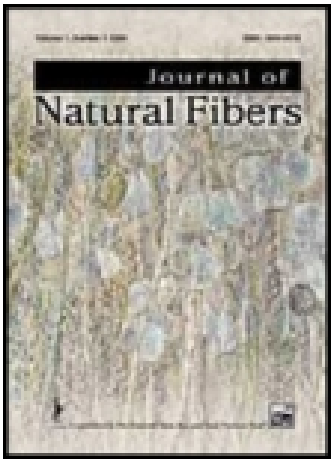

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Ernest Small [a] & Brenda Brookes [a]
[a] Biodiversity, National Program on Environmental Health , Agriculture and Agri-Food Canada , Ottawa , ON , Canada
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Temperature and Moisture Content for Storage Maintenance of Germination Capacity of Seeds of Industrial Hemp, Marijuana, and Ditchweed Forms of *Cannabis sativa*

ERNEST SMALL and BRENDA BROOKES
Biodiversity, National Program on Environmental Health, Agriculture and Agri-Food Canada, Ottawa, ON, Canada

Cannabis sativa *seeds of three industrial hemp cultivars, a medicinal strain of marijuana, and a ruderal strain were subjected to combinations of four temperatures (20°C, 5°C, −20°C, and −80°C) and three seed moisture contents (approximately 11%, 6%, and 4%) for 66 months. Storage of seeds with a moisture content of 11% at 20°C reduced the germinability of seeds of all varieties to zero in less than 18 months. Either reducing the temperature to at least 5°C or reducing the seed moisture content to at least 6% had a huge beneficial effect on maintaining seed viability. Additional reduction of temperature, but not additional reduction of moisture content had a small supplementary beneficial effect. No apparent benefit was noticed from oxygen-free seed storage.*

KEYWORDS Cannabis sativa, *industrial hemp, marijuana, ditchweed, germination, seed storage, germplasm*

INTRODUCTION

General Information on *Cannabis*

The genus *Cannabis* is economically important as (1) the source of a bast fiber (both the plant and the product are known as "hemp"), (2) the source of an oilseed (both the plant and the product are known as "hempseed"), and (3) the source of authorized medicinal drugs (both the plant and

Address correspondence to Ernest Small, National Program on Environmental Health, Agriculture and Agri-Food Canada, Ottawa, Ontario K1A 0C6, Canada. E-mail: Ernie.Small@agr.gc.ca

the product are known as "marijuana"). In addition, "wild" or "weedy" forms of hemp are common in many areas (in the United States, these are referred to as "ditchweed" because they are often found in moist ditches); these are also economically valuable as sources of germplasm for hemp breeding and as sources of low-quality fiber for certain purposes (J. D. Baker, personal communication, May 2, 2005). Considering both its positive and negative effects, *Cannabis* is one of the world's most significant crops.

Cannabis is usually regarded as having just one species, *Cannabis sativa* L. Small and Cronquist (1976) divided this into two subspecies, subsp. *indica* (Lam.) E. Small & Cronq. with relatively high amounts of the psychotomimetic chemical tetra-hydrocannabinol (THC), and subsp. *sativa* with low amounts of THC. In this study, the accession labeled "Medicinal" is assigned to subsp. *indica*, the remaining four accessions to subsp. *sativa*. Small and Cronquist (1976) divided subsp. *sativa* into two taxonomic varieties: var. *sativa*, which includes most forms domesticated for fiber and/or oilseed (and often known as "industrial hemp"), and var. *spontanea* Vavilov, which includes low-THC "wild" or "ruderal" forms commonly found in north temperate regions of the world. In this study, the accession labeled "Ruderal" is assigned to var. *spontanea*, and the cultivars "Carmen," "ESTA-1," and "USO-31" to var. *sativa*. Most cultivars grown in the Western world are "dual-purpose," employed both for fiber and oilseed production.

Until the middle of the nineteenth century, hemp rivaled flax as the chief textile fiber of vegetable origin. Subsequently, competition with tropical fibers and the growing reputation of *C. sativa* as an illicit recreational narcotic greatly suppressed the importance of hemp. After the Second World War, cultivation of hemp essentially ceased in most of the Western world. By the early 1990s, hemp cultivation resumed in Europe, and in 1998 in Canada, under special licensing. Especially in Canada, hemp is being developed more as an oilseed, but frequently also with fiber usage of the straw remaining after harvest. Indeed, it needs to be stressed that regardless of the principal product for which forms of *C. sativa* are grown, there are dozens of commercial applications for the fiber components. The authorized use of *C. sativa* as a prescription source of medicinal marijuana has also developed in Europe and Canada. The U.S. Federal Government to date has resisted the resurrection of *C. sativa* crops, and proscribes the cultivation of all forms of *C. sativa*. The suffocation of research on *C. sativa* that occurred during most of the twentieth century has retarded the legitimate twenty-first century development of industrial hemp, and this study is intended as a small contribution to the basic knowledge that is required. For comprehensive reviews of various aspects of *C. sativa*, see Small (1979, 2007), Small and Marcus (2002), and Small et al. (2003).

General Information on *Cannabis* Seed Germination

Technically, the propagules of *Cannabis* are fruits (achenes), but the common practice of referring to these as seeds is followed here. For commercial hemp production, the longevity of seeds decreases fairly rapidly to about 70%–80% after 2 years of storage in a sheltered but otherwise uncontrolled climate, and if not planted at least by then it is often recommended that they be discarded. In commercial practice, a minimum germinationof 85%–90% has been recommended (Bósca and Karus 1998).

Light has been reported to be a partial inhibitor of germination of hemp seed, including that of wild hemp (Haney and Kutscheid 1975). Commercial seed is generally planted 1–2 cm (sometimes to 4 cm) deep, sufficient for considerable shading, but also useful for moisture availability. However, all of the seeds utilized in the experiments reported here germinated readily under light. (A. R. McElroy has suggested to me that exposure to light while seeds are being dried conceivably could induce dormancy; this is a different consideration from how light intensity might immediately affect germination.) Optimal temperatures for germination vary with source, but are generally about 24°C, and this rather elevated temperature reflects a crop that is generally not planted early in the season because the seedling develops slowly at low temperatures. However, the seeds will often germinate at temperatures down to 0°C.

Most of the literature on industrial hemp seed germination is based on non-English literature, reflecting the fact that until recently the cultivation of *C. sativa* in the majority of the Western world has been prohibited since the Second World War. In one of the earliest studies, Goss (1924) tested germination of hemp seeds that had been buried in soil for 24 years, and observed no germination in tests conducted over several years. Kondo et al. (1950) found that hemp seeds, stored for 19 years with the desiccant calcium chloride, germinated, indicating the importance of controlling humidity.

Literature Review of Principal, Controlled Temperature, and Moisture Content Reports Concerning Longevity Preservation of *Cannabis* Seed

Crocioni (1950) studied seed moisture, temperature, air and light in relation to the longevity of hemp seeds of the Carmagnola variety stored at Bologna, Italy, for 3.5 years. He found that seed moisture and temperature were the most important factors, while air (oxygen availability) and diffused light instead of darkness were of uncertain influence. A temperature a few degrees above 0°C and a low seed-moisture content, up to 8.6%, were judged best for preserving germination capacity. Seeds of 10%–15% moisture content kept at high temperatures rapidly lost their germinating capacity. Seeds stored at low temperature retained satisfactory germination for 16 months, whatever the moisture content, and so did seeds of about 8% moisture content stored

at or below 27°C. Seeds stored longer than 16 months retained viability better at a seed-moisture content of about 6% than did seeds with a higher moisture content stored at a low temperature.

Toole et al. (1960) studied germination of Kentucky hempseed (much of which was of Italian origin). They reported that seeds stored at 5.7% moisture and 21°C did not decrease in germination after 6 years; seeds at 9.5% moisture maintained full viability for 5.5 years at both 0°C and −10°C.

Lemeshev et al. (1995) outlined plans for storage of *Cannabis* seeds at the Vavilov Research Institute Gene Bank in St. Petersburg, Russia, the largest germplasm collection of *Cannabis* seeds in the world. For their active collection (referred to as a working collection), used for short-term purposes of reproducing and distributing seed, the policy was to store the seeds at about 15°C and 10% moisture content. For "medium-term storage" (up to 10 years), collections were stored at 4°C–6°C and 7% moisture content. For long-term storage (10–20 years), the storage temperature was −20°C, and the moisture content was 6%.

Additional but less detailed reports on temperature and moisture requirements for conservation of germination capacity of hemp seeds are provided in Demkin and Romanenko (1978) and Laskos (1970).

Wild Seeds

"Wild" (ruderal or weedy) hemp, almost everywhere it occurs, was derived from plants that escaped from cultivation in past centuries, and re-evolved characteristics suited to wild existence. The seeds of wild plants have morphological features (small size, a camouflagic covering, and a basal seed abscission area) that easily distinguish them from the seeds of plants that are cultivated, either for fiber or illicit drugs (Small 1975). Also unlike the seeds of cultivated varieties of *Cannabis*, wild seeds of *Cannabis* are generally at least somewhat dormant and germinate irregularly, features that obviously adapt the plants to the environmental fluctuations typical of wild habitats. The dormancy requirement is typically satisfied by a period of cold treatment, aging, or some other natural condition furnished by nature. Haney and Kutscheid (1975) reported that seeds from wild Kansas populations declined in viability from 70% to 4.4% in 15 months of soil burial, an observation suggesting that seeds do not persist in a viable state in the soil for more than 2 or 3 years. Indeed, recommendations to control weedy volunteer hemp often mention that the site should be viewed for possible reappearance of the plant for 2 or 3 years (we have observed volunteer plants appearing for up to 4 years in experimental cultivation of wild plants in Ottawa). Haney and Kutscheid (1975) found that some fully mature Kansas wild hemp seeds could be germinated in the laboratory within 3 weeks of maturity in the fall, while seeds stored at room temperature reached maximum germinability in 3 months, but seeds stored at 5°C reached maximum germinability only after 5 months

(immature seeds, if viable, required a considerable period before they could be germinated). Janischevsky's (1924) study of Russian wild hemp seeds showed that fewer than 10% could be germinated immediately after maturation, but that repeated watering and drying cycles increased germination (water-soluble germination inhibitors may be present in wild hemp). Scholz (1957) and Vavilov (1926) noted that the germination of Russian wild hemp proceeds very slowly and intermittently, the seeds often remaining dormant for weeks or even months, with typically only 10% germinating promptly.

MATERIAL AND METHOD

The purpose of this study is to build on the general information reviewed above, for the practical purpose of establishing appropriate temperatures and seed moisture content for storing seeds of *C. sativa* in a viable state. All necessary licensing and security conditions for carrying out experiments with *C. sativa* were met. Information on the five accessions utilized is given in Table 1. All seeds for this study were received in early May of 2005, and experiments were initiated in the following month. Seeds utilized for experiments were first screened for uniformity: small, deformed, or otherwise obviously undesirable seeds were removed. Of the five accessions, only Medicinal and ESTA-1, which had been generated in 2004, had high germination. Seeds of Carmen and USO-31 were older, had not been stored under conditions that promote longevity, and had notably lower germination. Seeds of the wild variety, Feral, had a quite low germination rate, as is typical of wild seed.

Preparation of Seed Samples at Three Different Moisture Contents

The literature reviewed above suggested that for promoting seed longevity of hemp, 11% moisture content is too high, 6% is excellent, and it remains to be seen whether 4% is better for promoting seed longevity. Accordingly, the attempt was made to approximate these moisture contents in experimental seed samples. Maximum moisture content was obtained by placing samples of seeds for a week in a large closed container in which water was placed at the base to produce a humidity of 90%. Intermediate moisture content was achieved by placing seeds in a room with the humidity at 50% for a month. The lowest moisture content was obtained by placing the seeds, for a week, in a vacuum desiccator in which desiccant was placed at the base, with the apparatus subjected to pumping (500 mmHg vacuum) for an hour daily, with daily monitoring of seed moisture content (it was decided to avoid more extreme vacuuming, since there is no information on possible damage to seeds from this process). All of this preparation was carried out at 20°C, and seeds of all varieties were subjected to these procedures simultaneously

TABLE 1 Information on the five seed acquisitions examined

Variety	Medicinal	ESTA-1	Carmen	USO-31	Feral
Source	Prairie Plant Systems Inc., Saskatoon, SK	Arthur R. McElroy, PhytoGene Resources Inc., Orleans, ON	John D. Baker, Stonehedge Phytomedicinal Consulting Ltd., Stirling, ON	Great Plains Hempery Ltd. (TCV Farms Ltd.), Hemp Lady Products, Carberry, MB	John D. Baker, Stonehedge Phytomedicinal Consulting Ltd., Stirling, ON
Moisture content when received	Not determined	11.5	7.0	9.8	5.1
Germination percent when received[1]	99	85	55	37	36
1,000-seed weight (g) (oven-dried 24 h, 103°C)	14.5	18.1	18.8	15.8	14.6
Notes	This line is the marijuana supplied under license and prescription in Canada.	ESTA-1 is a Canadian cultivar bred by Dr. A. McElroy.	Carmen is a Canadian-bred cultivar, now under the ownership of the Ontario Hemp Alliance.	Accompanying literature stated that this was certified seed. USO cultivars are widely used in Europe.	This was identified as "breeder seed," tracing to a wild population in eastern Canada.

[1]The figures here are the actual germination percentages on receipt of these accessions. As noted in Section Material and Method, for experimentation, deformed and otherwise undesirable seeds were removed (most notably from "Carmen," which accordingly had a higher germination than noted here).

TABLE 2 Mean percent seed moisture content during experiment ($n = 500$ seeds for each cell, based on samples of 100 measured at each of the five times)

Variety	Lowest moisture content	Intermediate moisture content	Highest moisture content
Medicinal	4.1	5.7	10.5
ESTA-1	3.9	5.9	11.3
Carmen	4.0	5.8	11.2
USO-31	3.8	5.5	10.4
Feral	3.8	5.7	10.8
Means	3.9	5.7	10.9

and together in the same laboratory, to reduce experimental error. Seed moisture determinations, according to ISTA (2004), were made periodically for a month. Mean moisture contents achieved were 3.9%, 5.7%, and 10.9% (henceforth, these are referred to as nominally 4%, 6%, and 11%). As shown in Table 2, there were small differences in equilibrium moisture content of the different accessions, probably due in part to differences in ability to absorb moisture. The seed wall is quite hard, and may not be able to absorb much water, and so differences in seed wall thickness and proportion may account for the overall differences in ability to absorb water. The differences are minor and do not confound interpretation of the data.

Seed Storage Containers

Screw-cap glass vials (Fisher Brand 03-338C, 17 mm × 60 mm, 2 dram capacity) were used. At least 200 seeds each were placed in each for experimentation, generally resulting in about 3/4 of the vials being filled. The vials were closed hand-tight, as tightly as possible. To ensure that moisture content did not change (a possibility since screw-tops can loosen), on every occasion that a vial was employed as a source of 100 seeds for a germination test, moisture content was determined on another 100 seeds from the same vial. Screw-cap tightness was also checked at these times.

Standard Germination Test Procedure Adopted

Initial attempts to test germination of seeds on moist filter paper in petri plates or between wet paper towels indicated considerable variation in germination of the same seed samples, possibly because of the difficulty in maintaining moisture at a constant level. Moreover, under the high humidity that developed, fungi were active, causing disease. Partial sterilizing with Clorox did not make much difference. (We note that standard seed testing procedures of some commercial laboratories have sometimes produced much lower assessments of hempseed germination than claimed

by the producers, and there may be a need to assess hempseed viability test procedures.) Accordingly, it was decided to create a test system that closely mimicked nature. Seeds were germinated in a commercial substrate, the seeds buried shallowly, under a controlled light/dark regime, with appropriate controlled temperature and humidity. Under these conditions, the seeds were observed to germinate well and consistently. Several of the experimental vials stored at 11% moisture content and 20°C were affected by fungus. These were discarded and not used in the tests of viability.

For each germination test, 100 seeds were placed in a 10 cm × 25 cm container of Premier ProMix (potting and seeding (code 0442) substrate, 4 cm deep. (This is the same starting soil substitute for seeds that has been used in Canada's medicinal marijuana program. It is excellent, providing near-neutral pH, good nutrient balance, and good but not excessive water-holding capacity.) The seeds were scattered directly over the substrate, and lightly covered with 5 mm of the same material that had been screened through a sieve with 3.35 mm square openings. The containers had drainage holes. The "soil" mixture was soaked at the time of seeding, and it was not necessary to water again for 2 weeks of the germination test. Daylight regime consisted of: 16 h of light (provided by Agrosun® daylight-spectrum (color rendering index 93) fluorescent bulbs and a PAR of 100 $\mu mol/m^2/s$) at 60% relative humidity and 27°C, followed by 8 h of dark at 75% relative humidity and 20°C. A successfully germinated seed was judged to be one in which the young shoot had risen above soil level and the seedling appeared healthy. Seeds judged to have germinated were removed daily to prevent their interfering in any way with the germination of the remaining seeds. Generally, some seeds had germinated in a given sample after 2 days, and most seeds had germinated within 4 days. Two weeks was chosen as the cut-off date because very few seeds were observed to germinate after this period.

Controlled Temperature Conditions

Vials of seeds of the five accessions, prepared at three moisture content levels were placed in storage at four temperatures (20°C, 5°C, −20°C, and −80°C) providing 12 treatment combinations.

Schedule of Testing of Seed Germinability

Periodically (at 1, 6, 12, 18, and 66 months), one vial representing each of the 12 combinations of seed moisture content and temperature was withdrawn from storage. A sample of 100 seeds was employed for a germination test, and the remaining seeds in the vial were used to recheck moisture content.

Comparative Test of Seed Germinability After Storage in Air and in Nitrogen

As oxidation from storage in air is thought to affect seed longevity of some species, this factor was examined by comparing storage in air and in an oxygen-free atmosphere. Seeds of the five varieties were stored at two temperatures (20°C and 5°C), either in air or in 99.998% purified nitrogen, with germination tests conducted after 66 months. The samples used had a moisture content of 7%, achieved by equilibrating the seeds in a laboratory until this was achieved.

RESULTS AND DISCUSSION

Moisture content of the stored seeds was monitored to ensure that the containers used to store the seeds were moisture proof, neither gaining nor losing water. No evident changes in moisture content during the course of this study were observed.

Storage of seeds with a moisture content of 11% at room temperature (20°C) for 18 months reduced the viability of seeds of all varieties of *Cannabis* to zero (Table 3). It is clear that viability of *C. sativa* seeds deteriorates extremely rapidly at the very high moisture content of 11% when the seeds are stored at room temperature, and this combination of storage conditions is completely unsuitable for retaining seed viability. As can be seen in Table 3, the accessions with lower initial germinability, reflecting lower seed vigor, became completely inviable relatively quickly. However, storage of even very vigorous seed under such high moisture content and high temperatures is very unsuitable for retaining seed germinability for even 1 year (see Tables 4 and 5, for the accessions which had high initial germinability).

Germination percentages for the five *Cannabis* accessions at the three nominal moisture contents, four storage temperatures, and five times are shown in Tables 4–8, and means of the data for these five tables are shown in Table 9.

TABLE 3 Effects of maximum stress (20°C, 11% humidity) on time to seed inviability

Variety	Initial germination	Months to 99% seed inviability
Medicinal	99	18
ESTA-1	85	12
Carmen	55	6
USO-31	37	6
Feral	36	6

TABLE 4 Percent germination of medicinal variety (*n* for each cell = 100 seeds)

Time (months)	Percent moisture content (approx.)	Temperature (°C)			
		20	5	−20	−80
1	11	98	94	100	98
	6	100	100	99	99
	4	96	98	94	98
6	11	52	99	98	97
	6	91	98	100	100
	4	96	97	99	100
12	11	59	94	97	100
	6	97	92	96	100
	4	100	98	99	97
18	11	0	99	100	99
	6	95	100	100	100
	4	97	100	99	100
66	11	0	82	100	98
	6	100	100	100	100
	4	96	99	97	89

TABLE 5 Percent germination of variety ESTA-1 (*n* for each cell = 100 seeds)

Time (months)	Percent moisture content (approx.)	Temperature (°C)			
		20	5	−20	−80
1	11	82	86	85	86
	6	83	85	94	87
	4	78	84	86	87
6	11	2	86	90	89
	6	93	87	81	93
	4	88	91	93	86
12	11	0	84	82	88
	6	93	93	90	70
	4	91	85	89	88
18	11	0	79	89	89
	6	87	94	96	89
	4	88	91	94	95
66	11	0	3	90	91
	6	94	86	89	90
	4	91	87	88	89

Grand means (of all of the above data) showing seed germination in relation to the four temperatures are shown in Table 10. As can be seen, a substantial gain of germinability of about 18% was achieved by decreasing temperature from 20°C to 5°C, a small gain in germinability (less than 5%) was achieved by additionally decreasing the temperature to −20°C, but no gain in germinability was achieved by additional decrease to −80°C.

TABLE 6 Percent germination of variety Carmen (*n* for each cell = 100 seeds)

Time (months)	Percent moisture content (approx.)	Temperature (°C)			
		20	5	−20	−80
1	11	36	49	54	64
	6	61	66	70	76
	4	59	60	68	70
6	11	0	56	67	67
	6	81	78	81	71
	4	79	81	70	76
12	11	0	35	60	73
	6	73	70	80	70
	4	58	61	71	56
18	11	0	31	46	65
	6	62	84	77	68
	4	61	82	80	76
66	11	0	0	65	66
	6	43	68	82	63
	4	42	75	68	59

TABLE 7 Percent germination of variety USO-31 (*n* for each cell = 100 seeds)

Time (months)	Percent moisture content (approx.)	Temperature (°C)			
		20	5	−20	−80
1	11	7	33	27	15
	6	37	59	54	48
	4	39	48	40	44
6	11	1	15	35	26
	6	37	61	51	63
	4	46	61	62	63
12	11	0	14	23	34
	6	50	53	52	50
	4	34	44	49	52
18	11	0	3	25	29
	6	21	60	61	50
	4	29	59	73	60
66	11	0	0	39	40
	6	20	49	61	44
	4	14	49	61	58

Grand means (of all of the above data) showing seed germination in relation to the three seed moisture contents are shown in Table 11. As can be seen, a large gain of germinability of about 24% was achieved by decreasing soil moisture content from nominal 11% (actually 10.9%) to nominal 6% (actually 5.7%), but no gain in germinability was achieved by additionally decreasing seed moisture content to nominal 4% (actually 3.9%).

TABLE 8 Percent germination of Feral variety (*n* for each cell = 100 seeds)

Time (months)	Percent moisture content (approx.)	Temperature (°C)			
		20	5	−20	−80
1	11	15	14	17	30
	6	29	35	53	52
	4	40	43	40	53
6	11	0	34	30	26
	6	49	63	21	48
	4	63	65	42	44
12	11	0	21	15	49
	6	38	49	51	51
	4	32	36	58	36
18	11	0	17	28	36
	6	20	58	49	41
	4	27	32	60	64
66	11	0	0	36	32
	6	25	52	58	52
	4	21	58	65	57

TABLE 9 Mean germination of five varieties collectively (*n* for each cell = 500 seeds)

Time (months)	Percent moisture content (approx.)	Temperature (°C)			
		20	5	−20	−80
1	11	47.6	55.2	56.6	58.6
	6	62.0	69.0	74.0	70.4
	4	62.4	66.6	65.6	70.4
6	11	11.0	58.0	64.0	61.0
	6	70.2	77.4	66.8	75.0
	4	74.4	79.0	73.2	73.8
12	11	11.8	49.6	55.4	68.8
	6	70.2	71.4	73.8	68.2
	4	63.0	64.8	73.2	65.8
18	11	0.0	45.8	57.6	63.6
	6	57.0	79.2	76.6	69.6
	4	60.4	72.8	81.2	79.0
66	11	0.0	34.6	66.0	65.4
	6	56.4	71.0	78.0	69.8
	4	52.8	73.6	75.8	70.4

Grand means (of all of the above data) showing seed germination over the 66 months are shown in Table 12. Overall, seed germination decreased less than 4%, but this combined figure is misleading, as revealed by inspection of Tables 4–8. Only under conditions of very high humidity (11%) and very high temperature (usually −20°C, sometimes −5°C with weaker seeds) was seed germinability strongly affected, while under the conditions of either

TABLE 10 Grand means: Temperature ($n = 7{,}500$ seeds)

Temperature (°C)	Percent germination
20	46.6
5	64.5
−20	69.2
−80	68.8

TABLE 11 Grand means: Seed moisture content ($n = 10{,}000$ seeds)

Percent moisture content (approx.)	Percent germination
11	46.5
6	70.3
4	69.9

TABLE 12 Grand means: Time ($n = 6{,}000$ seeds)

Time (months)	Percent germination
1	63.2
6	65.3
12	61.3
18	61.9
66	59.5

low humidity or low temperature there was virtually no observable decrease in seed viability after 66 months.

The wild (feral) seeds germinated somewhat better after a period of storage at cold temperatures, a result that is consistent with the literature (Small et al. 2003). When received, 36% of the seeds germinated. Leaving aside the results for 20°C and 11% seed moisture content (which clearly reduced seed germination), the mean germination after 1 month of cold storage was 46%, and after 66 months was 57%. Some of the literature suggests that wild seeds of *Cannabis* require a period of cold stratification to overcome germination inhibitors (Small et al. 2003).

As can be seen in Table 13, no noticeable improvement in seed germination resulted from storing seeds in nitrogen rather than air. The seeds of *C. sativa* are known to be appreciably impermeable to air, as evidenced by the observation that the seed oil oxidizes (become rancid) with distressing rapidity once extracted (so preservation in cold, dark conditions is required for commercial purposes). The presence of the antioxidant vitamin E in the seeds would also provide protection against the deleterious effects of oxygen. These considerations likely explain why exclusion of oxygen did not improve seed germination.

TABLE 13 Comparison of percent germinability of seeds stored in air or nitrogen for 66 months (seed moisture content = 7%; *n* for each cell = 500 seeds)

	Storage in air		Storage in nitrogen	
Variety	20°C	5°C	20°C	5°C
Medicinal	95.8	97.4	94.2	98.2
ESTA-1	71.0	90.2	72.2	85.8
Carmen	21.0	88.2	25.6	83.2
USO-31	4.0	40.8	3.2	37.6
Feral	20.0	52.0	19.6	58.4
Means	42.4	73.7	43.0	72.6

In the above experiments, successful germination was judged to have occurred when a shoot emerged from the substrate and the seedling appeared healthy. This can be considered to be a minimum requirement for plant establishment. However, seedling vigor was not evaluated (for example, by measuring rate of growth), and it should not be concluded that seedling vigor paralleled germinability. Our impression was that storage conditions that maintained the rate of germinability did in fact also maintain high seedling vigor, but that storage conditions that notably reduced the rate of germinability also led to reduced seedling vigor.

CONCLUSIONS

To maintain germinability of seeds of *C. sativa*, they should not be stored under the ambient conditions usually encountered in the high-humidity areas where hemp is typically produced.

The literature and this study suggest that maintaining *C. sativa* seed at a moisture content of 5%–8% is sufficient to maintain substantial germinability for at least 6 years. A lower moisture content does not seem to improve germinability over this time interval.

The literature and this study suggest that maintaining *C. sativa* seed at a temperature of 5°C is sufficient to maintain substantial germinability for at least 6 years. A temperature of −20°C can improve germinability, but not greatly.

For commercial storage of *C. sativa* seed in a viable state for one to several seasons, the most economical investment would usually be drying the seed, at least to 8% but preferably to 6% moisture content and maintaining this level. Where this is difficult, seed should be kept refrigerated, at last at 5°C for periods of several years, but at lower temperatures for periods of the order of 10 years.

For long-term scientific or germplasm banking of *C. sativa* seed in a viable state for up to a decade, a moisture content of 6% coupled with a

storage temperature of −20°C is sufficient. Whether more extreme conditions would be of benefit for a longer period has not been determined.

Although the presence of oxygen hastens seed deterioration of some species, which can therefore profit from storage in an atmosphere such as nitrogen gas (thus excluding oxygen), *C. sativa* seeds do not seem to benefit from such treatment.

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