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Performance of Plastic Lining for Storage of Barley in Traditional Underground Structures (Matmora) in Morocco

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Underground conical shaped pits (matmora) are traditional on-farm grain storage structures in regions of Morocco where the rock formations are favourable, i.e., where sandstone and limestone formations occur together. Experiments were conducted in two such pits each of 4t capacity and filled with barley heavily infested with *Rhyzopertha dominica* (F.) and *Sitophilus granarius* (L.). One pit was lined with polyethylene and one with only the traditional straw layer. Temperatures were monitored remotely at 14 points in each pit every 4h for six months. Mean temperatures in the straw-lined pit were consistently higher than in the plastic-lined pit at all locations; 2·5°C higher in the top and centre; 3·0°C at the sides; and 1·0°C on the bottom. During six months of storage, barley moisture content on a wet basis (m.c.w.b.) in the straw-lined pits rose from 9·6 to 12·7% in the centre of the pit and to 21·4% at the top of the grain bulk. Mean live insects after an eight week incubation decreased from 474 to 33/kg. Mean percentage surface of disinfected kernels from which *Aspergillus flavus* Link developed was 23% after 6 months storage in the straw-lined pit. Moisture content in the plastic-lined pit rose from 9·6 to 9·8% at the centre and to 11·7% at the top of the bulk; mean live insects decreased from 709 to 18/kg, and the mean percentage surface of disinfected kernels from which *A. flavus* developed was 3·9%. Dry weight losses were 6·27% in the straw-lined pit and 0·97% in the plastic-lined pit. These results indicate that the present use of plastic lining reduces dry weight loss, loss of germinability, and incidence of medically important fungal populations. In the future, however, insect resistance to low oxygen atmospheres created by these structures may increase. Routine monitoring of this resistance should be initiated.

1. Introduction

Underground space is used by farmers as the main method of grain (barley, wheat) storage in many regions in Morocco. This type of storage predominates in areas where the earth composition and soil mechanics can support these structures. Limestone deposits or calcareous ('Ferrich') subsoils are typical of these areas. The nature of the subground influences the location of grain pits (matmora) because it affects the structural stability of the pit, the cost of construction, and the water circulation in the subsoil. Hard rocky subsoils offer excellent conditions for pit stability, but require too much time to create these manually dug pits. At the other end of the spectrum, easy-to-excavate soils usually have poor drainage properties. A compromise is reached by choosing a self-supporting subsoil with good drainage (Bartali[1]).

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Traditionally, these structures (matmora) have been lined with straw. Recently, locally produced plastic has been substituted for straw by some farmers. Inadequate sealing methods often occur with the use of plastic. These methods have allowed entry of water and exchange of gases. Using locally produced plastic, adequate sealing methods have recently been developed in Brazil for corn stored for 0·7 years and dry edible beans stored for 0·5 years, (Sartori;[2] Ferreira *et al.*[3]); in Minnesota for shelled corn stored for 3 years (Dunkel *et al.*[4]); and in Rwanda for dry edible beans stored for 1 year (Hanegreefs *et al.*[5]). In each of these experiments, the quality of the commodity was maintained.

We hypothesized that the storage losses presently experienced with Moroccan matmora could be significantly reduced. The present study was undertaken to evaluate the performance of locally manufactured plastic lining material and new sealing methods in reducing storage losses in matmora similar to those used on Moroccan farms. Specifically, we hypothesized that the straw trapped oxygen would allow insects and fungi to develop. The plastic was designed to stop gas exchange between the grain and the straw.

2. Materials and methods

2.1. *Site description*

Matmora were constructed on the campus of the Hassan II Agronomic and Veterinary Institute in Rabat. The soil in this location consists of a surface layer of top soil (10 cm); a layer of sand mixed with humus (20 cm); and a layer of sand (90 cm) (*Fig. 1*). This is underlaid by a clayey layer 'hamri' (115 cm). A friable sandstone-limestone or calcareous sandstone layer of 30 cm begins at 235 cm below the surface of the topsoil. Underneath this is a hard or non-friable sandstone-limestone layer, into which the matmora extends for 80 cm. Permeability to water was 22·7 cm/h for the sand layer and 5·8 cm/h for the clayey layer. The water table was at 20 m.

2.2. *Pit construction*

Pits were dug manually in January 1987 by two workers who specialize in such construction in a rural area of Morocco. Only traditional tools and methods were used in the construction. Each sub-cylindrical pit had a 4 t capacity. They were 3·2 m deep and 2·3 m wide at the bottom (*Fig. 1*). The entrance to each pit was 1 m diameter. Because of the deep sandy layer at this site, the entrance was 1·1 m in height and was stabilized by a 15 cm thick lining of bricks and cement. After construction, pits were burned in the traditional method to reduce relative humidity (r.h.) and kill insects and micro-organisms. Interior walls of both pits were covered with a 5 cm lining of wet clay mixed with straw. Fires were lit in the pits to hasten the drying process. This provided protection for the plastic liner without introducing another source of variation.

2.3. *Lining material*

In the traditional manner, a 10 cm thick layer of straw was placed on the bottom, sides and top of one pit. The wall lining was accomplished as the filling progressed. For the plastic liner, a locally produced plastic sheet, 0·18 mm thick, was formed into a bag with locally available tape. Permeability tests of plastic to water and oxygen were made at the School of Packaging, Michigan State University. Permeability to water was insignificant. Permeability to oxygen was 66 cm^3 per cm^2 of plastic during a 24 h period at 25°C. The plastic bag was introduced into the pit prior to filling and sealed with tape after filling and thermocouple insertion.

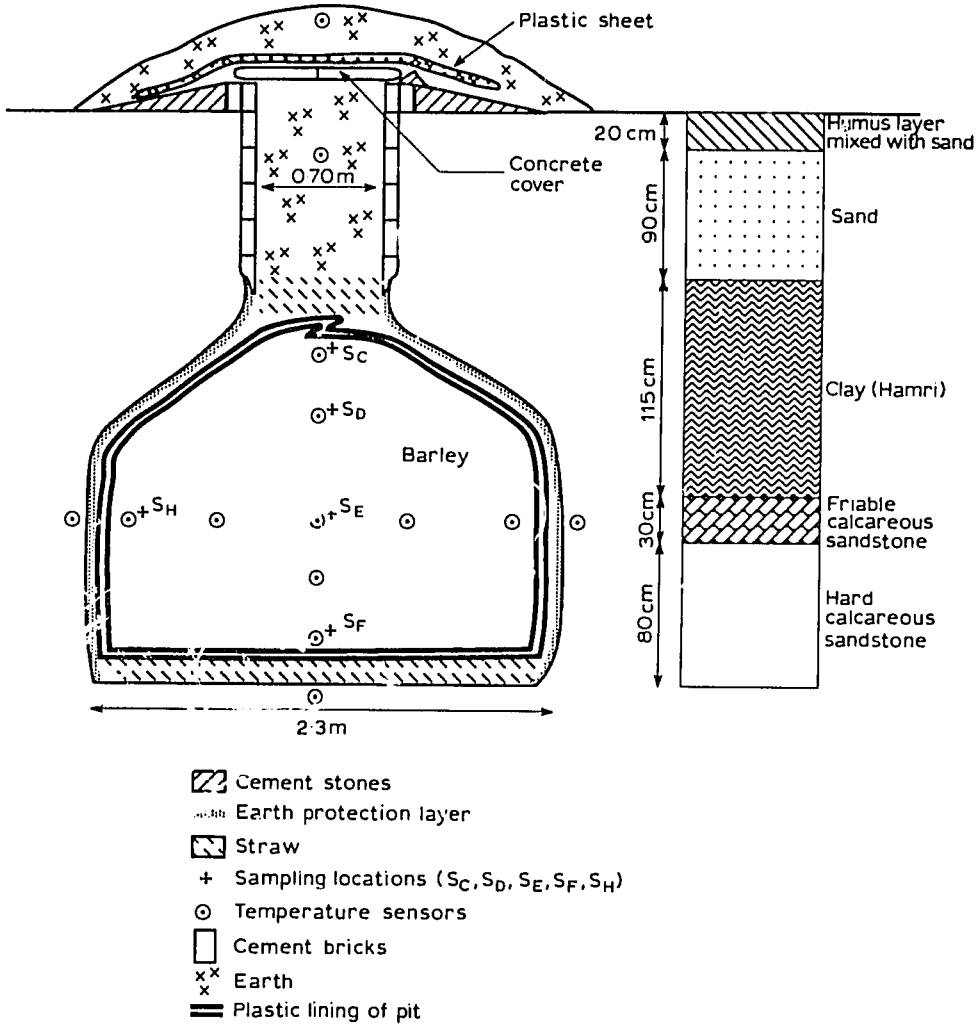


Fig. 1. Vertical section of plastic lined barley pit (Moroccan matmora) indicating placement of thermocouples (temperature sensors), soil layers in which the matmora were dug, and location of sampling sites for insect populations and quality analysis

2.4. *Pit filling*

Barley was harvested in June 1986 and purchased for animal feed. Pit filling occurred on April 27 and 28, 1987.

2.5. *Remote temperature measurement*

Fourteen thermocouples were installed in and around each pit as it was filled. Each of the 14 thermocouple wires (*Fig. 1*) were placed in a protective rigid plastic conduit which led underground from the pit to the instrument building, a distance of 10 m. At the instrument building, each thermocouple was connected to a battery operated data acquisition unit (UPAD) (Laboratoires Generaux de Recherche) which contained a microprocessor with 16K memory. After initialization, temperature measurements were

made and stored automatically every 4 h. Using a software program, DIALOGUE, and a portable Epson microcomputer, temperature measurements were retrieved from the site on magnetic tape every 10 days. They were then stored on the hard disk of an IBM-XT microcomputer for analysis.

2.6. *CO_2 measurement*

The capability to measure CO_2 became available only at the time of unloading. After removing the earth cover, but prior to opening the plastic or straw covering of the barley, plastic tubing was inserted 30 cm into the top of the grain mass. The plastic tubing was flushed by taking enough samples with the syringe to equal the volume of the plastic tubing between the syringe and the top of the grain. A sample was drawn across indicator tubes with a Matheson–Kitagawa (Model 8014–400A) syringe. The CO_2 level was determined colourimetrically in the prepared glass tubes (Matheson-Mitagawa 126SH range 1–20% CO_2).

2.7. *Sampling procedures*

Sampling was a function of the least number of samples needed to overcome individual variability and the greatest number of samples affordable. Four locations within each matmora were chosen for the intensive analyses; top of the bulk, middle, centre side and bottom (*Fig. 1*).

2.8. *Moisture content*

Water content of barley was determined on whole kernels. For the determination, a forced air oven was used at 103°C for 72 h. Wet and dry mass (weight) were measured and mean % m.c.w.b. was calculated.

2.9. *Quality analysis of barley*

At the beginning of the experiment, samples were examined for mass/unit volume and number and species of insects/kg after an eight week incubation of 450 g (divided into two replicates of 225 g) samples of barley. Following the storage period, 2 kg from each sample location (top, centre, side and bottom) were divided using a seed sample divider and the following were determined (*Fig. 2*): % impurities (by weight); % m.c. (by oven drying method); fungal growth from surface disinfected kernels; % dry weight loss (using weight/unit volume and m.c.); seed vigour and germination. Details of these analysis procedures for the barley samples are available in Afif.[6] Insects were examined both immediately after sieving of the sample and after an eight week incubation of clean barley at 25°C and 75% relative humidity (r.h). Numbers of insects live, dead, species, and life stage were recorded.

2.10. *Dry weight loss*

Loss was based on dry weight changes within five separate zones in the pits. Differences in these five zones were easily observable in grain in the straw-lined pit as it was being unloaded. In the plastic-lined pit, four of these zones displayed no visible difference.

The rate or % of the mean damage is given by

$$P_i V_i$$

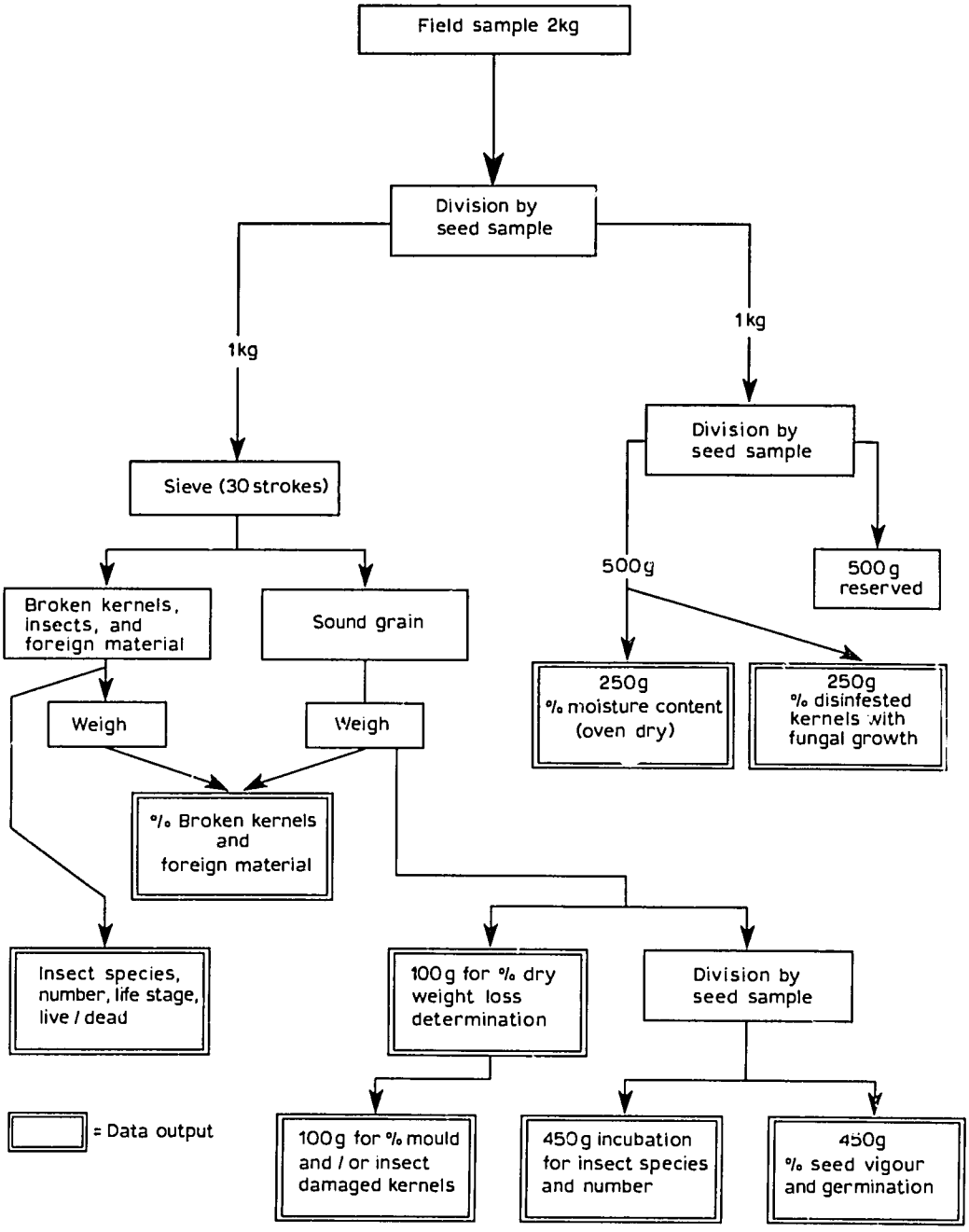


Fig. 2. Flow diagram for analysis of barley samples in plastic and straw-lined barley pits (Moroccan matmora)

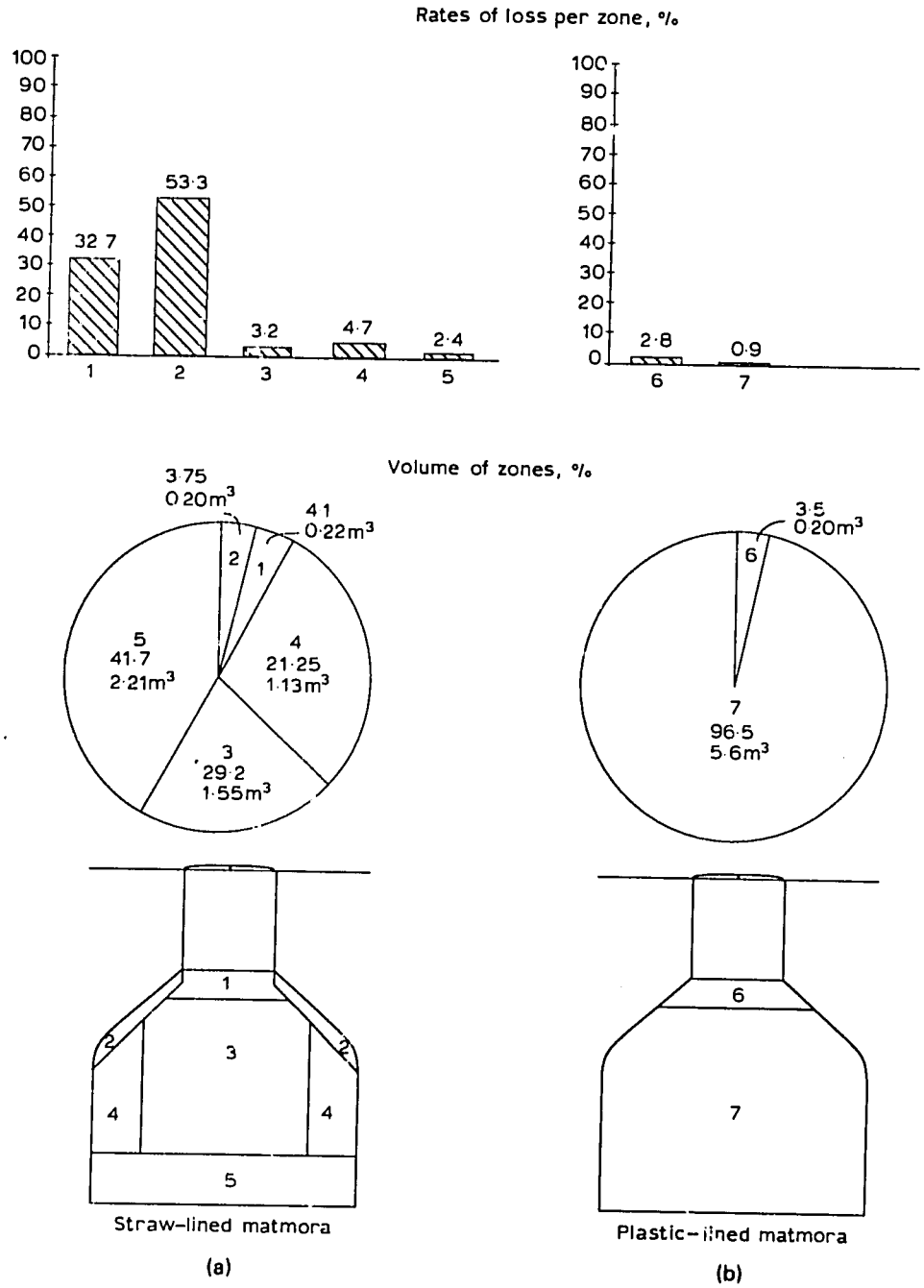


Fig. 3. Zones of matmora in which different levels of loss occurred in stored barley. (a) straw-lined matmora and (b) plastic-lined matmora. (The difference between total volumes is due to the volume occupied by straw in the straw-lined matmora)

where P_i = % of loss in the zone i and

V_i = % of the total volume contained in zone i

After storage there were distinct zones of quality in the barley mass. In each matmora these zones were different in size and location. For the straw-lined pit, the zones were as follows: centre top, just under opening (1); the top layer, but on the sides (2); the centre (3); the sides, not including top or bottom of the storage (4); and the bottom layer (5) (*Fig. 3a*). For the plastic-lined pit, the zones were as follows: the top layer (6) and all the rest of the bin (7) (*Fig. 3b*).

2.11. *Germination of studies*

Germination tests were done at the Direction de la Protection des Végétaux, du Controle Technique et de la Répression des Fraudes (DPVCTRF) laboratory. Four hundred seeds were randomly selected and divided into four replicates of 100 seeds each. These were placed between two layers of moistened germinating papers for seven days at 20°C, and 75% r.h., under white fluorescent lighting (photoperiod, 12 h light, 12 h dark). The first germination count was made on the fourth day. The final count was made on the seventh day. Normal, abnormal, decayed, and fresh but ungerminated seeds were recorded. Data were analyzed using an analysis of variance (ANOVA) and the Student-Newman-Keuls comparison of means (Nie *et al.*[7]).

3. Results

3.1. *Temperature patterns*

Soil temperatures at 0·1 m below the ground surface fluctuated in a periodic manner. Maximum daily temperatures occurred at about 15·00 h. During the 200 day test period, temperatures varied between 52 and 23°C near the soil-air interface at 0·1 m under the surface above the plastic-lined pit and between 55 and 27°C above the straw-lined pit (*Fig. 4(a)* and (*b*) sensor A). At 0·5 m below ground surface, temperatures remained markedly constant compared to that at 0·1 m. During the 200 day test period at 0·5 m below ground surface, temperatures varied between 28 and 26°C in the earth above the plastic-lined pit and between 29 and 25°C in the earth above the straw-lined pit (*Fig. 4(a)* and (*b*) sensor B).

In both straw and plastic-lined pits, barley remained at a temperature higher than the earth/rock surrounding it. In the straw-lined pit, temperatures obtained in the 12 locations in the barley were higher than the corresponding temperatures in the plastic-lined pit (P less than 0·001) (Sign test Snedecor and Cochran[8]). During the 200 day test period after the first 10 day equilibration period, temperatures varied between 30 and 22°C in the plastic-lined pit [*Figs 4(a)* and *5(a)*]. During the same time period, temperatures varied between 34 and 23°C in the straw-lined pit [Figs *4*(b) and *5(b)*].

3.2. *CO_2 measurement*

After six months of underground storage, CO_2 levels in straw and plastic-lined pits were 16% and 5% respectively.

3.3. *Moisture content*

Water content (% m.c.) of barley in the straw-lined pit increased significantly more than that in the plastic-lined pit (Table 1). At the top of the straw-lined grain bulk,

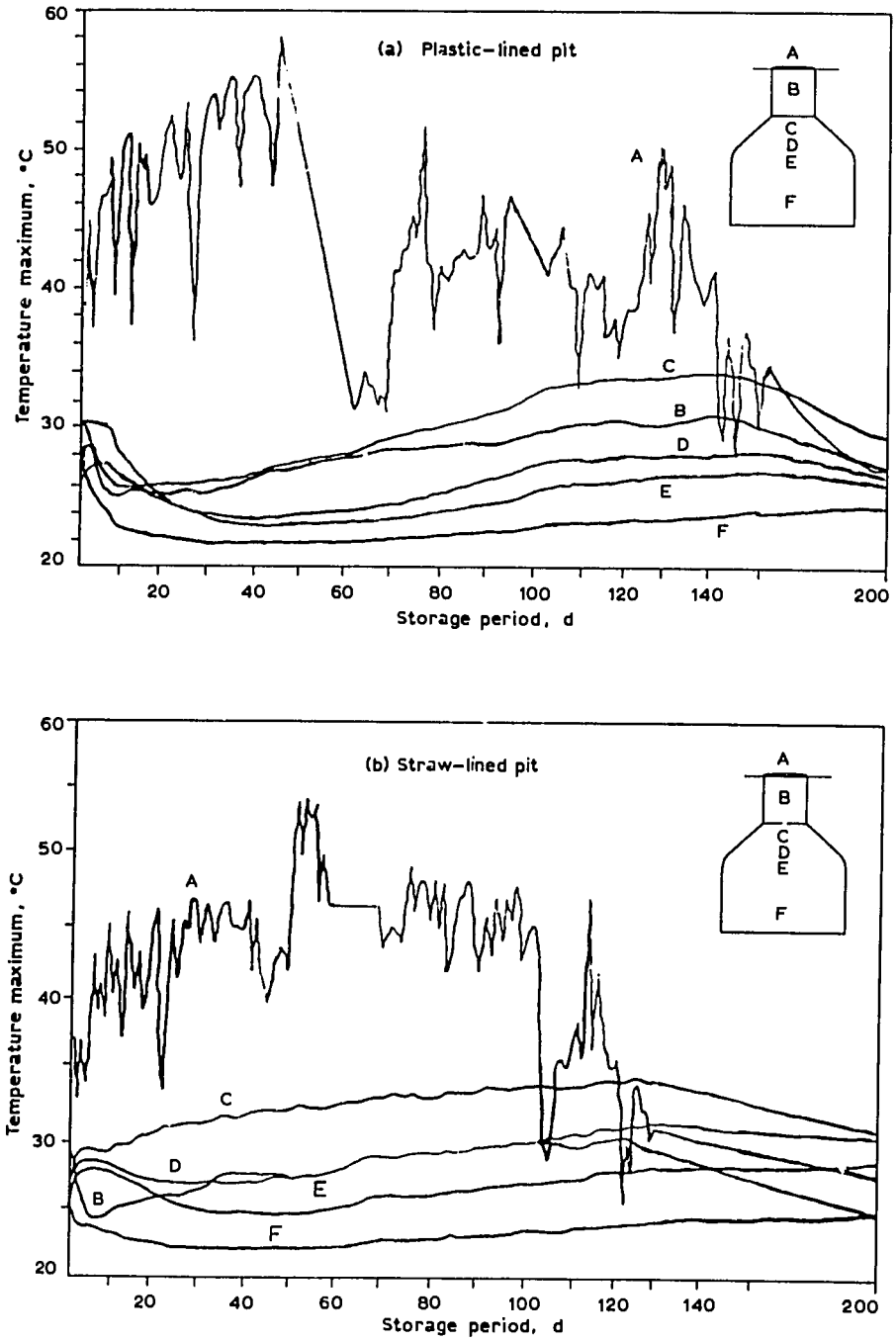
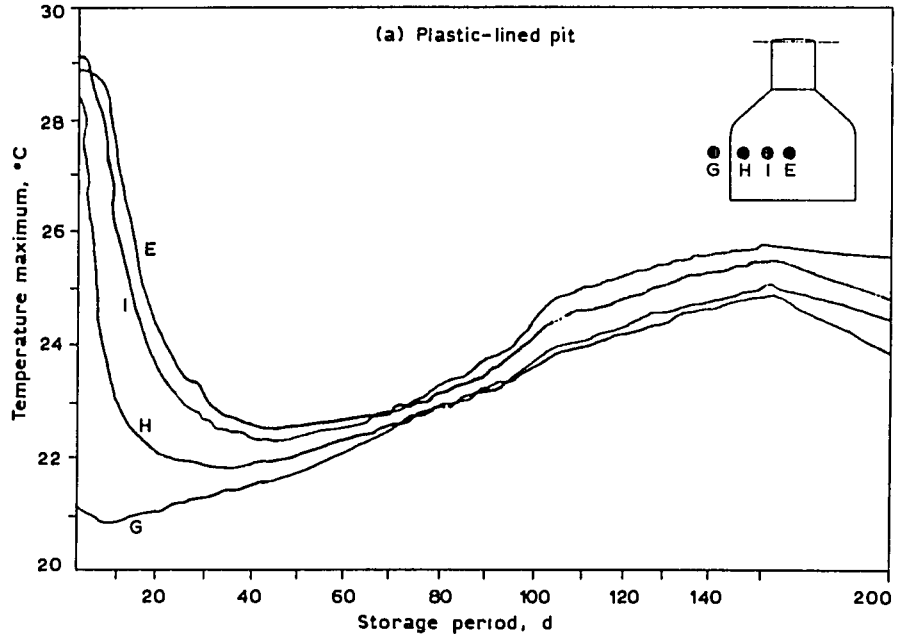


Fig. 4. Vertical gradient of temperatures in pits (Moroccan matmora) filled with barley (a) plastic-lined and (b) straw-lined. (Placement of sensors below ground surface: A = *1·0* m, B = *0·5* m; C = *1·2* m; D = *1·4* m; E = *1·7*; F = *2·2* m) *(Values between 150 and 200 d are an interpolation)*



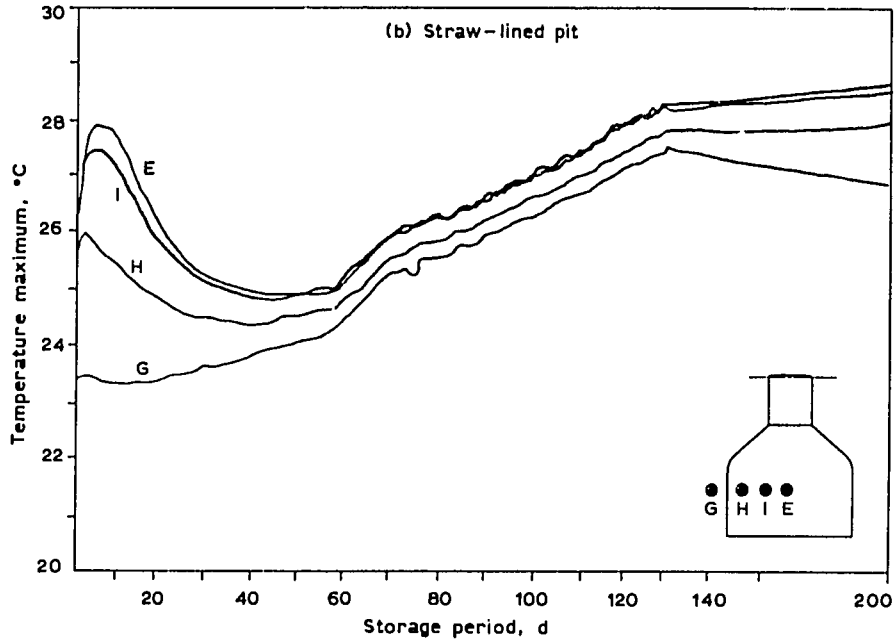


Fig. 5. Horizontal gradient of temperatures in pits (Moroccan matmora) filled with barley (a) plastic-lined pit and (b) straw-lined pit. (Placement of sensor G = 5 cm outside wall of matmora; H = 0·02 cm inside wall of matmora; I = 0·42 m inside wall of matmora; E = 0·82 m inside wall of matmora or the bin centre)

% m.c. more than doubled during the six months of storage (from 9·6 to 21·4%). In the plastic-lined pit, a significant increase from the initial % m.c. occurred only at the top of the bulk (from 9·6 to 11·7%). Mean % m.c. in the plastic-lined pit after six months storage was 10·1% (s.e. 0·4), significantly lower than that of the straw-lined pit (14·7% (s.e. 1·5) (P less than 0·05).

3.4. *Bulk density (mass/unit volume)*

Weight/unit volume, test weight, or density was higher in the plastic-lined pit than in the straw-lined pit but not significantly higher after six months storage (P greater than 0·05) (Table 1).

3.5. *Broken kernels and foreign material*

The percentage of broken and foreign material was not significantly different in the two pits after six months storage (P greater than 0·05) (Table 1).

3.6. *Damaged kernels*

Although the percentage of damaged kernels rose to 7·0% in the top of the bulk in the straw-lined pit, there was no significant difference between mean % damaged kernels in the plastic [3·9 s.e. 0·2)] and straw (4·7 s.e. 0·7) lined pits (P greater than 0·05) (Table 1).

3.7. *Dry mass (weight) loss*

The highest level of dry weight loss occurred in the straw-lined pit, particularly in the upper zones, 1 and 2. In these zones, the % loss reached 32·7 and 53·3% respectively. The mean total loss for the straw-lined matmora was 6·27%. On the other hand, the mean total loss in the plastic-lined matmora was 0·97%, with the highest zone of loss being the top portion, zone 6 [*Fig. 3(b)* and Table 2].

Dry weight loss, is only one type of loss experienced in matmora storage. Other losses, which were not measured, may be loss of nutritive value, loss of commercially valuable properties, and loss of volume.

Table 1

Physical properties of barley before and after six months underground (matmora) storage in Morocco

Time after underground storage, months	*Location of sample**	*Moisture content† (oven dry), %*		*Bulk density (weight per unit volume), t/m³*		*Weight of foreign material, %*		*Weight of damaged grain‡, %*	
		Plastic	*Straw*	*Plastic*	*Straw*	*Plastic*	*Straw*	*Plastic*	*Straw*
0	composite§	9·6	9·6	0·64	0·64				
6	top (S_C)	11·7	21·4	0·61	0·47	3·2	2·8	4·4	7·0
6	50 cm below top (S_D)	9·9	13·2	0·64	0·59				
6	centre (S_E)	9·8	12·7	0·64	0·59	1·4	1·2	3·6	3·8
6	centre side (S_H)	9·8	13·3	0·62	0·59	1·9	2·0	3·7	4·8
6	bottom (S_F)	9·5	13·0	0·64	0·60	2·4	2·3	4·0	3·9
6	mean ± S.E.	10·14 ±0·35	14·72 ±1·50	0·63 ±0·01	0·57 ±0·02	3·08 ±0·50	2·08 ±0·29	3·9 ±0·2	4·7 ±0·7

* Parentheses indicate exact locations in *Figs 1, 3, 4.*; † Whole kernels; 103°C; 72 h. ‡ Insect feeding damage and kernels with visible mould. § Composite = Four samples taken just before filling matmora.

Table 2

Comparison of dry weight loss in zones within the barley stored six months in underground pits (matmora) in Morocco

Storage treatment	*Zone*	*Volume, m^3*	*% of total volume*	*Dry weight* after storage, g/300 cm^3*	*Dry weight loss, %*
Plastic-lined pit	6	0·20	3·50	0·520	2·8
	7	5·60	96·50	0·530	0·9
Straw-lined pit	1	0·22	4·10	0·360	32·7
	2	0·20	3·75	0·250	53·3
	3	1·55	29·20	0·518	3·2
	4	1·13	21·25	0·510	4·7
	5	2·21	41·70	0·522	2·4

* Initial dry weight for all barley stored = 0·535 g/300 cm^3

3.8. *Seed vigour and germination*

Initial germination was 72% at the beginning of the underground storage period. After the six month storage period, there was a significant difference between mean number of kernels germinated from plastic and straw-lined pits [ANOVA and Student-Newman-Keuls test for means comparison (Nei *et al.*[7])]. This germination difference was primarily in the barley from the top of the matmora. In the barley from the straw-lined pit, germination decreased from 72 to 23% in the top portion of the grain mass during the six months of underground storage. In the barley from the plastic-lined pit, germination decreased from 72 to 70% in the top portion. Within treatments between replicates, there was no significant difference (Table 3). In the straw-lined pit, however, the top portion of the grain was significantly lower in germination than at all other locations tested within the same matmora. Temperature and moisture content conditions in the straw-lined pit, not the plastic-lined pit, were conducive to germination loss. This was not entirely reflected in the results (Table 3) probably due to the lack of fungal development in the low oxygen environment of the storage pits.

Table 3

Barley germination (±standard error) in field test after six months storage in plastic-lined and straw-lined underground pits (Moroccan matmora) (mean of four replicates; 100 seeds per replicate)

Pit lining	*Location*	*Mean number normal seedlings**	*Mean number abnormal seedlings*	*Mean number hard seeds†*	*Mean number fresh ungerminated seeds‡*	*Mean number of dead seeds*
Plastic	Top	70·8 ± 0·7b	2 ± 0·4	0	0	45·3 ± 2·1
	Centre	66·5 ± 0·6b	0·5 ± 0·3	0	0	33·3 ± 0·6
	Side	52·8 ± 2·3a	6·0 ± 1·1	0	0	24·5 ± 0·7
	Bottom	69·3 ± 1·0b	0·8 ± 0·2	0	0	28·5 ± 0·8
Straw§	Top	23	—	—	—	—
	Centre	63	—	—	—	—
	Side	57	—	—	—	—
	Bottom	70	—	—	—	—

* Letters which differ signify differences that are significant ($P = 0·05$) Student Newman Keuls comparison of means. † Seeds which do not imbibe. ‡ Seeds which do imbibe and do not germinate. § Composite = four samples taken just before filling matmora.

Table 4

Mean % surface disinfected barley kernels stored underground and from which storage fungi grew in malt-salt agar (29 ± 1°C) (four locations within pit; 50 kernels/location)

Fungal species	*Plastic-lined matmora location*					*Straw-lined matmora location*				
	1	2	3	4	*Mean*	1	2	3	4	*Mean*
Aspergillus candidus	0	16	10	29	13·75	18	12	34	78	35·50
Aspergillus clavatus	0	6	3	19	7·00	9	6	13	50	19·50
Aspergillus flavus	3	4	3	9	6·25	13	4	22	53	23·00
Aspergillus glaucus	0	2	8	9	4·75	10	7	18	42	19·25
Aspergillus ochraceus	0	0	0	13	3·25	0	0	0	0	0
Aspergillus niger	2	0	1	0	0·75	0	0	0	0	0
Aspergillus terreus	0	8	7	0	3·75	17	6	29	60	28·00

Matmora location: 1 = bottom; 2 = top; 3 = centre; 4 = side of the matmora.

3.9. *Fungal analysis*

Quantitatively, there was a significant difference between fungal growth in the two treatments (Table 4). There were over three times more kernels with *Aspergillus flavus* Link growth in the straw-lined pits than in the pits with plastic lining, over 2·5 times more *Aspergillus candidus*, and over five times more *Aspergillus glaucus*, respectively. Qualitatively, the same community of fungi were found in both treatments. This included eight species of *Aspergillus* and *Penicillium* spp.

Because of the human health hazard associated with *A. flavus*, the 23% of the kernels infested with *A. flavus* may have been considered a total loss. To determine if these kernels were a 100% loss, aflatoxin analyses would be needed. However, at the time of this study, this capability was not available in Morocco.

Table 5

Changes in insect species in barley before and after storage in straw- and plastic-lined pits in Morocco

Insect species	Time after harvest, months	Time after underground storage, months	*Insects per kg after incubation**					
			Plastic-lined pit			*Straw-lined pit*		
			Live	*Dead*	*Total*	*Live*	*Dead*	*Total*
Rhyzopertha	9	0	635	304	939	391	183	574
dominica	15	6	9	129	138	3	113	116
Sitophilus	9	0	52	26	78	83	87	170
granarius	15	6	5	17	22	8	35	43
Cryptolestes	9	0	22	30	52	0	4	4
ferrugineus	15	6	2	4	6	22	7	29
Tribolium	9	0	0	0	0	0	0	0
castaneum	15	6	2·0	0·5	2·5	7	25	32
Total	9	0	709	360	1069	474	274	748
	25	6	18	151	169	33	180	213
% Reduction			98	58	84	93	34	72

* 230 g for eight weeks

3.10. *Insect populations*

Barley used for this experiment was heavily infested with insects (Table 5). The dominant insect was the lesser grain borer, *Rhyzophertha dominica* (F.), an obligate internal feeder in the larval stage and also a strong feeder of sound grain in the adult stage. In this experiment, before underground storage, there were 635 live adults/kg of *R. dominica* after eight weeks of incubation. Under ideal conditions, indeed in some national grades and standards, there is a zero tolerance for this insect. This grain was seriously infested. Prior to underground storage, this barley also contained 52 live adult granary weevils, *Sitophilus granarius* (L.), per kg following an eight week incubation. Weevils are also obligate internal feeders in the larval stage and capable of attacking sound grain in the adult stage.

The rusty grain beetle, *Cryptolestes ferrugineus* (Stephens) and the red flour beetle, *Tribolium castaneum* (Herbst) were found in numbers lower than the obligate internal feeders in both initial and final samples. *Tribolium* spp. are non-obligate internal feeders. They prefer broken kernels and fine materials, and when available, other insects. *Tribolium* were not detected in the initial samples. After incubation of the final samples, the population of *T. castaneum* had risen to 2·5/kg in the plastic-lined pits and 32/kg in the straw-lined pits. *Cryptolestes* can enter the kernel through minute cracks in the

Table 6

Distribution of insect infested barley after six months underground storage in straw- and plastic-lined pits in Morocco

Location in matmora	Insect species	Insects per kg after incubation					
		Plastic-lined pit			Straw-lined pit		
		Live	Dead	Total	Live	Dead	Total
	Rhyzopertha dominica	33	254	287	13	57	70
	Sitophilus granarius	14	13	27	30	18	48
	Cryptolestes ferrugineus	9	13	22	83	1	84
	Tribolium castaneum	5	1	6	26	54	80
	Total	61	267	342	152	130	282
	Rhyzopertha dominica	2	70	72	0	114	114
	Sitophilus granarius	2	27	29	0	24	24
	Cryptolestes ferrugineus	0	0	0	0	5	5
	Tribolium castaneum	0	0	0	0	9	9
	Total	4	97	101	0	152	152
	Rhyzopertha dominica	0	53	53	0	167	167
	Sitophilus granarius	1	21	22	3	60	63
	Cryptolestes ferrugineus	0	2	2	4	18	22
	Tribolium castaneum	0	1	1	0	27	27
	Total	1	57	78	7	272	279
	Rhyzopertha dominica	0	137	137	0	112	112
	Sitophilus granarius	1	5	6	0	38	38
	Cryptolestes ferrugineus	0	1	1	0	3	3
	Tribolium castaneum	1	0	1	0	10	10
	Total	2	143	145	0	163	163

pericarp. In the plastic-lined pit *C. ferrugineus* decreased from 52 to 6/kg but increased from 4 to 29/kg in the straw-lined pit, after incubation (Table 5).

There was a wide variation in the numbers of insects in different locations within each pit after the storage period (Table 6). In the plastic-lined pit, 61 of the 68 live insects obtained from the 4 kg sample set were found in the top of the grain mass. In the straw-lined pit, 152 of 159 live insects in the 4 kg sample set were located in the top of the grain bulk. The most dramatic reduction was in live insects in the plastic-lined pits. There was also a 24% greater reduction in the insect population and 44% less insects/kg in the plastic-lined pit. This should also have contributed to a lower percentage of damaged kernels in the plastic-lined pit. Of the four species groups, *Rhyzopertha* showed the greatest reduction, 99%, in both plastic and straw-lined pits. Hymenopterous parasites were found only in the plastic-lined pit in one of the samples after incubation (26·4 adults/kg).

4. Discussion

4.1. *Dry weight loss*

When m.c. of the grain is removed from the weight/unit volume data, changes in dry weight can be determined. Dry weight changes are those which change the grain mass but not the volume. One cause of dry weight loss is internal feeding of insects. This is also measured in the percentage of damaged kernels. Another cause of dry weight loss is due to use of the grain endosperm by fungi inside the kernel, particularly by those fungi that form a mycelial mat. These fungi may not germinate at all on the outer surface of the kernel. If they do not germinate on the outer surfaces, then the result of their damage can only be measured in dry weight loss and will not appear as a percentage of kernels with visible mould damage.

On the other hand, in this experiment, certain zones of the straw-lined pit experienced over 50% dry weight loss (Table 2), but visible mould growth, in the upper centre (1) and lateral (2) zones, covered 100% of the kernels. Local practices would consider all of these kernels unfit for consumption. To thoroughly represent loss, consumer practices need to be combined with dry weight loss. Thus, although dry weight losses for these two zones were only 33 and 53% respectively, in practice loss would have been 100%.

4.2. *Insect activity*

The underground environment significantly reduced the total live insect population within six months after placement in the matmora (98% in the plastic-lined pit and 93% in the straw-lined pit). In both pits, live insects present after storage were concentrated at the top of the grain bulk indicating enough oxygen was leaking in through the seal to support growth and development.

Of significant concern is the rise of *C. ferrugineus* and *T. castaneum* populations during the six month storage period. Levels of oxygen at the close of the experiment should have prevented an increase in insect populations. The lethal effect of low oxygen atmospheres containing appreciable quantities of CO_2 (greater than 1%) is known to be from the lack of oxygen not the presence of CO_2 (Bailey[9]). However, the presence of CO_2 even at levels of a few % assists the action of low oxygen atmospheres against some insects (Bailey and Banks[10]); (Calderone and Navarro[11]).

Tolerence to low oxygen atmospheres varies widely between developmental stages within insect species and between insect species. In general, pupae are the most tolerent stage and adults the most susceptible (Banks[12]). There is some disagreement in the literature as to the most tolerant species (Bailey and Banks[10]), but *Sitophilus* spp. are

probably most tolerant. Other species, such as *Tribolium* spp. may be even more tolerant (Banks[12]). No information is yet available in the literature for the oxygen tolerance of *C. ferrugineus*. One reason for the rise of *C. ferrugineus* in the straw-lined pit may be that these insects were able to tolerate the high CO_2/low oxygen atmosphere and were stimulated by the growth of fungi on which the insect feeds (Sinha[13]).

Temperature and moisture content conditions were within the boundaries for insect damage in both the plastic- and straw-lined pits throughout the storage period (*Fig. 6*). In above ground storage, these conditions would probably yield a much higher proportion of insect damage than in the pits due to low oxygen atmospheres and inaccessibility of the buried barley.

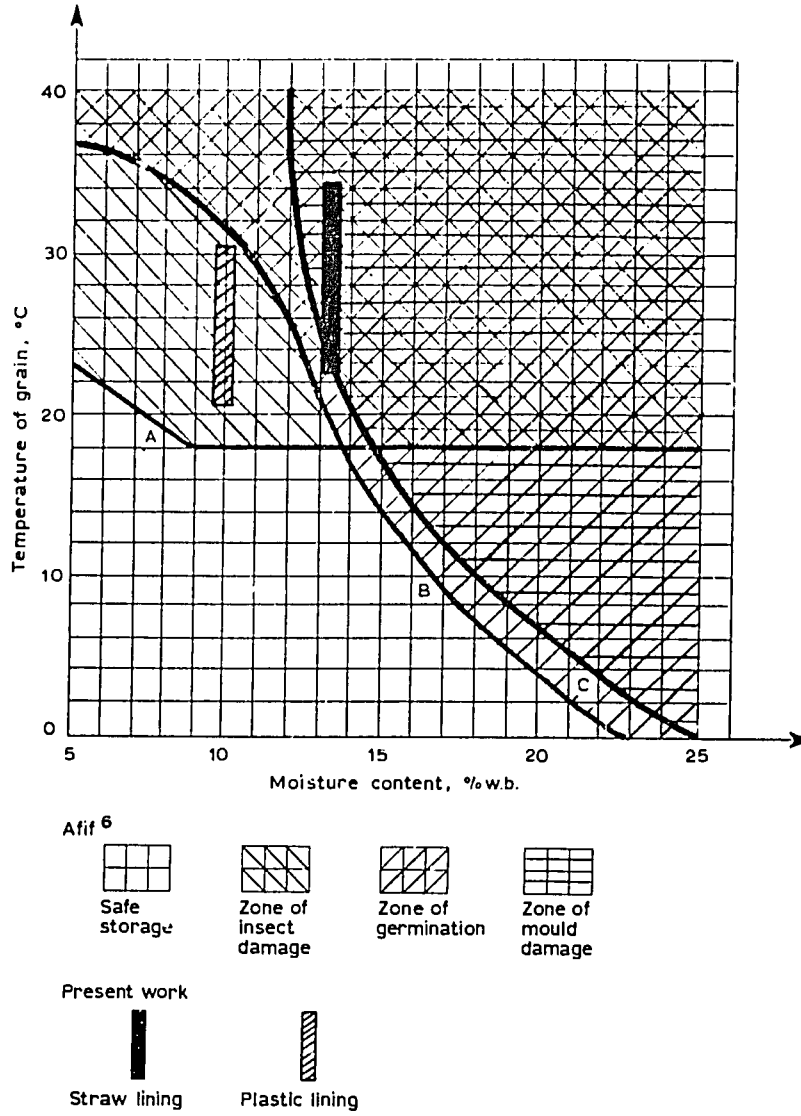


Fig. 6. Conditions for the safe storage of barley in relation to temperature and moisture content conditions observed in straw- and plastic-lined matmora

Because Moroccan farmers have utilized sealed storages for centuries, it is possible that certain species have developed resistance to levels of CO_2/oxygen normally encountered in matmora. The continual successful use of underground and hermetic storage over thousands of years is a tribute to the durability of the system. Insects, however, do possess anaerobic metabolic pathways and, thus could, at least in theory, adapt to survive periods of low oxygen. Most important is that some insect species can delay their development under low oxygen atmospheres. This character could be naturally selected for during widespread use of underground storage. Monitoring of such resistance in Morocco should be an important management tool.

4.3. *Fungal growth*

It was surprising to observe no significant rise in the percentage of damaged kernels due to visible mould growth in the straw-lined pit even though its % m.c. was significantly elevated compared to the plastic-lined pit. In both straw-lined and plastic-lined pits, the greatest loss due to fungi occurred at the top of the grain bulk. In the top section of both pits, there were significantly more live insects, more fungal infestation, and significantly more dead seeds. Moisture content was also higher in the top region of both pits. Two factors could account for these phenomena. Oxygen could have been higher in that area, thereby supporting higher populations of insects and those fungi which require high levels of oxygen. The increase in moisture content could have been a result of increased respiration of insects and fungi in that area.

Higher levels of dead seeds in the top regions of both pits are probably a result of the higher percentage of fungal infested seed in that area. Temperature and moisture conditions in the straw-lined pit, not the plastic-lined pit, were ideal for fungal development during the entire 200 day test period (*Fig.* 6). Although the percentage of fungal growth was elevated in the straw-lined pit, it may have been even greater if oxygen levels had not been reduced by the sealing of the grain bulk. Clearly, conditions for maintenance of good quality barley were not as ideal in the straw-lined pit as they were in the plastic-lined pit.

4.4. *Temperature profiles*

The higher temperatures in the straw-lined pit are not entirely explained by insect activity. It was only in the surface of the grain bulk that live insect numbers were high enough at the end of the experiment to generate measurable heat differences. A total of 152 insects/kg were obtained on the surface of the barley in the straw-lined pit, over 2·5 times as many insects than at that level in the plastic-lined pit. It is possible that towards the end of the six months storage period this heat diffused throughout the bulk causing the entire bulk in straw to be warmer than that in plastic. Another equally likely possibility is that initially, there were much higher live insect populations throughout both of the bins (474/kg in the straw-lined pits; 709/kg in the plastic-lined pits). The heat and metabolic water they produced may have lasted only a brief period in the plastic-lined pits before the high CO_2, low O_2 severely diminished the insect population. Not enough H_2O may have been produced to cause fungal populations to flourish.

On the other hand, in the straw-lined pits, insect populations may have experienced a much slower decline in O_2 and hence had greater numbers of live individual insects for more days. More H_2O would have been produced from metabolic activities, resulting in an increase in % m.c. and an increase in fungal growth. More heat would have been produced from the activity of these insects and the resulting internal fungi. The most plausible explanation of higher temperatures throughout grain in the straw-lined

matmora is that much of the heat was produced by the microbial action in the straw liner which surrounded the barley.

5. Conclusions

The underground environments prevent the entry of insects into grain after storage. The data show that if live, destructive insects enter with the grain, populations are reduced by 84 and 72% in plastic and straw-lined pits, respectively. Deleterious fungi, those which cause grain weight loss and produce toxins with carcinogenic and feed refusal properties, were two to four times more abundant in barley stored in the straw-lined than in the plastic-lined matmora. Seed viability during the storage period underground decreased from 72 to 23% in some regions of the straw-lined pit and only from 72 to 53% in the most infested area of the plastic-lined pit.

Dry weight loss, which is caused by a combination of insect and fungal development and loss of seed viability, depends on a combination of grain temperatures, % equilibrium r.h., and oxygen concentration in the grain mass. The addition of a tightly sealed plastic lining to the traditional matmora construction created an environment which did not support high levels of dry weight loss. Although there is the possibility that moisture migrated from the soil to the grain in the straw-lined pit, adequate moisture alone is not sufficient for growth of insects and fungi. Insects and loss-causing storage fungi also require adequate levels of oxygen.

From the results of this study we hypothesize that the straw-lined matmora may trap significant quantities of oxygen both inside and between the segments of straw. This oxygen may have been sufficient to allow growth of numerous *Aspergillus* and *Penicillium* species which could have resulted in the decreased seed viability in the straw-lined pit. The survival of any insects in these sealed environments should be further investigated for the possibility of a genetic tolerance to low oxygen levels in Moroccan storage insect populations which have been exposed to matmora for millennia.

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