Safe storage guidelines for rye

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Sathya, G., Jayas, D.S. and White, N.D.G. 2008. **Safe storage guidelines for rye**. Canadian Biosystems Engineering/Le génie des biosystèmes au Canada **50**: 3.1-3.8. Safe storage guidelines for grains at different moisture contents and storage temperatures are essential to know how long seed can be held without deterioration. Rye samples with 10.0, 12.5, 15.0, and 17.5% moisture content (wet basis) were stored at 10, 20, 30, and 40ºC for 16 weeks. Germination, moisture content, visible and invisible microflora, and free fatty acid (FFA) values were monitored periodically. Germination rate decreased significantly with increase in moisture content, temperature, and storage period (α=0.05). Moisture content of the samples stored at 10ºC increased with time, whereas that of samples stored at 30 and 40ºC decreased. Visible mold appeared in all the 17.5% moisture samples and in all the samples stored at 40ºC. *Penicillium spp*. and *Aspergillus glaucus* group were the predominant fungi in almost all samples throughout the study. Fat Acidity Value (FAV) increased with increasing moisture content, temperature, and storage time (α=0.05). Safe storage guidelines with respect to initial moisture content and temperature were developed based on the drop in germination and appearance of visible mold. Rye with ≤12.5% moisture content stored at ≤ 20ºC would be safe for at least 15 weeks, whereas rye with ≥ 15% moisture content stored at 40ºC would have less than a week to complete drying and cooling. **Keywords:** rye, moisture content, temperature, safe storage guidelines.

Des recommandations pour l'entreposage sécuritaire des grains à différentes teneurs en eau et températures d'entreposage sont essentielles pour savoir combien de temps les grains peuvent être conservés sans détérioration. Des échantillons de seigle ayant une teneur en eau de 10,0, 12,5, 15,0 et 17,5% (base humide) ont été entreposés à 10, 20, 30 et 40ºC pendant 16 semaines. Les paramètres suivants ont été mesurés périodiquement : germination, teneur en eau, microflore visible et invisible et acides gras libres. Le taux de germination a diminué de façon significative avec des augmentations de la teneur en eau, de la température et de la durée d'entreposage (α=0,05). La teneur en eau des échantillons entreposés à 10ºC a augmenté avec le temps, contrairement à celles des échantillons entreposés à 30 et 40ºC qui ont plutôt diminué. De la moisissure visible est apparue parmi tous les échantillons à une teneur en eau de 17,5% ainsi que dans tous les échantillons entreposés à 40ºC. Les groupes *Penicillium spp*. et *Aspergillus glaucus* étaient les espèces prédominantes dans presque tous les échantillons de cette étude. Les valeurs d'acide gras augmentaient avec une augmentation de la teneur en eau, de la température et de la période d'entreposage (α=0,05). Des recommandations pour un entreposage sécuritaire qui tiennent compte de la teneur en eau initiale et de la température ont été développées en considérant la réduction de la germination et l'apparence de moisissure visible. L'entreposage du seigle à une teneur en eau inférieure ou égale à 12,5% et à une température de 20ºC ou moins s'est avéré sécuritaire pour une période d'au moins 15 semaines. Toutefois du seigle entreposé à une teneur en eau supérieure ou égale à 15% et à 40ºC se conserverait moins d'une semaine sans séchage et refroidissement. **Mots clés**: seigle, teneur en eau, température, recommandations d'entreposage sécuritaire.

INTRODUCTION

In Canada, most cereal crops are seeded in April or May and harvested in the autumn (fall). Sometimes unexpected weather conditions during harvest cause the crop to be harvested at high moisture levels which are not suitable for safe and prolonged storage, or occasionally, farmers may not even complete the harvest before winter. For example, in 1996 only 50% of the cultivated wheat crop was harvested because of wet autumn weather (Anonymous 1997).

Moisture content and temperature of the grain during harvest determine the safe storage period. Drying and cooling of freshly harvested, moist, warm grain is an important operation before it goes for processing or storage (Bala 1997). The grain can be dried in a heated air dryer and cooled or ambient air can be used to slightly dry and cool the grain within the bin. The choice of either of the conditioning systems depends on the grain condition and weather patterns. If the harvested grain can be held for a long enough period at the harvested moisture and temperature conditions without any significant spoilage, then the farmer can use ambient air drying and reduce the energy cost. However, this may not be effective for moist and warm grain as the use of ambient air is slower than heated-air drying**.** Rates of drying and of cooling also depend on the available time for that particular operation. Even grain with safe initial moisture content can spoil if the storage conditions are poor. Therefore, guidelines must be developed for all the common grains at all possible moisture and temperature conditions the grain may be subjected to after harvest, to provide farmers information on the number of days available for completion of post-harvest conditioning operations.

Rye (*Secale cereale* L.) accounts for 1.2% of the total world cereal production and is the second major raw material for the bread industry next to wheat. Canada has a substantial share in the world's rye trade. Although it is not a major producer, Canada exports more than half of its production every year. Swathing of fall rye may begin at around 45% seed moisture content, which is called the milk stage. Rye has no virtual dormancy, therefore, this can result in pre-harvest sprouting. Delayed swathing may increase the risk of shattered grain heads. Hence, judgment must be made to balance the risks of sprouting and shattering. Swathed rye is field dried and threshed at around 22% moisture content (Hartman 1999). It should have 14% or less moisture content and for long term storage it needs to be dried further to 12% moisture content. Rye which goes for milling and baking has to meet specified commercial and hygienic standards. Therefore, early harvesting and proper drying before storage are necessary (Weipert 1996).

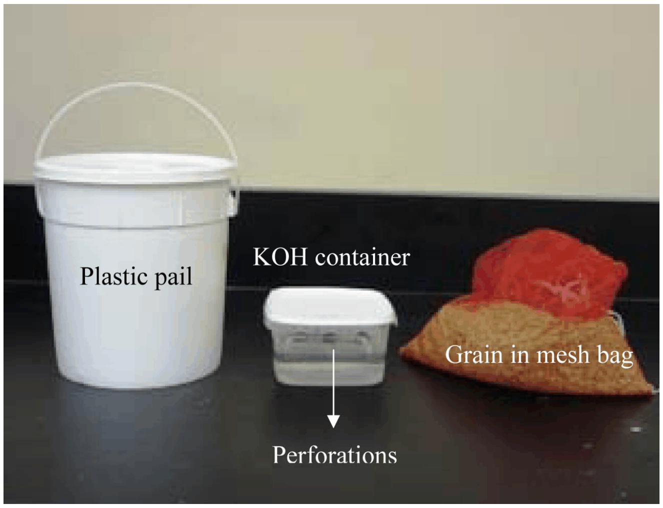

Fig. 1. Experimental setup.

Safe storage of grain may be defined as the time period for which the grain can be stored without any significant loss in its quality and quantity. Seed maturity and condition, moisture content, storage temperature, storage time, molds, insects, mites, dockage, climate, and storage and handling methods are the factors that affect the quality of the stored grain (Jayas 1995). Among all these factors, seed moisture and temperature are the important abiotic variables which need to be monitored continuously and controlled to prevent grain spoilage (Sinha 1973; Mills and Sinha 1980; White 1995; Jayas and White 2003). Germination, fat acidity value (FAV), mold growth, physical appearance, and nutritive values are factors that need to be monitored to assess the condition of the stored grain (Muir 2001).

Germination is the first and most sensitive factor to assess the deterioration level of any stored grain. Free fatty acids (FFA) are produced by breakdown of lipids by the process of hydrolysis caused by enzymatic secretions from the associated microorganisms of the grain. Therefore, FAV has been used as an index to monitor the condition of stored grain. The appearance of mold is another indicator of grain spoilage during storage.

Several studies have been conducted to assess the changes in the quality of different commodities during storage: wheat (Wallace et al. 1983), rapeseed (Mills and Sinha 1980), canola meal (White and Jayas 1989), wild rice and rice (White and Jayas 1996), hull-less and hulled oats and barley (White et al. 1999a), solin (White et al. 1999b), and flax seed (White and Jayas 1991). However, safe storage guidelines based on grain moisture content and storage temperature are available only for wheat (Mills 1989). As only limited data are available on the deterioration of rye, the objective of this work was to monitor the quality changes of rye stored at different moisture and temperature conditions and to develop safe storage guidelines from the measured quality parameters.

MATERIALS AND METHODS

Sample preparation and storage conditions

Hartman (1999) reported that fall rye may be swathed, followed by field drying without any quality loss, but it should not be artificially dried after combining until the kernel moisture is less than 20%. Therefore, the moisture content can be anywhere below 20% before it goes for any post-harvest treatment. Rye with 14% moisture content is considered as straight grade, whereas ≤ 13% moisture content is considered safe for prolonged storage. Hence, the 10.0-17.5% moisture content range was chosen for this storage study. Two levels above safe and two below were chosen for this storage study. Fall rye samples (harvested in 2004) were obtained from Agriculture and Agri-Food Canada, Winnipeg and reconditioned to 10.0, 12.5, 15.0, and 17.5% moisture contents (wet mass basis). The conditioned samples were stored at -5ºC until used for the study.

Four environmental chambers (E15 and C1010, CONVIRON, Controlled Environments Limited, Winnipeg, MB) were used to maintain temperatures of 10, 20, 30, and 40ºC with a relative humidity (RH) of 50±5%. The 10-40ºC range was based on the possible temperatures the grain would undergo during and after harvest. The average daily temperature of the Canadian prairies is around 25ºC during normal harvesting periods (Muir and Jayas 2001) and cereal grains like rye can be about eight degrees above the ambient temperature after lying in the swath (Prasad et al. 1978).

Equilibrium relative humidity (ERH) of the 10.0, 12.5, 15.0, and 17.5% moisture content samples (60, 75, 85, and 90% RH, respectively) were maintained using potassium hydroxide (KOH) solutions of specific gravities of 1.285, 1.211, 1.147 and 1.108, respectively (Solomon 1951).

Experimental setup

About 400 ml of KOH solution were placed in a sealed plastic container with perforations on the outer surface above the solution level and placed inside a plastic pail (5.5 L). Two kilograms of conditioned rye were placed in a mesh bag and placed over the KOH-filled container inside the pail, which had a lid loosely fitting on the top (Fig. 1). Three replications were made for each temperature and moisture combination. The grain in the mesh bag was mixed thoroughly and samples were taken at regular intervals for quality analysis. The study was carried out for 16 weeks and no further quality measurements were carried out once the germination of a sample dropped to 0%.

Table 1. Changes in germination of rye stored at 10°C (n=3).

Storage period (wk)	Moisture content (% wb)			
	10.0	12.5	15.0	17.5
0	92.0a* ± 0.0**	92.0a ± 0.0	92.0a ± 0.0	92.0a ± 0.0
1	92.0a ± 0.0	86.7ab ± 2.3	82.7abc ± 4.6	62.7b ± 2.3
2	92.0a ± 2.8	77.3cdefg ± 5.7	86.7abc ± 2.8	57.3bcd ± 5.7
3	86.7abc ± 2.3	82.7bcd ± 2.3	88.0ab ± 4.0	58.7bc ± 2.3
4	86.7abc ± 6.1	81.3bcde ± 2.3	80.0bcde ± 4.0	50.7cde ± 6.1
5	85.3abc ± 8.3	77.3cdefg ± 2.3	81.3abcd ± 6.1	50.7cde ± 2.3
6	88.0ab ± 6.9	78.7cdef ± 6.1	78.7bcdef ± 6.1	45.3e ± 6.1
7	82.7bc ± 2.3	74.7efg ± 4.6	80.0bcde ± 6.9	48.0de ± 10.6
8	81.3bcd ± 2.3	74.7efg ± 2.3	76.0cdefg ± 12.0	48.0de ± 14.4
9	82.7bc ± 2.3	72.0fg ± 0.0	70.7defgh ± 8.3	49.3cde ± 6.1
10	82.7bc ± 4.6	84.0bc ± 6.9	61.3hi ± 2.3	30.7f ± 2.3
11	81.3bcd ± 2.3	76.0defg ± 4.0	77.3bcdefg ± 4.6	24.0fg ± 8.0
12	74.7d ± 6.1	72.0fg ± 0.0	60.0hi ± 13.9	32.0f ± 6.9
13	80.0cd ± 4.0	70.7g ± 2.3	69.3efgh ± 6.1	14.7gh ± 4.6
14	84.0bc ± 4.0	72.0fg ± 6.9	68.0fgh ± 8.0	14.7gh ± 4.6
15	82.7bc ± 2.3	74.7efg ± 6.1	66.7gh ± 2.3	17.3gh ± 6.1
16	80.0cd ± 4.0	74.7efg ± 4.6	50.7i ± 4.6	10.7h ± 2.3

* Values followed by the same letter in a column are not significantly different by least significant difference (LSD) comparison of means.
** Standard deviation

Table 2. Changes in germination of rye stored at 20°C (n=3).

Storage period (wk)	Moisture content (% wb)			
	10.0	12.5	15.0	17.5
0	92.0a* ± 0.0**	92.0a ± 0.0	92.0a ± 0.0	92.0a ± 0.0
1	89.3ab ± 2.3	86.7ab ± 2.3	80.0abc ± 4.0	61.3b ± 6.1
2	85.3abcd ± 4.6	73.3cdef ± 6.1	76.0bcd ± 10.6	48.0cd ± 14.4
3	81.3bcde ± 8.3	73.3cdef ± 4.6	70.7bcdef ± 12.2	58.7bc ± 8.3
4	85.3abcd ± 8.3	80.0bcd ± 6.9	81.3ab ± 4.6	44.0de ± 4.0
5	85.3abcd ± 6.1	76.0cde ± 10.6	74.7bcde ± 6.1	54.7bcd ± 16.7
6	77.3de ± 2.3	73.3cdef ± 2.3	78.7bc ± 2.3	44.0de ± 10.6
7	80.0cde ± 8.0	80.0bcd ± 4.0	62.7efg ± 2.3	32.0efg ± 4.0
8	82.7bcde ± 2.3	82.7abc ± 4.6	68.0cdef ± 8.0	33.3ef ± 8.3
9	82.7bcde ± 2.3	78.7bcd ± 2.3	48.0i ± 10.6	29.3fg ± 9.2
10	78.7cde ± 2.3	70.7def ± 2.3	64.0defg ± 4.0	20.0gh ± 4.0
11	86.7abc ± 2.3	73.3cdef ± 2.3	54.7ghi ± 4.6	8.0h ± 6.9
12	76.0e ± 4.0	70.7def ± 11.5	49.3hi ± 2.3	10.7h ± 4.6
13	80.0cde ± 6.9	70.7def ± 9.2	42.7ij ± 6.1	13.3h ± 4.6
14	78.7cde ± 6.1	70.7def ± 8.3	61.3fgh ± 8.3	10.7h ± 6.1
15	78.7cde ± 2.3	64.0f ± 8.0	49.3hi ± 12.9	20.0gh ± 4.0
16	80.0cde ± 4.0	66.7f ± 6.1	30.7j ± 9.2	8.0h ± 4.0

* Values followed by the same letter in a column are not significantly different by least significant difference (LSD) comparison of means.
** Standard deviation

Grain quality assessment

Germination rate was measured every week by placing 25 seeds per sample on a Whatman No. 3 filter paper in a 90 mm diameter Petri dish saturated with 5.5 ml of distilled water. The dishes were incubated at 22±1ºC for seven days and the number of seeds germinated was counted (Wallace and Sinha 1962).

Moisture content of the samples was measured every week by drying approximately 10 g of grain per sample in a convection oven at 130ºC for 16 hours (ASAE 2003) and expressed as percentage on wet mass basis.

Appearance of visible mold was monitored every week by visually inspecting the samples. Invisible microflora species were identified at four week intervals by placing 25 seeds on a Whatman No. 3 filter paper in a 90 mm diameter Petri dish saturated with 5.5 ml of 7.5% aqueous sodium chloride (NaCl) solution. The plates were incubated at 25ºC for seven days and the microfloral species were identified using a dissection microscope (Mills et al. 1978).

Free fatty acid values (FAV) were measured every two-week interval using Goldfisch fat extractors and KOH titration (Schroth et al. 1998).

Statistical Analysis

Effects of moisture content, temperature, and storage period on germination rate and FAV were analyzed using analysis of variance (ANOVA) using a three factorial design model (4 moisture contents × 4 temperatures × 16 weeks). Changes in germination and FAV over the storage period were analyzed using least significant difference (LSD) means of comparison with a 95% confidence interval.

RESULTS and DISCUSSION

Wallace et al. (1983) studied the effect of abiotic variables such as temperature, moisture content, and storage time on the biotic variables such as the seed and its microflora. They used seed germination, grain grade, and FAV as the indicators of grain deterioration.

Germination

Changes in germination of stored rye samples over time are given in Tables 1-4. The initial germination rate of the rye was 92%. Changes in germination with respect to moisture contents and temperatures were noticed in the first week of the study. At 10ºC, the germination of the 10.0 and 12.5% moisture content samples remained above 80 and 75%, respectively, throughout the study, whereas that of the high moisture samples decreased over time. At 20ºC, only the 10% moisture content samples maintained about 80% germination throughout the experiment. Even at 20ºC or below, the rye grain with 17.5% moisture or more has to be dried within a week to avoid loss in seed viability. At 30ºC, germination of the 10.0 and 12.5% moisture samples remained above 80% for three weeks. However, germination of all the samples decreased over time. The 17.5% moisture samples reached 0% germination during the 13th week of the study. At 40ºC, and the 17.5 and 15.0% moisture samples reached 0% germination during the 5th and 7th weeks of storage, respectively. At 30 and 40ºC, even the dry grain was susceptible

Table 3. Changes in germination of rye stored at 30°C (n=3).

Storage period (wk)	Moisture content (% wb)			
	10.0	12.5	15.0	17.5
0	92.0a* ± 0.0**	92.0a ± 0.0	92.0a ± 0.0	92.0a ± 0.0
1	85.3ab ± 2.3	80.0b ± 4.0	76.0b ± 0.0	53.3c ± 2.3
2	81.3bc ± 2.3	80.0b ± 6.9	73.3bc ± 4.6	69.3b ± 6.1
3	81.3bc ± 2.8	78.7bc ± 2.8	69.3bc ± 2.8	53.3c ± 5.6
4	76.0cd ± 6.9	72.0bc ± 4.0	61.3cde ± 6.1	50.7c ± 6.1
5	69.3de ± 2.3	70.7c ± 2.3	56.0de ± 8.0	37.3d ± 4.6
6	66.7e ± 2.3	70.7c ± 6.1	64.0bcd ± 13.9	30.7d ± 6.1
7	74.7cd ± 2.3	70.7c ± 2.3	49.3ef ± 4.6	22.7e ± 2.3
8	58.7f ± 2.3	50.7de ± 10.1	42.7fg ± 9.2	21.3e ± 6.1
9	65.3ef ± 9.2	57.3d ± 6.1	36.0gh ± 4.0	13.3f ± 6.1
10	69.3de ± 4.6	46.7e ± 2.3	33.3ghi ± 8.3	5.3g ± 4.6
11	64.0ef ± 4.0	48.0e ± 6.9	26.7hi ± 8.3	2.7g ± 2.3
12	69.3de ± 6.1	44.0e ± 4.0	25.3hi ± 10.1	1.3g ± 2.3
13	69.3de ± 4.6	48.0e ± 4.0	26.7hi ± 9.2	0.0g ± 0.0
14	69.3de ± 2.3	49.3de ± 2.3	32.0ghi ± 10.6	-
15	66.7e ± 2.3	48.0e ± 4.0	24.0hi ± 4.0	-
16	58.7f ± 4.6	46.7e ± 6.1	22.7i ± 4.6	-

* Values followed by the same letter in a column are not significantly different by least significant difference (LSD) comparison of means.
** Standard deviation

Table 4. Changes in germination of rye stored at 40°C (n=3).

Storage period (wk)	Moisture content (% wb)			
	10.0	12.5	15.0	17.5
0	92.0a* ± 0.0**	92.0a ± 0.0	92.0a ± 0.0	92.0a ± 0.0
1	76.0bc ± 4.0	64.0bc ± 4.0	37.3b ± 2.3	20.0b ± 4.0
2	70.0bcde ± 6.0	70.7b ± 10.1	22.7c ± 16.2	2.7c ± 4.6
3	76.0bc ± 10.6	62.7bc ± 10.1	10.7cd ± 2.3	6.7c ± 8.3
4	74.7bcd ± 6.1	54.7cd ± 11.6	17.3c ± 8.3	5.3c ± 2.3
5	78.7b ± 8.3	54.7cd ± 16.1	12.0cd ± 10.6	0.0c ± 0.0
6	76.0bc ± 6.9	38.7ef ± 10.1	4.0d ± 0.0	-
7	66.7cdef ± 2.3	34.7ef ± 10.1	0.0d ± 0.0	-
8	77.3b ± 2.3	46.7de ± 6.1	-	-
9	72.0bcd ± 4.0	29.3f ± 11.6	-	-
10	57.3fg ± 8.3	40.0ef ± 10.6	-	-
11	65.3def ± 4.6	33.3ef ± 6.1	-	-
12	61.3efg ± 11.5	33.3ef ± 4.6	-	-
13	66.7cdef ± 2.3	41.3def ± 4.6	-	-
14	58.7fg ± 4.6	36.0ef ± 6.9	-	-
15	54.7g ± 2.3	30.7f ± 8.3	-	-
16	53.3g ± 6.1	29.3f ± 4.6	-	-

* Values followed by the same letter in a column are not significantly different by least significant difference (LSD) comparison of means.
** Standard deviation

to spoilage. The 10.0 and 12.5% moisture samples would have 3 weeks for cooling at 30ºC and less than a week at 40ºC. Effects of initial moisture content, storage temperature, and storage period on germination rate were significant (α=0.05). Germinability of the grain is the first and foremost factor used to assess the storability of the stored product (Pomeranz 1992). If the germination rate decreases below 90% of the initial germination rate, then the storage condition has to be considered as unsafe and protective measures need to be taken (Schroth et al. 1998; Karunakaran et al. 2001). As moisture content increases, most types of grains become sensitive to injury or death by increasing storage temperatures (Christensen and Kaufmann 1969). Germinability of grain has a negative correlation with storage temperature and storage fungi (Wallace and Sinha 1962).

Moisture content

Potassium hydroxide solutions of different specific gravities were used to maintain the ERH of the grain samples, so that the initial moisture contents 10.0, 12.5, 15.0, and 17.5% remained constant throughout the storage period. But the KOH solutions could not maintain the required RH values over 16 weeks, due to evaporation of water from the solutions at higher temperatures (Solomon 1951).

Changes in the moisture contents of stored rye samples over time are given in Fig. 2. Almost all the stored rye samples showed changes in their initial moisture content over time. At 10ºC, moisture contents of all the rye samples increased over time. At 20ºC, the 17.5% moisture content samples lost moisture, the 15.0% moisture samples remained almost constant; and the 10.0 and 12.5% moisture samples increased in moisture content over time. At 30ºC, the 10.0 and 12.5% moisture samples remained almost constant in moisture level throughout the study, whereas, the 15.0 and 17.5% moisture samples lost moisture over time. At 40ºC, all the samples lost moisture over the storage period. In general, moisture contents of all the samples stored at 10ºC increased with time. At 20ºC, the low initial moisture samples increased in water content. At 30 and 40ºC, nearly all the samples decreased in moisture content with time. The rate of decrease in moisture content increased with increased initial moisture content and storage temperature.

Microflora

As fungi cause deterioration in stored grain quality, it is important to quantify the presence of fungi which will give some indication of the magnitude of deterioration that has occurred. The time of appearance of visible mold and respective germination rate of rye is shown in Table 5. Visible mold appeared in all the 17.5% moisture content samples irrespective of the storage temperature and in all the samples stored at 40ºC, regardless of the moisture content. The 17.5% moisture content samples stored at 20, 30, and 40ºC had visible mold appear in the very first week of analysis. The storage temperature should be below 20ºC and the moisture content should be below 15.0% to avoid visible mold. According to Wallace et al. (1983) all seeds having visible mold had a musty odor although all musty seeds did not necessarily show the appearance of visible mold. Mustiness and off-odors are often associated with increased storage fungi and decreased germination rate.

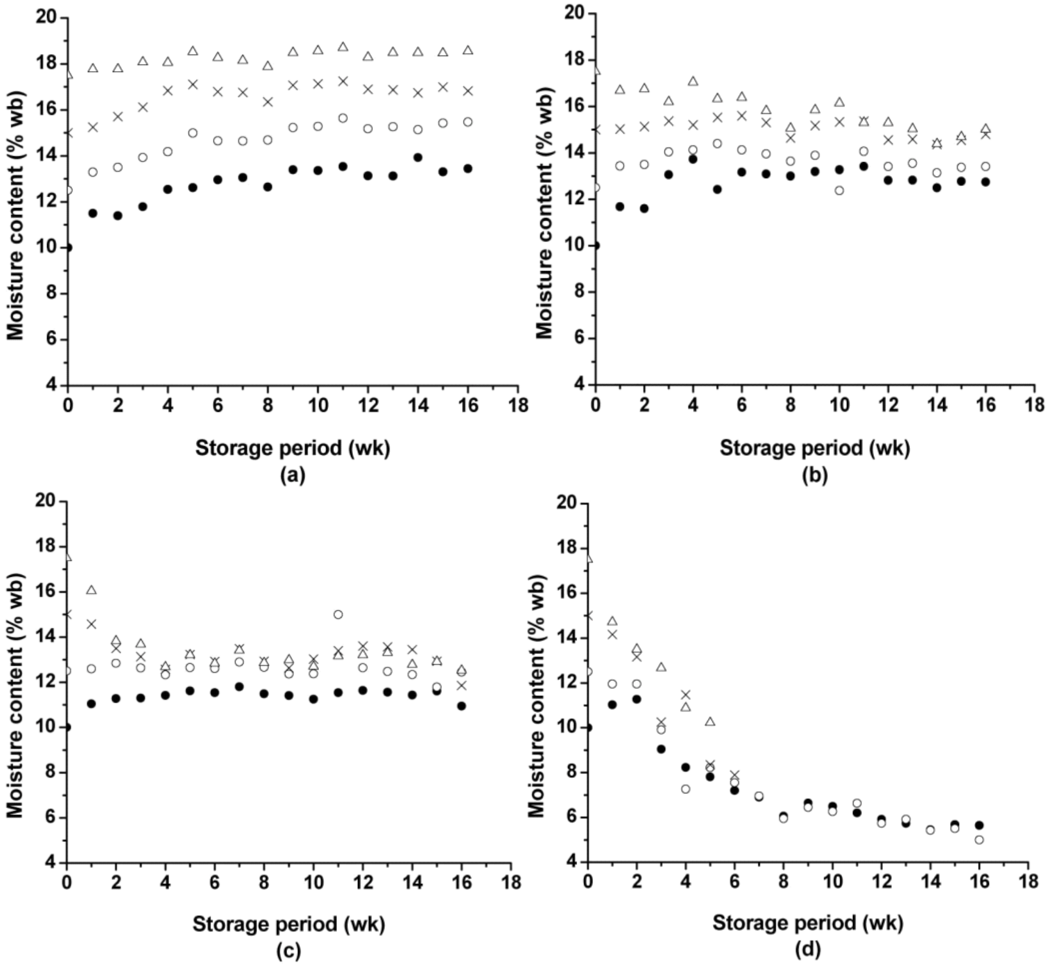

Fig. 2. Changes in moisture contents of rye with respect to time: (a) 10°C; (b) 20°C; (c) 30°C; (d) 40°C. Initial moisture content: • 10.0%; ○ 12.5%; ▾ 15.0%; △ 17.5%.

Table 5. Time (wk) of the first appearance of visible mold and respective mean germination (%) of rye.

Temperature (°C)	Initial moisture content (% wb)			
	10.0	12.5	15.0	17.5
10	-	-	-	2 57 ± 4.6
20	-	-	-	1 61 ± 6.1
30	-	9 54 ± 16.2	5 56 ± 8.0	1 53 ± 2.3
40	10 57 ± 8.3	5 55 ± 16.2	1* 37 ± 2.3	1* 20 ± 4.0

*Visible mold might have occurred before this time because of the length of time interval between sampling dates.

Initially, samples had a high number of seeds infected by *Penicillium spp*. with *Aspergillus* and *Penicillium spp*. being predominant in all samples throughout the study. At 10 and 20ºC, *Penicillium spp*. was dominant during the early stages of storage and the number of seeds infected with *A. glaucus* group increased with storage time. *Aspergillus candidus* Link and *Hormodendrum* were present in almost all samples but occurred less frequently. *Aspergillus ochraceus* Wilhelm increased with moisture content and storage period. At 20ºC also, *Penicillium spp*. were the dominating species followed by *A. glaucus* group and *Hormodendrum*. There were few seeds infected by *Fusarium* and the number of seeds infected with *Rhizopus (f.)* increased with storage time. At 30 and 40ºC, *A. glaucus* group was the dominant species. Similar to samples stored at low temperatures, at 30 and 40ºC also, the number of seeds infected with *A. ochraceus* increased with moisture content and storage period. *Aspergillus wentii* Wehmer and *A. candidus* Link were the other two *Aspergillus* species present in the samples.

Fungal growth and its metabolic activity cause loss in germinability of seed and contaminate the grain. Fungal deterioration and mycotoxin production are two significant signs of poor grain quality. Fungi require a minimum moisture content and temperature below which they can not grow (Abramson 1991; Frisvad 1995).

FAV

Biochemical changes cause a loss in the nutritive value (change in carbohydrates, proteins, lipids, and vitamins) of the grain (Pomeranz 1992). Oxidative or hydrolytic changes occur in lipids over time. In whole grain, hydrolytic changes are more common; hence, FAV is considered one of the important factors in assessing the condition of stored grain. However, FAV has a limitation in that a given mold species may produce a large amount of FFA and consume part of this, hence FAV can not directly be correlated with the presence of fungi (Christensen and Kaufmann 1969). As there is no absolute FFV to correlate with deterioration, however, many researchers have used the relative change in FAV (Sinha 1983; Schroth et al. 1998; Karunakaran et al. 2001) as a measure of deterioration.

Changes in FAV of stored rye samples over time are given in Tables 6-9. Initially, the FAV of rye was 15 mg KOH/100 g of dry grain. At 10ºC, the FAV of the 10.0, 12.5, 15.0, and

Table 6. Changes in FAV of rye stored at 10°C (n=3).

Storage period (wk)	Moisture content (% wb)			
	10.0	12.5	15.0	17.5
0	14.7bc* ± 1.3**	14.7cd ± 1.3	14.7c ± 1.3	14.7c ± 1.3
2	19.9a ± 4.4	19.2a ± 1.3	17.7ab ± 2.2	18.4b ± 3.4
4	15.5bc ± 2.2	15.5bcd ± 2.2	16.2bc ± 1.3	16.2bc ± 1.3
6	17.0b ± 1.3	17.0abc ± 1.3	15.5bc ± 2.2	14.0c ± 1.3
8	14.7bc ± 1.3	15.5bcd ± 2.2	15.5bc ± 0.0	16.2bc ± 1.3
10	13.3c ± 2.2	13.3d ± 2.2	15.5bc ± 0.0	18.4b ± 1.3
12	17.0ab ± 1.3	17.7ab ± 0.0	19.2a ± 1.3	19.2b ± 2.6
14	16.2bc ± 1.3	16.2bc ± 2.6	16.2bc ± 3.9	25.8a ± 6.4
16	15.5bc ± 2.2	17.7ab ± 0.0	14.8c ± 3.4	25.8a ± 1.3

* Values followed by the same letter in a column are not significantly different by least significant difference (LSD) comparison of means.
** Standard deviation

Table 7. Changes in FAV of rye stored at 20°C (n=3).

Storage period (wk)	Moisture content (% wb)			
	10.0	12.5	15.0	17.5
0	14.7bc* ± 1.3**	14.7c ± 1.3	14.7d ± 1.3	14.7c ± 1.3
2	19.9a ± 0.0	19.9ab ± 2.2	20.7b ± 2.6	22.9b ± 1.3
4	17.0b ± 1.3	17.0bc ± 1.3	14.8d ± 1.3	14.0c ± 1.3
6	13.3c ± 2.2	15.5c ± 2.2	16.2cd ± 2.6	22.9b ± 3.4
8	16.2b ± 1.3	17.0bc ± 1.3	18.4bc ± 1.3	22.9b ± 3.4
10	14.8bc ± 1.3	14.0c ± 1.3	19.2b ± 1.3	22.9b ± 1.3
12	17.0b ± 1.3	19.2ab ± 1.3	19.9b ± 0.0	33.2a ± 0.0
14	16.2b ± 1.3	21.4a ± 1.3	23.6a ± 1.3	34.7a ± 6.4
16	15.5bc ± 2.2	14.7c ± 3.4	18.4bc ± 1.3	33.9a ± 2.5

* Values followed by the same letter in a column are not significantly different by least significant difference (LSD) comparison of means.
** Standard deviation

Table 8. Changes in FAV of rye stored at 30°C (n=3).

Storage period (wk)	Moisture content (% wb)			
	10.0	12.5	15.0	17.5
0	14.7d* ± 1.3**	14.7d ± 1.3	14.7e ± 1.3	14.7c ± 1.3
2	20.7ab ± 1.3	24.3ab ± 0.0	20.7bc ± 1.3	26.5a ± 5.9
4	18.4bc ± 1.3	13.3d ± 9.7	17.0de ± 1.3	18.4bc ± 3.4
6	20.6ab ± 2.6	21.4abc ± 1.3	21.4b ± 1.3	23.6ab ± 2.6
8	17.7c ± 0.0	18.4bcd ± 1.3	18.4cd ± 1.3	25.8a ± 4.6
10	19.2bc ± 1.3	21.4abc ± 1.3	22.9b ± 1.3	22.9ab ± 2.6
12	22.1a ± 2.2	17.7cd ± 4.4	21.4b ± 1.3	25.1a ± 2.6
14	22.8a ± 1.3	25.1a ± 1.3	28.0a ± 1.3	27.3a ± 3.4
16	18.4bc ± 1.3	21.4abc ± 1.3	22.1b ± 3.9	25.1a ± 2.6

* Values followed by the same letter in a column are not significantly different by least significant difference (LSD) comparison of means.
** Standard deviation

17.5% moisture content rye samples remained nearly unchanged until week 10 and then it increased gradually over time. At 20ºC, there was a gradual increase in FAV of samples with increasing moisture content and time. There was not much difference in the values of 10.0, 12.5, and 15.0% moisture content samples stored at 10 and 20ºC, but the FAV of the 17.5% moisture samples stored at 20ºC more than doubled to 34 mg KOH/100g of dry grain by the 16th week. The 17.5% moisture content samples stored at 40ºC had the highest FAV of 42 mg KOH/100g of dry grain by the fourth week of storage. At all the four storage temperatures, FAV increased with moisture content and storage period. The effects of moisture content, temperature, and storage period on the FAV of rye were significant (α=0.05). The high storage temperature and grain moisture level favors mold proliferation, which further results in increased chemical changes. The result is in accordance with Wallace et al. 1983, who reported that FAV has a positive correlation with moisture content of stored grain and *Penicillium spp.* There were no noticeable color changes in the stored samples over time; however, the high moisture grains (15.0 and 17.5% m.c.) stored at high temperatures (30 and 40ºC) were musty.

Estimated safe storage life

Germination is the most sensitive, effective, and simple method of determining the condition of a grain bulk at the farm level. As other quality parameters such as FAV and identification of microfloral species require training and expensive equipment, germination alone can be considered for developing safe storage guidelines.

Safe storage period was defined as the time for which the germination of the samples remains above 80% of their initial germination (> 73.6%) with no appearance of visible mold. The number of weeks the samples maintained 80% or more of their initial germination was plotted against the initial moisture content and storage temperature to get the estimated safe storage guidelines (Fig. 3).

CONCLUSIONS

Rye samples with 10.0, 12.5, 15.0, and 17.5% initial moisture content stored at 10, 20, 30, and 40ºC were studied for 16 weeks. At 20ºC only the high moisture samples lost moisture over time, whereas at 30 and 40ºC, all the samples gradually dried over the first four weeks which simulated near-ambient aeration conditions. Grain condition was assessed by periodically monitoring germination, moisture content, visible and invisible microflora, and FAV. Safe storage guidelines based on weeks in storage were plotted with respect to initial moisture content and temperature. Rye with ≤12.5% moisture content stored at ≤ 20ºC would be safe for >15 weeks, 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 available time for corrective action decreased with increased moisture content and temperature.

Table 9. Changes in FAV of rye stored at 40°C (n=3).

Storage period (wk)	Moisture content (% wb)			
	10.0	12.5	15.0	17.5
0	14.7d* ± 1.3**	14.7c ± 1.3	14.7c ± 1.3	14.7b ± 1.3
2	20.6a ± 2.6	19.2ab ± 3.4	20.6b ± 1.3	28.0ab ± 5.1
4	19.2ab ± 3.4	19.9ab ± 2.2	19.2bc ± 5.6	42.0a ± 11.7
6	14.8d ± 0.0	18.4abc ± 1.6	26.6a ± 3.1	-
8	15.5cd ± 3.8	17.0bc ± 1.3	-	-
10	19.2ab ± 1.3	21.4a ± 3.4	-	-
12	17.0bcd ± 1.0	21.4a ± 2.6	-	-
14	18.4abc ± 1.3	19.2ab ± 3.4	-	-
16	17.0bcd ± 1.3	17.7abc ± 2.2	-	-

* Values followed by the same letter in a column are not significantly different by least significant difference (LSD) comparison of means.
** Standard deviation

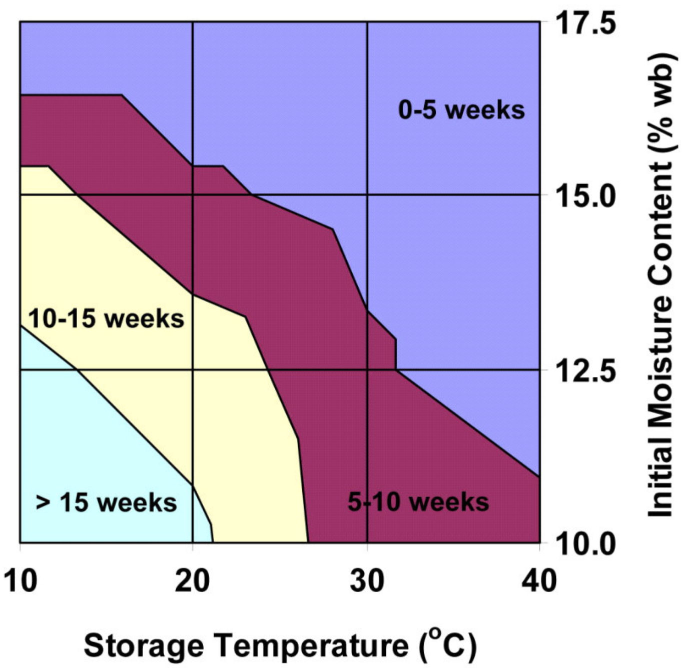

Fig. 3. Estimated safe storage life of rye based on 20% decrease in the initial germination and no visible mold. Periods of safe storage are indicated.

ACKNOWLEDGEMENT

We thank the Canada Research Chairs program for the financial assistantship.

REFERENCES

Abramson, D. 1991. Development of moulds, mycotoxins and odors in moist cereals during storage. In *Cereal grain. Mycotoxins, fungi and quality in drying and storage*, ed. J. Chelkowski, 119-147. Amsterdam, NH, Netherlands: Elsevier.

Anonymous. 1997. Harvest yields high quality. In *Grain Matters* 1-2. Winnipeg, MB: Canadian Wheat Board.

ASAE. 2003. Moisture measurement - Unground Grain and Seeds. ASAE S352.2. In *ASAE Standards* 2003, 555. St. Joseph, MI: ASABE.

Bala, B.K. 1997. *Drying and Storage of Cereal Grains*. Enfield, NH: Science Publishers Inc.

Christensen, C.M. and H.H. Kaufmann. 1969. *Grain storage: The role of fungi in quality loss*. Minneapolis, MN: University of Minnesota Press.

Frisvad, C.J. 1995. Mycotoxins and mycotoxigenic fungi in storage. In *Stored-Grain Ecosystems,* eds. D.S. Jayas, N.D.G. White and W.E. Muir, 251-288. New York, NY: Marcel Decker Inc.

Hartman, M. 1999. Harvesting and storage of fall rye. http://www1.agric.gov.ab.ca/$department/deptdocs.nsf/all/crop4460 (2006/04/26).

Jayas, D.S. 1995. Mathematical modeling of heat, moisture, and gas transfer 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 Decker Inc.

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

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.

Mills, J.T. 1989. *Spoilage and Heating of Stored Agricultural Products: Prevention, Detection and Control*. Ottawa, ON: Agriculture Canada.

Mills, J.T and R.N. Sinha. 1980. Safe storage periods of farm-stored rapeseed based on mycological and biochemical assessment. *Postharvest Pathology and Mycotoxins* 70(6): 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.

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. and D.S. Jayas. 2001. Temperature of stored grains and oilseeds. In *Grain Preservation Biosystems*, ed. W.E. Muir, 95-142. Winnipeg, MB, Department of Biosystems Engineering, University of Manitoba.

Pomeranz, Y. 1992. Biochemical, functional and nutritive changes during storage. In *Storage of Cereal Grains and Their Products*, eds. J.A. Anderson and A.W. Alcock, 55-141. St.Paul, MN: American Association of Cereal Chemists.

Prasad, D.C., W.E. Muir and H.A.H. Wallace. 1978. Characteristics of freshly harvested wheat and rapeseed. *Transactions of the ASAE* 21(4): 782-784.

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(3): 201-205.

Sinha, R.N. 1973. Interrelations of physical, chemical, and biological variables in the deterioration of stored grains. In *Grain Storage: Part of a System*, eds. R.N. Sinha and W.E. Muir, 15-47. Westport, CT: The AVI Publishing Company, Inc.

Sinha, R.N. 1983. Effects of stored-product beetle infestation on fat acidity, seed germination, and microflora of wheat. *Journal of Economic Entomology* 76(4): 813-817.

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

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, 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.

Weipert, D. 1996. Rye and triticale. In *Cereal Grain Quality*, eds. R.J. Hendry and P.S. Kettlewell, 205-224. London, UK: Chapman & Hall.

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

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

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. 1996. Deterioration during storage in wild rice, Zizania palustris, and polished basmati rice, *Oryza sativa*, and potential for insect infestation. *Seed Science and Technology* 24: 261-271.

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.