe, 1979; Galliard, 1989). White et al. (1999a) studied quality changes of hull-less and hulled oats and barley with the same initial moisture content under various storage conditions (different temperatures and relative humidity (RH)). In their project, samples were stored at 10^{o} C, 20^{o} C, and 30^{o} C and 50%, 65%, and 80% RH for oats and 35%, 50%, 65%, and 80% RH for

barley. Potassium hydroxide (KOH) solutions with different concentrations had two applications in their study: (1) controlling the RH to desired levels (Solomon, 1951), and (2) absorbing carbon dioxide. One hundred seeds of each sample were removed as various times. Changes in FAV, moisture contents, germination and microflora of grains were tested monthly in a one year study. All samples deteriorated more rapidly in storage at high temperature (30^{o} C) and moisture conditions (15.0% MC for the oat; and 15.8% MC for the barley) than those at low temperatures (10^{o} C and 20^{o} C) and moisture conditions (10.0% and 12.5% for the oat; and 9.0%, 11.0%, and 12.6% MC for the barley). These results were similar to the previous works of Sinha et al. (1979) and Sinha (1969), which have indicated that infestation by insects or mites had no effect on the grain at low temperature ($\leq 20^{o}$ C) but became more serious at high temperature ($> 20^{o}$ C). The effect of oil content on determination of the parameters was not found. Their research also showed that under high moisture content and temperature, use of FAV as the safe storage criterion needed to be chosen carefully, especially if the seed was used for planting. The researchers used RH to obtain different moisture contents of samples after 1 month of storage. This may pose risk to gain the proper moisture contents within proper time because one month interval may be too long to analyze FAV and germination changes because these values can change rapidly at high moisture and high temperatures. It was suggested to condition the grains to desired moisture contents before storage; and remove small amount of samples every one or two weeks for analysis.

Another study on the relationship between soybean seed quality and fatty acids was carried out by Trawatha et al. (1995). They stored three soybean cultivars at different temperatures, 20ºC, 30ºC and 40°C, and sampled periodically for germination and vigour test. They found that fatty acids in the lipid fraction did not change in their total amount, while free linolenic acid and linoleic acids increased about two-fold during seed deterioration. There was no relationship between quality of the seed and the activity of lipoxygenase. But the quality of the seed was correlated with both E-2-hexenal content and the free linoleic acid. According to their results, spoilage of the grain may be caused by the membrane collapse and toxicity of the produced peroxidation substance, attributing to the FFA. The FAV is a requisite factor in indicating quality of stored grain.

2.3.5. Storage period and safe storage guidelines

Mills (1996) indicated that the minimum moisture content that causes the unacceptable quality of the stored grain is affected by the desired storage time. Karunakaran et al. (2001) studied deterioration rates of wheat (*Triticum aestivum* L. cv. AC `Barrie') with different moisture contents stored at constant or changing temperatures. They found that safe storage times of wheat at 19% MC and constant temperatures were from 2.5 d at 30ºC and 35ºC to 37 d at 10ºC, and at 17% MC were 5, 7, and 15 d at 35°C, 30°C, and 25ºC, respectively. They determined deterioration rates of wheat at 19% MC and step decreasing temperatures (35°C-25°C, 30°C-20°C, 25°C-20°C, and 20°C-15ºC) and predicted the safe storage times. Since temperatures

of different locations and seasons may vary largely, a wider range of temperatures should be set as the storage conditions of grain in further studies.

Safe storage guidelines of normal canola (~ 40% oil contents) with respect to biochemical and microbial measures were developed by Sathya et al. (2009a). They stored canola samples with 7.5%, 10.0%, 12.5% and 15.0% initial MC at 10ºC, 20º C, 30º C and 40°C for 16 wk. The seeds at 10°C maintained the initial moisture contents, but seeds lost moisture at 20º C, 30º C, and 40°C during the the study. Appearance of initial visible mould, invisible mould, FAV, moisture content and germination of the seed were determined every two or four weeks. The safe storage guidelines for normal canola were developed with respect to initial moisture content and storage temperature using the measured quality parameters. They found that seed germination decreased with the increase of temperature and moisture content. Although under 30°C and 40°C, the stored grain dried in the first 4 wk, deterioration occurs early enough for detection. Under the temperatures from 10°C to 40°C, storage period and moisture content positively affected the FAV. Finally they developed safe storage guidelines as in Fig 2.1: "canola with < 10.0% moisture content at < 20°C would not deteriorate for at least 15 wk, whereas the 12.5% and 15.0% moisture content seeds at > 25°C needed to be dried within a week to avoid spoilage". They did a thorough study in quality changes of stored canola with different initial moisture contents at several temperatures and RH; and developed the safe storage guidelines that would be beneficial to farmers and industries for maintaining canola quality during storage.

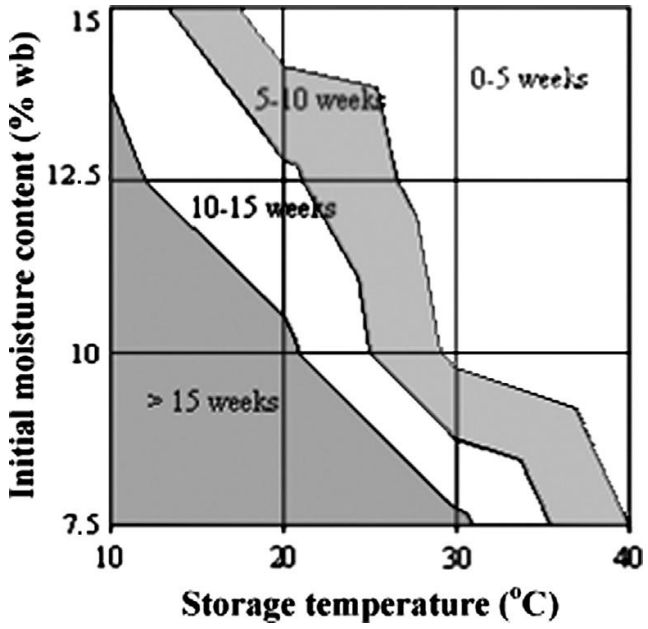

Fig. 2.1 Safe storage guidelines for canola based on 20% decrease in the initial seed germination and no visible mould (Sathya et al., 2009a).

However, the guidelines may not be suitable for the storage areas that have continuing high RH or do not have good drying systems.

Sathya et al. (2009b) developed safe storage guidelines for rye. They stored samples with 10.0, 12.5, 15.0, and 17.5% MC at 10°C, 20°C, 30°C, and 40ºC for 4 months. Similar to Sathya et al. (2009a), appearance of initial visible mould, invisible mould, FAV, moisture content and germination of the seeds were determined every two or four weeks. According to their study, temperature, moisture content and time of storage had significant effects on the germination of the rye. As storage time increased, moisture content of the seeds increased at 10ºC but decreased at 30°C and 40ºC. All the samples at 17.5% MC or at 40 ºC were found to be infected by visible mould. Fungal study found that *Penicillium spp*. and *Aspergillus glaucus* group were predominant all the time on most of the seeds. Storage period, temperature and moisture content positively affected the FAV. The safe storage guidelines of rye were developed as shown in Fig. 2.2. "Rye with ≤ 12.5% moisture content stored at ≤ 20ºC would be safe for >15 wk, whereas rye with 17.5% moisture content stored at 40ºC would have less than a week for post-harvest treatments like drying and cooling." The researchers comprehensively studied quality changes of rye with different initial MC at various temperatures. The methods of setting up environmental chambers and quality determination are easy to follow and valuable to other researchers in this area. However, similar to Sathya et al. (2009a), it is better to keep the moisture contents of grain constant during storage, in order to know the storability of grains with high

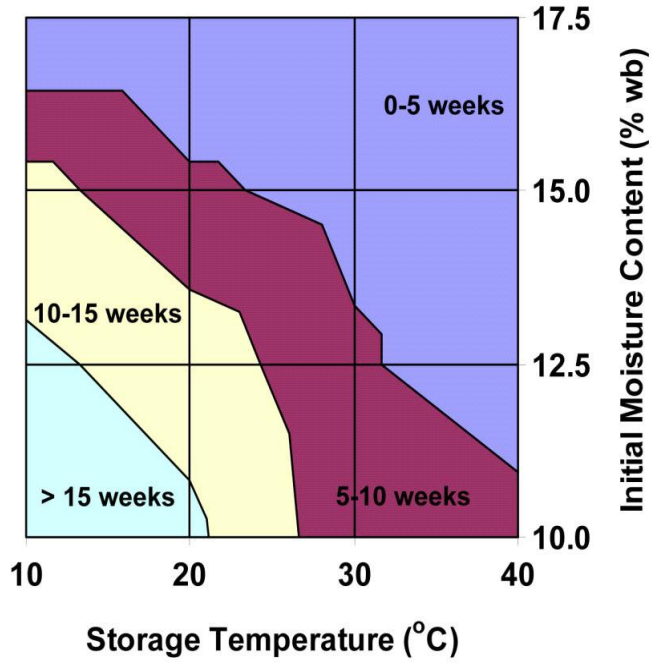

Fig. 2.2 Estimated safe storage life of rye based on 20% decrease in the initial germination and no visible mould (Sathya et al., 2009b).

moisture contents without any drying process.

Rajarammanna et al. (2010) monitored the deterioration of rye at 10%, 12.5%, 15% and 17.5% initial MC stored at 10°C, 20°C, 30°C and 40°C for 4 months. Moisture contents of all samples were maintained constant during the study. The results of this study (case 1) were compared with the results of Sathya et al. (2009b) (case 2) that showed the deterioration of rye as seeds slowly dry. Rajarammanna et al. (2010) concluded that at 10°C for cases 1 and 2 germination stayed constant for samples at all the moisture contents, but at other temperatures germination of samples at high moisture content decreased significantly. At lower temperatures (10°C and 20°C), the FAV were constant in both cases. However, in case 1, at 30°C and 40°C, FAV of the rye seeds increased with an increase in temperature and moisture content. Initial visible mould was found earlier in case 1. *Penicillium* spp. and *Aspergillus glaucus* group were the predominant fungal species present in both the cases throughout the study. The rate of deterioration was significantly different between the two cases. Maintaining moisture content during the study was one of the most important keys of developing safe storage guidelines for grains.

Nithya et al. (2011) stored durum wheat at 10°C, 20°C, 30°C and 40°C for 3 months and determined its safe storage guidelines by studying the deterioration rates. Durum wheat samples at 15%, 16%, 17%, 18%, 19% and 20% initial MC were used. Appearance of initial visible mould, invisible mould, FAV, moisture content, germination, and ochratoxin production of the seeds were determined every two or

four weeks. The results showed that germination was significantly affected by temperature, moisture content, the time of storage. Safe storage guidelines of durum wheat were developed as shown in Fig 2.3. Durum wheat samples with 15% and 16% MC could be stored for 3 months with high seed quality at 10°C and 20°C, but they could be only stored for 4 wk at 30°C. At 40°C, the stored wheat at any moisture content should be dried within one week in order to maintain high grain quality.

Jayas and White (1989) studied safe storage conditions of canola meal. Canola meal is a by-product of crushing canola seeds, when the edible oil is removed for human consumption. It is a main source of feed protein for animals (Jayas et al., 1988). Jayas and White (1989) stored canola meal for 12 months at temperatures of 10°C, 20°C, 30°C, 40°C, and 50°C and moisture contents from 6.3% to 11.5%. Moisture contents, colour changes, FAV and microfloral infection were tested regularly. Discolouration of the sample from yellow-green to brown was observed at 50ºC and 10% MC in 1 month. Discolouration was found on all samples at 50°C, and at 10.4% or 11.5% MC at 40°C by the end of the 3rd month. Samples at lower moisture content also deteriorated slowly with increase of storage time and their FAV was generally higher than 88 mg KOH/100 g meal that was almost double the initial FAV. Fungal study indicated that *Penicillium* spp were predominant at 10°C and 20°C throughout the study, but less than the *Aspergillus glaucus* group at 40°C and 50°C. Canola meal could be stored safely for a long period (> 12 months) at temperatures below 30°C and 7% MC, but it could not be stored safely for more than

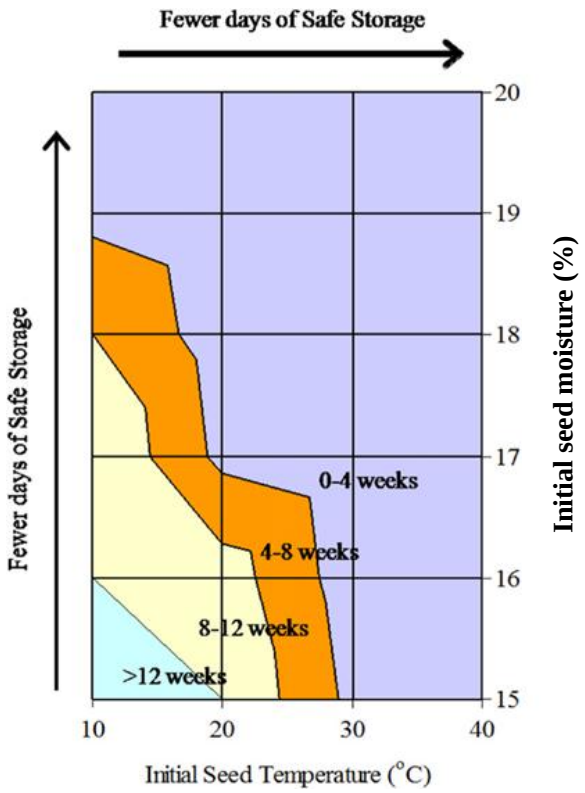

Fig. 2.3 Estimated safe storage life of durum wheat (Nithya et al., 2011)

3 months at 40°C and 6% MC. Deterioration was fast at 50°C and even the meal at low moisture content (6%-8%) could be stored for only 1 month. Comparing with canola seeds canola meal is relatively easier to be attacked by fungi, which may accelerate the deterioration rate of the meal. The information of safe storage conditions and quality changes of canola meal during storage can be a good reference for developing safe storage guidelines of canola seeds.

2.3.6. Canola storage in non-aerated bins

The canola bulk ecosystem contained interactive biotic and abiotic factors. In this ecosystem, dormant autotrophs (the canola seeds) supply accommodation and food to microflora, insects and mites (Dunkel, 1992). Microflora, insects and mites respire, consume canola, and produce moisture, carbon dioxide and heat (Pronky et al., 2004). High moisture contents and infection of insects, microflora, and mites could produce hot spot in non-aerated bins. Hot spot causes dramatic changes of temperature, relative humidity (RH), air composition, and distribution of insect and microfloral species (Jian and Jayas, 2012). Microflora accumulated in or around the hot spot. Respiration of microflora induced expansion of the initial hot spot, and the temperature may increase up to 65ºC (Sinha and Wallace, 1966). Ambient temperatures have significant effects on either enlarging or drying out the hot spot (Wallace et al., 1976). Temperature gradients within the grain bulk cause air convection and moisture migrates in non-aerated bins. In fall and winter, ambient temperature is cooler than temperature of the grain bulk. Cold air close to bin wall

tends to move from top to bottom, and warm air close to centre tended to move from bottom to top of the bin. Moisture traveled with the warm air and condensed on the top of canola bulk. The moisture zone on top of grain bulk is likely to get mouldy and produce a hot spot. The situation reverses in spring and summer (CCC, 2012, see Fig. 2.4).

Safe storage guidelines developed from laboratory analysis needed to be validated using data collected from in-bin storage (White, 1992). Laboratory data were collected at constant temperature and moisture content, while conditions (moisture content, temperature, foreign material, microflora etc.) were more complex at different locations in a storage bin. All factors of grain deterioration should be considered in order to develop proper safe storage guidelines of grain (White, 1992).

2.3.6.1. Factors affecting canola storage in non-aerated bins Mills and Sinha (1980) studied rapeseeds stored in the laboratory and in farm bins for 5 months. They developed guidelines of the safe storage time for rapeseed at different temperature and moisture content using laboratory data, and validated the guidelines with data collected from rapeseed storage in 15 farm bins. They found that rapeseed with moisture content above 8% could not be stored for a long period. Safe storage of grains and oilseeds is also related to type of storage bins. Muir et al. (1977) found that some physical properties of the grain were significantly different due to different types of storage bins.

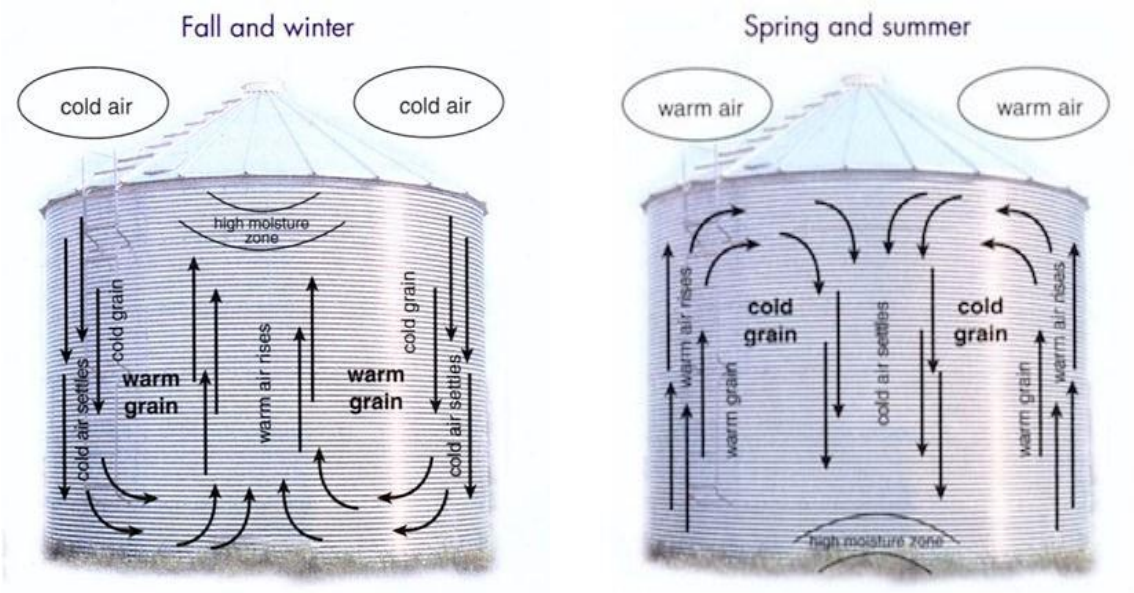

Fig. 2.4 Moisture migration in stored canola (CCC, 2012).

In a large non-aeration bin, a grain bulk is directly affected by ambient weather conditions. Centre of the grain bulk can retain the heat it had when loaded; and the grain close to the bin wall will have the similar conditions as ambient weather (Jayas et al., 1994; Jayas and White, 2003). In the winter of Canada, centres of large grain bulks can be 40ºC to 45ºC warmer than the ambient temperature and moisture is transported to the top-centre of the bulk by air convection currents. This leads to increased moisture levels and grain deterioration (Jayas, 1995; Sinha et al., 1973).

3. MATERIALS AND METHODS

3.1. Physical Properties of High and Low Oil Content Canola

3.1.1. Canola

Three high and one low oil content canola cultivars, purchased from farmers living south of Winnipeg, Manitoba, were used. The three high oil content canola seeds were 45H29 (45.4% ± 0.12% oil content, referred to as H-H), Nex4 105 (45.4% ± 0.35% oil content, referred to as H-N), and Invigor 5440 (47.1% ± 0.27% oil content, referred to as H-I). The one low oil content canola was 5525 Clearfield (42.4% ± 0.07% oil content, referred to as L-C). The initial moisture contents of H-H, H-I and H-N and L-C were 5.7%, 4.8%, 4.5% and 5.0%, respectively. Moisture contents were determined by drying triplicate samples of 10 g each at 130^{o} C for 4 h (ASABE, 2009). Twenty kilograms of H-H and L-C were conditioned to 8%, 10%, and 12% moisture content. Thirty kilograms of H-I and H-N were conditioned to 8%, 10%, 12% and 14% MC. For example, for conditioning 30 kg of canola from 4.5% to 8% MC, 1140 mL sterilized water was poured into the canola seeds. The water and the canola seeds were mixed in a grain mixer (Model: BigCat, Type B, Red Lion Inc., Winnipeg, Manitoba, Canada) for 0.5 h, placed in plastic bags, and stored at 5ºC for 7 d. After 7 d of storage, the canola seeds were mixed again and moisture contents were measured. If moisture contents were different from the desired moisture contents, the canola seeds were re-conditioned by repeating the above mentioned procedure using different quantities of water.

Physical properties were measured 1 day after the canola seeds reached the desired moisture contents. The physical properties measured were: minor and major axes of canola seeds, bulk densities, emptying and filling angles of repose and coefficients of friction against structural materials. All physical properties were measured at room temperature (22ºC ± 2ºC). After this physical property testing, H-I and H-N at the same moisture content were mixed with the mass ratios of 1:1 (referred to as H-M_a), 1:2 (referred to as H-M_b) and 2:1 (referred to as H-M_c) with 5 min mixing time for obtaining uniformly mixed canola seeds. Physical properties of the mixed canola were tested and compared to physical properties of H-I and H-H.

3.1.2. Measurement of major and minor axes of seeds

One hundred seeds of H-H at moisture content of 8%, 10% and 12% MC, and 100 seeds of H-I and H-N and L-C at 10% MC were randomly chosen. Major and minor axes of canola seeds were measured by using a caliper to the precision of 0.02 mm, under a dissecting microscope. Major axis was the longest axis of a seed; and minor axis was the longest axis that was perpendicular to the major axis. Major and minor axes are also referred to length and width of canola seeds, respectively.

3.1.3. Bulk density

Bulk density was measured using the method developed by the Canadian Grain Commission (Canadian Grain Commission, 2010) briefly reproduced here. Canola was filled into a hopper with top-opening of 170 mm in diameter, bottom-opening of 38 mm in diameter and height of 160 mm. A slide gate at the bottom of the hopper

was used to control the flow of canola seeds. The hopper was placed on the top of a 0.5 L cup. The slide gate was 45 mm above the top rim of the cup. Canola flowed from the hopper and sufficiently over-filled the cup. A round wooden rod was used to remove the canola beyond the top rim of the cup (Jian et al., 2012). The mass of canola inside the cup was measured to a precision of 0.001 g. There were three replicates for each canola variety and moisture content.

To verify whether oil content influenced the kernel density, kernel densities of H-H and L-C at moisture contents of 8%, 10%, 12% and 14% were determined using a pycnometer (Model 1305, Micromeritics Instrument Corporation, Norcross, GA). Testing was conducted at room temperature and helium was used as the inert gas to replace the intergranular air inside the bulk of the tested canola.

3.1.4. Emptying and filling angles of repose

Emptying and filling angles of repose of canola were determined by following the methods described by Irvine et al. (1992) briefly reproduced here. There were three replicates for each canola at each moisture content. A transparent plastic box (430 mm long, 200 mm wide and 430 mm high) was used. The box was hand-filled to an approximate depth of 350 mm for each replication. The sample was then allowed to flow freely through a 200 mm long and 50 mm wide opening at the bottom of one wall of the plastic box. Emptying angles were calculated based on the measured grain lengths in the vertical and horizontal directions of the sloped profile. Filling angles of repose were measured in a box (1220 mm long, 100 mm wide and 760 mm high). The

box was filled from a hopper with a slide gate which was located at the top of the box (800 mm from the bottom of the box). The hopper had a square shape and had a 53 mm^2 opening. Filling angle was determined by measuring the seed depth at two points along a known horizontal distance of the grain pile.

3.1.5. Coefficient of friction

Coefficients of friction against four structural surfaces (galvanized steel, plywood, steel-trowelled concrete, and wood-floated concrete) were determined by following the method described by Irvine et al. (1992), briefly reproduced here. The structural surfaces were attached to a tilting surface. A frame, which enclosed an area of 305×255 mm^2, was placed on the structural surface. Canola seeds were filled inside the frame to a depth of 18 mm. The frame was lifted slightly so only canola was in contact with the surface. One end of the surface was then raised slowly until the frame and canola started to slide on the structural surface. The tangent value of this raised angle was the determined friction coefficient.

3.1.6. Pressure on bin walls

Janssen (1895) developed an equation for determine horizontal loads on a bin wall as follows:

$$P_h = (wR/\mu)(1 - \exp(-\mu Kh/R)) \quad (3.1)$$

$$w = \rho g/1000 \quad (3.2)$$

$$K = (1 - \sin\Phi)/(1 + \sin\Phi) \quad (3.3)$$

where,

P_h = lateral bin wall pressure (kN m^{-2}) at depth h,

w = specific weight of stored material (kN m^{-3}),

R = hydraulic radius of storage structure (m),

μ = coefficient of friction of stored material on bin wall materials,

h = height of material (m),

ρ = the bulk density (kg m^{-3}) of material,

g = gravitational constant (9.81 m s^{-2}),

K = the ratio of lateral to vertical pressure, and

Φ = internal friction angle of a material (Ketchum, 1919).

If the bulk is homogeneous, internal friction angle is equal to the filling angle of repose (Patil, 2007). Stewart (1968) found that using angles of repose of sorghum to replace internal friction angles produced errors; however, the errors may or may not be significant depending on sensitivity of the internal friction angle in the equations. Inside storage bins, internal friction angle is bigger than angle of repose because grain kernels at the surface are more loosely packed than those inside the bulk (McCabe and Smith, 1976). Therefore, internal friction angles were considered to be 5º more than filling angles of repose in this study.

To evaluate the sensitive values of factors in Eq. (3.1), following assumptions were made:

1) Canola seeds were stored in cylindrical bins;

2) Ratios of depth of grain over diameter of bin (h/D) were 1, 2, 3, 4 and 5 (Singh (Jayas) and Moysey, 1985);

3) Ratios of h/R were 2, 4, 6, 8 and 10, and the maximum, mean and minimum values of h/R were 2, 5 and 10;

4) The maximum, mean and minimum of bulk density of canola at different moisture contents were the measured data in this study;

5) The internal friction angle was the measured data of filling angle of repose plus 5°; and

6) Coefficients of friction against structural materials of canola with high oil content were from 0.25 to 0.46, 0.25 to 0.51, 0.25 to 0.47 and 0.28 to 0.41 at 8%, 10%, 12% and 14% MC, respectively; and low oil content canola were from 0.24 to 0.36, 0.26 to 0.34 and 0.25 to 0.37 at 8%, 10% and 12% MC, respectively (tested in this study).

During the calculation of the sensitive value of the factors ($\Delta P_h/\Delta$factor), the minimum or maximum values of the determined factor were used, while the mean values of other factors were used. For example, the following data were used to calculate the sensitivity value of internal friction angle (the determined factor) at each moisture content of high or low oil content canola:

1) Minimum and maximum value of internal friction angle;

2) Range of internal friction angle. For example, high oil content canola at 8% MC: maximum friction angle – minimum friction angle = $31^o - 24^o = 7^o$; and

3) The values of internal friction angle from minimum to maximum with an increment of 10% of the range (total eleven values).

Lateral wall pressure (P_h), $\Delta P/\Delta$factor were calculated using each of the eleven values and mean values of other factors. The maximum value of the calculated $\Delta P/\Delta$factor was the determined sensitivity value of the factor.

Percentages of pressure differences (%) between high and low oil content canola were calculated as:

$$P_d = (P_H - P_L) \times 100/P_L \quad (3.4)$$

where,

P_d = the percentage pressure difference (%) between high and low oil content canola,

P_H = the horizontal pressure produced by high oil content canola (kN m^{-2}), and

P_L = the horizontal pressure produced by low oil content canola (kN m^{-2}).

P_H and P_L were calculated using the same procedure described above.

In reality, moisture contents of canola seeds might exceed the range of 8% to 14%. Sometimes farmers load canola with extremely high (about 18%) (followed by drying or aeration) or low (about 6%) moisture contents. Therefore, it was important to estimate pressure differences of high and low oil content canola with extreme moisture contents. To calculate P_d at the extremely high or low moisture content, the following data were used: bulk densities of high oil content canola at 6% and 18% MC (estimated using the equation developed by Jian et al., 2013); bulk densities of

low oil content canola at 6% and 18% MC (using data published by Sokhansanj and Lang, 1996); filling angles of repose (using data published by Fayed and Skocir, 1997); internal friction angle (estimated as 25° to 45°); and coefficient of friction of high and low oil content canola (using data in this study).

3.1.7. Data analysis

Statistical test was conducted at $\alpha = 0.05$ level (SAS, 2010). Student *t*-test was used to analyze oil content effects on minor and major axes of canola at 10% MC, and moisture content effects on bulk densities of canola. Tukey test was used to analyze moisture effects on minor and major axes of H-H kernels, angles of repose and coefficients of friction against structural surfaces of each canola and the mixed high oil content canola seeds. Factorial test was used to analyze the effects of oil and moisture content on bulk densities, angles of repose and coefficients of friction against structural surfaces.

To evaluate differences of physical properties between high and low oil content canola, data of low oil content canola from two published studies (Razavi et al., 2009; Çahşır et al., 2005) were used. Widths, lengths, bulk densities and angles of repose of low oil content canola (varieties: Okapi and SLM) were calculated from regression equations developed by Razavi et al. (2009). Coefficient of friction of rapeseed on plywood was calculated from regression equation developed by Çahşır et al. (2005).

3.2. Small Scale Chamber Study

3.2.1. Canola

Initial conditions of high (H-H, H-I and H-N) and low (L-C) oil content canola were described in section 3.1.1. Two hundred kilograms of each of the four varieties were conditioned to 8%, 10%, 12% and 14% MC (wet basis). Using the procedure described in section 3.1.1. The conditioned canola seeds were stored in plastic bags at 5ºC for 7 d, and were mixed again for 0.5 h. Moisture contents of the tempered canola seeds were tested by oven-drying in triplicates at 130ºC for 4 h (ASABE, 2009).

3.2.2. Storage condition

The experimental setup and procedures were the same as described by Sathya et al. (2009). During the 20 wk storage period and to maintain constant moisture contents, the tempered canola seeds were kept inside mesh bags and were stored inside 20 L plastic pails which held potassium hydroxide (KOH) solution. Potassium hydroxide solution with different concentrations were made to maintain ERH of 70%, 83%, 91% and 96% (Solomon, 1951), and these ERH values corresponded to 8%, 10%, 12% and 14% moisture contents of canola seeds, respectively (modified Henderson equation, ASABE, 2007). Inside the pails, three mesh bags containing the same moisture content canola were laid on top of a mesh plate. The mesh plate was used to separate the canola seeds from the KOH solution. Two of the mesh bags, which contained 2 kg canola seeds each, were used as buffer. The middle mesh bag, which contained 1 kg canola seeds, was used for the testing of germination, FAV, and

visible and invisible mould. Moisture content of canola seeds inside the middle mesh bag was measured every 2 wk (ASABE, 2009). If the measured moisture content was one percent point different from the desired moisture content, canola seeds inside the buffer bags were replaced with the desired moisture content canola seeds. The pails were stored inside four environmental chambers (Model: C1010, CONVIRON, Controlled Environments Limited, Winnipeg, MB), and the temperatures of the environmental chamber were set at 10ºC, 20ºC, 30ºC and 40ºC, respectively. The temperature sensor of the environmental chamber had ±0.5ºC error. Relative humidity of the four chambers was set at 70 ± 5%. There were totally 48 loosely sealed pails inside each chamber.

3.2.3. Data collection

There were three replicates at each tested temperature and moisture content. Every 2 wk, about 20 g canola seeds were sampled from each middle mesh bag. The 20 g samples were used to determine the germination, FAV, and visible mould of canola seeds. The sampling was terminated 2 wk after germination of the canola became 0%, if germination of the canola was 0% before 20 wk storage time.

Germination was determined by following the method developed by Wallace and Sinha (1962). Twenty-five seeds were placed on Whatman No.3 filter paper in a petri dish. The filter paper was soaked with 5.5 mL sterilized water. The canola seeds were incubated at room temperature (22 ± 2ºC) for 7 d. Germination was counted after the incubation period.

To determine the visible mould, visual inspection on the canola sample was conducted. Invisible mould was determined every 4 wk by following the method reported by Mills et al. (1978). Whatman No.3 filter paper was saturated with 5.5 mL of 7.5% aqueous sodium chloride solution. Twenty-five canola seeds were placed on the filter paper. After 7 d of incubation, invisible mould of canola seeds was identified using a dissecting microscope.

Free fatty acid values were determined as milligrams of KOH needed to neutralize acids in 100 g of dry canola. Oil of five grams of dried and ground samples was extracted using a Goldfisch fat extractor and petroleum ether. The oil was placed in a solution of toluene-phenolphthalein-ethanol. FAV in extracted fat was titrated using a standardized KOH solution (Schroth et al., 1998).

3.2.4. Data analysis

Paired *t*-test of germination of canola with 8%, 10%, 12% and 14% MC at 30ºC, and with 8% MC at 40ºC was conducted between two high oil content canola cultivars, or between one high and one low oil content canola cultivars at $\alpha = 0.05$ level (SAS, 2010). The reason for choosing these temperature and moisture content combinations was that the germination of canola seeds at other storage conditions did not significantly change (Student *t*-test) or dropped to 0 in less than 2 wk. Factorial test was conducted to analyze the effect of storage time and moisture content on germination and FAV of canola (SAS, 2010). Regression between germination and storage time was conducted using SigmaPlot software (SigmaPlot, 2010). More than

20 linear or non-linear equations were tested. Polynomial equations that had the largest R^2 were chosen. Correlation between germination and FAV of H-H and L-C was conducted using Spearman Rank Order Correlation (SigmaPlot, 2010). Storage time for 20% initial germination loss was used to develop safe storage guidelines of high oil content canola. To obtain normal distributed data, germination for factorial tests was transformed to arcsine (McDonald, 2009).

3.3. Large Scale Bin Study

3.3.1. Canola

High oil content (~45%) canola seeds (H-N) were loaded into three bins. Each bin contained approximately 21 tonnes of canola seeds. Initial moisture contents of canola in bin 1, 2 and 3 were 7.9 ± 0.3%, 8.2 ± 0.3% and 8.3 ± 0.2%, respectively. The acceptable moisture content of stored canola in an elevator is 10%. Canola at 10% MC and lower is considered as dry and marketable (MAFRI, 2013). The moisture contents of loaded H-N were lower than the designated dry moisture content (10%), and the canola needed to be conditioned. Therefore, additional humidifiers were run 24 h/day to increase humidity in the air of the environmental room, and the wet air was blown into bins from bottoms of the canola bulk until moisture contents of canola seeds reached 10%. Canola seeds were stored inside the bins for 4 months.

3.3.2. Storage condition

Three welded-steel bins were used to store H-N. These three bins were structurally identical. Each of them was approximately 2.74 m in diameter and 5.03 m

height (from floor to the top of the cylindrical portion). The bins had flat bottoms with fully perforated floors.

The bins were inside an environmental room which was located inside the Canadian Wheat Board Centre for Grain Storage Research located at the campus of the University of Manitoba. Temperatures and RH in the environmental room were controlled by a computer system (DELTA) to simulate the Western Canadian storage conditions (from September to December in the year 2010). The simulated weather data were collected by Environment Canada, at Winnipeg Forks station. Ambient temperatures ranged from 23.3°C to -26.2ºC. Relative humidity ranged from 29% to 95%. The temperatures and RH were changed automatically by DELTA system every 6 h (0, 6, 12 and 18 o′ clock of each simulated day).

3.3.3. Sampling

A T-handle standard probe (1.83 m long) was used to take samples every week for 16 wk. Samples were collected at the grain height of 0.25, 1.27 and 2.29 m from floor (referred to as L1, L2 and L3, respectively) (Fig.3.1). The probe (opening faced down and closed) was inserted from sampling ports on the bin at each depth, and turned 180º to keep the opening facing up and then opened. Canola seeds fell into the probe immediately because of gravity. The opening was closed after seed collection and the probe was pulled out. Canola seeds in the probe were poured out. Samples close to bin walls (0.13 m to bin walls, referred to as Sw) and at centres (1.09 m to bin walls, referred to as Sc) were collected (Fig.3.1). Canola seeds at 3.30 m height of the

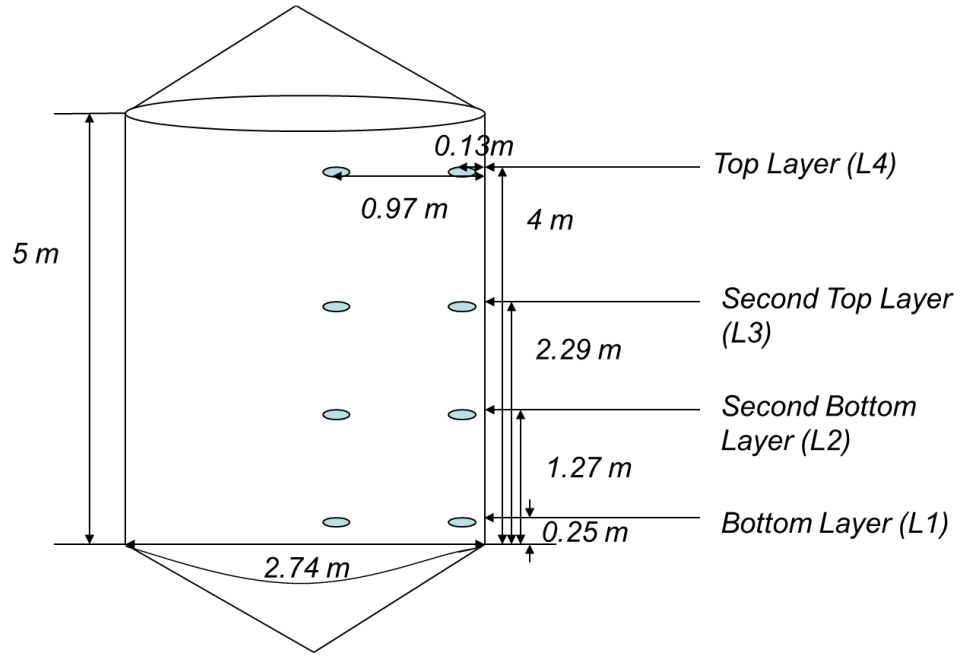

Fig. 3.1 Model of the storage bin and sampling locations in canola bulk. The bin was symmetric.

canola bulks were scooped from the top opening of the bin, and considered to be samples at the top layers (referred to as L4). Canola seeds at the top layers were also sampled at two locations: 0.13 and 1.09 m to the bin walls (Fig. 3.1).

3.3.4. Data collection

Methods of determining moisture contents, germination, visible and invisible mould and FAV were the same as described in 3.2.3, except that moisture contents were determined every week instead of every two weeks. Temperatures of seeds at each sampling location were calculated using a computer model developed by Jian et al. (2005). Initial temperature (18.7ºC) used in this model was the temperature at noon of the simulated September 28th, 2010 that was the day of turning off the humidifier.

3.3.5. Data analysis

Tukey tests were conducted to analyze the effects of storage time on moisture content and FAV of canola seeds, respectively, at $\alpha = 0.05$ level (SAS, 2010). Germination of canola seeds was predicted using a mathematical model (Jian et al., 2014).

4. RESULTS AND DISCUSSION

4.1. Physical Properties of High and Low Oil Content Canola

4.1.1. Seed dimension

The sizes of H-N had greater variation than those of other varieties (Fig 4.1). Minor and major axes increased significantly with increasing of moisture content (Tukey test: F=5.82, p=0.0033 for minor axis and F=5.24, p=0.0058 for major axis, respectively). This trend was the same as that reported in the literature (Çahşır et al., 2005).

Minor and major axes between low oil content and any of the high oil content canola had significant differences (Table 4.1). Means of minor axis of L-C were lower than those of H-H, but higher than those of H-N (Fig. 4.1). Means of major axis of L-C were lower than those of H-H, but higher than those of H-N (Fig. 4.1). Both means of minor and major axes of L-C were close to those of H-I (Fig. 4.1).

Widths (minor axes) of two low oil content canola varieties (Okapi, referred to as L-O, and SLM, referred to as L-S) are 1.53 and 1.51 mm, respectively; and lengths (major axes) are 1.95 and 1.96 mm, respectively (Razavi et al. 2009). Minor axes of L-O and L-S were larger than those of H-N, but smaller than those of H-H and H-I; major axes of L-O and L-S were larger than all of the three high oil content canola seeds. These results suggested that minor and major axes of canola seeds were not dependent on oil content.

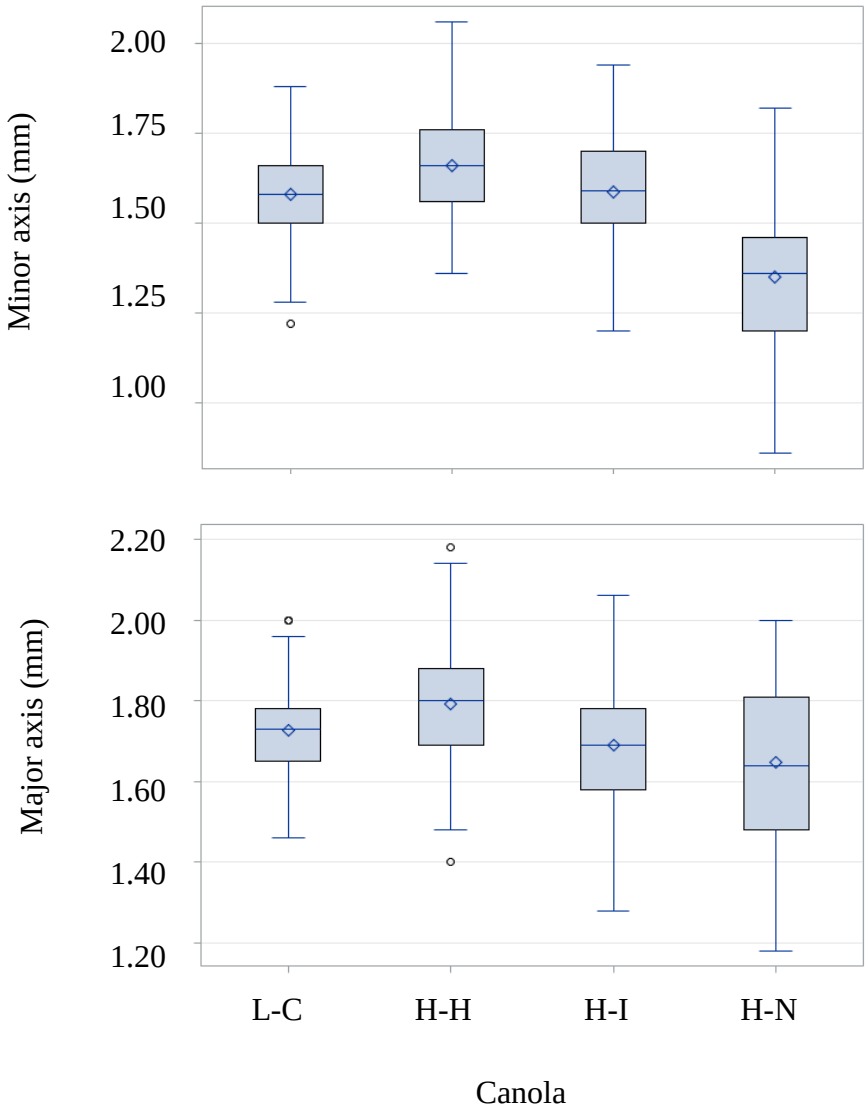

Fig. 4.1 Distributions of minor or major axes (mm) of canola seeds at 10% MC. Middle line in the box shows the median of minor or major axes, error bars above and below the box are maximum and minimum non-outliers. Dots show the 5^{th}/95^{th} percentile outliers. Diamonds show mean values.

Table 4.1 Size comparison (Student *t*-test) between high and low oil content canola at 10% MC

Canola [a]	Minor axis		Major axis	
	t	P	t	P
H-H	1.50	0.0441	1.80	0.0036
H-I	1.85	0.0025	2.69	<0.0001
H-N	2.45	<0.0001	3.51	<0.0001

[a] Standard *t*-test between two varieties (one of the high oil and the low oil content canola seeds).

4.1.2. Bulk density

Bulk densities of H-N were 630±7.6, 649±2.9, 637±6.7 and 637±0.7 kg m^{-3} at 8%, 10%, 12% and 14% MC, respectively (Fig. 4.2). These values are close to the values reported by Jian et al. (2012) for H-N as: 653.3±0.7, 654.0±0.0, 648.0±1.2 and 628.7±1.3 kg m^{-3} at 7.5%, 9.5%, 11.5% and 13.5% MC, respectively. Except H-H, bulk densities of H-I, H-N and L-C increased with increase of moisture content from 8% to 10% and decreased with further increase of moisture content from 10% to 14% (Fig. 4.2). Bulk densities of H-N were significantly affected by moisture content between 8% and 14% MC and 12% and 14% MC (Table 4.2). Bulk densities of H-M_c significantly increased with increase of moisture content from 8% to 10%, but decreased with increase of moisture content from 10% to 14% (Table 4.2 and Fig. 4.2). Bulk densities of canola under other tested conditions were not significantly affected by moisture content (Table 4.2). Bulk densities of canola seeds were low when they were too dry or too wet, because shrinking or swelling of seeds leads to larger spaces among seeds. Bulk densities of different varieties might reach their maximum value at different moisture contents.

Bulk densities had significant differences between H-I and H-N ($F=15.22$, $p<0.0001$). Bulk densities of mixed seeds were between bulk densities of pure seeds of H-I and H-N (Fig. 4.2). Therefore, mixing of high oil content canola might not increase or decrease the bulk density of the mixture. Bulk densities of low oil content canola were significantly higher than that of any pure or mixed high oil content canola

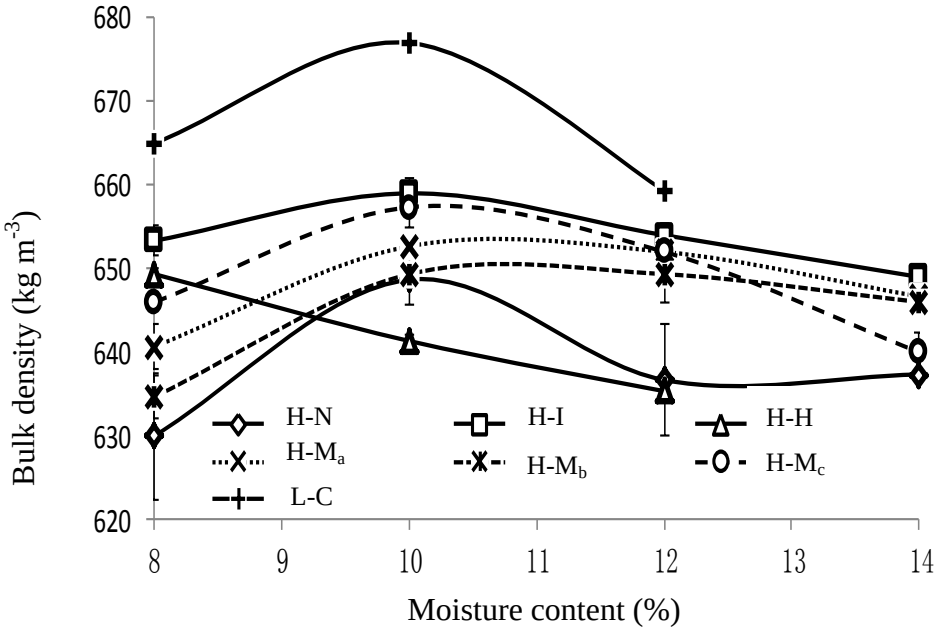

Fig. 4.2 Bulk densities of high and low oil canola when moisture content increased from 8% to 14%.

Table 4.2 Effect of moisture content on bulk densities of canola seeds

Canola	Comparison between moisture contents (%)[a]											
	8 - 10		8 - 12		8 - 14		10 - 12		10 - 14		12 - 14	
	t	P	t	P	t	P	t	P	t	P	t	P
H-H	1.00	1.00	1.00	1.00			1.00	1.00				
H-I	1.93	0.60	2.15	0.63	4.00	0.40	2.15	0.63	4.00	0.40	1.86	0.70
H-N	6.79	0.26	1.29	0.87	129.0	0.02	5.26	0.32	19.0	0.10	100.0	0.02
L-C	1.29	0.88	2.25	0.62			1.75	0.73				
H-M_a	16.0	0.12	1.69	0.74	4.00	0.40	27.0	0.07	4.00	0.40	6.75	0.26
H-M_b	4.00	0.40	1.56	0.78	5.33	0.32	6.25	0.28	1.33	0.86	8.33	0.21
H-M_c	∞	<0.0001	∞	<0.0001	∞	<0.0001	1.44	0.82	1.08	0.96	1.33	0.86

[a] Comparisons were between two moisture contents.

∞ Standard deviation was zero due to identical results of the three replicates.

(Table 4.3 and Fig. 4.2). Bulk densities of low oil content canola, Candle (referred to as L-Ca) and Torch (referred to as L-T), at 8.1% MC are 677 and 664 kg m^{-3} (Muir and Sinha, 1988; Downey, 1990), which were also higher than bulk densities of high oil content canola at 8% MC. Therefore, bulk densities of canola decreased with increasing of oil content. The reason might be that oil is lighter than other components of kernels. Kernel densities of L-C were higher than those of H-H (Fig. 4.3). Therefore, differences of kernel densities between high and low oil content canola might lead to their bulk density differences.

4.1.3. Emptying and filling angles of repose

Maximum difference between the lowest and highest of emptying and filling angles were 3.7º and 1.5º, respectively. This result suggested that moisture content in the tested range did not influence the repose angles very much (Fig. 4.4). In general, emptying angles decreased, increased, and decreased again when moisture content changed from 8% to 10%, 10% to 12%, and 12% to 14%, respectively; and filling angles of H-N decreased, but of H-I, H-N and L-C increased with increase of moisture content (Fig. 4.4). Emptying and filling angles of all mixtures decreased, except the filling angle of H-M_a (Fig. 4.4). Statistical tests also did not show a consistent trend (Table 4.4 and 4.5). For example, emptying and filling angles of repose of L-C were significantly different from those of the pure and mixed high oil content canola; except emptying angle of H-M_c (Table 4.5). Increasing moisture contents might increase the adhesion and reduce friction among seeds. Increasing adhesion and

Table 4.3 Effect of oil and moisture content on bulk densities of canola seeds

Canola [a]		Oil content		Moisture content		Oil × Moisture [b]	
		F	P	F	P	F	P
Pure	H-H	1582.03	<0.0001	132.84	<0.0001	82.22	<0.0001
	H-I	121.53	<0.0001	39.45	<0.0001	12.82	0.0010
	H-N	65.27	<0.0001	7.92	0.0064	1.02	0.3896
Mixture	H-M_a	142.29	<0.0001	21.04	0.0001	13.02	0.0010
	H-M_b	206.04	<0.0001	24.18	<0.0001	16.26	0.0004
	H-M_c	173.79	<0.0001	43.45	<0.0001	11.68	0.0015

[a] Factorial test between two varieties (one of the high oil and the low oil content canola).

[b] Interaction effect between oil and moisture contents.

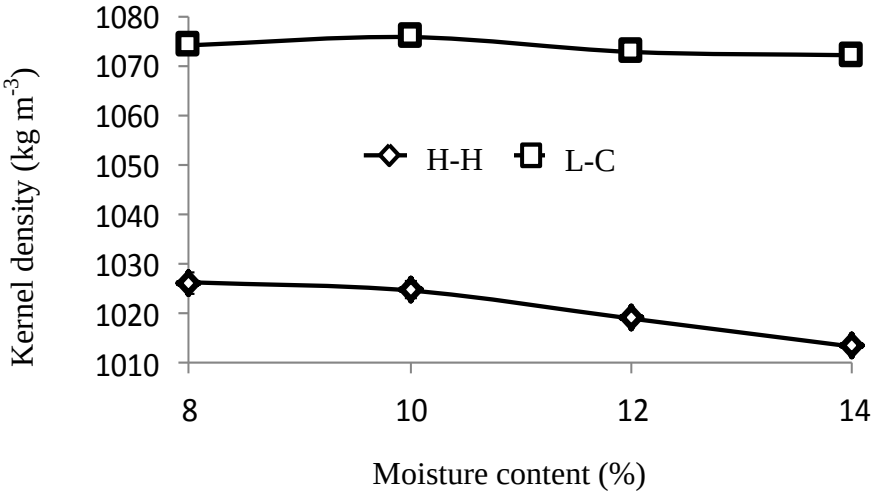

Fig. 4.3 Kernel densities of high and low oil canola when moisture content increased from 8% to 14%.

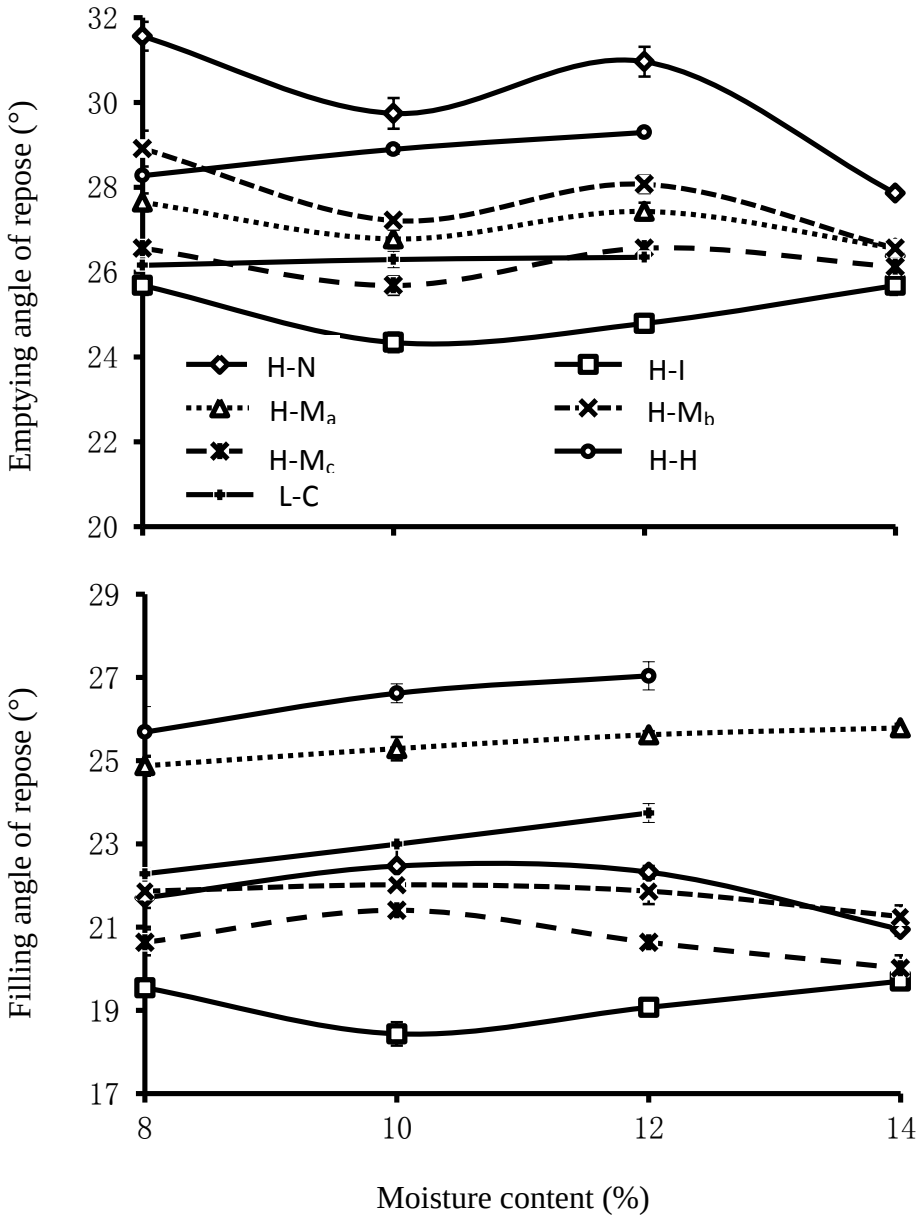

Fig. 4.4 Angles of repose of high and low oil content canola when moisture content increased from 8% to 14%.

Table 4.4 Effect of moisture content on emptying and filling angles of repose of canola seeds

Canola [a]		Emptying angle of repose (°)		Filling angle of repose (°)	
		F	P	F	P
Pure	H-H	48.22	0.0002	2.65	0.1496
	H-I	9.00	0.0061	8.60	0.0070
	H-N	29.19	0.0001	2.3	0.1536
	L-C	0.59	0.5848	20.48	0.0021
Mixture	H-M_a	7.61	0.0099	4.18	0.0470
	H-M_b	19.11	0.0005	1.32	0.3347
	H-M_c	7.29	0.0112	5.40	0.0252

[a] Tukey test between 8% to 14% MC.

Table 4.5 Effect of oil and moisture content on emptying angles of repose of canola seeds

Factor	Canola [a]		Oil content		Moisture content		Oil ×Moisture [b]	
			F	P	F	P	F	P
Emptying angle	Pure	H-H	894.56	<0.0001	17.12	0.0003	7.96	0.0063
		H-I	79.54	<0.0001	5.51	0.0200	8.80	0.0044
		H-N	436.92	<0.0001	5.56	0.0196	6.99	0.0097
	Mixture	$H\text{-}M_a$	49.47	<0.0001	2.71	0.1067	4.03	0.0458
		$H\text{-}M_b$	108.78	<0.0001	6.88	0.0102	9.47	0.0034
		$H\text{-}M_c$	0.00	0.9802	7.43	0.0079	8.92	0.0042
Filling angle	Pure	H-H	171.90	<0.0001	9.63	0.0032	0.13	0.8753
		H-I	704.14	<0.0001	7.47	0.0078	17.31	0.0003
		H-N	7.15	0.0202	3.83	0.0516	0.85	0.4515
	Mixture	$H\text{-}M_a$	205.71	<0.0001	16.29	0.0004	1.72	0.2199
		$H\text{-}M_b$	30.06	0.0001	4.53	0.0343	4.55	0.0339
		$H\text{-}M_c$	181.95	<0.0001	9.78	0.0030	10.02	0.0028

[a] Factorial test between two varieties (one of the high oil and the low oil content canola).

[b] Interaction effect between oil and moisture contents.

reducing friction would result in increase of emptying angle and reducing of filling angle (Cetin, 2007; Razavi et al., 2009). The reason why some of the pure seeds or mixtures tested in this study did not follow this trend is not known.

Emptying and filling angles of H-I were the lowest of the four varieties; emptying angles of H-N and filling angles of H-H were the highest (Fig. 4.4). The angles of mixed canola and L-C were in between the angles of repose of pure high oil content canola. Razavi et al. (2009) reported that emptying angles of rapeseeds (L-O and L-S) with moisture content of 8% to 14% were from 26.4° to 27.0° and from 27.7° to 28.1°; and their filling angles were from 27.6° to 26.1° and from 28.3° to 27.5°, respectively. Emptying angles of these two low oil content canola seeds were in between the emptying angles of high oil content canola tested in this study, but their filling angles were higher than those of high oil content canola. Therefore, angles of repose might depend on varieties and seed surface and be independent of oil content.

4.1.4. Coefficients of friction against structural surfaces

Oil content significantly affected the coefficients of friction except for H-I (Table 4.6). Coefficients of friction of high oil content canola seeds against the four structural surfaces were significantly affected by moisture content, except that H-H on plywood and steel-trowelled concrete, H-I on steel trowelled concrete, H-N on wood-floated concrete, and H-M_a and H-M_c on steel-trowelled concrete (Table 4.7). Coefficients of friction of L-C were not significantly affected by moisture content (Table 4.7). Coefficients of friction of high oil content canola either increased or

Table 4.6 Effect of oil and moisture content on coefficients of friction of canola seeds

Factor	Statistic	Pure			Mixture		
		H-H	H-I	H-N	H-M_a	H-M_b	H-M_c
				Galvanized steel			
Oil content	F	49.98	2.36	44.60	7.04	16.57	20.14
	P	<0.0001	0.1504	<0.0001	0.0211	0.0016	0.0007
Moisture	F	2.97	2.85	2.77	1.91	3.21	0.70
content	P	0.0896	0.0973	0.1029	0.1911	0.0764	0.5160
Oil	F	1.15	1.12	2.01	3.98	3.50	12.13
×Moisture [b]	P	0.3481	0.3571	0.1763	0.0474	0.0633	0.0013
				Wood-floated concrete			
Oil content	F	402.62	3.79	132.22	79.61	113.55	41.94
	P	<0.0001	0.0753	<0.0001	<0.0001	<0.0001	<0.0001
Moisture	F	2.38	2.89	0.80	4.07	3.32	2.26
content	P	0.1345	0.0947	0.4734	0.0448	0.0713	0.1474
Oil	F	8.03	9.66	0.34	0.20	0.04	0.17
×Moisture [b]	P	0.0061	0.0032	0.7175	0.8245	0.9634	0.8474
				Plywood			
Oil content	F	298.67	11.86	84.20	36.90	64.02	16.22
	P	<0.0001	0.0049	<0.0001	<0.0001	<0.0001	0.0017
Moisture	F	0.31	0.63	1.36	1.06	1.18	0.14

content	P	0.7395	0.5500	0.2929	0.3769	0.3406	0.8672
Oil	F	2.17	1.23	0.69	0.54	1.26	1.70
×Moisture [b]	P	0.1573	0.3257	0.5158	0.5977	0.3189	0.2247
				Steel-trowelled concrete			
Oil content	F	855.56	51.77	114.31	28.92	56.14	4.67
	P	<0.0001	<0.0001	<0.0001	0.0002	<0.0001	0.0516
Moisture	F	0.44	1.48	0.05	0.49	1.50	0.39
content	P	0.6555	0.2661	0.9551	0.6218	0.2618	0.6823
Oil	F	3.56	0.93	2.31	2.66	0.85	1.20
×Moisture [b]	P	0.0610	0.4226	0.1417	0.1107	0.4498	0.3340

[a] Factorial test between two varieties (one of the high oil and the low oil content canola).

[b] Interaction effect between oil and moisture contents.

Table 4.7 Effect of moisture content on the coefficient of friction of canola seeds at 8% to 12% MC

Statistic	Pure				Mixture		
	H-H	H-I	H-N	L-C	H-M_a	H-M_b	H-M_c
				Galvanized steel			
F	7.0	12.67	12.00	1.98	15.17	∞	39.56
P	0.0270	0.0021	0.0025	0.2180	0.0012	<0.0001	<0.0001
				Wood-floated concrete			
F	31.20	27.93	2.87	0.72	11.33	12.00	8.00
P	0.0007	0.0001	0.1039	0.5227	0.0030	0.0025	0.0086
				Plywood			
F	4.20	5.78	6.93	0.84	6.56	28.00	6.33
P	0.0723	0.0211	0.0129	0.4776	0.0151	0.0001	0.0166
				Steel-trowelled concrete			
F	4.75	3.89	5.58	1.08	1.83	5.58	0.89
P	0.0580	0.0553	0.0231	0.3966	0.2192	0.0231	0.4872

[a] Tukey test between 8% to 12% MC.

∞ Standard deviation was zero due to identical results of the three replicates.

decreased with increasing of moisture content (Fig. 4.5). Çahşır et al. (2005) observed an increasing trend in the friction coefficient when moisture content increased from 4.7% to 24.0%. From 8% to 14% MC, coefficient of friction of rapeseed increase by 0.0174 and 0.0246 on galvanized steel and plywood surfaces, respectively (Çahşır et al., 2005). Except on wood-floated concrete, coefficients of friction of L-C were between those of high oil content canola (Fig. 4.5). Coefficients of friction of H-I were the lowest in tested canola seeds on plywood, galvanized steel and steel-trowelled concrete surfaces (Fig. 4.5). Coefficients of friction of the tested canola seeds were the lowest on galvanized steel, and the highest on wood-floated concrete.

Coefficients of friction of rapeseed on plywood are 0.25, 0.26, 0.26 and 0.27 at 8%, 10%, 12% and 14% MC, respectively (Çahşır et al., 2005). Muir and Sinha (1988) studied the low oil content canola (L-Ca and L-T) at 8.1% MC and found that coefficients of external friction of L-Ca against galvanized steel, steel-trowelled and wood-floated concrete were 0.24, 0.30 and 0.39; and coefficients of L-T against these three surfaces were 0.28, 0.29 and 0.38, respectively. The coefficients of friction of these low oil content canola seeds were higher than those of H-I, but lower than those of other high oil content canola seeds. Therefore, the coefficient of friction of high oil content canola seeds may not be higher than that of low oil content canola seeds.

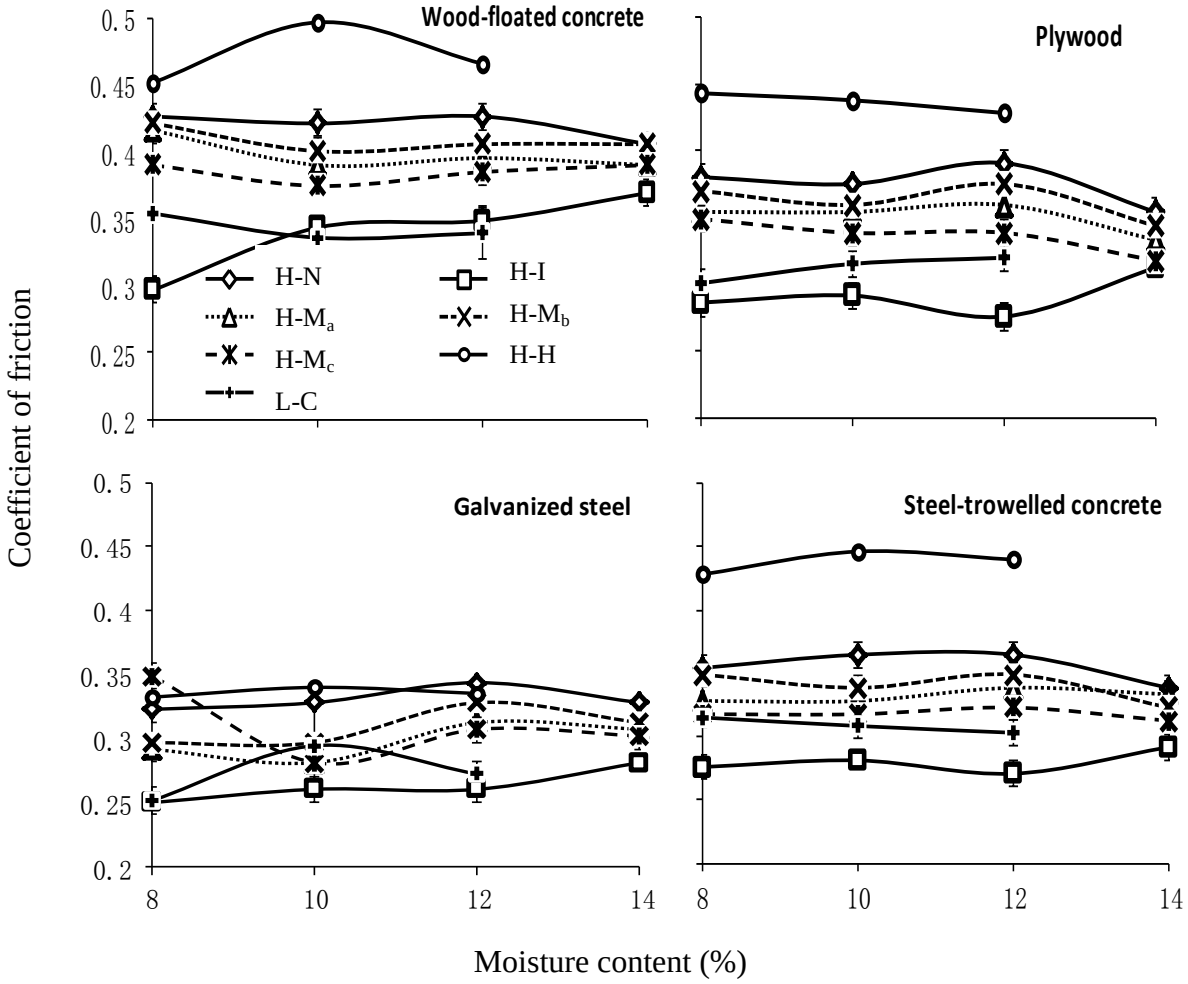

Fig. 4.5 Coefficient of friction of high oil content canola when moisture content increased from 8% to 14%.

4.1.5. Pressure on bin walls

The first, second and third most sensitive factors were h/R, internal friction angle and coefficients of friction, respectively (Table 4.8). The minimum horizontal pressures of high oil content canola were 5, 13 and 10 percent higher than low oil content canola; but the maximum horizontal pressures of high oil content canola were 20, 24 and 18 percent lower than low oil content canola at 8%, 10% and 12% MC, respectively (Table 4.9). Horizontal pressures of high oil content canola on bin walls were lower than those of low oil content canola at both 6 % and 18% MC (Table 4.10). Therefore, bins used to store low oil content canola could be used to store the newly released high oil content canola.

4.2. Small Chamber Study

4.2.1. Moisture content during storage

During the entire storage period, moisture content of canola seeds with initial moisture content of 8%, 10% and 12% had smaller change than those of the canola seeds with initial moisture content of 14%. The maximum changes of moisture contents of canola seeds at 8%, 10%, 12% and 14% initial moisture contents were 1.38%, 1.2%, -1.58% and -2.25%, respectively. Canola with 14% initial moisture content at lower temperatures had a smaller moisture change than the canola at higher temperatures (Fig. 4.6). The deviation from the initial moisture contents might be caused by the experimental setup (Sathya et al., 2009a). Potassium hydroxide solution is widely used in relative humidity control. However, changes in moisture contents

Table 4.8 Minimum, maximum and mean values of factors affecting horizontal pressure on bin walls; and the maximum sensitive values of pressures caused by the factors

Canola	MC (%)	Factor	Minimum	Maximum	Mean	10% of the range [a]	Sensitive value [b]
H-H, H-I and H-N combined	8	Φ	24	31	27	0.7	1
		ρ	616	656	644	4	0
		μ	0.25	0.46	0.35	0.021	1
		h/R	2	10	5	0.8	6
	10	Φ	23	32	28	0.9	1
		ρ	640	662	650	2.2	0
		μ	0.25	0.51	0.35	0.026	1
		h/R	2	10	5	0.8	5
	12	Φ	24	33	28	0.9	1
		ρ	630	656	642	2.6	0
		μ	0.25	0.47	0.36	0.022	1
		h/R	2	10	5	0.8	5
	14	Φ	24	31	27	0.7	1
		ρ	636	651	643	1.5	0
		μ	0.28	0.41	0.34	0.013	0
		h/R	2	10	5	0.8	6

L-C	8	Φ	27	27	27	0	0
		ρ	664	667	665	0.3	0
		μ	0.24	0.36	0.31	0.012	0
		h/R	2	10	5	0.8	6
	10	Φ	28	28	28	0	0
		ρ	675	678	677	0.3	0
		μ	0.26	0.34	0.31	0.008	0
		h/R	2	10	5	0.8	6
	12	Φ	28	29	29	0.1	0
		ρ	658	660	659	0.2	0
		μ	0.25	0.37	0.31	0.012	0
		h/R	2	10	5	0.8	6

[a] Range = |maximum - minimum|

[b] Maximum sensitive value (kN m^{-2}).

Φ – Internal repose angle (º).

ρ -- Bulk density (kg m^{-3}).

R -- Radius of the structure (m).

μ -- Coefficient of friction.

h -- Depth of the grain (m).

Table 4.9 Minimum and maximum pressures produced by high and low oil content canola

Pressure	Value	Moisture content (%)		
		8	10	12
P_H (kN m^{-3})	Min.	41	43	41
	Max.	29	27	27
P_L (kN m^{-3})	Min.	39	38	38
	Max.	36	36	33

P_H -- Horizontal pressure produced by high oil content canola (kN m^{-3}).

P_L -- Horizontal pressure produced by low oil content canola (kN m^{-3}).

Table 4.10 Values of factors for calculating horizontal pressures on bin walls

Canola	MC (%)	Factor	Minimum	Maximum
H-H, H-I and H-N combined	6	ρ	644 [a]	644 [a]
		Φ	25	45
		K	0.41	0.17
		u	0.25	0.51
		h/R	2.00	10
		P	19	29
	18	ρ	569	569
		Φ	25	45
		K	0.41	0.17
		u	0.25	0.51
		h/R	2.00	10
		P	16	26
L-C	6	ρ	672	672
		Φ	25	45
		K	0.41	0.17
		u	0.24	0.37
		h/R	2.00	10
		P	19	33
		P_d [a]	-5	-14

18	ρ	661	661
	Φ	25	45
	K	0.41	0.17
	u	0.24	0.37
	h/R	2.00	10
	P	19	33

Φ – Internal repose angle (º).

ρ -- Bulk density (kg m^{-3}).

R -- Radius of the structure (m).

μ -- Coefficient of friction.

h -- Depth of the grain (m).

P -- Horizontal pressure produced by canola (kN m^{-3}).

K – the ratio of lateral to vertical pressure.

[a] Bulk densities were estimated using the equation developed by Jian et al. (2013) and only one value was found.

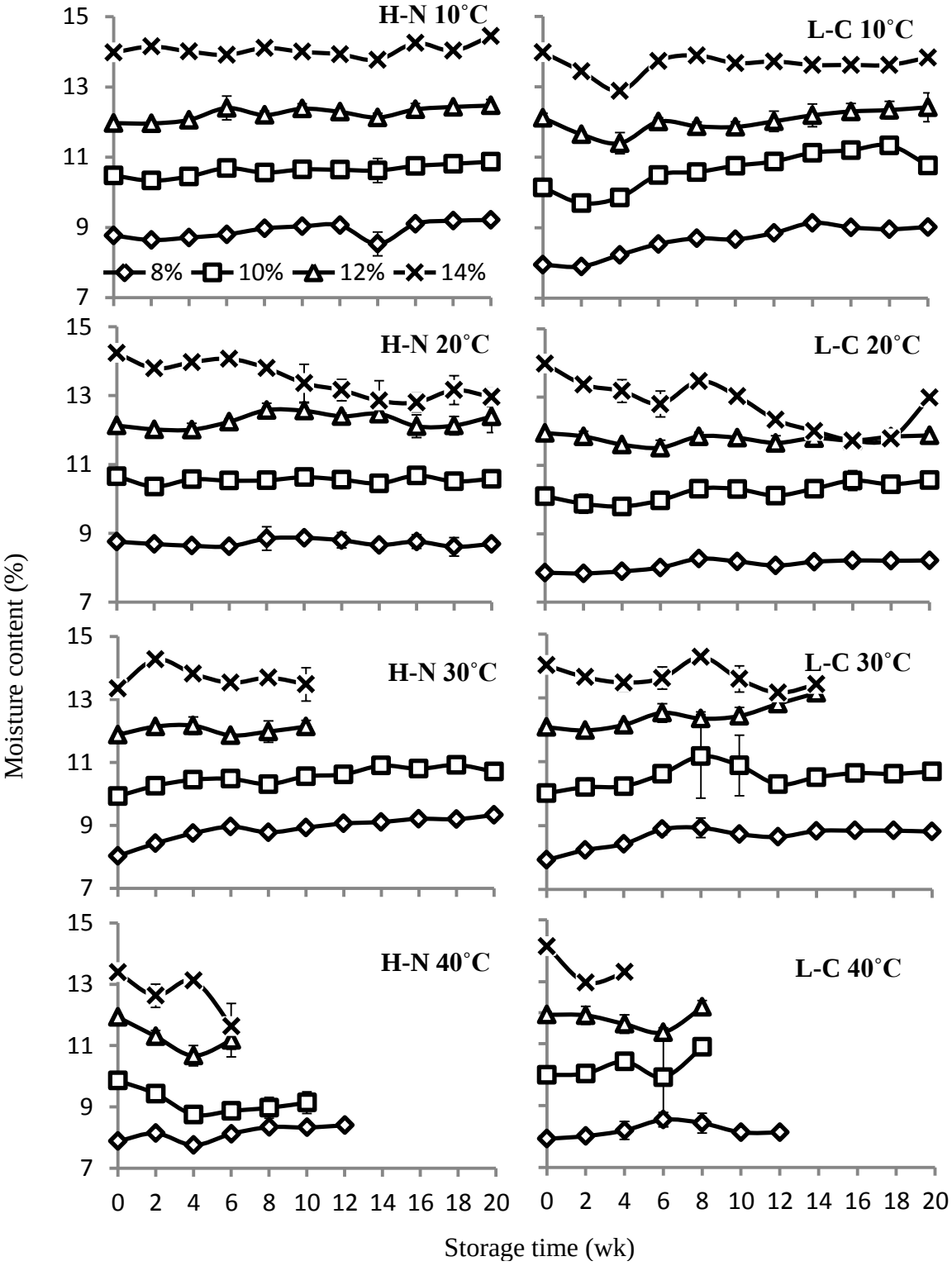

Fig. 4.6 Moisture contents (%) of high (H-N) and low (L-C) oil content canola during 20 wk storage period.

have been seen (Solomon, 1951; Sathya et al., 2009a). Sathya et al. (2009a) reported that moisture contents of canola decreased at 20ºC, 30ºC and 40ºC. Solomon (1951) also mentioned errors in the humidity control if KOH solutions lose or absorb too much water during storage. Humidity produced by solutions also decreases with increasing temperature. Therefore, quality changes of high and low oil content canola cultivars were tested under constant temperatures and slightly fluctuating moisture contents in this study.

4.2.2. Germination

Germination decreased with increase of storage time at ≥20ºC (Fig. 4.7). Germination between different varieties was significantly different in most cases (Table 4.11). These differences might be caused by: 1) different moisture changes during the storage period (Fig. 4.6); 2) different initial germinations of the canola varieties; and 3) different storability of the canola varieties. The initial germination of H-H, H-I, H-N, and L-C were 100.0 ± 0.0%, 96.7 ± 0.7%, 96.0 ± 4% and 96.0 ± 4%; respectively. Therefore, the comparisons (Paried *t*-test) between H-I and H-N and between H-N and L-C were used to evaluate the difference between the cultivars. There was significant difference in the germination between H-N and L-C except the 14% MC canola stored at 30ºC, while there was no significant difference between H-I and H-N except the 8%, 12% and 14% MC canola stored at 30ºC. Various cultivars of high oil content canola are mixed during commercial storage in Canada. Therefore, we assumed there was no difference in germination between high oil content canola

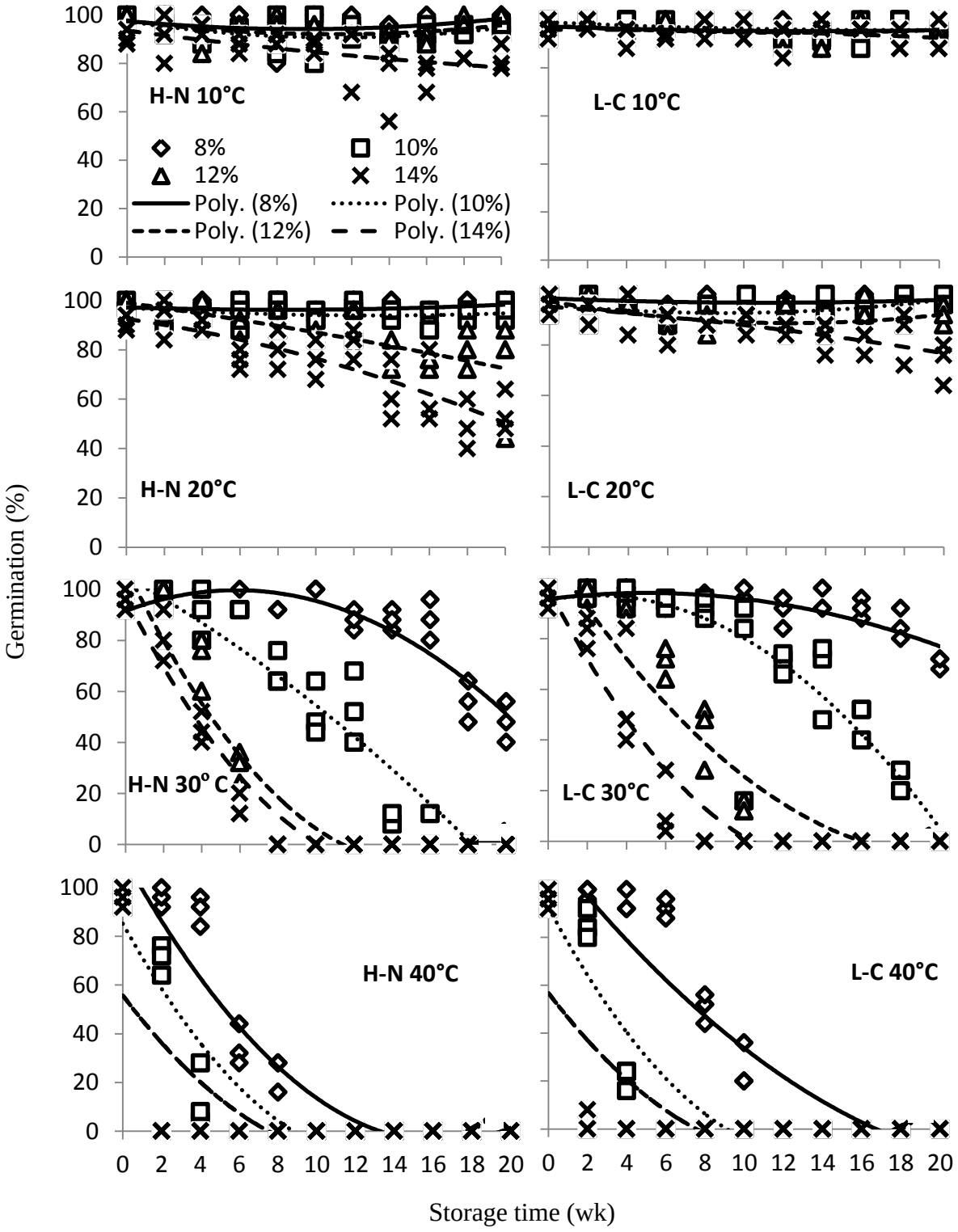

Fig. 4.7 Germination (%) of high (H-N) and low (L-C) oil content canola during 20 wk storage period. In the graph, lines were the predicted germination of the canola by using the polynomial equations (Table 4.13).

Table 4.11 Statistics of germination between two high (H-I and H-N) oil content canola cultivars or between one high (H-N) and one low (L-C) oil content canola cultivars with 8% to 14% MC at 30ºC and 40ºC

Temperature (ºC)	MC (%)	Canola [a]			
		H-I vs. H-N		H-N vs. L-C	
		t	p	t	p
30	8	-3.48	0.0015	-3.08	0.0042
	10	1.62	0.1158	-4.62	<0.0001
	12	3.53	0.0013	-3.68	0.0009
	14	2.26	0.0306	-0.80	0.4293
40	8	-1.12	0.2719	-3.28	0.0025

[a] Paired *t*-test between two varieties.

cultivars, while the high oil content canola cultivars had a faster rate of germination decrease than that of the low oil canola cultivars (Fig. 4.7).

Germination of canola seeds were significantly affected by storage time and moisture contents, except for a few exceptions (Table 4.12). The reason for these exceptions was that the germination of canola at 10ºC and low moisture contents (8% and 10%) did not change significantly (Student *t*-test) in the 20 wk storage period. Germination of canola seeds at higher moisture contents (12% and 14%) decreased more dramatically than those at lower moisture contents (8% and 10%) with increased storage time (Fig. 4.7). Increase of temperature also stimulated the loss of germination with increased storage time (Table 4.13 and Fig. 4.7). For example, 8% MC canola at 10º and 20ºC had no germination loss. At 40ºC, germination of canola at all moisture contents decreased to 0% in ≤20 wk (Fig. 4.7). The relationship between germination and storage time for the canola seeds followed a quadratic equation (Table 4.13).

4.2.3. Visible and invisible mould

The time (wk) of the first appearance of visible mould is shown in Table 4.14. Visible mould was found on all seeds with 12% and 14% MC, except H-N at 10°C (Table 4.14). No visible mould was found on high oil content canola with 8% MC, but it was found on low oil content canola with 8% MC at 30ºC in 18 wk (Table 4.14).

Pronyk et al. (2004) considered the first sign of visible mould as a signal of canola deterioration, and concluded that the first appearance of visible mould might not happen before 5% initial germination loss. Our results did not suggest that the first

Table 4.12 Effect of storage time (wk) and moisture content (%) on germination of high and low oil content canola seeds stored at temperatures of 10°C, 20°C, 30°C and 40°C

T (°C)	Canola [a]	Storage time (wk)		MC (%)		Storage time × MC [b]	
		F	P	F	P	F	P
10	H-H	1.91	0.0539	10.74	<0.0001	1.31	0.1655
	H-I	15.66	<0.0001	11.92	<0.0001	2.27	0.0017
	H-N	3.11	0.0019	21.82	<0.0001	1.47	0.0843
	L-C	2.67	0.0068	1.55	0.2069	1.19	0.2605
20	H-H	3.84	0.0002	6.66	0.0004	0.99	0.4945
	H-I	18.50	<0.0001	85.97	<0.0001	3.71	<0.0001
	H-N	7.88	<0.0001	65.39	<0.0001	2.90	<0.0001
	L-C	4.42	<0.0001	22.63	<0.0001	1.31	0.1644
30	H-H	189.22	<0.0001	516.25	<0.0001	19.42	<0.0001
	H-I	175.82	<0.0001	268.02	<0.0001	12.17	<0.0001
	H-N	216.04	<0.0001	545.29	<0.0001	22.44	<0.0001
	L-C	138.36	<0.0001	461.35	<0.0001	17.35	<0.0001
40	H-H	628.10	<0.0001	373.96	<0.0001	70.17	<0.0001
	H-I	417.65	<0.0001	125.24	<0.0001	43.12	<0.0001
	H-N	575.11	<0.0001	224.18	<0.0001	56.39	<0.0001
	L-C	472.78	<0.0001	362.49	<0.0001	62.29	<0.0001

[a] Factorial test of the canola at different moisture contents and storage times.

[b] Interaction effect between storage time (wk) and moisture contents (%).

Table 4.13 Relationship between germination (%) and storage time (wk) of high (H-N) and low (L-C) oil content canola seeds with 8% to 14% MC at 10ºC to 40ºC

Canola	T (°C)	MC (%)	Parameter ∓			
			a	b	c×10^{-2}	R^2
H-N	10	8	–	–	–	–
		10	97.5	-1.2	5.3	0.20
		12	97.8	-1.0	4.7	0.17
		14	93.6	-1.0	1.3	0.30
	20	8	–	–	–	–
		10	–	–	–	–
		12	99.0	-1.2	-1.3	0.55
		14	–	–	–	–
	30	8	91.6	2.8	-2.4	0.82
		10	100 ∓	-4.2	-8.7	0.91
		12	100 ∓	-15.3	5.1	0.92
		14	97.1	-14.9	5.2	0.94
	40	8	100 ∓	-14.3	4.4	0.91
		10	85.2	-14.4	5.4	0.85
		12	55.7	-10.6	4.2	0.54
		14	55.7	-10.6	4.2	0.54
		8	–	–	–	–

	10	10	–	–	–	–
		12	–	–	–	–
		14	–	–	–	–
		8	–	–	–	–
	20	10	96.0	-0.8	4.3	0.14
		12	97.4	-1.4	-5.8	0.26
		14	95.2	-0.6	-1.8	0.52
L-C		8	95.7	0.9	-9.4	0.64
	30	10	95.2	1.5	-3.0	0.85
		12	100 ╒	-11.8	2.9	0.92
		14	100	-15.1	5.2	0.91
		8	100 ╒	-10.3	1.9	0.88
	40	10	92.4	-15.3	5.6	0.86
		12	56.7	-10.7	4.2	0.56
		14	56.7	-10.7	4.2	0.56

╤ Parameters in the quadratic equation $G = a + bt + ct^2$, where G = germination (%) of canola seeds, and t = storage time (wk).

╒ The value was larger than 100. During calculation it was assigned as 100 when the predicted G was >100.

"–" indicated germination did not change during 20 wk storage period.

Table 4.14 Time (wk) of the first appearance of visible mould on high and low oil content canola seeds

Temperature (°C)	Canola	Time of first appearance of mould (wk)			
		MC (%)			
		8	10	12	14
10	H-H	–	–	20	10
	H-I	–	–	14	10
	H-N	–	–	–	10
	L-C	–	–	20	8
20	H-H	–	18	12	4
	H-I	–	18	10	8
	H-N	–	–	10	8
	L-C	–	18	10	4
30	H-H	–	10	6	4
	H-I	–	14	14	4
	H-N	–	14	6	4
	L-C	18	6	4	2
40	H-H	–	8	6	4
	H-I	–	10	2	2
	H-N	–	10	4	2
	L-C	–	6	2	2

"–" Visible mould was not observed during 20 wk storage period.

appearance of visible mould exactly related to seed deterioration. The first visible mould was observed on some canola seeds with quite high or low germination (Table 4.14 and Fig. 4.7). For example, 12% MC H-H at 20ºC had 3% loss of the initial germination when the first visible mould appeared, while the 10% MC L-C at 20ºC had no germination loss when the first visible mould appeared (Table 4.14 and Fig. 4.7). At 30ºC, germinations of H-H, H-I and H-N with 10% MC reduced 39%, 84% and 87%, respectively when the first visible mould appeared (Table 4.14 and Fig. 4.7). At 40ºC, no visible mould was observed on canola seeds with 8% MC when germination of canola seeds was 0% (Table 4.14 and Fig. 4.7). Therefore, although visible mould showed evidence of deterioration, it was not a reliable factor that could be used to predict safe storage time of canola.

At the beginning of the storage, *Penicillium* spp., *Aspergillus glaucus* group and *Aspergillus candidus* were the predominant fungi on canola seeds. Small amount of seeds were infected by *Alternaria alternata* and *Cladosporium* sp. (Table 4.15). The canola used in this study had been kept at low moisture contents before testing. This might explain the reason why storage fungi (*Penicillium, A. glaucus* and *A. candidus*) were at higher infection levels than field fungi (*Alternaria alternata* and *Cladosporium)* at beginning of the study. *Penicillium, A. glaucus* and *A. candidus* were prevalent throughout the entire storage period (Table 4.15). At the end of storage, infection of *Alternaria alternata* and *Cladosporium* on most of high and low oil canola seeds decreased to 0% (Table 4.15). More seeds were infected by *Penicillium,*

Table 4.15 Microfloral infection (%) of high (H-N) and low (L-C) oil content canola seeds with 8%, 10%, 12% and 14% MC at 10ºC to 40ºC at the beginning and end of 20 wk storage

Canola	T (ºC) [a]	Microflora	Infection (%)							
			MC (%)							
			8		10		12		14	
			Initial	End	Initial	End	Initial	End	Initial	End
	10	*Penicillium*	37	0	21	11	9	77	89	95
		Alternaria [a]	7	5	5	1	16	7	17	3
		Cladosporium	1	0	0	5	11	3	12	1
		A. glaucus gr. [b]	29	0	16	0	3	8	4	1
		A. candidus [c]	19	0	8	0	8	4	1	36
	20	*Penicillium*	48	39	19	79	9	100	75	93
		Alternaria [a]	4	0	3	0	7	0	3	4
		Cladosporium	0	0	1	0	4	0	0	0
		A. glaucus gr. [b]	1	0	0	4	11	41	1	41
		A. candidus [c]	37	13	17	4	72	0	81	21
H-N	30	*Penicillium*	25	3	93	75	91	65	93	51
		Alternaria [a]	0	0	0	0	1	3	3	3
		Cladosporium	4	4	0	0	0	0	0	0
		A. glaucus gr. [b]	11	8	9	100	45	51	23	21

		A. candidus [c]	4	3	8	0	20	13	68	84
	40	*Penicillium*	21	9	12	–	100	–	100	–
		Alternaria [a]	1	0	0	–	0	–	0	–
		Cladosporium	0	0	0	–	0	–	0	–
		A. glaucus gr. [b]	37	45	21	–	8	–	0	–
		A. candidus [c]	1	0	1	–	3	–	17	–
		Penicillium	29	27	28	48	31	85	100	100
		Alternaria [a]	16	8	12	8	11	7	9	1
	10	*Cladosporium*	5	28	28	15	16	7	3	0
		A. glaucus gr. [b]	41	20	77	64	64	31	65	29
		A. candidus [c]	43	12	16	0	24	28	37	69
		Penicillium	15	56	12	29	61	19	96	77
		Alternaria [a]	7	0	8	3	8	0	4	0
	20	*Cladosporium*	13	0	28	9	3	0	0	0
		A. glaucus gr. [b]	36	21	16	49	11	16	19	8
		A. candidus [c]	52	83	35	28	72	89	100	91
L-C		*Penicillium*	59	85	41	73	63	100	100	92
		Alternaria [a]	0	0	0	0	1	0	0	0
	30	*Cladosporium*	0	0	1	0	0	0	0	0
		A. glaucus gr. [b]	37	35	24	84	52	15	99	49
		A. candidus [c]	84	45	41	13	65	93	48	63

	Penicillium	19	41	48	97	97	28	97	0
	Alternaria [a]	0	0	0	0	0	0	0	0
40	*Cladosporium*	0	0	0	0	0	0	0	0
	A. glaucus gr. [b]	84	85	96	65	64	9	31	0
	A. candidus [c]	61	37	7	1	0	20	15	0

[a] *Alternaria alternata*.

[b] *Aspergillus glaucus* gr.

[c] *Aspergillus candidus.*

Initial – Microfloral species were determined at the 4th week of storage.

End – Microfloral species were determined at the end of storage. At 30ºC and 40ºC, invisible mould was determined by the time the germination was 0%.

"–" indicated data were not available because the invisible mould was determined only at the 4th wk due to germination was 0% before or by the 4th wk.

A. glaucus and *A. candidus* at higher temperatures (30ºC and 40ºC) and higher moisture contents (12% and 14% MC) (Table 4.15). Similarly, FAO (2013) reported that *Penicillum* spp. and *Aspergillus* spp. were the most common moulds of stored feedstuff. They multiply rapidly on canola seeds when temperature is above 25ºC and moisture content is above 10%.

4.2.4. Free fatty acid value

Fatty acid values of high and low oil content canola significantly increased with increase of storage time and moisture content, except that of H-H at 10ºC and 20ºC (Table 4.16). At the beginning of the storage, FAV of H-N with 8%, 12% and 14% MC at 40ºC increased with the increase of storage time, but dramatically dropped after several weeks of storage (Fig. 4.8). Similarly, FAV of L-C at 10% and 12% MC increased from 0 to 6 wk, but not at 8 wk (Fig. 4.8). The dramatic drop of FAV might be due to oxidation of free fatty acids of canola seeds at high temperature (40ºC) (Knothe and Dunn, 2003).

White and Jayas (1991) used a 1.5-fold increase of FAV as a critical value to estimate safe storage period of rapeseed. Canola at high temperatures (30ºC and 40ºC) reached 1.5-fold of initial FAV earlier than that at low temperatures (10ºC and 20ºC) (Table 4.17 and Fig. 4.7). Increase of temperature increased the rate of seed deterioration. Germination and FAV had negative correlation at any tested storage condition with few exceptions (Table 4.18). If a correlation coefficient was less than -0.5, it was counted as a strong correlation, this strong correlation only happened at

Table 4.16 Effect of storage time (wk) and moisture content (%) on FAV of high and low oil content canola seeds with 8%, 10%, 12% and 14% MC at 10°C, 20°C, 30°C and 40°C

T	Canola [a]	Storage time (wk)		MC (%)		Storage time × MC [b]	
(°C)		F	P	F	P	F	P
	H-H	0.70	0.7210	2.63	0.0551	0.73	0.8296
10	H-I	121.11	<0.0001	45.14	<0.0001	6.41	<0.0001
	H-N	262.30	<0.0001	94.08	<0.0001	4.75	<0.0001
	L-C	5.85	<0.0001	4.28	0.0072	0.83	0.7067
	H-H	3.48	0.0007	2.20	0.0941	1.15	0.3045
20	H-I	440.40	<0.0001	720.22	<0.0001	30.76	<0.0001
	H-N	643.88	<0.0001	389.78	<0.0001	19.47	<0.0001
	L-C	3.33	0.0010	27.42	<0.0001	1.65	0.0382
	H-H	7.69	<0.0001	36.69	<0.0001	2.62	0.0009
30	H-I	52.22	<0.0001	50.94	<0.0001	2.29	0.0039
	H-N	47.42	<0.0001	38.69	<0.0001	5.55	<0.0001
	L-C	22.78	<0.0001	45.22	<0.0001	6.88	<0.0001
	H-H	88.86	<0.0001	43.63	<0.0001	7.03	<0.0001
40	H-I	104.10	<0.0001	19.13	<0.0001	5.61	<0.0001
	H-N	354.47	<0.0001	96.32	<0.0001	107.54	<0.0001
	L-C	49.67	<0.0001	21.22	<0.0001	10.99	<0.0001

[a] Factorial test of the canola with 8%, 10%, 12% and 14% MC and in different storage times.

[b] Interaction effect between storage time (wk) and moisture contents (%).

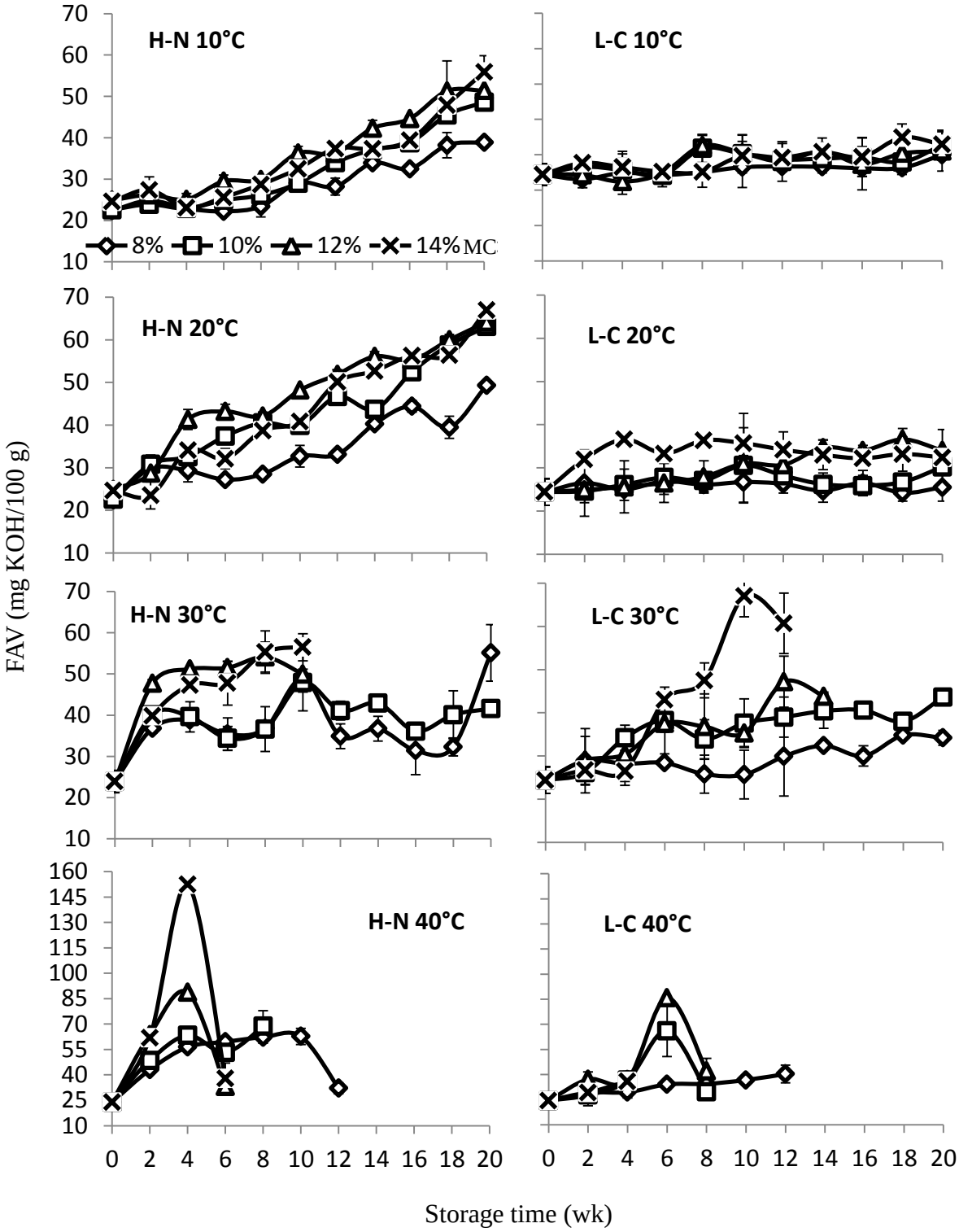

Fig. 4.8 Free fatty acid value of high (H-N) and low (L-C) oil content canola during 20 wk storage period.

Table 4.17 Time (wk) for FAV to reach 1.5-fold of its initial value

T (ºC)	Canola	Time for FAV to reach 1.5-fold of initial value (wk)			
		MC (%)			
		8	10	12	14
10	H-H	–	–	–	–
	H-I	–	16	16	10
	H-N	18	12	14	12
	L-C	–	–	–	–
20	H-H	–	–	–	–
	H-I	16	10	14	4
	H-N	14	6	4	8
	L-C	–	–	–	–
30	H-H	–	–	–	2
	H-I	6	2	2	4
	H-N	2	2	2	2
	L-C	–	10	6	6
40	H-H	6	2	2	2
	H-I	2	2	2	2
	H-N	2	2	2	2
	L-C	10	4	4	–

"–" indicated FAV did not reach 1.5-fold at the end of the study.

Table 4.18 Relationship between germination (%) and FAV (mg KOH/100 g of seed) of high (H-N) and low (L-C) oil content canola seeds

Canola	T (°C)	MC (%)							
		8		10		12		14	
		C [a]	P [b]	C [a]	P [b]	C [a]	P [b]	C [a]	P [b]
H-N	10	0.06	0.74	-0.22	0.22	-0.14	0.43	-0.68	0.00
	20	0.08	0.65	-0.22	0.21	-0.75	0.00	-0.76	0.00
	30	0.04	0.82	-0.35	0.04	-0.67	0.00	-0.91	0.00
	40	-0.40	0.07	-0.73	0.00	-0.73	0.01	-0.73	0.01
L-C	10	-0.06	0.72	-0.41	0.02	-0.02	0.93	-0.33	0.06
	20	-0.09	0.62	-0.27	0.12	-0.23	0.20	0.00	0.98
	30	-0.43	0.01	-0.57	0.00	-0.84	0.00	-0.92	0.00
	40	-0.77	0.00	-0.74	0.00	-0.72	0.00	-0.37	0.31

[a] Correlation coefficient.

[b] Parameter that determines the significance of the relationship between germination and FAV.

The germination and FAV tend to increase together, if C value is positive and $P < 0.050$; the germination tends to decrease while the FAV increases, if C value is negative and $P < 0.050$; and there is no significant relationship between the germination and FAV, if $P > 0.050$.

higher temperatures and moisture contents for H-N, while L-C had strong correlation at the following tested conditions: 12% and 14% MC at 30ºC, and 8%, 10% and 12% MC at 40ºC. Therefore, FAV could not be used to predict germination at most of the tested storage conditions.

4.2.5. Safe storage guidelines

Safe storage guidelines for high oil content canola were developed based on 20% loss of initial germination for H-H and H-N from the initial germination of 100.0 ±0.0% and 96.0 ±4%, respectively (Fig. 4.9). Safe guidelines for low oil content canola based on L-C were similar to the guideline recommended by Canadian Grain Commission (2013). For example, from both the safe storage guidelines of Canadian Grain Commission (2013) and our study (Fig. 4.9), low oil content canola at 8% initial MC had no deterioration at temperatures lower than 30^{o} C, and at 10% initial MC had no deterioration at temperatures lower than 20^{o} C in 20 wk storage. At the same storage conditions, high oil content canola had the same or shorter safe storage times as the low oil content canola (Fig. 4.9). For example, low oil content canola with 12% and 14% MC at 20ºC could be safely stored for 5 and 4 wk longer than high oil content canola, respectively (Fig. 4.9). Therefore, high oil content canola must be stored at lower moisture contents than low oil canola at corresponding temperatures.

The high and low oil content canola varieties in this study, were obtained from the same farm and harvest year. In reality, the year to year and geographic variance might affect storabilities of canola seeds. Therefore, the developed safe storage

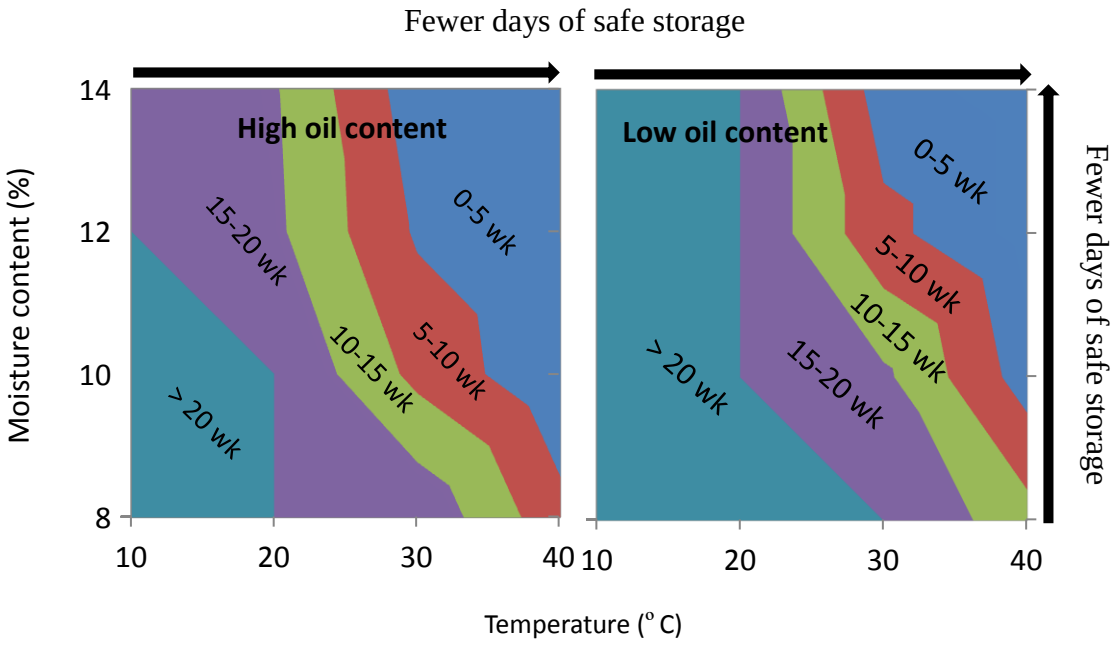

Fig. 4.9. Safe storage guidelines of high (H-H and H-N) and low oil content canola (L-C). The experiment was conducted for 20 wk. So "＞20 wk" in the graph meant that the canola seeds had no deterioration at the end of this study, and could be safely stored for 20 wk. However, the upper limit of their safe storage time was unsure.

guidelines of high oil content canola have their limitation. The guidelines might not workable for canola seeds planted in other years or farms. Further studies to verify the effectiveness of the new safe storage guidelines for high oil content canola are needed.

4.3. Large Scale Bin Study

4.3.1. Moisture content

Initial moisture contents of canola seeds were between 8.4% and 9.4%, except those at L4 (between 5.3% and 6.8%) (Fig. 4.10). The RH was controlled to be 95% to 98% in the first 4 wk to rapidly increase moisture contents of canola seeds. At the fourth week of storage, moisture contents of canola in bins 1, 2 and 3 were between 8.4% and 9.9%, 8.9% and 10.2%, and 8.5% and 11.4%, respectively. From the 5 wk to the end of storage, RH of the environmental room was simulated RH from the September 29th to December in 2010 of Winnipeg Forks Station.

Moisture contents of canola significantly increased with increase of storage time, except the seeds of L2Sw in bin 3 (Table 4.19, Fig. 4.10). Moisture content of canola seed at L4 increased faster than those at other layers with increase of storage time. At the same layer, moisture content of canola at the wall increased faster than those of canola at the centre, except at L4 (Fig. 4.10). For example, in bin 1, moisture content of canola seeds increased 8.7% and 9.2% at the wall and centre of L4, respectively, but increased 0.7% and decreased 0.3% at L3, respectively. The highest moisture content increase was at the centre of L4 in each bin. This was in accordance with the

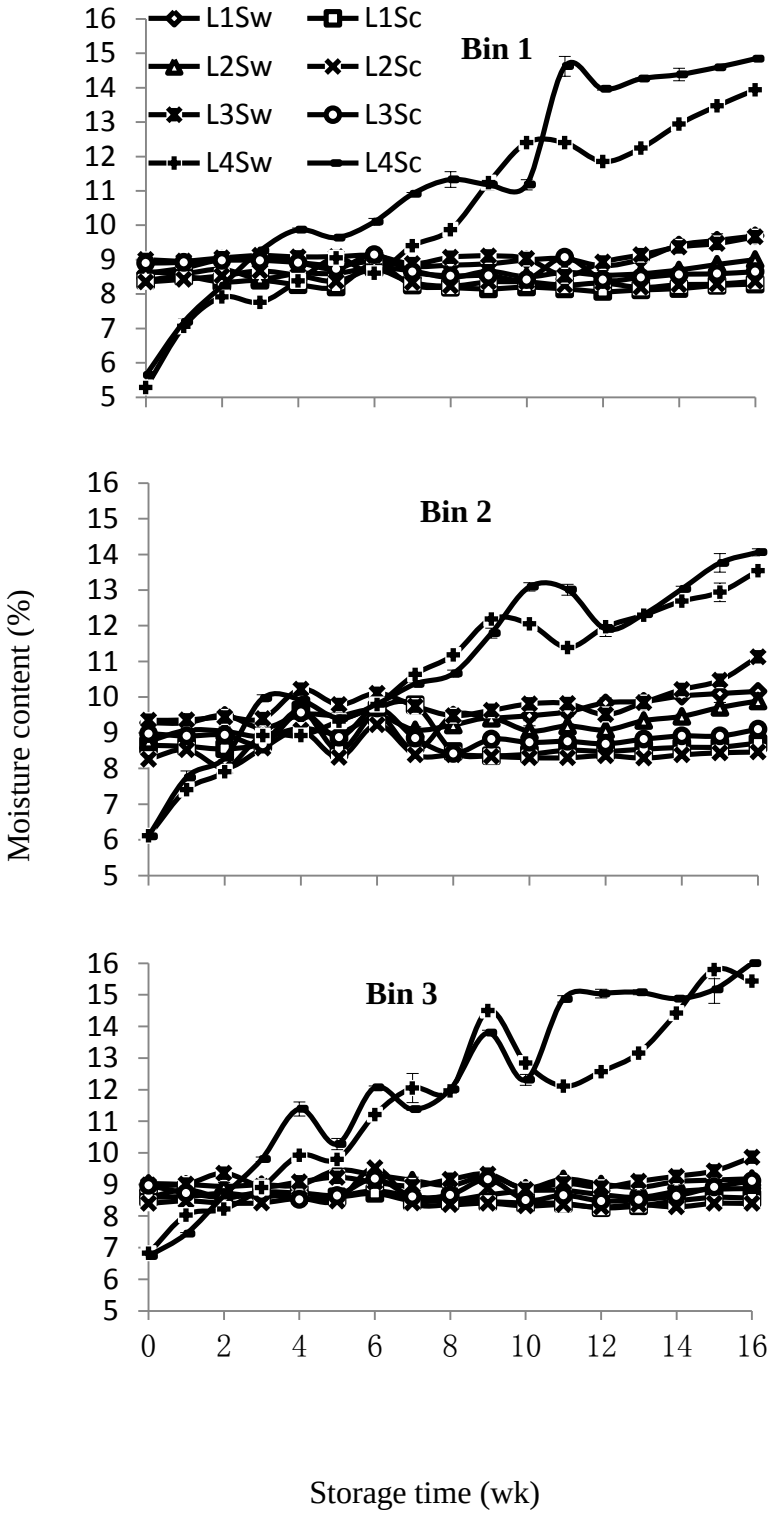

Fig. 4.10 Moisture content (%) of H-N during 16 wk storage in the large bin study.

Table 4.19 Effect of storage time (wk) on moisture content of H-N in large scale study

Location[a]	Storage bin					
	1		2		3	
	F	P	F	P	F	P
L1Sw	16.43	<0.0001	18.39	<0.0001	2.64	0.0085
L1Sc	14.54	<0.0001	26.11	<0.0001	4.18	0.0002
L2Sw	7.81	<0.0001	5.27	<0.0001	1.47	0.1675
L2Sc	14.54	<0.0001	17.95	<0.0001	12.97	<0.0001
L3Sw	37.32	<0.0001	17.74	<0.0001	11.62	<0.0001
L3Sc	15.95	<0.0001	25.07	<0.0001	10.45	<0.0001
L4Sw	1032.78	<0.0001	442.65	<0.0001	302.37	<0.0001
L4Sc	531.82	<0.0001	316.60	<0.0001	374.41	<0.0001

[a] Tukey test between 0 to 16 wk.

statement of the Canola Council of Canada (2012). The main reason might be that the RH inside the environmental lab might be high; grain temperature was higher than the environmental room; and cold air travelled from outside to inside of the bins, so that condensation at the wall and roof of the bins was produced. Some condensation also happened at the bottom of bins because of the perforated floor. Temperature gradients of intergranular air in a grain bulk cause moisture migration (Muir, 2000). Because the bins were small, the moisture diffusion could be fast and caused increase of moisture content at the centre of the bins. Small hot spots also caused a dramatic increase of moisture contents at some locations.

4.3.2. Germination

Initial germination of canola seeds was between 71% and 96%. Germination of canola seeds was above 70% in 12 wk storage with a few exceptions (Fig. 4.11). Germination of some canola seeds was lower than 70% at 14 and 16 wk, but large standard errors were observed (Fig. 4.11).

Germination of canola seeds was predicted in Table 4.20 using the model reported in Jian et al. (2014. The predicted germination was slightly decreased (less than 6%). The tested germination was close to the predicted germination in most cases, especially before 12 wk (Fig. 4.11 and Table 4.20). This meant that real storage conditions coincided with the storage guidelines developed in the small chamber study that deterioration did not happen at low temperatures and low moisture contents. However, some tested germination decreased much more than the predicted

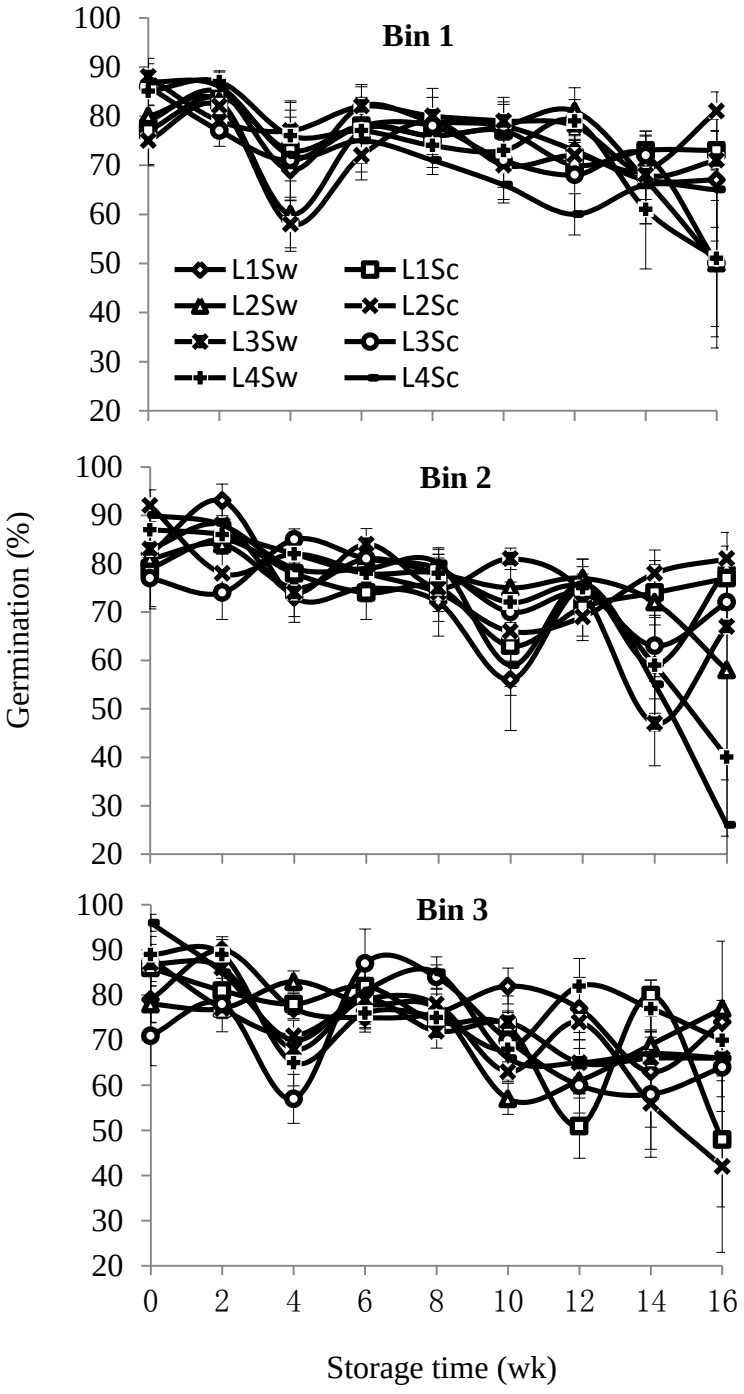

Fig. 4.11 Germination (%) of H-N during 16 wk storage in the large bin study.

Table 4.20 Predicted germination (%) of H-N in a large bin study from 6 wk to 16 wk

Bin Location[a]		Predicted germination (%)					
		Storage time (wk)					
		6	8	10	12	14	16
1	L1Sw	82.0	81.9	81.9	81.9	81.9	81.9
	L1Sc	78.0	77.9	77.9	77.9	77.9	77.9
	L2Sw	77.0	76.9	76.9	76.9	76.9	76.9
	L2Sc	71.9	71.8	71.5	70.9	70.9	70.5
	L3Sw	81.9	81.9	81.8	81.8	81.8	81.8
	L3Sc	77.9	77.7	77.4	76.8	76.8	76.4
	L4Sw	76.9	76.6	76.2	75.5	75.5	75.5
	L4Sc	74.3	73.3	73.1	71.2	71.2	71.1
2	L1Sw	74.9	74.8	74.8	74.8	74.8	74.8
	L1Sc	73.9	73.9	73.9	73.8	73.8	73.8
	L2Sw	80.9	80.8	80.8	80.8	80.8	80.8
	L2Sc	77.9	77.7	77.4	76.9	76.8	76.5
	L3Sw	83.7	83.6	83.6	83.5	83.5	83.5
	L3Sc	80.8	80.6	80.3	79.6	79.5	79.1
	L4Sw	77.5	76.6	76.3	75.6	75.6	75.5
	L4Sc	78.5	77.9	77.3	76.6	76.6	76.6
3	L1Sw	75.0	74.9	74.9	74.9	74.9	74.9
	L1Sc	82.0	81.9	81.9	81.9	81.9	81.9
	L2Sw	77.9	77.9	77.9	77.8	77.8	77.8
	L2Sc	78.8	78.7	78.4	77.8	77.8	77.5
	L3Sw	78.9	78.9	78.8	78.9	78.9	78.9
	L3Sc	86.9	86.7	86.4	85.8	85.7	85.3
	L4Sw	74.0	72.4	71.9	71.0	71.0	70.9
	L4Sc	77.2	75.5	75.1	71.9	71.9	71.8

germination (Fig. 4.11 and Table 4.20). The reason might be that hot spots were produced in canola bulks with high moisture contents at some locations in bins. Temperatures of these hot spots were much higher than the predicted temperatures using the model of Jian et al. (2005); and the high temperatures and moisture contents caused fast deterioration of canola seeds. Differences between the tested and predicted germination might also be caused by operational errors.

4.3.3. Visible and invisible mould

Visible mould was first observed earlier than that of the small chamber study. At the 6^{th} wk, visible mould was first observed on the seeds at L3 and L4 and the centre location of L2 in bin 1; at L4 and the wall of L3 in bin 2; and at L4 in bin 3 (Table 4.21). Germination of all these samples with visible mould was above 70%. Low initial germination and high water activities in the first 4 wk might be the reason of the early presence of visible mould.

Storage fungi (*Penicillium* and *A. glaucus*), and the field fungi (*Cladosporium*) were the three predominant fungal species on canola seeds in this study. Increase of moisture contents of canola seeds at some locations might be the reason that *Cladosporium* was predominant (Table 4.22). Small amount of *Alternaria*, *Aspergillus candidus*, *A. ochraceus* and *A. niger* were found on the kernels (Table 4.22).

Table 4.21 The time (wk) of first appearance of visible mould and respective germination (%) of H-N in large bin study in 16 wk

Storage bin	Canola location							
	L1Sw	L1Sc	L2Sw	L2Sc	L3Sw	L3Sc	L4Sw	L4Sc
Bin 1	8, 79	8, 76	8, 76	6, 72	6, 82	6, 78	6, 77	6, 75
Bin 2	8, 72	–	10, 75	–	6, 84	–	6, 78	6, 79
Bin 3	–	–	–	–	10, 74	10, 70	6, 76	6, 81

"–" indicated no visible mould appeared during 16 wk storage time.

Table 4.22 Microfloral infection (%) of H-N at the beginning and end of storage in three bins, simulating Winnipeg Forks Station weather conditions from September to December 2010

Storage period	Sampling location	Percent of seeds infected by						
		A. glaucus [a]	*A. candidus* [b]	*A. ochraceus* [c]	*A. niger* [d]	*Penicilium*	*Cladosporium*	*Alternaria* [e]
Initial	B1L1Sw	7				12	61	1
	B1L1Sc	33	1			11	12	
	B1L2Sw	11				23	36	
	B1L2Sc	19				17	25	
	B1L3Sw	1				91	24	
	B1L3Sc	9				57	13	
	B1L4Sw	28	1			32	8	4
	B1L4Sc	20	4			36	5	
	B2L1Sw	21	1			12	17	
	B2L1Sc	31	1			20	27	
	B2L2Sw	19	3			11	20	
	B2L2Sc	23				20	13	4

	B2L3Sw	7				24	23	
	B2L3Sc	23			1	21	28	
	B2L4Sw	23	7			15	9	
	B2L4Sc	24	3			17	13	4
	B3L1Sw	21				25	8	1
	B3L1Sc	35	5			23	9	1
	B3L2Sw	32				23	13	1
	B3L2Sc	36				25	8	
	B3L3Sw	27				40	8	1
	B3L3Sc	48	1		1	27	13	
	B3L4Sw	27	1			12	4	3
	B3L4Sc	24				9	4	4
End	B1L1Sw	63	1			28	45	1
	B1L1Sc	44	1			8	17	1
	B1L2Sw	21				20	37	
	B1L2Sc	27				19	31	
	B1L3Sw	45		1		43	17	
	B1L3Sc	52				48	17	
	B1L4Sw	36	3			27	19	7
	B1L4Sc	53	9			65	21	
	B2L1Sw	41	1			17	41	

B2L1Sc	36	1		19	3	
B2L2Sw	25	3	1	17	36	3
B2L2Sc	37	1		7	31	
B2L3Sw	28			9	49	
B2L3Sc	41			51	10	
B2L4Sw	39			7	27	
B2L4Sc	83	1		23	33	
B3L1Sw	15	1		15	71	13
B3L1Sc	37	1	1	24	20	5
B3L2Sw	47			23	31	
B3L2Sc	52			23	5	
B3L3Sw	33	1		45	28	
B3L3Sc	45	1		53	9	
B3L4Sw	24	1		72	36	
B3L4Sc	64	4	1	47	23	

[a] *Aspergillus glaucus* gr.

[b] *Aspergillus candidus.*

[c] *Aspergillus ochraceus.*

[d] *Aspergillus niger.*

[e] *Alternaria alternata*.

Initial – Microfloral species were determined at the 4th week of storage.

End – Microfloral species were determined at the 16th week of storage.

4.3.4. Free fatty acid value

FAV of canola seeds at all locations changed significantly with increasing storage time, except those at the centre of L3 in bin 1 and at the wall of L3 in bin 3 (Table 4.23). Initial FAV of canola seeds were between 21.4 and 33.8, 23.8 and 40.0, and 21.6 and 38.5 mg KOH/100 g dry seed in bin 1, 2 and 3, respectively. The FAV increased to between 30.3 and 55.5, 33.8 and 44.2, and 32.7 and 42.5 mg KOH/100 g dry seed in bin 1, 2 and 3, respectively, when deterioration of canola was first detected.

Table 4.23 Effect of storage time (wk) on FAV of H-N in large scale study

Location[a]	Storage bin					
	1		2		3	
	F	P	F	P	F	P
L1Sw	8.44	<0.0001	16.69	<0.0001	8.44	<0.0001
L1Sc	8.00	0.0001	3.24	0.0183	7.92	0.0001
L2Sw	11.12	<0.0001	15.11	<0.0001	8.71	<0.0001
L2Sc	10.57	<0.0001	8.00	0.0001	4.87	0.0025
L3Sw	9.27	<0.0001	15.90	<0.0001	2.51	0.0500
L3Sc	2.05	0.0977	4.33	0.0047	5.28	0.0016
L4Sw	20.83	<0.0001	10.84	<0.0001	9.23	<0.0001
L4Sc	26.73	<0.0001	5.92	0.0009	6.89	0.0003

[a] Tukey test between 0 to 16 wk.

5. CONCLUSIONS AND RECOMMENDATIONS

This was an overall study on determing storage properties of new varieties of high oil content canola (from 45% to 47% oil content). These properties were significant in designing storage and handling facilities, and keeping high quality and marketability of canola seeds.

5.1. Conclusions

1) Physical properties of mixed canola seed were in between those of the two varieties of canola seeds.

2) Ratio of depth to hydraulic radius of the bin was the most sensitive factor affecting wall pressures.

3) Bins used to store low oil content canola could be used to store high oil content canola.

4) The first appearance of visible mould could not be used to predict safe storage time of canola seeds.

5) Germination and FAV of high and low oil content canola under a few storage conditions had a strong negative correlation relationship. However, FAV could not be used to predict germination at most of the tested storage conditions.

6) To safely store high oil content canola, it must have lower moisture contents than that of low oil content canola at corresponding temperatures.

7) The developed safe storage guidelines of high oil content canola were in accordance with the results of the large bin study in most cases.

5.2. Recommendations

1) The range of moisture content of canola seeds in this study was from 8% to 14%. This range could be increased from 6% to 18%; because effects of moisture content on canola seeds tended to be clearer at a wider range, and more accurate prediction of horizontal pressures on bin walls could be produced.

2) Canola seeds used as buffer in the small chamber study were renewed when the significant change of moisture content was observed. However, moisture contents of several canola samples still changed by more than 1% MC. Therefore, for keeping constant moisture content, canola seeds used as buffers should be renewed regularly (every month) even before large change of moisture content is observed.

3) High and low oil content canola seeds used in this study were obtained from the same farm and planted in the same year. Grain quality and storability might be affected by these year to year and geographic variations. Therefore, it was suggested to collect information of high oil content canola planted at different locations (at least 3 different years and 10 different farms) to verify the new safe storage guidelines in a further study.

6. REFERENCES

Abramson, D., R.N. Sinha, and J.T. Mills. 1980. Mycotoxin and odour formation in moist cereals during granary storage. *Cereal Chemistry* 57: 346-51.

Aibara, S., I.A. Ismail, H. Yamashita, H. Ohta, F. Sekiyama, and Y. Morita. 1986. Changes in rice bran lipids and free amino acids during storage. *Agricultural and Biological Chemistry* 50: 665-673.

Airy, W. 1897. The pressures of grain. *Minutes of Proceedings of the institute of civil engineers* 131: 347-358.

Anderson, J.A. and A.W. Alcock. 1954. *Storage of Cereal Grains and Their Products.* St. Paul, MN: American Association of Cereal Chemists.

ASABE Standards. 2009. S352.2: Moisture Measurement – Underground Grain and Seeds. St. Joseph, MI.: American Society of Agricultural and Biological Engineers.

ASABE. 2010. *Standards 2010.* St. Joseph, MI: American Society of Agricultural and Biological Engineers.

Ayerst, G. 1965. Water activity-its measurement and significance in biology. *International Biodeterioration Bulletin* 1: 13-26.

Bakker-Arkema, F.W., C.Fontana, G.L. Pedawa, and I.P. Schisler. 1983. *A Comparison of Drying Rates of Different Grains.* Paper 83-3009. St. Joseph, MI: Am. Soc. Agric. Eng. 16 p.

Becker, R. 2008. Fatty acids in food cereal grains and grain products. Pages: 303-316 in: *Fatty Acids in Foods and Their Health Implications*. 3rd ed. Chow, C.K. Lexington, KY: University of Kentucky.

Berezin, O.Y., Y. I. Tur'yan, I. Kuselman, and A. Shenhar. 1996. Rapid and complete extraction of free fatty acids from oilseeds for acid value determination. *Journal of the American Oil Chemists' Society* 73: 1707-1711.

Bradbeer, J.W. 1988. Seed viability and vigour. In *Seed Dormancy and Germination*, eds. J.W. Bradbeer, 95-109. New York, US: Springer.

Brogan, I.W. 1986. Control of rapeseed quality for crushing. In *Oilseed Rape*, eds. D.H. Scarisbrick and R.W. Daniels, 282-300. London, UK: Collins.

Çahşır S., T. Marakoğlu, H. Öğüt, and Ö. Öztürk. 2005. Physical properties of rapseed (*Brassica napus oleifra L.*). *Journal of Food Engineering* 69: 61-66.

Canola Council of Canada (CCC). 2012. Storage of Canola. Available at http://www.canolacouncil.org/canola-encyclopedia/storage-management/storage-of-canola/.

Canadian Grain Commission (CGC). 2010. Official grain grading guide. Winnipeg, MB: Canadian Grain Commission.

Canadian Grain Commission (CGC). 2013. Safe storage guidelines. http://www.grainscanada.gc.ca/storage-entrepose/ssg-de-eng.htm.

Cenkowski, S. and Q. Zhang. 1995. Engineering properties of grains and oilseeds. In: *Stored-grain ecosystems*, D.S. Jayas, N.D.G. White and W.E. Muir (ed.), New York: Marcel Dekker, Inc. p. 411-463.

Chen, C.C. 2000. A rapid method to determine the sorption isotherms of peanuts. *Journal of Agricultural Engineering Research* 75: 401-408.

Chen, C. and R.V. Morey. 1989. Equilibrium relative humidity (ERH) relationships for yellow-dent corn. *Transactions of the American Society of Agricultural Engineers* 32: 999-1006.

Christensen, C.M. and H.H. Kaufmann. 1969. *Grain Storage: The Role of Fungi in Quality Loss.* Minneapolis, MN: University of Minnesota Press.

Chung, J.H. and L.R. Verma. 1989. Determination of friction coefficients of beans and peanuts. *Transaction of the ASAE* 32: 745-750.

Clayton, T. A. and W.R. Morrison. 1972. Changes in flour lipids during the storage of wheat flour. *Journal of the Science of Food and Agriculture* 23: 721-736.

Canadian Wheat Board (CWB). 2014. CWB announces 2012-13 initial payments for canola.http://www.cwb.ca/news/14/cwb-announces-2012-13-initial-payments-for-canola

Cetin, M. 2007. Physical properties of barbunia bean (Phaseolus vulgaris L. cv. 'Barbuniz') seed. *Journal of Food Engineering* 80: 353-358.

Daun, J.K. and L.D. Burch. 1984. Oilseeds grading – quality control in oilseeds marketing. *Journal of the American Oil Chemists' Society* 61: 1117-1122.

Delourme, R., C. Falentin, V. Huteau, V. Clouet, R. Horvais, B. Gandon, S. Specel, L. Hanneton, J. E. Dheu, M. Deschamps, E. Margale, P. Vincourt, and M. Renard. 2006. Genetic control of oil content in oilseed rape (Brassica napus L.). *Theoretical and Applied Genetics* 113: 1331-1345.

Donald, W.W. and C.J. Mirocha. 1977. Chitin as a measure of fungal growth in stored corn and soyabean seed. *Cereal Chemistry* 54: 466-474.

Downey, R.K. 1990. Canola: A quality brassica oil seed. . In *Advances in New Crops,* 211-215. J. Janick and J.E. Simon eds. Portland, OR: Timber Press.

Dunkel, F.V. 1992. The stored grain ecosystem: A global perspective. *Journal of Stored Products Research* 28: 73-87.

Elias, S.G. and L.O. Copeland. 1997. Evaluation of seed vigor tests for canola. *Seed Technology* 19: 78-87.

Elias, S.G. and L.O. Copeland. 2001. Cropping systems: Physiological and harvest maturity of canola in relation to seed quality. *Agronomy Journal* 93: 1054-1058.

Fayed, M.E. and T.S. Skocir. 1997. *Mechanical Conveyors*, *Selection and Operation*. Lancaster, PA: Technomic Publishing CO. Inc.

Fraser, B.M. and W.E. Muir. 1981. Airflow requirements predicted for drying grain with ambient and solar-heated air in Canada. *Transactions of the American Society of Agricultural Engineers* 24: 208-210.

Fraser, B.M., S.S. Verma, and W.E. Muir. 1978. Some physical properties of

fababeans. *Journal of Agricultural Engineering Research* 23: 53-57.

Frey, K.J. and E.G. Hammond. 1975. Genetics, characteristics, and utilization of oil in caryopses of oat species. *Journal of the American Oil Chemists' Society* 52: 358-362.

Food and Agriculture Organization of the United Nations (FAO), 2013. Available at www.fao.org/docrep/x5738e/x5738e0e.htm.

Galliard, T. 1989. Rancidity in cereal products. In *Rancidity in Foods.* 2nd ed. J.C. Allen and R.J. Hamilton, 141-157. London, UK: Elsevier.

Hamer, A., J. Lacey, and N. Magan. 1991. Use of an automatic electrolytic respirometer to study the respiration of stored grain. Pages: 321-330. In *Proceedings of 5th International Working Conference on Stored Product Protection,* ed. F. Fleurat-Lessard & P. Ducom. Bordeaux, France: INRA.

Hamer, A., J. Lacey, and N. Magan. 1992. Respiration and fungal deterioration of stored grains. Pages: 65-66. In *Extended abstracts, International Symposium on Stored Grain Ecosystems,* ed. D.S. Jayas, N.D.G. White, W.E. Muir & R.N. Sinha. Winnipeg, MB: University of Manitoba.

Hindy, F. I., O. M. Kamel, and M. I. Shoughy. 2003. Some engineering factors affecting the performance of in-bin drying system for soybean grain. *Misr Journal of Agricultural Engineering* 20: 585-604.

Homdork, S., H. Fehrmann, and R. Beck. 2000. Influence of different storage conditions on the mycotoxin production and quality of *Fusarium*-infected wheat grain. *Journal of Phytopathology* 148: 7-15.

Hornok, L. and A. Jagicza. 1973. Fluorescent antibody staining of *Fusarium culmorum. Acta Phytopathologica Academiae Scientiarum Hungaricae* 8: 357-63.

Hulasare, R.B., M.N.N. Habok, D.S. Jayas, and N.D.G. White. 2001. Near equilibrium moisture content values for hull-less oats. *Applied Engineering in Agriculture* 17: 325-328.

Irvine, D.A., D.S. Jayas, N.D.G. White, and M.G. Britton. 1992. Physical properties of flaxseed, lentils, and fababeans. *Canadian Agricultural Engineering* 34: 75-81.

Izli, N., H. Unal, and M. Sincik. 2009. Physical and mechanical properties of rapeseed at different moisture content. *International Agrophysics* 23: 137-145.

Jain, P.C., J. Lacey, and L. Stevens. 1991. Use of API-Zym strips and 4-nitrophenyl substrates to detect and quantify hydrolytic enzymes in media and grain colonised with *Aspergillus, Eurotium* and *Penicillium* spp. *Mycological Research* 95: 834-842.

Jain, R. K. and S. Bal. 1997. Physical properties of pearl millet. *Journal of Agricultural Engineering Research* 66: 85-91.

Janssen, H.A. 1895. Versuche uber Getreidedruck in Silozenllen. *Zeitschrift des Vereines Deutscher Ingenieure* 39: 1045-1049.

Jayas, D.S. 1995. Mathematical modeling of heat, moisture, and gas transfer in stored-grain ecosystems. In *Stored-grain Ecosystems*. Jayas, D.S., N.D.G. White, and W.E. Muir (Eds.). New York, NY: Marcel Dekker Inc. p. 527-567.

Jayas, D.S. 2003. Equilibrium moisture content. In *Encyclopedia of Agricultural, Food, and Biological Engineering, Heldman,* D.R. (Eds). New York, NY: Marcel Dekker Inc. p. 264-267.

Jayas, D.S., K. Alagusundaram, G. Shunmugam, W.E. Muir, and N.D.G. White. 1994. Simulated temperatures of stored grain bulks. *Canadian Agricultural Engineering* 36: 239-245.

Jayas, D.S., D.A. Kukelko, and N.D.G. White. 1988. Equilibrium moisture-equilibrium relative humidity relationship for canola meal. *Transations of the American Society of Agricultural Engineers* 31: 1585-1588.

Jayas, D.S. and N.D.G. White. 1989. Safe storage conditions and infestation potential of canola meal by fungi and insects. *Journal of Stored Products Research* 25: 105-114.

Jayas, D.S. and N.D.G. White. 2003. Storage and drying of grain in Canada: Low cost approaches. *Food Control* 14: 255-261.

Jenike, A.W., J.R. Johanson, and J.W. Carson. 1973. Bin loads. Part 4: Funnel flow bins. *ASME Journal of Engineering for Industry* 95: 13-16.

Jian F.J. and D.S. Jayas. 2012. The ecosystem approach to grain storage. *Agricultural Research* 2: 148-156.

Jian, F., D.S. Jayas, and N.D.G. White. 2012. Thermal conductivity, bulk density, and germination of a canola variety with high oil content under different temperatures, moisture contents, and storage periods. *Transactions of the ASABE* 55(5): 1837-1843.

Jian, F., D.S. Jayas, and N.D.G. White. 2013. Specific heat, thermal diffusivity, and bulk density of genetically modified canola with high oil content at different moisture contents, temperatures, and storage times. *Transactions of the American Society of Agricultural Engineers* 56: 1077-1083.

Jian, F., D.S. Jayas, N.D.G. White, and K. Alagusundaram. 2005. A three-dimensional, asymmetric, and transient model to predict grain temperatures in grain storage bins. *Transactions of the American Society of Agricultural Engineers* 48: 263-271.

Jian, F., K. Sun, V. Chelladurai, D.S. Jayas, N.D.G. White. 2014. Quality changes in high and low oil content canola during storage: part II – mathematical models to predict germination. *Journal of Stored Products Research* (In press).

Jones, N.R. 1969. The meaning and importance of relative humidity. *Annual Symposium Proceedings* 4: 2-7.

Kaleemullah, S. and J.J. Gunasekar. 2002. Moisture dependent physical properties of arecanut kernels. *Biosystems Engineering* 82: 331-338.

Karunakaran, C., W.E. Muir, D.S. Jayas, N.D.G. White, and D. Abramson. 2001. Safe storage time of high moisture wheat. *Journal of Stored Product Research* 37: 303-312.

Kaspersson, A. 1986. The role of fungi in deterioration of stored feeds. PhD Thesis, Department of Microbiology, Uppsala, Sweden: Swedish University of Agricultural Sciences.

Ketchum, M.S. 1919. *Design of walls, bins and grain elevators.* New York, N.Y.: McGraw Hill Book Company Inc.

King, A.D., J.I. Pitt, L.R. Beuchat, and J.E.L. Corry. 1986. *Methods for the Mycological Examination of Foods*. New York, NY: Plenum.

Knothe, G. and Dunn, R.O., 2003. Dependence of oil stability index of fatty compounds on their structure and concentration and presence of metals. *Journal of the American Oil Chemists' Society* 80: 1021–1026.

Kreyger, J. 1972. Drying and storage of grains, seeds and pulses in temperate climates. Publication 205, Wageningen, the Netherland: IBVL.

Lacey, J., S.T. Hill, and M.A. Edwards. 1980. Microorganisms in stored grains: their enumeration and significance. *Tropical Stored Product Information* 39: 19-33.

Lvin, J.B. 1970. Analytical evaluation of pressures of granular materials on silo walls. *Journal of Power Technologies* 4: 280-285.

Magan, N. 1993. Early detection of fungi in stored grain. *International Biodeterioration & Biodegradation* 32: 145-160.

Manitoba Agriculture, Food and Rural Initiatives (MAFRI). 2013. http://www.gov.mb.ca/agriculture/crops/cropproduction/faa25s02.html. Accessed 12nd June 2013.

Mannino, S. and J. Wang. 1992. Electrochemical methods for food and drink analysis. *Electroanalysis* 4: 835-840.

Manuwa, S.I. and G. Afuye. 2004. Moisture-dependent physical properties of soybean (var TGX1871-5E). *Nigerian Journal of Industrial and System Studies* 3: 45-53.

Manuwa, S.I. 2007. Moisture-dependent physical properties of improved soybean 'var TGX1448-2E'. *Journal of Food Science and Technology* 44: 371- 374.

Marfleet, I.C., N. Magan, and J. Lacey. 1991. The relationship between fungal biomass ergosterol and grain spoilage. Pages: 405-412. In *Proceedings of the 5th International Working Conference on Stored Product Protection,* ed. F. Fleurat- Lesard & P. Ducom. Bordeaux, France: INRA.

McCabe, W.L., and J.C. Smith. 1976. *Unite Operations of Chemical Engineering.* 3rd edition. New York, N.Y.: McGraw-Hill Book Company Inc.

McDonald, J.H., 2009. Tests for one measurement variable: data transformations. In McDonald, J.H. (Ed.), *Handbook of Biological Statistics*. Sparky House Publishing, Baltimore, pp. 160–164.

McMillan, N.D., O. Finlayson, F. Fortune, M. Fingleton, D. Daly, D. Townsend, D.D.G. McMillan, and M.J. Dalton. 1992. The fibre drop analyser: a new

multianalyser analytical instrument with applications in sugar processing and for the analysis of pure liquids. *Measurement Science and Technology* 3: 746-764.

Metzger, J.F. and W.E. Muir. 1983. Aeration of stored wheat in the Canadian Prairies. *Canadian Agricultural Engineering* 25: 127-137.

Mills, J.T. 1996. Quality of stored cereals. In *Cereal Grain Quality*, ed. R.J. Hendry and P.S. Kettlewell, 441-478. London, UK: Chapman & Hall.

Mills, J.T. 1989. Spoilage and heating of stored agricultural products: Prevention, detection and control. Ottawa, ON: Agriculture Canada.

Mills J.T. and Sinha R. N. 1980. Safe storage period for farm-stored rapeseed based on mycological and biochemical assessment. *Phytopathology* 70: 541-547.

Mills, J.T., R.N. Sinha, and H.A.H. Wallace. 1978 Multivariate evaluation and isolation techniques for fungi associated with stored rapeseed. *Phytopathology* 68: 1520-1525.

Mohsenin, N.N. 1978. Physical properties of plant and animal materials. New York, NY: Gordon and Breach Science Publisher.

Mohsenin, N. N. 1986. *Physical Properties of Plant and Animal Materials.* 2nd ed. New York, N.Y.: Gordon and Breach Science.

Money, N.P. 1998. Why oomycetes have not stopped being fungi. *Mycological Research* 102, 767-768.

Muir, W.E. 2000. Monitoring the quality and condition of stored grain. In *Grain Preservation Biosystems,* ed. W.E. Muir. Winnipeg, MB: Department of Biosystems Engineering, University of Manitoba.

Muir, W.E. 2001. Changes in grain moisture content during storage. In *Grain Preservation Biosystems,* ed. W.E. Muir, 143-159. Winnipeg, MB: Department of Biosystems Engineering, University of Manitoba.

Muir, W.E., S. Cenkowski, and Q. Zhang. 2000. Chapter 15: Physical characteristics of grain bulks. In *Grain Preservation Biosystems,* ed. W.E. Muir. Winnipeg, MB: Department of Biosystems Engineering, University of Manitoba.

Muir, W.E. and R.N. Sinha. 1988. Physical properties of cereal and oilseed cultivars grown in western Canada. *Canadian Agricultural Engineering* 30: 51-55.

Muir, W.E., R.N. Sinha, and H.A.H. Wallace. 1977. Comparison of the storage characteristics of three types of farm granaries. *Canadian Agricultural Engineering* 19: 20-24.

Nelson, S. O. 2002. Dimensional and density data for seeds of cereal grain and other crops. *Transactions of ASAE* 45, 165−170.

Nishiba, Y., T. Sato, and I. Suda. 2000. Convenient method to determine free fatty acid of rice Using thin-layer chromatography and flame-ionization detection system. *Cereal Chemistry* 77: 223-229.

Nithya, U., V. Chelladural, D.S. Jayas, and N.D.G. White. 2011. Safe storage guidelines for durum wheat. *Journal of Stored Products Research* 47:

328-333.

Ohta, H., S. Aibara, H. Yamashita, F. Sekiyama, and Y. Morita. 1990. Post-harvest drying of fresh rice grain and its effects on deterioration of lipids during storage. *Agricultural and Biological Chemistry* 54: 1157-1164.

Oxley, T.A., S.W. Pixton, and R.W. Howe. 1960. Determination of moisture content in cereals—I. Interaction of type of cereal and oven method. *Journal of the Science of Food and Agriculture* 11: 18-25.

Paetkau, T.F. and H.M. Lapp. 1972. Drying and storage of rapeseed. Publication No. 23. Vancouver, BC: Rapeseed Association of Canada.

Papavizas, G.C. and C.M. Christensen. 1957. Grain storage studies. XXV. Effect of invasion by storage fungi upon germination of wheat seeds and upon development of sick wheat. *Cereal Chemistry* 34: 350-359.

Parde, S.R., A. Johal, D.S. Jayas, and N.D.G. White. 2003. Physical properties of buck wheat cultivars. *Canadian Biosystems Engineering* 45: 3.19-3.22.

Patil, K.D. 2007. Properties and handling of particulate solids. In *Mechanical Operations: Fundamental Principles and Applications*, 2nd ed. 1.36-1.38. K.D. Patil. Pune, Maharashtra, India: Nirali Prakashan Pvt Ltd.

Pixton, S.W. 1967. Moisture content—its significance and measurement in stored products. *Journal of Stored Products Research* 3: 35-47.

Pixton, S.W. and S. Henderson. 1981. The moisture content-equilibrium relative humidity relationships of five varieties of Canadian wheat and of Candle

rapeseed at different temperatures. *Journal of Stored Products Research* 17: 187-190.

Pixton, S.W. and S. Warburton. 1971. Moisture content/relative humidity equilibrium of some cereal grains at different temperatures. *Journal of Stored Products Research* 6: 283-293.

Pixton, S.W., S. Warburton, and S.T. Hill. 1975. Long-term storage of wheat-III: Some changes in the quality of wheat observed during 16 years of storage. *Journal of Stored Products Research* 11: 177-185.

Pixton, S.W. and S. Warburton. 1977. The moisture content/ equilibrium relative humidity relationship and oil composition of rapeseed. *Journal of Stored Products Research* 13: 77-81.

Plattner, I. and I.R. Hall. 1995. Parasitism of non-host plants by the mycorrhizal fungus *Tuber melanosporum*. *Mycological Research* 99: 1367-1370.

Pomeranz, Y. 1992. Biochemical, functional and nutritive changes during storage. Pages: 55–142. In: *Storage of Cereal Grains and Their Products*, 4th ed. D.B. Sauer. St. Paul, MN: American Association of Cereal Chemists.

Pronyk, C., W.E. Muir, N.D.G. White, and D. Abramson. 2004. Carbon dioxide production and deterioration of stored canola. *Canadian Biosystems Engineering* 46: 3.25-3.33.

Rajarammanna, R., D.S. Jayas, and N.D.G. White. 2010. Comparison of deterioration of rye under two different storage regimes. *Journal of Stored Products Research* 46: 87-92.

Rao, G.A., D.E. Riley, and E.C. Larkin. 1985. Comparison of the thin layer chromatography/flame ionization detection system with other methods for the quantitative analysis of liver lipid contents in alcoholfed rats and controls. *Lipids* 20: 531-535.

Raymer, P.L. 2002. Canola: An emerging oilseed crop. Pages: 122-126. In: *Trends in New Crops and New Uses,* eds. J. Janick and A. Whipkey, Alexandria, VA: ASHS Press.

Razavi, S.M.A., S. Yeganehzad, and A. Sadeghi. 2009. Moisture dependent physical properties of canola seeds. *Journal of Agricultural Science and Technology* 11: 309-322.

Rusinek, R. and M. Molenda. 2007. Static and kinetic friction of rapeseed. *Journal of Agricultural Engineering Research* 53: 14-19.

Sahasrabudhe, M. R. 1979. Lipid composition of oats. *Journal of the American Oil Chemists' Society* 56: 80-84.

SAS. 2010. *SAS User Guider, release 9.22.* Cary, NC: SAS Institute.

Sathya, G., D.S. Jayas, and N.D.G. White. 2009a. Safe storage guidelines for canola as the seeds slowly dry. *Canadian Biosystems Engineering/ Le ge´nie des biosyste`mes au Canada* 51: 3.29-3.38.

Sathya, G., D.S. Jayas, and N.D.G. White. 2009b. Safe storage guidelines for rye. *Canadian Biosystems Engineering/ Le ge´nie des biosyste`mes au Canada* 50: 3.1-3.8.

Sauer, D.B., R.A. Meronuck, and C.M. Christensen. 1992. Microflora. In *Storage of Cereal Grains and Their Products*, ed. D.B. Sauer, 313-340. St. Paul, MN: American Association of Cereal Chemists.

Savic, T.B., T. Kricka, N. Voca, V. Jurisic, and A. Matin. 2009. Effect of storage temperature on rapeseed quality. *Agriculturae Conspectus Scientificus* 74: 143-147.

Schroth, E., W.E. Muir, D.S. Jayas, N.D.G. White, and D. Abramson. 1998. Storage limit of wheat at 17% moisture content. *Canadian Agricultural Engineering* 40: 201-205.

Schweizer, H., P. Schibli, and H. Neukom. 1974. The composition of wheat flour lipids and its changes during storage and rollerdrying. *Schweizer Landwirtschaft Forschung* 13: 395-404.

Seitz, L.M., D.B. Sauer, R. Burroughs, H.E. Mohr, and J.D. Hubbard. 1979. Ergosterol as a measure of fungal growth. *Phytopathology* 69: 1202-1203.

Seitz, L.M., D.B. Sauer, H.E. Mohr, and D.F. Faldis. 1982. Fungal growth and dry matter loss during bin storage of high moisture corn. *Cereal Chemistry* 59: 9-14.

Shibuya, N., T. Iwasaki, H. Yanase, and S. Chikubu. 1974. Studies on deterioration of rice and milled rice during storage. *Journal of the Japanese Society for Food*

Science and Technology 21: 597-603.

SigmaPlot. 2010. User's Guide, release 12.0. Systat Software, Inc., Chicago, IL.

Singh (Jayas), D. and E.B. Moysey. 1985. Grain bin wall pressure: theoretical and experimental. *Canadian Agricultural Engineering* 27: 43-48.

Sinha, R. N. 1969. Reproduction of stored grain insects on varieties of wheat, oats, and barley. *Annals of the Entomological Society of America* 62: 98-102.

Sinha, R.N. 1973. Ecology of storage. *Annual Technology of Agriculture (Paris)* 22: 351-369.

Sinha, R.N. and H.A.H. Wallace. 1966. Ecology of insect-induced hot spots in stored grain in Western Canada. *Researches on Population Ecology* 8: 107-132

Sinha, R.N. and H.A.H. Wallace. 1977. Storage stability of farm-stored rapeseed and barley. *Canadian Journal of Plant Science* 57: 351-365.

Sinha, R. N., H.A.H. Wallace, J.T. Mills, and R.I. McKenzie. 1979. Storability of farm-stored hull-less oats in Manitoba. *Canadian Journal of Plant Science* 59: 949-957.

Sinha, R.N., G. Yaciuk, and W.E. Muir. 1973. Climate in relation to deterioration of stored grain. A multivariate study. *Oecologia* 12: 69-88.

Singh, D. and E.B. Moysey. 1985. Grain bin wall pressure: theoretical and experimental. *Canadian Agricultural Engineering* 27: 43-48.

Sokhansanj, S, and W. Lang. 1996. Prediction of kernel and bulk volume of wheat and canola during adsorption and desorption. *Journal of Agricultural Engineering Research* 63: 129-136.

Solomon, M. E. 1951. Control of humidity with potassium hydroxide, sulfuric acid or other solutions. *Bulletin of Entomological Research* 42: 543-554.

Sternberg, S. 1994. The emerging fungal threat. *Science* 266: 1632-1634.

Steward, B.R. 1968. Effect of moisture content and specific weight on internal-friction properties of sorghum grain. *Transaction of American Society of Agricultural and Biological Engineers* 11: 260-262.

Sukurai, Y. and H. Shiota. 1977. On the convenient method for glucosamine estimation in koji. *Agricultural and Biological Chemistry* 41: 619-24.

Swain, A., M. Allen, B.H. Schneider, F. Taylor, and A.P.F. Turner. 1989. Biocheck -- a mediated amperometric microbial activity monitor. In *Society for Applied Bacteriology Technical Series, 25. Rapid Microbiological Methods for Food, Beverages and Pharmaceuticals,* eds. C.J. Stannard, S.B. Petittand & F.A. Skinner, 213-225. Oxford, UK: Blackwells.

Takano, K. 1989. Studies on the mechanism of lipid-hydrolysing in rice bran. *Journal of the Japanese Society for Food Science and Technology* 36: 519-524.

Taser, O.F., E. Altuntas, and E. Ozgoz. 2005. Physical properties of hungarian and common vetch seeds. *Journal of Applied Sciences* 5: 323-326.

Tipples, K. H. 1995. Quality and nutritional changes in stored grain. In *Stored grain ecosystems,* eds. D.S. Jayas, N.D.G. White and W.E. Muir, 325-351. New York, NY: Marcel Dekker Publ. Co.

Tothill, I.E., D. Harris, and N. Magan. 1992. The relationship between fungal growth and ergosterol in wheat grain. *Mycological Research* 1 I: 965-970.

Trawatha S.E., D.M. Tekrony, and D.F. Hildebrand. 1995. Relationship of soybean seed quality to fatty acid and C_6-aldehyde levels during storage. *Crop Science* 35: 1415-1422.

Tuma, D., R.N. Sinha, W.E. Muir, and D. Abramson. 1989. Odor volatiles associated with microflora in damp ventilated and non-ventilated bin-stored bulk wheat. *International Journal of Food Microbiology* 8: 103-119.

Wallace, H.A.H. and R.N. Sinha. 1962. Fungi associated with hot spots in farm stored grain. *Canadian Journal of Plant Science* 42: 130-141.

Wallace HAH, Sinha RN, and Mills JT. 1976. Fungi associated with small wheat bulks during prolonged storage in Manitoba. *Canadian Journal of Botany* 54: 1332–1343.

Wallace, H.A.H., P.L. Sholberg, R.N. Sinha, and W.E. Muir. 1983. Biological, physical and chemical changes in stored wheat. *Mycopathologia* 82: 65-72.

Walters, J.K. 1973. A theoretical analysis of stress in silos with vertical walls. *Chemical Engineering Science* 28: 13-21.

Warnock, D.W. 1973. Use of immunofluorescence to detect mycelium of *Alternaria, Aspergillus,* and *Penicillium* in barley grains. *Transactions of the British Mycological Society* 61: 547-52.

Weete, J.D. 1980. Lipid Biochemistry of Fungi and other Organisms. Pages: 388. New York, NY: Plenum Press.

Welch, R.W. 1977. The development of rancidity in husked and naked oats after storage under various conditions. *Journal of the Science of Food and Agriculture* 28: 269-274.

White, N.D.G. 1992. A multidisciplinary approach to stored-grain research. *Journal of Stored Products Research* 28: 127-137.

White, N.D.G. 1995. Insects, mites, and insecticides in stored-grain ecosystems. In *Stored Grain Ecosystems,* eds. D.S. Jayas, N.D.G. White and W.E. Muir, 123-167. New York, NY: Marcel Dekker Publ. Co.

White, N.D.G., R.N. Sinha, and W.E. Muir. 1982. Intergranular carbon dioxide as an indicator of deterioration in stored rapeseed. *Canadian Agricultural Engineering* 24: 43-49.

White, N.D.G. and D.S. Jayas. 1991 Factors affecting the deterioration of stored flaxseed including the potential of insect infestation. *Canadian Journal of Plant Science* 71: 327-335.

White, N.D.G. and D.S. Jayas. 2001 Physical properties of canola and sunflower meal pellets. *Canadian Biosystems Engineering* 43: 3.49-3.52.

White, N.D.G., R.B. Hulasare, and D.S. Jayas. 1999a. Effects of storage conditions on quality loss of hull-less and hulled oats and barley. *Canadian Journal of Plant Science* 79: 475-482.

White, N.D.G., J.T. Mills, E.O. Kenaschuk, B.D. Oomah, and P. Dribnenki. 1999b. Quality changes occurring in stored solin, high linolenic acid and standard flaxseed (*Linum usitatissimum* L.). *Canadian Journal of Plant Science* 79: 35-42.

White, N.D.G. and R.N. Sinha. 1980 Changes in stored-wheat ecosystems infested with two combinations of insect species. *Canadian Journal of Zoology* 58: 1524-1534.

White, N.D.G., R.N. Sinha, and W.E. Muir. 1982. Rapid determination of seed germination potential to measure quality loss in stored wheat. *Canadian Journal of Plant Science* 62: 1045-1048.

Xiao, X.B. and J. Yang. 2002. A modified method for determination of fatty acid value. *Grain Storage* 2: 9-12.

Yasumatsu, K., S. Moritaka, and S. Wada. 1966a. Studies on cereals. IV. Volatile carbonyl compounds of cooked rice. *Agricultural and Biological Chemistry* 30: 478-482.

Yasumatsu, K., S. Moritaka, and S. Wada. 1966b. Studies on cereals. V. Stale flavor of stored rice. *Agricultural and Biological Chemistry* 30: 483-486.

Zeman, I., M. Rann, and L. Winterová. 1986. Chromatographic analysis of fatty acid

dimers. Comparison of gas-liquid chromatography, highperformance liquid chromatography and thin-layer chromatography with flame ionization detection. *Journal of Chromatography* 354: 283-292.

Zhou, S.Y. and R.G. Ackman. 1996. Interference of polar lipids with the alkalimetric determination of free fatty acid in fish lipids. *Journal of the American Oil Chemists' Society* 73: 1019-1023.

Zia-Ur-Rehman, H. Farzana, and S.I. Zafar. 2002. Nutritional changes in maize (*Zeamays*) during storage at three temperatures. *Food Chemistry* 77: 197-201.