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Evaluation of zeolite seed 'Drying Beads®' for drying rice seeds to low moisture content prior to long-term storage

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Summary

Four experiments were carried out using zeolite seed Drying Beads® to dry freshly harvested rice seeds to low (genebank) moisture content. The beads were mixed with 120 g of seeds in different ratios (between 0 and 3 beads-to-seed, by weight), sealed inside moisture-proof bags or heat-sealed laminated aluminium foil packets and placed in temperature controlled environments for drying and/or storage. The first experiment confirmed that the beads dry seeds very rapidly. The final moisture content of the seeds depended on the ratio of beads to seeds and, to some extent, on the temperature, with slightly more drying at 30°C compared with 15 or 5°C. When seeds were stored with the beads at either 5 or -20°C, seeds continued to dry. In the first two experiments, insufficient beads (bead-to-seed ratios of 0.97 and 1.06) were used to reach the target moisture content of 6.1%. The lowest moisture content reached was 4.2%, when the quantity of beads was three-times that of seeds. Germination was similar for seeds stored for 371 days at 5°C either with or without the beads after the same initial drying treatment. There was lower germination of seeds dried at low temperature and then stored at -20°C; however, this was attributed to dormancy. Whilst the water uptake isotherms confirmed the high capacity of the beads compared with silica gel, particularly at low relative humidity, the beads do not work to full capacity in a bead-seed system and the adsorption properties appeared to change. Further work is required to optimise the use of these beads for drying seeds to target moisture contents, without either under-drying which could lead to undesirable high rates of viability loss, or unnecessary and perhaps detrimental over-drying.

Introduction

In contrast to the bulk drying of large volumes of seed carried out by commercial seed and grain companies, genebanks often dry relatively small volumes of seed. It may be necessary to dry many different samples at any one time, but it is vital that the seeds from different accessions (i.e., plants or plots) be kept separate. It is also important that the quality of the seeds is not compromised, since this will reduce the longevity of the seeds in genebank storage.

The 1994 FAO/IPGRI Genebank Standards recommend drying seed germplasm as soon as possible after receipt, at 10-25°C and 10-15% RH, either in a drying chamber or using a desiccant, most commonly silica gel. Drying to equilibrium with these conditions

should mean that the seeds reach a target moisture content of 3-7% (fresh weight basis, FW), depending on the composition of the seed being dried. However, for some genebanks, particularly those in developing countries in wet tropical regions of the world, it may be difficult and costly to maintain a drying chamber or room of sufficient size to ensure the efficient drying of large numbers of freshly harvested germplasm samples, especially if power failures are a likely occurrence (Somado *et al*., 2006). It should also be noted that 10-25°C and 10-15% RH may not be the optimum drying conditions to maximise seed quality. For instance, it may be better to dry prematurely harvested seeds under conditions that simulate the conditions that would be experienced by the developing seed *in situ* (Probert *et al*., 2007), and Crisostomo *et al*. (2011) reported higher seed quality for eight of ten rice (*Oryza sativa* L.) germplasm samples (different accessions) initially dried using a heated-air batch-dryer, rather than in the genebank dryroom (15% RH, 15°C).

Desiccant drying in a closed container is often suggested as a low-technology method to reduce the moisture content of seed germplasm. Suitable desiccants include silica gel (sodium silicate), lithium chloride, calcium chloride, molecular sieve, charcoal and even other seed (Probert, 2003). The principle of drying using a desiccant is that the dry desiccant will take up moisture from the wet seed until the two come to equilibrium. How much water the desiccant adsorbs from the seed and how quickly it does so depends on a number of factors, including the ratio of desiccant to seeds, temperature, and the affinity of the desiccant for water. It may also be necessary to refresh the desiccant to ensure that seeds reach the target moisture content.

Aluminium silicate ceramics are a type of molecular sieve with very small, uniform pores where water molecules can be adsorbed. Small balls of this molecular sieve material are being marketed as seed 'Drying Beads®' with professed advantages over other desiccants including greater affinity for water, particularly at low humidity; more rapid drying; and no hysteresis effect, which reduces the amount of water that can be adsorbed following regeneration. The beads can be regenerated by heating to 200°C for 3-4 hours.

The aim of this study was to examine the potential of the drying beads to dry rice seed to the low moisture contents required for long-term genebank storage. Specifically, in the first experiments we aimed to dry freshly harvested seeds to two moisture levels, monitoring the rate of drying and the effect of storage over 1 year with or without the drying beads on seed germination. Since we did not reach the target moisture content in the first experiments, we subsequently carried out two further experiments that aimed to determine the final moisture content of seeds dried using different ratios of seed-to-bead and hence provide practical recommendations on the use of the beads for drying rice seeds to target moisture contents.

Materials and methods

Four experiments were carried out, between February 2011 and April 2012, as summarised in box 1.

Seed lots and desiccants

For experiments A and B, 50 kg of mature seeds of rice variety RD 31 were obtained from Pathum Thani Rice Research Center, Thailand, on 1 February 2011. Seeds had been harvested that day using a combine harvester and were transported to the laboratory at Prachin Buri Rice Research Center in a plastic seed bag. Upon arrival, five samples were taken using a spike sampler inserted at random within the seed bulk for determination of seed moisture content; the bulk was left, in the seed bag, in the laboratory until the following day when the experiment commenced.

For experiment C, a bulk lot of mature seeds of variety NSIC 148, grown at the International Rice Research Institute (IRRI), Los Baños, Philippines, was harvested on 9 June 2011 and threshed before transfer to the laboratory. Five samples of 5 g each were taken at random from the bulk seed for initial moisture content determination. Two further samples were taken to determine seed equilibrium relative humidity (eRH). The drying experiment was started immediately. This experiment was repeated starting 30 October 2011 (experiment D; also conducted at IRRI) using freshly harvested and threshed mature seeds of IR841. Samples were taken at random from the bulk lot for testing initial seed eRH (four samples) and moisture content (four samples).

The Drying Beads® used in all these experiments were provided by Rhino Research (Phichit, Thailand). Prior to setting up experiments A and B, the capacity of the beads as supplied was stated as 20%. For experiments C and D, the capacity of the beads was evaluated by placing them over water in a sealed container. The silica gel used in experiments C and D was sourced locally (Laguna, Philippines).

Moisture content and eRH determination

Seed moisture content was determined using the high constant temperature oven method (ISTA, 2005). Seed samples were ground in a blender [Phillips (experiments A and B) or Krups (experiments C and D)] and then weighed as two or three samples of approximately 5 g into pre-weighed aluminium crucibles. Samples were then dried in an oven at 130°C for two hours, cooled over silica gel for one hour, and reweighed. Moisture contents were calculated on a % fresh weight (FW) basis.

Seed eRH was determined at room temperature (approximately 24°C). Sufficient sample (intact seeds) was taken to fill a 3.2 ml sample holder, which was placed in the measuring chamber of an AW-D10 water activity station used in conjunction with a HygroLab 3 display unit (Rotronic South East Asia Pte. Ltd., Singapore). Measurements [water activity (= eRH/100) and temperature] were recorded once the readings had stabilised, typically after 20-40 minutes (longer for lower water activity).

Experiment A: Drying with beads, storage without beads

Samples of 120 g of seeds were weighed and mixed with either 116 g of drying beads (for drying to a target moisture content of 6.1% FW, hereafter referred to as 'T6.1') or 127 g of drying beads (for drying below the target moisture content, hereafter referred to as 'Excess') and then sealed inside 170 × 120 mm (L × W) press-seal plastic bags. The target moisture content is the expected equilibrium moisture content when rice seeds are dried at 15% RH and 15°C (Royal Botanic Gardens Kew, 2008). In total, 144 bags were prepared

for each seed-to-bead ratio and 48 bags for each seed-to-bead ratio placed at each of 5, 15 and 30°C (a domestic fridge, Global Refrigeration incubator model GN-22F and bench-top Binder laboratory oven model FED53, respectively).

One bag for each seed-to-bead ratio × temperature was removed after each of 0, 1, 3, 5, 8 and 12 hours, and 1, 2, 3, 7, 14 and 28 days (the 1-hour sample was removed five minutes early). Each bag was opened, seeds and beads quickly separated using a sieve, and beads immediately weighed (to determine the amount of water adsorbed by the beads). One sample of approximately 16 g of seeds was used for moisture content determination (three replicates) and four lots of 20 g (18 g from day 3 to take into account lower moisture content and therefore weight of seeds) were each heat-sealed inside moisture-proof 120 × 90 mm (L × W) laminated aluminium foil packets (hereafter, 'aluminium foil packets'); two of these were placed at both 5 and -20°C (domestic fridge and freezer, respectively). The remaining seeds were placed over water overnight to avoid the risk of imbibition damage during subsequent germination. Seeds were sown as two replicates of 50 seeds each, on 10 layers of tissue paper wetted with distilled water in 90 mm diameter Petri dishes. The seeds were incubated at 35°C for 16 hours in the light and at 15°C for eight hours in the dark and checked regularly for germination. A seed was scored as germinated when the secondary leaf appeared through the primary leaf. After 28 days, part of the hull was removed from non-germinated seeds and returned to the same germination conditions for seven days before taking a last count of germinated seeds.

After 28 or 371 days (53 weeks) storage, packets were removed from storage and allowed to equilibrate to room temperature. They were then opened and approximately 11 g used for moisture content determination (two replicates) with the remaining seeds placed over water overnight then sown as two replicates of 50 seeds each (three replicates in the case of the last samples, dried 28 days and stored 471 days), as above. Seeds in the Petri dishes were placed to germinate at 30°C in the dark and scored as before. After 14 days, part of the hull was removed from non-germinated seeds. They were then returned to 30°C and scored again after seven days.

Experiment B: Drying with beads, storage with beads

Samples of 120 g of seeds were weighed and mixed with either 116 g of drying beads (for drying to target moisture content, 'T6.1') or 127 g of drying beads (for drying below target moisture content, 'Excess') and then heat-sealed inside 240 × 160 mm (L × W) aluminium foil packets. In total, 96 packets were prepared for each seed-to-bead ratio and 32 packets of each placed at 5, 15 and 30°C, as for experiment A.

Four packets for each seed-to-bead ratio × temperature were removed after each of 5 and 8 hours, and 1, 2, 3, 7, 14 and 28 days and two placed at each of 5 and -20°C for storage of seeds with beads. After 28 or 371 days, packets were removed from storage and allowed to equilibrate to room temperature. They were then opened, seeds and beads separated using a sieve, and beads immediately weighed (to determine amount of water adsorbed by the beads). One sample of approximately 16 g of seeds was used for moisture content determination (three replicates) and one sample of approximately 10 g was placed over water for sowing the next day. Seeds were set to germinate as described for experiment A.

Box 1. Summary of the four experiments.

Experiment A: Drying with beads, storage without beads

Initial seed moisture content: 23.2% FW

Two bead-to-seed ratios: 0.9667 (T6.1) and 1.0583 (Excess); 120 g seeds
Three drying temperatures: 5, 15 and 30°C
12 drying periods: 0, 1, 3, 5, 8 and 12 hours; 1, 2, 3, 7, 14 and 28 days
Two storage temperatures: 5 and -20°C
Two storage periods: 28 and 371 days

Total number of samples: $2 \times 3 \times 12 \times 2 \times 2 = 288$

Experiment B: Drying with beads, storage with beads

Initial seed moisture content: 23.2% FW

Two bead-to-seed ratios: 0.9667 (T6.1) and 1.0583 (Excess); 120 g seeds
Three drying temperatures: 5, 15 and 30°C
Eight drying periods: 5 and 8; 1, 2, 3, 7, 14 and 28 days
Two storage temperatures: 5 and -20°C
Two storage periods: 28 and 371 days

Total number of samples: $2 \times 3 \times 8 \times 2 \times 2 = 192$

Experiment C: Drying with beads or silica gel – different ratios

Initial seed moisture content: 18.3% FW

Two desiccants: silica gel and drying beads
Nine ratios: 0, 0.67, 0.75, 0.83, 0.92, 1, 1.08, 1.17, 1.25; 120 g seeds
One drying temperature: 15°C
One drying period: 28 days

Experiment D: Drying with beads or silica gel and moisture adsorption isotherms

Initial seed moisture content: 22.6% FW

Two desiccants: silica gel and drying beads
Nine ratios: 0, 0.4, 6, 0.8, 1, 1.2, 1.4, 1.6, 1.8, 2, 3; 120 g seeds
One drying temperature: 15°C
One drying period: 90-95 days

At the time of the last sampling (seeds dried with the beads for 28 days and stored for 371 days), after separating and weighing the beads and seeds, the beads were placed over water in a sealed container at room temperature and reweighed at regular intervals for up to 40 days, in order to confirm bead capacity.

Experiment C: Drying using different ratios of desiccant (beads or silica gel): seed and germination testing

Samples of 120 g of seeds were mixed with 0, 80, 90, 100, 110, 120, 130, 140 or 150 g of freshly regenerated drying beads or silica gel and heat-sealed inside 120 × 90 mm (L × W) aluminium foil packets. Only one packet was prepared for each desiccant × desiccant-to-seed ratio. The packets were placed in a temperature-controlled room at 15°C. At the same time, two samples of 100 g of both silica gel and drying beads were placed over water overnight to determine the total capacity for water uptake (by weight) of the desiccants. The initial moisture content of the seeds was determined using five replicate samples of approximately 5 g each; initial seed eRH was determined for two samples sufficient to each fill a 3.2 ml sample holder.

After 28 days, packets were removed from storage and allowed to equilibrate to room temperature before they were opened one at a time, the seeds and desiccant (beads or silica gel) separated using a sieve, and both the seeds and the desiccant weighed to determine how much water had moved between the two. Samples of seeds and beads were then taken to determine seed eRH (two samples sufficient to fill a 3.2 ml sample holder from each packet) and five samples of seeds (approximately 5 g each from each packet) were used for moisture content determination. A sample of 200 seeds was used for germination testing, sown as eight subsamples of 25 seeds each on two layers of filter paper in 90 mm diameter Petri dishes at 30°C with 12 hours light day^{-1}. Seeds were checked for germination after 2, 3, 4, 5, 7 and 14 days. Finally, a sample of the remaining seeds from each packet was evaluated for proportion by weight, of broken or cracked seeds.

Experiment D: Drying using different ratios and determination of moisture adsorption (desiccant) and desorption (seed) isotherms

Two 50 g samples of silica gel and of drying beads were placed over water to determine the total capacity for water uptake (by weight) of the desiccants. The weight of each of these samples was measured after 1, 2, 3 and 7 days (at a similar time each day). Samples of 120 g of seeds were mixed with 0, 48, 72, 96, 120, 144, 168, 192, 216, 240 or 360 g of freshly regenerated drying beads or silica gel and heat-sealed inside 120 × 90 mm (L × W) aluminium foil packets. The packets were placed in a temperature-controlled room at 15°C. After 90-95 days, packets were removed, allowed to equilibrate to room temperature and then opened for eRH and moisture content determination.

To determine the seed moisture desorption isotherm, four samples of 5 g from the bulk seed lot were placed over non-saturated lithium chloride solutions (Hay *et al*., 2008) to give approximately 15, 20, 30, 40, 50, 60, 70 and 80% RH or over silica gel or drying beads within 165 × 110 × 65 mm (L × W × D) sandwich boxes with a rubber seal. All the boxes were placed at 15°C. After 90-95 days, seed samples were removed from the boxes and eRH and moisture content determined. To determine the desiccant

adsorption isotherms, samples of 20 g of each desiccant were placed in 120 × 90 mm (L × W) aluminium foil packets to which 0.4, 0.8, 1.2, 1.6, 2.0, 2.2, 2.4, 2.8, 3.0, 3.2, 3.4, 3.6, 3.8 or 4 ml water was added (two replicates per ratio for each desiccant). The packets were heat-sealed, gently shaken to mix and placed at 15°C. After 90-95 days, packets were removed and allowed to equilibrate to room temperature. The desiccant was then re-weighed and two samples used for eRH determination.

Data analysis

All analyses were carried out using GenStat Release 14.1 (VSN International Ltd.). A two-sample *t*-test was used to compare proportions of cracked seeds (experiment C) and to compare the moisture contents of seeds dried either by mixing with drying beads and sealing inside aluminium foil packets or by placing over drying beads in a sandwich box (experiment D). The FITNONLINEAR directive was used to fit the D'Arcy-Watt equation (D'Arcy and Watt, 1970) to the seed eRH and moisture content data determined independently (i.e. as a desorption isotherm equilibrating at different eRHs) and for seeds dried using either desiccant, in which:

$$\mathrm{WC} = \frac{K'K\,(\mathrm{RH}/100)}{1+K\,(\mathrm{RH}/100)} + c\,\rho/\rho_o + \frac{k'k\,(\mathrm{RH}/100)}{1+k\,(\mathrm{RH}/100)}$$

where *K*, *K'*, *c*, *k* and *k'* are parameters that relate to the number and strength of different water-binding sites. The fitted relationship for WC vs. RH was subsequently converted from dry weight to a fresh weight basis. The D'Arcy-Watt equation was also fitted to the bead water uptake-eRH data; the data obtained by adding water to the beads was fitted independently of that for beads used to dry seeds. Linear regression analysis with groups was used for the silica gel water uptake-eRH data.

Results

Experiments A and B

There was a very rapid uptake of water by the beads and a concomitant decline in the moisture content of the seeds regardless of either the ratio of beads to seeds or the temperature (experiment A; figure 1). As a proportion of the initial weight, the rate of uptake slowed earlier the lower the drying temperature; the rate of moisture loss from the seeds correspondingly slowed sooner the lower the drying temperature. The final moisture content reached also depended on the drying temperature, being slightly lower the higher the drying temperature (figure 1; tables 1 and 2). For example, for T6.1 seeds, the final moisture content after 28 days mixed with the beads was 10.5, 10.2 and 10.1% FW for seeds dried at 5, 15 and 30°C, respectively. The final moisture content, for both ratios of beads to seeds, was considerably higher than the target moisture content of 6.1% FW. The moisture content of the seeds was generally maintained in the aluminium foil packets during storage at 5 or -20°C for 371 days (tables 1 and 2).

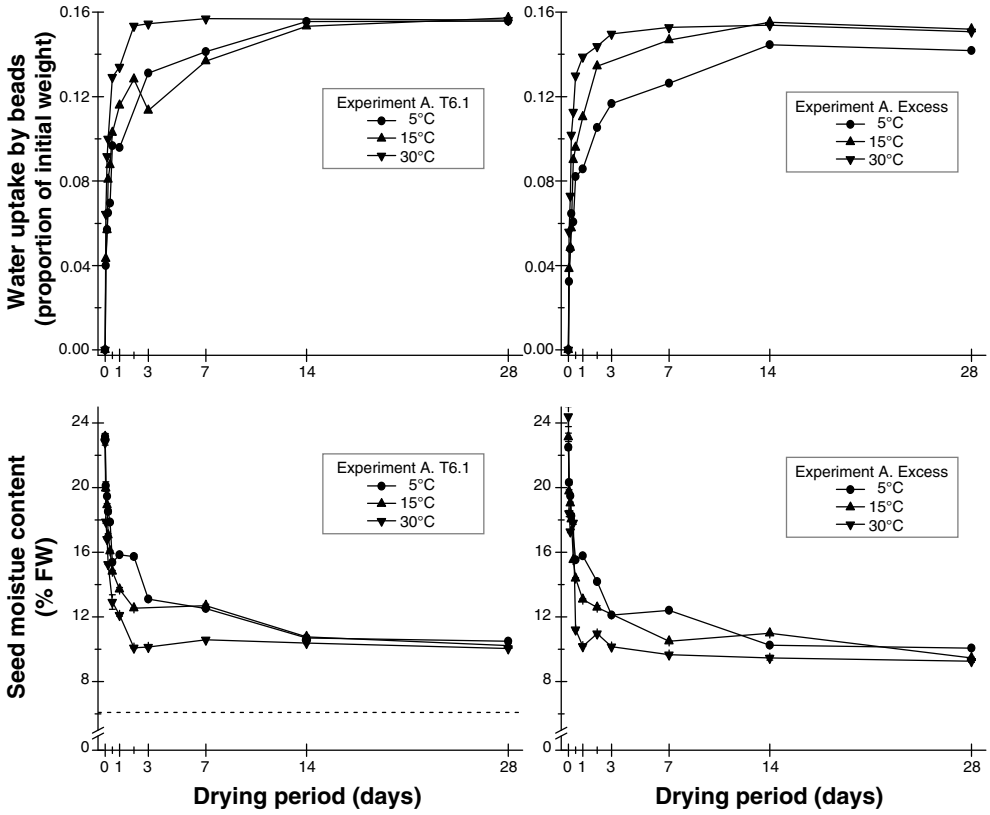

Figure 1. Water uptake by zeolite seed drying beads and moisture content of rice seeds during drying at three temperatures with two bead-to-seed ratios (experiment A): 116 g:120 g (T6.1) and 127 g:120 g (Excess). Also shown (dashed line) is the target moisture content of 6.1% FW.

There were further declines in seed moisture content when aluminium foil packets of seeds mixed with beads were transferred for storage at 5 or -20°C after 'drying' at 5, 15 or 30°C for up to 28 d (experiment B; cf. table 3 with table 1 and table 4 with table 2). After 28 days of storage at 5°C, the moisture content of the seeds was similar regardless of the initial drying period or temperature, with the exception of seeds dried for five hours (0.2083 days) at 5 or 15°C (tables 3 and 4). The mean moisture content did depend however, on the quantity of beads to seeds, ranging from 9.9 to 10.1% FW for seeds dried using 116 g of beads (T6.1) and from 8.8 to 9.1% FW for seeds dried using 127 g of beads (Excess). After 28 days of storage at -20°C, the moisture content of the seeds still varied depending on the initial drying period, for example between 16.1 and 8.6% FW, 16.2 and 8.8% FW, or 11.5 and 8.4% FW for seeds dried at 5, 15 or 30°C, respectively. Movement of moisture from the seeds to the beads did continue, even at this low temperature, most notably for seeds dried using the larger quantity of beads (table 4).

Table 1. Moisture contents during drying and following storage for experiment A with a bead-to-seed ratio of 0.9667 ('T6.1').

Drying period (days)	Mean seed moisture content (± s.e., where shown)					
	Initial†	Stored at 5°C		Stored at -20°C		Mean
		28 days‡	371 days‡	28 days‡	371 days‡	
Dried at 5°C						
0	23.2 ± 0.18	23.0	23.0	23.6	23.4	23.2
0.0382 (55 minutes)	20.1 ± 0.25	20.2	21.1‖	20.4	20.1‖	20.4
0.125 (3 hours)	19.5 ± 0.04	18.9	19.7‖	19.4	19.2‖	19.3
0.2083 (5 hours)	18.5 ± 0.13	-	-	19.2	18.4	18.7
0.3333 (8 hours)	17.9 ± 0.06	17.3	18.3	18.5	18.4	18.1
0.5 (12 hours)	15.4 ± 0.05	15.7	16.4‖	15.5	15.6‖	15.7
1	15.9 ± 0.03	16.1	12.0	15.9	15.6	15.1
2	15.7 ± 0.14	15.8	12.9	16.0	16.5	15.4
3	13.1 ± 0.06	13.0	10.8	12.9	12.0	12.4
7	12.5 ± 0.08	11.9	12.0	11.9	11.9	12.0
14	10.7 ± 0.04	10.3	10.1	10.5	10.2	10.4
28	10.5 ± 0.04	10.5	9.9	10.7	9.7	10.3
Dried at 15°C						
0	23.2 ± 0.20	23.0	22.7	23.5	23.7	23.2
0.0382 (55 minutes)	20.0 ± 0.19	19.9	21.4‖	19.9	19.9‖	20.2
0.125 (3 hours)	18.9 ± 0.09	19.1	19.7‖	19.0	19.1‖	19.2
0.2083 (5 hours)	17.1 ± 0.08	-	18.0	17.3	17.3	17.4
0.3333 (8 hours)	16.1 ± 0.04	16.2	16.9	16.1	16.7	16.4
0.5 (12 hours)	14.9 ± 0.08	15.2	15.5‖	15.1	15.2‖	15.2
1	13.7 ± 0.13	14.0	16.0	14.2	13.7	14.3
2	12.5 ± 0.03	13.1	12.8	13.5	13.4	13.1
3	14.4 ± 0.09	14.1	14.6	14.5	14.7	14.5
7	12.7 ± 0.09	12.5	-	12.2	11.9	12.3
14	10.8 ± 0.09	10.7	10.4	10.8	10.2	10.6
28	10.2 ± 0.12	10.5	10.0	10.4	9.8	10.2
Dried at 30°C						
0	22.8 ± 0.16	23.3	21.8	23.4	-	22.8
0.0382 (55 minutes)	17.9 ± 0.09	17.9	19.6‖	18.4	18.3‖	18.4
0.125 (3 hours)	16.8 ± 0.04	15.9	16.8‖	16.0	16.2‖	16.3
0.2083 (5 hours)	15.3 ± 0.02	-	15.3	15.0	15.1	15.2
0.3333 (8 hours)	11.6 ± 0.18	11.8	11.6	11.4	11.8	11.6
0.5 (12 hours)	12.9 ± 0.04	12.4	-	12.2	12.6‖	12.5
1	12.1 ± 0.08	12.1	-	12.2	12.0	12.1
2	10.1 ± 0.04	10.8	10.3	10.7	10.5	10.5
3	10.1 ± 0.03	10.6	9.9	10.7	10.1	10.3
7	10.6	10.4	10.0	10.3	10.1	10.3
14	10.4 ± 0.05	10.1	9.7	10.2	9.7	10.0
28	10.1 ± 0.01	9.8	9.4	10.1	9.0	9.7

†Mean ± standard error of three samples of approximately 5 g each; ‡mean of two samples of approximately 5 g each; ‖sampled 1 d later.
- Indicates missing or spurious result.

Table 2. Moisture contents during drying and following storage for experiment A with a bead-to-seed ratio of 1.0583 ('Excess').

Drying period (days)	Mean seed moisture content (± s.e., where shown)					
	Initial†	Stored at 5°C		Stored at -20°C		Mean
		28 days‡	371 days‡	28 days‡	371 days‡	
Dried at 5°C						
0	22.5 ± 0.15	23.5	21.9	22.9	22.6	22.7
0.0382 (55 minutes)	20.3 ± 0.15	19.7	19.7‖	19.7	20.1‖	19.9
0.125 (3 hours)	19.5 ± 0.06	19.6	18.5‖	19.6	19.5‖	19.3
0.2083 (5 hours)	18.3 ± 0.16	18.2	17.3	18.1	17.5	17.9
0.3333 (8 hours)	-	-	14.1	13.3	13.2	13.5
0.5 (12 hours)	15.5 ± 0.03	15.9	-	15.7	16.1‖	15.8
1	15.8 ± 0.06	15.9	16.4	15.8	15.9	16.0
2	14.2 ± 0.06	14.5	14.0	14.1	14.2	14.2
3	12.1 ± 0.01	12.3	-	13.1	13.7	12.8
7	12.4 ± 0.07	12.0	12.2	11.7	11.6	11.9
14	10.2 ± 0.08	10.3	9.9	10.2	9.4	10.0
28	10.1 ± 0.10	10.4	9.6	9.8	9.6	9.9
Dried at 15°C						
0	23.1 ± 0.26	22.8	21.5	23.3	23.1	22.8
0.0382 (55 minutes)	19.8 ± 0.11	20.0	21.0‖	19.7	20.4‖	20.2
0.125 (3 hours)	19.1 ± 0.07	18.9	19.2‖	18.8	19.0‖	19.0
0.2083 (5 hours)	18.1 ± 0.07	18.9	18.9	18.6	19.5	18.8
0.3333 (8 hours)	15.5 ± 0.01	15.5	-	15.5	15.2	15.4
0.5 (12 hours)	14.4 ± 0.04	14.5	15.0‖	14.6	14.7‖	14.6
1	13.1 ± 0.03	13.4	14.1	13.9	13.7	13.6
2	12.2 ± 0.06	12.3	11.9	11.8	11.8	12.0
3	13.8 ± 0.08	13.7	13.3	13.6	13.6	13.6
7	10.5 ± 0.02	10.2	9.9	10.2	9.7	10.1
14	11.0 ± 0.04	10.8	10.4	9.5	10.6	10.5
28	9.5 ± 0.05	9.5	8.9	9.4	8.8	9.2
Dried at 30°C						
0	24.4 ± 0.62	23.0	23.2	23.1	22.7	23.3
0.0382 (55 minutes)	18.4 ± 0.20	19.1	19.4‖	18.5	18.4‖	18.8
0.125 (3 hours)	17.3 ± 0.08	16.9	17.5‖	16.8	16.8‖	17.1
0.2083 (5 hours)	14.7 ± 0.06	14.7	14.7	13.9	14.8	14.6
0.3333 (8 hours)	17.8 ± 0.09	-	17.6	-	18.3	17.9
0.5 (12 hours)	11.2 ± 0.04	11.2	11.8‖	11.3	11.1‖	11.3
1	10.2 ± 0.01	10.5	10.4	10.2	10.3	10.3
2	11.0 ± 0.10	10.4	10.2	10.4	10.2	10.4
3	10.2 ± 0.04	10.1	9.4	10.0	8.9	9.7
7	9.7 ± 0.05	9.4	9.0	9.2	8.9	9.2
14	9.5 ± 0.15	9.2	8.8	9.4	8.7	9.1
28	9.3 ± 0.08	9.2	8.5	9.2	8.4	8.9

†Mean ± standard error of three samples of approximately 5 g each; ‡mean of two samples of approximately 5 g each; ‖sampled 1 d later.
- Indicates missing or spurious result.

Table 3. Moisture contents following different drying and storage periods for experiment B with a bead-to-seed ratio of 0.9667 ('T6.1').

Drying period (days)	Seed moisture content (mean ± s.e.†)			
	Stored at 5°C		Stored at -20°C	
	28 days†	371 days‡	28 days†	371 days‡
Dried at 5°C				
0.2083 (5 hours)	11.2 ± 0.08*	8.4	13.6 ± 0.07	10.4
0.3333 (8 hours)	9.7 ± 0.05	8.9	14.4 ± 0.10	9.7
1	9.9 ± 0.06	9.3	12.7 ± 0.09	10.1
2	10.4 ± 0.03	9.7	13.8 ± 0.14	11.0
3	9.8 ± 0.08	8.7	11.8 ± 0.01	9.9
7	10.0 ± 0.04	9.4	12.8 ± 0.03	9.9
14	10.1 ± 0.09	9.3	10.3 ± 0.03	10.0
28	9.5 ± 0.02	8.3	9.3	9.0
Mean ± s.e.	*9.9 ± 0.11*	*9.0 ± 0.18*		*10.0 ± 0.20*
Dried at 15°C				
0.2083 (5 hours)	11.0 ± 0.03*	9.0	13.9 ± 0.09	10.4
0.3333 (8 hours)	10.3 ± 0.04	10.0	13.1 ± 0.02	10.6
1	9.9 ± 0.06	9.8	13.3 ± 0.25	10.9
2	10.2 ± 0.02	9.9	11.4 ± 0.07	10.5
3	10.1 ± 0.19	10.1	12.0 ± 0.04	10.1
7	9.8 ± 0.03	9.5	11.3 ± 0.07	10.1
14	10.1 ± 0.25	9.1	-	9.7
28	9.5 ± 1.84	8.7	9.6 ± 0.06	9.0
Mean ± s.e.	*10.0 ± 0.10*	*9.5 ± 0.18*		*10.2 ± 0.21*
Dried at 30°C				
0.2083 (5 hours)	10.1 ± 0.10	9.0	13.7 ± 0.03	10.0
0.3333 (8 hours)	9.7 ± 0.04	10.3	14.3 ± 0.14	9.6
1	9.9 ± 0.05	9.7	10.8 ± 0.05	9.9
2	10.0 ± 0.09	8.9	10.4 ± 0.08	10.4
3	10.1 ± 0.17	8.8	9.5 ± 0.06	9.0
7	9.7 ± 0.02	9.2	9.7 ± 0.04	9.6
14	10.0 ± 0.03	8.8	-	9.5
28	9.7 ± 0.03	8.9	9.1 ± 0.03	8.9
Mean ± s.e.	*9.9 ± 0.06*	*9.2 ± 0.19*		*9.6 ± 0.18*

†Mean ± standard error of three samples of approximately 5 g each; ‡mean of two samples of approximately 5 g each.
* Not included in column mean.
- Indicates missing or spurious result.

Table 4. Moisture contents following different drying and storage periods for experiment B with a bead-to-seed ratio of 1.0583 ('Excess').

Drying period (days)	Seed moisture content			
	Stored at 5°C		Stored at -20°C	
	28 days†	371 days‡	28 days†	371 days‡
Dried at 5°C				
0.2083 (5 hours)	9.3 ± 0.02	7.8	16.1 ± 0.19	10.3
0.3333 (8 hours)	8.8 ± 0.10	8.5	12.7 ± 0.08	9.9
1	9.3 ± 0.05	8.5	12.5 ± 0.08	9.9
2	9.7 ± 0.07	8.6	14.2 ± 0.03	(12.8)
3	9.0 ± 0.07	7.7	11.8 ± 0.08	10.2
7	8.6 ± 0.06	8.0	10.0 ± 0.03	8.4
14	8.8 ± 0.14	7.8	8.4 ± 0.14	8.8
28	8.9 ± 0.11	8.2	8.6 ± 0.10	7.8
Mean ± s.e.	*9.1 ± 0.13*	*8.1 ± 0.13*		
Dried at 15°C				
0.2083 (5 hours)	8.7 ± 0.10	8.2	16.2 ± 0.03	8.6
0.3333 (8 hours)	9.2 ± 0.00	8.7	15.3 ± 0.07	(11.5)
1	9.0 ± 0.07	8.6	13.0 ± 0.14	9.3
2	9.4 ± 0.06	8.7	11.3 ± 0.07	10.3
3	8.7 ± 0.09	7.6	11.0	9.6
7	8.4 ± 0.05	8.0	10.0 ± 0.04	8.6
14	9.0 ± 0.03	8.0	8.0 ± 0.07	8.7
28	8.8 ± 0.05	7.9	8.8	8.1
Mean ± s.e.	*8.9 ± 0.11*	*8.2 ± 0.15*		
Dried at 30°C				
0.2083 (5 hours)	9.1 ± 0.12	8.1	11.5 ± 0.04	10.3
0.3333 (8 hours)	8.8 ± 0.08	8.7	12.9 ± 0.08	9.7
1	9.0 ± 0.03	7.7	10.9 ± 0.03	9.9
2	9.3 ± 0.12	8.6	10.0 ± 0.02	9.2
3	8.7 ± 0.04	7.6	8.3 ± 0.06	7.8
7	8.5 ± 0.07	8.0	8.7 ± 0.00	8.4
14	8.9 ± 0.01	7.1	7.8 ± 0.16	7.1
28	8.2 ± 0.07	7.8	8.4 ± 0.02	7.6
Mean ± s.e.	*8.8 ± 0.12*	*8.0 ± 0.19*		

†Mean ± standard error of three samples of approximately 5 g each; ‡mean of two samples of approximately 5 g each.

Results in parentheses were found to have a lower amount of beads than specified due to experimental error (121 g instead of 127 g) and were not included in the calculation of the mean (where shown).

The beads from experiment B samples dried for 28 days, stored for 371 days and placed over water at room temperature continued to adsorb water (figure 2). The rate of water uptake was fastest over the first couple of days and then gradually slowed. After 40 days, the mean amount of water taken up by the beads had increased from 15.5 to 17.0% when the beads were separated from the seeds, to a mean of 31.5% (s.e. 0.39) of their initial (pre-drying) weight for the 12 samples. The total end amount of water adsorbed did not appear to be influenced by the drying or storage temperatures.

The germination of seeds sown immediately after drying for up to 28 d (no storage; experiment A only) or after storage for 28 days (experiments A and B) varied considerably due to dormancy. Hence, only data after storage for 371 days are shown (figure 3). For seeds stored at 5°C without the beads (experiment A), there was generally high germination (≥ 95%) of seeds dried at least two days using either bead-to-seed ratio; for seeds stored at 5°C with the beads (experiment B), there was high germination of all samples (dried for at least five hours). Germination was lower for seeds that had been stored at -20°C. For seeds dried at 30°C, germination increased the longer the drying period, reaching ≥ 95% if they had spent at least 14 days drying at this temperature. For seeds dried at 5 or 15°C, 35-65% of the seeds were still dormant, even after 28 days of drying at these temperatures. Removal of a portion of the seed coat after 14 days in the germination test did release the dormancy from some of these seeds; for example, final germination of T6.1 seeds dried 28 days at 15°C and stored without the beads for 371 days reached 90%.

Experiment C

Beads placed over water overnight took up 17.5% ($n = 2 \times 100$ g) of their weight. The initial eRH of the seeds was 91.6% at 26.4°C ($n = 2$) and the initial moisture content was 18.3% FW ± s.e. 0.24 ($n = 5$) (figure 4). The greater the ratio (by weight) of desiccant to seeds, the lower the eRH and moisture content of the seeds after 28 days in a closed desiccant-seed system. On a weight ratio basis, the drying beads were more efficient than the silica gel in reducing seed moisture content at ratios greater than 0.75; at the lowest ratio (0.67), the silica was more efficient. Using the highest ratio of 1.25, the final eRH and moisture content of seeds dried using silica gel were 31.4% and 7.8% FW, respectively, compared with eRH 5.9% and moisture content 5.1% FW for seeds dried using drying beads. The moisture content achieved by drying using the beads was always higher than that expected if the beads adsorbed 17.5% of their weight (figure 4B). The eRH of the seeds was similar to that of the beads after 28 days of drying (figure 4A). In contrast, there was some discrepancy between the seeds and the silica gel in their final eRH.

There was generally high germination (97-99%) of seeds dried using either desiccant (figure 4A). The only treatment in which viability was compromised was the treatment with no desiccant and for which seed moisture content remained at 18.3% FW; the viability of these seeds declined to 91.3% after 28 days at 15°C in the aluminium foil packets. The proportion of seeds that were cracked was not significantly different between seeds that had been dried using silica gel and seeds dried using the beads (data not shown; including all samples, test for equality of variances, $F_{7,7} = 1.50$, $P = 0.61$; test for equality of means, $t = 0.86$, d.f. = 14, $P = 0.403$).

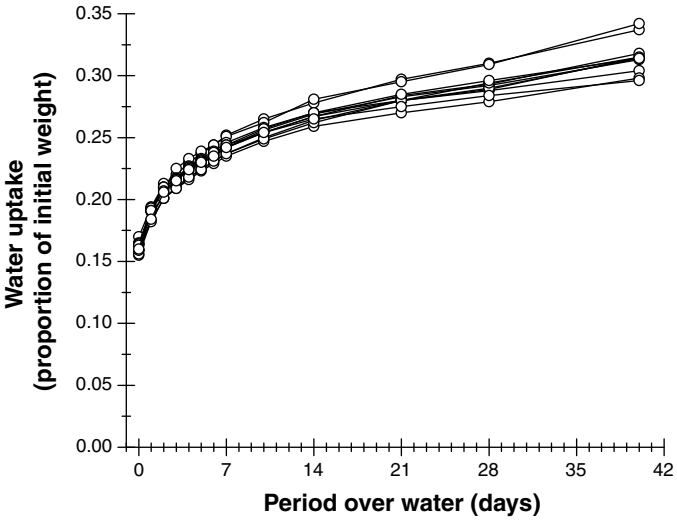

Figure 2. Uptake of water by the beads at the end of experiment B as a proportion of the initial weight before mixing with seeds for drying (i.e. 116 or 127 g). Samples had been dried for 28 days using two bead-to-seed ratios at 5, 15 and 30°C and stored for 371 days at 5 or -20°C.

Experiment D

For experiment D, the initial eRH of the seeds was 96.2 % ± s.e. 0.87 at 24.6°C and their initial moisture content was 22.6% FW ± s.e. 0.21 (n = 4) (figure 5). When placed over water for seven days, the beads adsorbed water to 23% of their initial weight (17.4% in the first 24 hours) and the silica gel adsorbed water to 30% of its initial weight (17.9% in the first 24 hours; figure 5B inset). Similar patterns of decline in seed, silica gel or bead eRH and seed moisture content were observed in experiment D as for C (cf. figures 5 and 4). The non-linearity of the relationship between seed eRH and the ratio of desiccant to seed weight is more apparent since there were more samples with lower desiccant-to-seed ratios (figure 5A).

The eRH of seeds was similar to that of the desiccant for ratios less than 0.8 or 1.4 for silica gel or beads, respectively. At higher ratios, there was generally a greater discrepancy in eRH between seeds and desiccant when the desiccant was silica gel rather than beads. The lowest seed eRH reached was 19% for seeds dried with silica gel (cf. 13% for the silica gel) and 0.9% for seeds dried with beads (cf. 3.2% for the beads; figure 5A). In terms of seed moisture content, the beads were more effective than silica gel when the ratio was greater than 1.4 (figure 5B). The lowest seed moisture contents reached using a desiccant-to-seed ratio of 3 were 6.6 and 4.2% FW for silica gel and beads, respectively; seeds dried over beads in a sandwich box reached a significantly lower moisture content than seeds dried by sealing inside an aluminium foil packet (3.5% FW; $t = 6.97$, $P < 0.001$).

There was no difference in the relationship between seed moisture content and eRH for seeds dried by placing at different relative humidities or using either desiccant, and

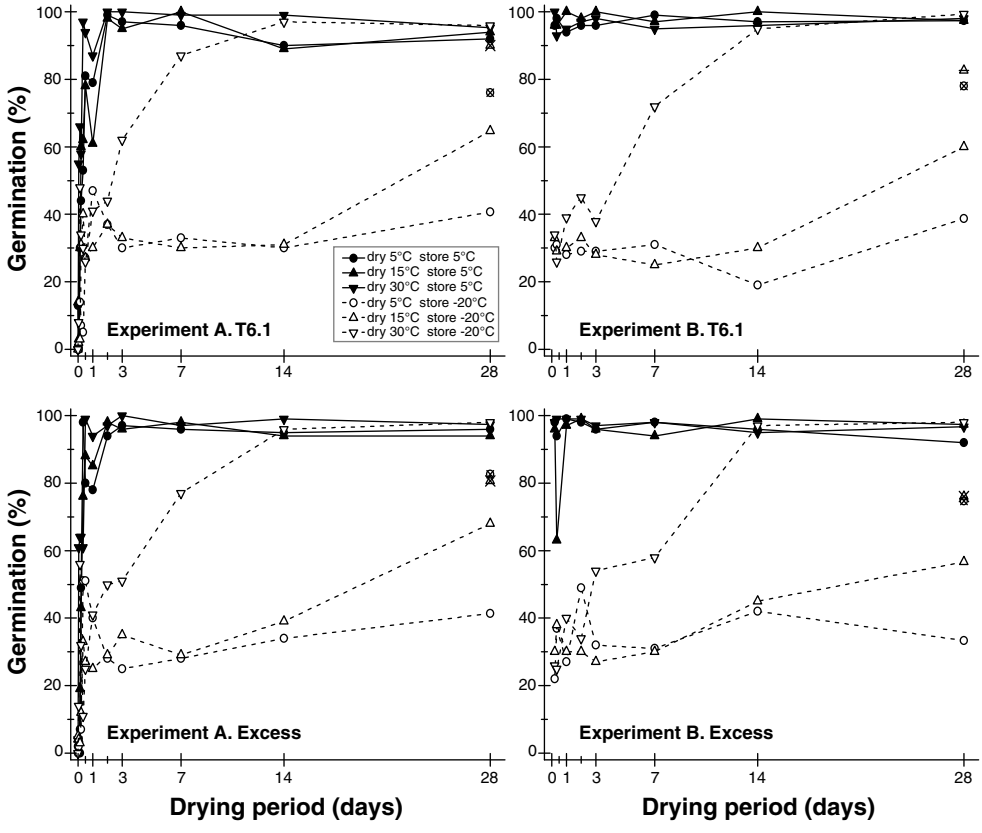

Figure 3. Germination of rice seeds after drying for different periods of time at three temperatures using two bead-to-seed ratios, followed by storage after removing the beads (experiment A) or in the same sealed packet with the beads (experiment B) for 371 days at 5 or -20°C. Additional points at 28 days (with a line through the symbol) indicates the final germination after removing a portion of the seed coat after 14 days in the germination test.

the D'Arcy Watt equation fitted the seed moisture content-eRH relationship well (variance accounted for = 98.7%; figure 6A). The shapes of the adsorption isotherms for the two desiccants were very different and also differed depending on whether the isotherm was determined by measuring the eRH of the desiccant after adding water and sealing inside aluminium foil packets or by measuring the eRH of desiccant that had been used to dry seeds (figure 6B). The bead isotherms were S-shaped and could be modelled using the D'Arcy-Watt equation (equation 2; variance accounted for = 99.0 and 96.7% for the isotherms determined by adding water or after drying seeds, respectively). In contrast, there was a linear relationship between water uptake and eRH for silica gel. As for the drying beads, the isotherm was shifted downwards to lower amounts of water uptake for a given eRH after drying seeds; the divergence increased as the amount of water taken up increased (variance accounted for by fitting two separate lines, 96.7%).

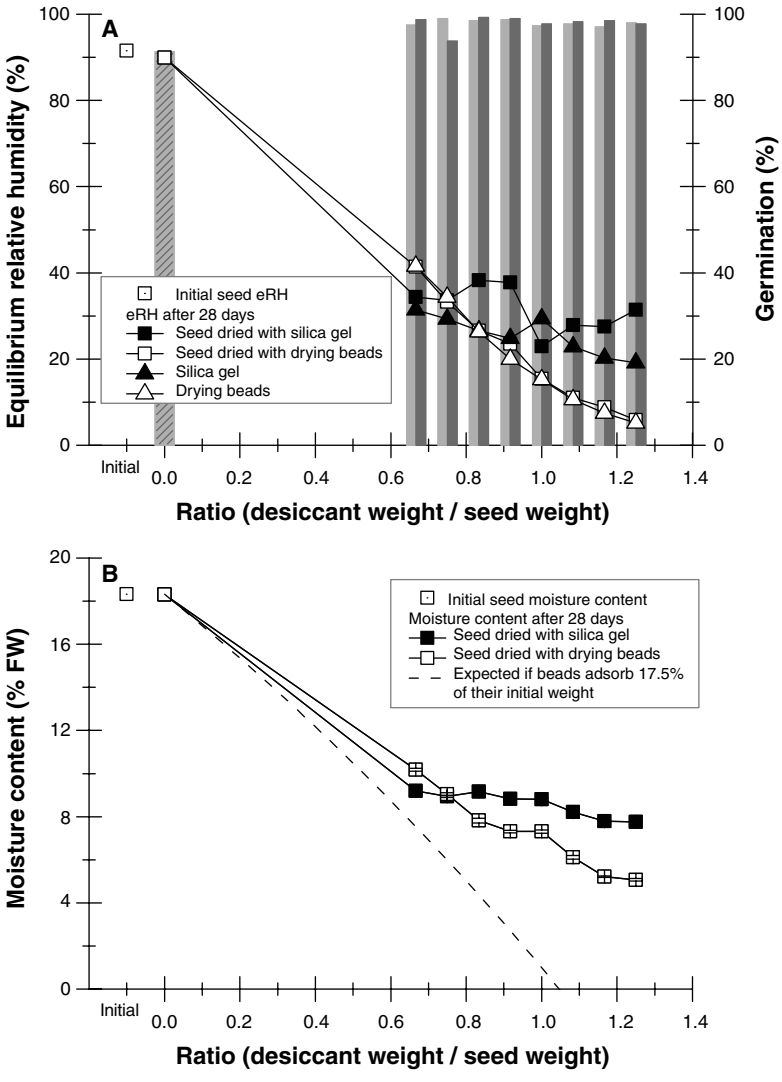

Figure 4. Results for experiment C. (**A**) eRH of rice seeds and desiccant (silica gel or drying beads) and (**B**) moisture content (mean ± s.e.) of rice seeds after 28 days of drying in heat-sealed laminated aluminium foil packets at 15°C using different ratios of desiccant to seeds. Also shown in (**A**), the germination of seeds stored for 28 days without desiccant (hashed column) and after drying with drying beads (light grey columns) or silica gel (dark grey columns); and in (**B**), the expected moisture content of seeds dried with beads if the beads took up as much water as they adsorbed overnight when placed over water in a sealed container at room temperature (17.5% FW; dashed line).

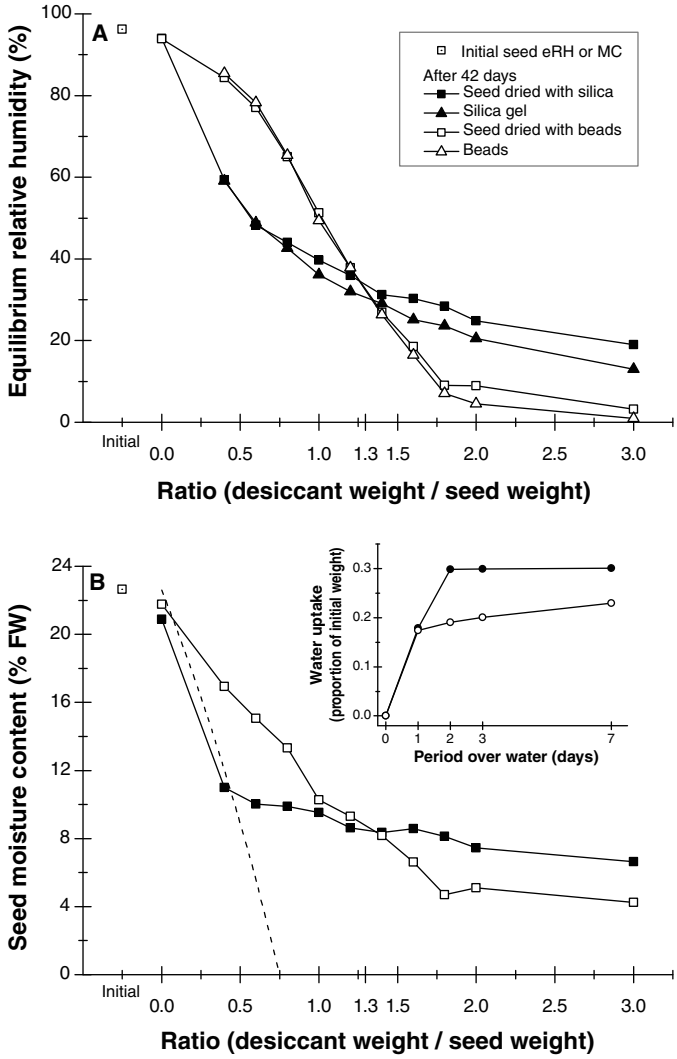

Figure 5. Results for experiment D. (**A**) eRH of rice seeds and desiccant (silica gel or drying beads) and (**B**) moisture content of rice seeds after 42 days drying in heat-sealed laminated aluminium foil packets at 15°C using different ratios of silica gel (solid squares) or beads (open squares) to seed. Also shown in (**B**), the expected moisture content of seeds dried with beads if the beads took up as much water as they adsorb when placed over water in a sealed container at room temperature for seven days (30.1%; dashed line). The inset graph in **B** shows the uptake of water by silica gel (solid circles) or beads (open circles) when samples of approximately 60 g were placed over water in a sealed container at room temperature for seven days ($n = 2$).

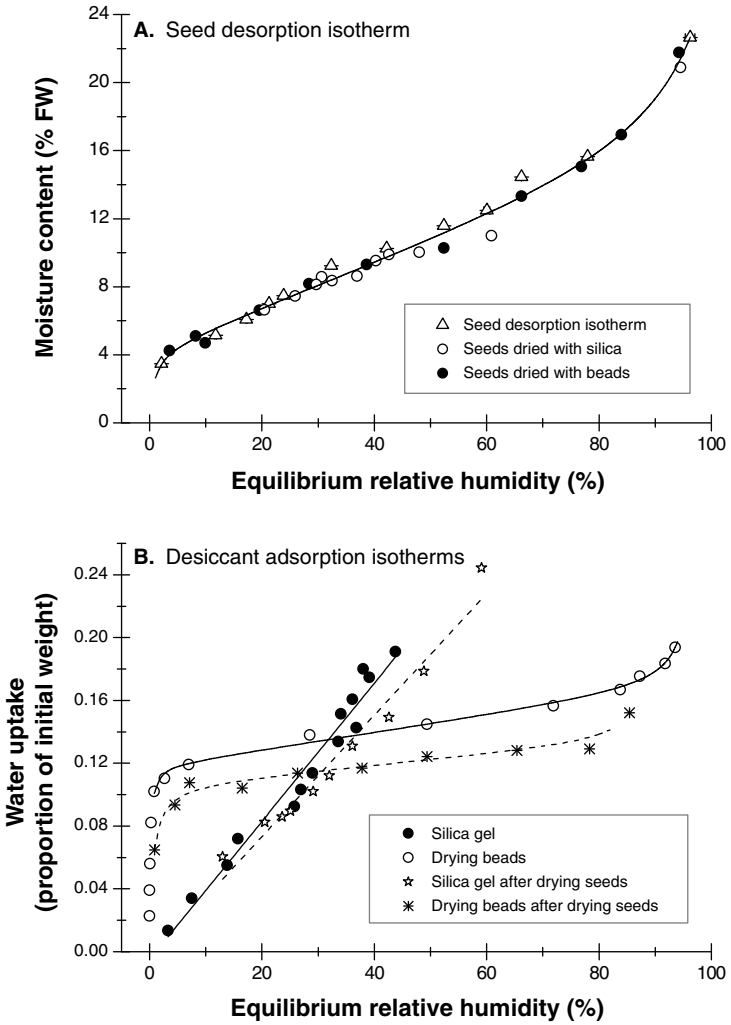

Figure 6. (**A**) Rice seed moisture desorption isotherm (experiment D). Seeds were either dried over different concentrations of LiCl, silica gel or drying beads in closed sandwich boxes (open triangles), or were dried using different ratios of desiccant to seeds (circles; data shown in figure 5). The curve shown is the result of fitting the D'Arcy-Watt equation to the data: K' = 0.044 (s.e. 0.0064), K = 139 (143), c = 0.132 (0.0267), k' = 0.0140 (0.00950), k = 0.933 (0.0561); variance accounted for = 98.7%. (**B**) Desiccant adsorption isotherm (experiment D). The solid curve is the result of fitting the D'Arcy-Watt equation to the data generated by adding water to the beads for eRH ≥ 0.8%: K' = 0.119 (s.e. 0.0032), K = 684 (203), c = 0.052 (0.0087), k' = 0.0011 (0.00100), k = 1.026 (0.0304); variance accounted for = 99.0%. The dashed curve is the result of fitting the same equation to the data for beads used to dry seeds (excluding data for eRH ≥ 78.3% due to high leverage): K' = 0.107 (s.e. 0.0057), K = 169 (42.0), c = 0.031 (0.0288), k' = 0.0008 (0.00676), k = 1.123 (0.249); variance accounted for = 96.7%. The data for silica gel was fitted using linear regression analysis with groups (data collection method): intercept = -0.005 (0.0065), slope = 0.0044 (0.00022) for data generated by adding water to the silica gel; intercept = -0.004 (0.011), slope = 0.0039 (0.00032) for silica gel used to dry seed; variance accounted for = 96.7%.

Discussion

The importance of drying to extend the longevity of orthodox seeds is undisputed. For genebank storage, where the aim is to maintain the viability of seeds for many decades, it is recommended that seeds be dried to moisture contents between 3 and 7% FW and efforts are made to ensure that the seeds are not able to take up moisture during storage by using air-tight containers, such as heat-sealed laminated aluminium foil packets (FAO/IPGRI, 1994). Controlled drying of multiple samples of relatively small volumes of seed can, however, be problematic, especially if a reliable drying chamber is not available; using a desiccant offers a practical alternative. Silica gel has been the desiccant that is most widely used and obtainable, but zeolite Drying Beads® are becoming available around the world and are already being promoted as a new technology for drying horticultural seeds in a number of developing countries (UC Davis, 2009). One of the advantages of the beads over silica gel is their high affinity for water molecules particularly at low RH, as confirmed by the moisture adsorption isotherms determined either by adding liquid water directly to the desiccant or by determining water uptake after drying seeds (figure 6B). Although the silica gel isotherms were linear, the bead isotherms were S-shaped. The very high value of the *K* parameter when the D'Arcy-Watt equation was used to model the bead isotherm data is indicative of the high affinity for water at low RH. Further, the high ratio of *K'/k'* indicates the high number of strong water-binding sites over multimolecular water-binding sites.

Not surprisingly then, the beads were indeed able to dry rice seeds to low moisture content. When a bead-to-seed ratio of 3 was used, the seed moisture content was reduced to 4.2% FW (3.4% eRH; experiment D, figure 5B). This moisture content was considerably lower than the moisture content reached when silica gel was used at the same ratio, although the silica used in these experiments (C and D) was not refreshed during drying, as is recommended (Rao *et al*., 2006). For drying to higher moisture contents (> 9-10% in these experiments), silica gel was more efficient on a weight ratio basis. For seed producers or sellers who do not need to maintain seeds with high viability and quality for very many years, silica gel may be satisfactory if a desiccant system of drying is being sought, although other factors such as regenerability and cost need to be taken into account.

At the outset of this study, we were working on the basis that the beads would adsorb as much water in a bead-seed system as they did when they were placed over water; it was also assumed that the beads would adsorb all the water that they could within a couple of days and hence bead capacity could be relatively quickly and easily determined. The calculation of the ratio of beads to seeds required to reach the target moisture content of 6.1% FW was made on this basis, with an expected bead capacity of 20% and having tested the initial moisture content of the seeds. However, there was a large discrepancy between this target moisture content and the actual moisture content reached, even after 28 days of drying (figure 1). Furthermore, even when an excess of beads was used, moisture content of 6.1% FW was not reached. Clearly, the beads did not work to their full potential capacity in our bead-seed system and calculating the quantity of beads to use is not as straightforward as expected.

This became more apparent following experiment D: the moisture adsorption (water uptake as a proportion of initial weight) isotherm of the beads after drying rice seeds shifted downwards (i.e. lower amounts of water uptake for a given eRH) compared with the isotherm determined by adding water directly to the beads, across the entire eRH range where measurements were made (figure 6B). Similarly, the water uptake-eRH relationship for silica gel varied depending on how the data was derived. Differences in adsorption behaviour of beads depending on how they have been used is further suggested by the difference in moisture content of seeds dried with the beads in tightly packed aluminium foil packets and of seeds dried by placing seeds over beads in a sandwich box, for the purpose of determining the seed desorption isotherm in Experiment D (figure 6A). Less efficient seed drying has also been observed when beads and seeds have been mixed and packed under vacuum (J. van Asbrouck, pers. comm.). Packing the beads and seeds tightly and therefore limiting the availability of air may alter the adsorption capacity of the beads, although why this effect appeared to be permanent (i.e. was still apparent when the eRH of the beads was determined using the same water activity measuring equipment) is not clear.

It may nonetheless be possible to estimate the quantity of beads to use based on the seed desorption isotherm and the bead adsorption isotherm in a tightly packed bead-seed system (figure 6). Isotherm data are available for a range of mainly food crop species or can be estimated using Cromarty's equation if seed oil content is known [Cromarty *et al.*, 1982; also available online (Royal Botanic Gardens Kew, 2008)]. Seed desorption isotherms should be relatively constant between seed lots within a species, whilst the bead adsorption isotherm in a bead-seed system might be predicted to be constant for different seed lots within a species but will vary depending on the initial capacity of the beads. Initial bead weight should be close to the dry weight of the beads, but it may depend on how the beads have been regenerated and stored (i.e. how much water they have already adsorbed). Since isotherms vary with temperature, if a degree of preciseness is required, drying should still be carried out in a temperature-controlled environment. It has also become clear during the course of this study that when the beads are placed over water, after an initial, very rapid uptake of water, water continues to be adsorbed for quite some time (figure 2; figure 5B inset). It may therefore be necessary to develop a standard method for determining a baseline indication of capacity to use in the ratio calculations. There may always be a temptation to use an even greater quantity of beads. However, without care, there may be a risk of drying the seeds to a moisture content lower than the critical moisture content, below which there are no further benefits in terms of increasing longevity (Ellis *et al*., 1995).

Although we did not use sufficient beads to reach the target moisture content in experiments A and B, the data do show the rapid rates of drying achieved using the drying beads (figure 1, tables 1-4). The initial rate of drying did not vary depending on the bead-to-seed ratio or on the temperature, but the point at which drying started to slow was earlier the lower the temperature of drying or the lower the ratio. Furthermore, drying did continue even during storage at -20°C. The rates of drying with silica were not determined, but it certainly appears that these rates of drying were very much faster than might be achieved by placing a sample of seeds in a dryroom (15% RH, 15°C;

Crisostomo *et al*., 2011). This rapid drying did not appear to impair germination ability, with germination observed after drying for 28 days (figure 4A) or drying and storage for 371 days (figure 3); however, such a fast rate of drying may be detrimental to the quality of less mature seeds (Probert *et al*., 2007; Hay and Probert, 2012). Neither did drying using the beads result in a higher proportion of cracked or broken seeds (experiment C). Low germination was observed only in experiment A for samples in which viability might have been expected to be lost due to a shorter drying period and hence a higher storage moisture content, or in experiments A and B, when some of the seeds were still dormant.

At harvest, rice seeds generally show a degree of physiological dormancy that may be overcome by after-ripening (Seshu and Dadlani, 1991), typically a dry heat treatment (50°C) of seven days (ISTA, 2005). Significant proportions of the seeds that were stored at -20°C after drying were still dormant after one year with the exception of seeds initially dried at 30°C for 14 or 28 days (figure 3). In contrast, if seeds were stored at 5°C, dormancy continued to be broken during storage (cf. open and solid symbols in figure 3). Crisostomo *et al*. (2011) suggested that it may be better to dry seeds of tropical species at a higher temperature than that recommended for genebanks (FAO/IPGRI, 1994) and certainly there is no evidence from the current study that drying at 30°C might be detrimental. It is possible that the seeds were exposed to even higher temperatures since there is an exothermic reaction when the beads adsorb water and this may have further accelerated the release of dormancy from the rice seeds. However, for very wet seeds and for species other than rice, this could be a potential drawback when drying seeds with high ratios of beads to seeds.

To conclude, we have found that seeds can be rapidly dried to low moisture contents by mixing with Drying Beads® and sealing them in a suitable air-tight bag or box. The final moisture content reached will depend on the initial capacity of the beads for water, the initial moisture content of the seeds, bead-to-seed ratio and, to some extent, the temperature of drying. Drying could be monitored, perhaps every few hours, to avoid the potential risk of over-drying, for example by regularly weighing the seeds after separating them from the beads (a simple and fast procedure) or taking a small sample for a moisture content test. If more convenient, seeds can be stored with the beads for some time (e.g. up to one year) without a detrimental effect on the seeds. Otherwise, further work is required to determine a protocol for calculating optimum bead-to-seed ratios to reliably dry seeds to target moisture contents; seed moisture desorption isotherms may be a key component of such a protocol. Protocols may need to be adjusted for different species to take into account different compositions and hence water desorption characteristics.

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