Moisture desorption and absorption isotherms for seeds of some cultivars of *Triticum aestivum* and *Triticum durum* wheat

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Moisture desorption and absorption isotherms for 50 seeds each of cultivated varieties belonging to *Triticum aestivum* and *Triticum durum* in five replications were recorded at 30°C and 85% RH (relative humidity). Hysteresis loops were established for all varieties from the average seed masses, normalized to equal curve heights for meaningful and effective comparison. It is observed that the total area enclosed under the normalized hysteresis curves for different varieties is different. Curiously enough, the hysteresis loops for seeds of well-known cultivated rainfed varieties enclose smaller area compared to the hysteresis loops for seeds of varieties cultivated under irrigated high-fertility conditions. Percentage hydration of seeds after one cycle of dehydration and rehydration indicates that seeds of well-established rainfed varieties have small negative values, whereas the values are positive and high for the seeds of irrigated varieties. Further, the rates of both dehydration and rehydration for seeds of rainfed varieties are smaller compared to those for the seeds of irrigated varieties. It is believed that this observation offers considerable potential as a laboratory test for screening, or at least short-listing, of varieties to the advantage of wheat breeders, agronomists and seed scientists, particularly working for agriculture in arid and semi-arid regions.

Most materials of plant origin and the seeds exhibit sigmoidal hysteresis in the absorption and desorption of water[1]. These curves vary in their shape and extent due to the differences in moisture-absorbing and moisture-holding potentialities. Babbitt[2,3] and later Hubbard *et al.*[4] plotted the hysteresis effect in moisture sorption of wheat over the full range (0–100%) of relative humidity (RH) for the first time and observed the maximum hysteresis effect between 12 and 44% RH without any consistent differences in the extent of hysteresis with temperature changes. Wheat, whole or with pericarp and seed-coat removed, reached near-equilibrium moisture contents within 40 h and the increase thereafter was slow. These results for wheat were confirmed later by Pixton and Warburton[5]; a bulk of the moisture absorption in wheat is believed to take place in the first 4–6 h. Most of the hysteresis studies on materials of plant origin have been confined to equilibrium moisture contents in relation to different relative humidities, water potentials and moisture tensions. Hysteresis have, however, seldom been studied with respect to the time of absorption and desorprtion, keeping temperature and relative humidity constant[2,3,5–20]. It is known that full or partial hydration of seeds of many crop species, followed by subsequent dehydration as a pre-sowing treatment (called 'priming') not only increases the rate, uniformity and level of seed germination but also imparts drought, heat, frost and salinity resistance to the plants emerging from the 'primed seeds' under field conditions[6–11]. Several cycles of priming on leaves of different plants at 30°C have been reported[8,9] to result in the decrease of hysteresis and, finally, its disappearance[13]. Furthermore, investigations have been reported in the literature showing that the rate of moisture loss from excised plants of drought-tolerant cultivars is lower than that from the drought-susceptible ones[21–23]. In the background of this knowledge, interesting data on moisture hysteresis with respect to the time of absorption and desorption for seeds of some well-known wheat cultivars belonging to *Triticum aestivum* and *Triticum durum* are presented and discussed in this paper.

Materials and methods

Seed materials

Seeds of 17 cultivated wheat varieties belonging to *Triticum aestivum*, grown in 1991 crop season at IARI farm under standard agronomic practice of irrigated and rainfed cultivations, were collected from the Division of Seed Science and Technology, IARI. Seeds of two uncultivated species *Triticum vavilovii* and *Triticum sphaerococcum* were obtained from the Division of Plant Physiology, IARI. Seeds of 18 cultivated wheat varieties belonging to *Triticum durum*, grown in 1991 crop season at P.K.V. Akola, Maharashtra farm were acquired from the Senior Wheat Breeder. In addition, seeds of MACS-9 variety grown at the Regional Station of IARI at Indore, Madhya Pradesh, were also collected.

Initial seed conditioning

Fifty seeds each of all the varieties in five replications were taken in small petri-plates. The seed lots were conditioned to maximum vapour absorption of moisture for 50 h at 30°C and 85% RH within the chest of an incubator in darkness.

Initial mass of seeds

The initial masses of conditioned seed lots were obtained by weighing individually on Dhona single-pan electrical balance up to the fifth place of decimal.

Moisture desorption

Conditioned replicates of seeds of all varieties were allowed to dehydrate at 30°C in an incubator and the progressive loss in the masses of seed replicates was recorded at two-hour intervals for 10 h. The seeds were further left to dehydrate overnight at 30°C for 15 h within the incubator and their dry masses measured again the next morning. The series of masses of seeds in averages of five replications during the dehydration cycle are given in Columns 3–8 of Table 1, Part A and Part B, for varieties of *Triticum aestivum* and *Triticum durum*, respectively.

Rehydration of seeds

The dry seeds (Table 1, Column 8, Part A and Part B) were then subjected to rehydration by exposing them in darkness to 85% RH at 30°C within the chest of the incubator. The progressive increase in the masses of seeds as a result of moisture absorption with respect to time was again followed at two-hour intervals for 10 h. The series of masses of seeds in averages of five replications during the rehydration cycle are given in Columns 9–13 of Table 1, Part A and Part B. The seeds were then left at 30°C and 85% RH for 50 h for maximum rehydration for 50 h and their saturated masses are given in Column 14 of Table 1, Part A and Part B.

Normalization of dehydration and rehydration isotherms

The average masses of seeds during the dehydration (Columns 3–8, Table 1, Part A and Part B) and rehydration cycles (Columns 9–13, Table 1, Part A and Part B) were independently normalized to equal curve heights. Masses of seeds during the dehydration cycle (Columns 3–8, Table 1) were normalized by dividing each mass value with the average mass of initially saturated seeds (Column 2, Table 1, Part A and Part B). Likewise, the average masses of seeds during the rehydration cycle (Columns 9–14, Table 1, Part A and Part B) were normalized by dividing each mass value with the average mass of fully saturated seeds after rehydration (Column 14, Table 1, Part A and Part B). Serial numbers 2, 4, 6, 8, . . . , 38 in Part A and serial numbers 40, 42, 44, . . . , 74 in Part B of Table 1 give the normalized average masses of seeds of individual wheat varieties studied.

Hysteresis curves and area enclosed by them

Hysteresis curves for seeds of each variety were established from the normalized mass values from dehydration and rehydration cycles. Curves for only two *Triticum aestivum* varieties, namely, K-65 and Sonalika, are reproduced in Figures 1 and 2, respectively. Likewise Figures 3 and 4 represent the hysteresis curves for the two *Triticum durum* varieties MACS-1967 and AKW-381, respectively. The *X*- and *Y*-axis intervals were uniformly maintained constant for all the hysteresis curves drawn. The areas enclosed by the hysteresis loops for seeds of each variety were measured with the help of a compensating planimeter and the data are given in Column 3 of Tables 2 and 3 for *Triticum aestivum* and *Triticum durum* varieties, respectively.

Agronomic production conditions

Column 2 in Tables 2 and 3 gives the agronomic production conditions for the respective varieties of the two species *Triticum aestivum* and *Triticum durum*.

Results and discussion

Extent of hydration of seeds

A critical observation of the data (Columns 2 and 14, Table 1, Part A and Part B) shows that the masses of saturated seeds before dehydration and after rehydration vary within the same seeds, indicating basic differences in their extent of hydration. In 8 of the 17 *Triticum aestivum* varieties, the average mass of saturated seeds after rehydration (Column 14) decreased from their initial saturated mass before dehydration (Column 2) cycle. In all other varieties, there is a varying but definite increase in the mass of saturated seeds after rehydration cycle, indicating increased hydration of seeds. Such an increase in the extent of hydration after successive cycles of dehydration and rehydration with progressive loss of hysteresis has been previously shown[13] in respect of wheat and ragi leaves. For the varieties of *Triticum durum* (Columns 2 and 14, Table 1, Part B), however, there is a decrease in the average mass of saturated

Table 1. Data on variation in mass of seeds of wheat varieties belonging to – *Part A*: Two uncultivated species *Triticum sphaerococcum* and *Triticum vavilovii*, and *Triticum aestivum*; *Part B*: Belonging to *Triticum durum*

Sl No.	Name of wheat variety	Initial mass of conditioned seeds at 30°C and 85% RH (g)	Dehydration cycle: Mass of 5 replicates of 50 seeds (g)					Av. dry mass of seeds at 30°C (5 replicates) (g)	Rehydration cycle: Mass of 5 replicates of 50 seeds (g)					Av. mass of saturated seeds after rehydration at 30°C and 85% RH (g)
			2 h	4 h	6 h	8 h	10 h		2 h	4 h	6 h	8 h	10 h	
	1	2	3	4	5	6	7	8	9	10	11	12	13	14
PART A														
	T. sphaerococcum													
1	Av. mass (g)	1.48136	1.46312	1.45258	1.44606	1.44110	1.42159	1.39917	1.41394	1.42297	1.43038	1.43933	1.50472	1.49932
2	Normalized	1.00000	0.9876	0.9805	0.9761	0.9728	0.9596	0.9445	0.9430	0.9490	0.9540	0.9599	1.0035	1.00000
	T. vavilovii													
3	Av. mass (g)	1.56616	1.54587	1.53414	1.52645	1.52117	1.50082	1.47712	1.49606	1.50851	1.51774	1.52709	1.59312	1.58651
4	Normalized	1.00000	0.9870	0.9795	0.9746	0.9712	0.9582	0.9431	0.9429	0.9508	0.9566	0.9625	1.0040	1.00000
	Triticum aestivum													
	WH-157													
5	Av. mass (g)	2.32834	2.30897	2.30492	2.28540	2.27712	2.24256	2.20593	2.22399	2.23701	2.24664	2.25696	2.33425	2.37038
6	Normalized	1.00000	0.9916	0.9899	0.9815	0.9779	0.9631	0.9474	0.9382	0.9437	0.9477	0.9521	0.9847	1.00000
	WL-711													
7	Av. mass (g)	1.98670	1.96050	1.94707	1.93577	1.92647	1.91921	1.89161	1.90421	1.90989	1.91462	1.91837	1.92128	1.98029
8	Normalized	1.00000	0.9868	0.9800	0.9743	0.9696	0.9660	0.9521	0.9615	0.9644	0.9668	0.9687	0.9702	1.00000
	K-68													
9	Av. mass (g)	2.23509	2.19353	2.19103	2.17834	2.16821	2.16019	2.12891	2.14212	2.14860	2.15221	2.15584	2.15875	2.23607
10	Normalized	1.00000	0.9814	0.9802	0.9746	0.9700	0.9664	0.9525	0.9579	0.9608	0.9624	0.9641	0.9654	1.00000
	DL 153-2													
11	Av. mass (g)	2.31006	2.29008	2.26845	2.25589	2.24563	2.23781	2.20757	2.22223	2.22839	2.23349	2.23742	2.24099	2.30801
12	Normalized	1.00000	0.9913	0.9819	0.9765	0.9721	0.9687	0.9556	0.9628	0.9655	0.9677	0.9694	0.9709	1.00000
	WL-410													
13	Av. mass (g)	1.77756	1.75814	1.74301	1.73283	1.71946	1.71769	1.69278	1.70429	1.70949	1.71375	1.71712	1.71998	1.77026
14	Normalized	1.00000	0.9890	0.9805	0.9748	0.9673	0.9663	0.9523	0.9627	0.9656	0.9680	0.9699	0.9715	1.00000
	Mukta													
15	Av. mass (g)	2.13588	2.11252	2.09423	2.07658	2.07281	2.06533	2.03644	2.05005	2.05610	2.06085	2.06456	2.06770	2.13010
16	Normalized	1.00000	0.9890	0.9804	0.9722	0.9704	0.9669	0.9534	0.9624	0.9652	0.9674	0.9692	0.9707	1.00000
	Sonalika													
17	Av. mass (g)	2.29104	2.27085	2.25772	2.24683	2.23861	2.20383	2.16655	2.18117	2.19712	2.20697	2.21905	2.32335	2.32788
18	Normalized	1.00000	0.9911	0.9854	0.9807	0.9771	0.9619	0.9456	0.9369	0.9438	0.9480	0.9532	0.9980	1.00000
	HD-2009													
19	Av. mass (g)	1.98780	1.95710	1.94363	1.93265	1.92346	1.91634	1.89089	1.90922	1.91327	1.91689	1.91938	1.92131	2.00089
20	Normalized	1.00000	0.9845	0.9777	0.9722	0.9676	0.9640	0.9512	0.9541	0.9562	0.9580	0.9592	0.9602	1.00000

Contd. . .

Sl No	Name of wheat variety	Initial mass of conditioned seeds at 30°C and 85% RH (g)	Dehydration cycle: Mass of 5 replicates of 50 seeds (g) 2 h	4 h	6 h	8 h	10 h	Av. dry mass of seeds at 30°C (5 replicates) (g)	Rehydration cycle: Mass of 5 replicates of 50 seeds (g) 2 h	4 h	6 h	8 h	10 h	Av. mass of saturated seeds after rehydration at 30°C and 85% RH (g)
	1	2	3	4	5	6	7	8	9	10	11	12	13	14
	HD-2329													
21	Av mass (g)	2.31992	2.28756	2.27277	2.26023	2.23923	2.23068	2.19905	2.21558	2.21965	2.22312	2.22592	2.22804	2.34300
22	Normalized	1.00000	0.9860	0.9796	0.9742	0.9652	0.9615	0.9478	0.9456	0.9473	0.9488	0.9500	0.9509	1.00000
	K-65													
23	Av mass (g)	2.41721	2.37880	2.36187	2.34764	2.33673	2.32689	2.29439	2.31138	2.31514	2.31836	2.32106	2.32297	2.40230
24	Normalized	1.00000	0.9841	0.9771	0.9712	0.9667	0.9626	0.9491	0.9621	0.9637	0.9650	0.9661	0.9669	1.00000
	K-8020													
25	Av. mass (g)	2.21662	2.17643	2.16073	2.13720	2.13622	2.12699	2.09513	2.11553	2.11493	2.11823	2.12046	2.12241	2.21037
26	Normalized	1.00000	0.9818	0.9747	0.9641	0.9637	0.9595	0.9451	0.9570	0.9568	0.9583	0.9593	0.9602	1.00000
	WH-147													
27	Av mass (g)	2.08980	2.05392	2.03924	2.02535	2.01522	2.00644	1.97749	1.99252	1.99595	1.99906	2.00166	2.00352	2.08141
28	Normalized	1.00000	0.9828	0.9758	0.9691	0.9643	0.9601	0.9462	0.9572	0.9589	0.9604	0.9616	0.9625	1.00000
	K-8027													
29	Av mass (g)	2.02767	1.99473	1.98154	1.96878	1.95927	1.95122	1.91562	1.93624	1.93903	1.94169	1.94384	1.94545	2.01405
30	Normalized	1.00000	0.9837	0.9772	0.9709	0.9662	0.9622	0.9447	0.9613	0.9627	0.9640	0.9651	0.9659	1.00000
	Kalyansona													
31	Av. mass (g)	1.95223	1.91779	1.90326	1.89145	1.88227	1.87430	1.84802	1.86553	1.86951	1.87207	1.87543	1.87737	1.95977
32	Normalized	1.00000	0.9823	0.9749	0.9688	0.9641	0.9600	0.9466	0.9519	0.9539	0.9552	0.9569	0.9579	1.00000
	IWP-72													
33	Av. mass (g)	1.79951	1.77248	1.76100	1.75163	1.74356	1.73747	1.71473	1.72976	1.73288	1.73574	1.73770	1.73947	1.80790
34	Normalized	1.00000	0.9849	0.9786	0.9733	0.9689	0.9655	0.9528	0.9567	0.9585	0.9600	0.9611	0.9621	1.00000
	C-306													
36	Av. mass (g)	2.36332	2.31096	2.29249	2.27414	2.26086	2.25008	2.21521	2.23301	2.23832	2.24262	2.24649	2.25050	2.234582
36	Normalized	1.00000	0.9778	0.9700	0.9622	0.9566	0.9520	0.9373	0.9519	0.9541	0.9560	0.9576	0.9593	1.00000
	NI-5439													
37	Av. mass (g)	2.12457	2.07156	2.05586	2.04707	2.03564	2.02630	1.99595	2.01632	2.02256	2.02776	2.03243	2.03697	2.12954
38	Normalized	1.00000	0.9750	0.9676	0.9635	0.9581	0.9537	0.9394	0.9468	0.9497	0.9522	0.9543	0.9565	1.00000
PART B														
	T. duram AKW-1811													
39	Av. mass (g)	1.79672	1.75779	1.74038	1.72817	1.71777	1.70918	1.68437	1.69993	1.70596	1.71037	1.71132	1.71391	1.78001
40	Normalized	1.00000	0.9783	0.9686	0.9618	0.9560	0.9512	0.9374	0.9550	0.9583	0.9608	0.9614	0.9628	1.00000
	AKW-1071													
41	Av mass (g)	1.94774	1.90489	1.88549	1.87202	1.86068	1.85145	1.82318	1.83978	1.84662	1.85158	1.85288	1.85546	1.92892
42	Normalized	1.00000	0.9780	0.9680	0.9611	0.9553	0.9505	0.9360	0.9537	0.9573	0.9599	0.9605	0.9619	1.00000

Contd. . .

Sl No.	Name of wheat variety	Initial mass of conditioned seeds at 30°C and 85% RH (g)	Dehydration cycle: Mass of 5 replicates of 50 seeds (g) 2 h	4 h	6 h	8 h	10 h	Av. dry mass of seeds at 30°C (5 replicates) (g)	Rehydration cycle: Mass of 5 replicates of 50 seeds (g) 2 h	4 h	6 h	8 h	10 h	Av. mass of saturated seeds after rehydration at 30°C and 85% RH (g)
	1	2	3	4	5	6	7	8	9	10	11	12	13	14
	NP-404													
43	Av. mass (g)	2.79923	2.72823	2.71141	2.68608	2.67292	2.66247	2.63210	2.65809	2.66348	2.67183	2.67178	2.67560	2.78494
44	Normalized	1.00000	0.9746	0.9686	0.9595	0.9548	0.9511	0.9402	0.9544	0.9563	0.9593	0.9593	0.9607	1.00000
	DWR-162													
45	Av. mass (g)	2.19728	2.15528	2.13412	2.11933	2.10647	2.09610	2.06431	2.08205	2.08906	2.09429	2.09545	2.09821	2.17722
46	Normalized	1.00000	0.9808	0.9712	0.9645	0.9586	0.9539	0.9394	0.9562	0.9595	0.9619	0.9624	0.9637	1.00000
	Bijaga-yellow													
47	Av. mass (g)	2.52042	2.45789	2.42604	2.40468	2.39344	2.38356	2.35432	2.37676	2.38339	2.38922	2.38894	2.39226	2.50193
48	Normalized	1.00000	0.9751	0.9625	0.9540	0.9496	0.9457	0.9341	0.9499	0.9526	0.9549	0.9548	0.9561	1.00000
	MACS-1967													
49	Av. mass (g)	2.83442	2.78935	2.76369	2.74623	2.73187	2.71903	2.67848	2.69729	2.70478	2.72051	2.72205	2.72501	2.81323
50	Normalized	1.00000	0.9840	0.9750	0.9688	0.9638	0.9592	0.9449	0.9587	0.9614	0.9670	0.9675	0.9686	1.00000
	Bijaga-red													
51	Av. mass (g)	2.32188	2.27154	2.24311	2.22509	2.21543	2.20672	2.17998	2.19923	2.20512	2.21144	2.21116	2.21513	2.30442
52	Normalized	1.00000	0.9783	0.9660	0.9583	0.9541	0.9504	0.9388	0.9543	0.9569	0.9596	0.9595	0.9612	1.00000
	Meghdoot													
53	Av. mass (g)	2.84320	2.32497	2.74635	2.72337	2.70957	2.69803	2.66219	2.68640	2.69149	2.69907	2.69914	2.70243	2.82632
54	Normalized	1.00000	0.9795	0.9659	0.9578	0.9530	0.9489	0.9363	0.9504	0.9522	0.9549	0.9550	0.9561	1.00000
	Raj-1555													
55	Av. mass (g)	3.32833	3.25507	3.22226	3.19698	3.18147	3.16933	3.12576	3.14472	3.15038	3.15949	3.15881	3.16255	3.30241
56	Normalized	1.00000	0.9779	0.9681	0.9605	0.9558	0.9522	0.9391	0.9522	0.9539	0.9567	0.9565	0.9576	1.00000
	JU-12													
57	Av. mass (g)	2.42549	2.38150	2.35098	2.33486	2.32263	2.31349	2.28479	2.30531	2.30884	2.31519	2.31598	2.31884	2.41699
58	Normalized	1.00000	0.9818	0.9692	0.9626	0.9575	0.9538	0.9419	0.9538	0.9552	0.9578	0.9582	0.9594	1.00000
	AKW-3018													
59	Av. mass (g)	3.95966	3.88856	3.85312	3.82670	3.80348	3.78475	3.72278	3.74721	3.75698	3.76572	3.76870	3.77331	3.92381
60	Normalized	1.00000	0.9820	0.9730	0.9664	0.9605	0.9558	0.9401	0.9549	0.9574	0.9597	0.9604	0.9616	1.00000
	MACS-2496													
61	Av. mass (g)	2.09036	2.05070	2.03064	2.01651	2.00463	1.99461	1.96357	1.97995	1.98730	1.99341	1.99496	1.99756	2.08103
62	Normalized	1.00000	0.9810	0.9715	0.9646	0.9589	0.9541	0.9393	0.9514	0.9549	0.9578	0.9586	0.9598	1.00000
	MACS-9 (Akola)													
63	Av. mass (g)	1.95308	1.91591	1.89558	1.88243	1.87243	1.86331	1.83722	1.85629	1.86291	1.86864	1.86945	1.87181	1.95188
64	Normalized	1.00000	0.9809	0.9705	0.9638	0.9587	0.9540	0.9406	0.9510	0.9544	0.9573	0.9577	0.9589	1.00000

Contd. . .

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	1	2	3	4	5	6	7	8	9	10	11	12	13	14
	MACS-9 (Indore)													
65	Av. mass (g)	3.38546	3.32328	3.29229	3.26816	3.25454	3.24281	3.20170	3.22343	3.23011	3.23445	3.23505	3.23847	3.37478
66	Normalized	1.00000	0.9816	0.9724	0.9653	0.9613	0.9578	0.9457	0.9551	0.9571	0.9584	0.9585	0.9596	1.00000
	N-59													
67	Av. mass (g)	2.35894	2.31946	2.29779	2.28287	2.27125	2.26052	2.28898	2.24930	2.25711	2.26394	2.26548	2.26820	2.35984
68	Normalized	1.00000	0.9832	0.9740	0.9677	0.9628	0.9582	0.9449	0.9531	0.9564	0.9593	0.9600	0.9611	1.00000
	Raj-911													
69	Av. mass (g)	2.65375	2 60194	2.57725	2.55608	2.54320	2.53229	2.48614	2.50836	2.51290	2.51890	2.51967	2.52269	2.63718
70	Normalized	1.00000	0.9804	0.9711	0.9631	0.9583	0.9542	0.9368	0.9511	0.9528	0.9551	0.9554	0.9565	1.00000
	A-9-30-1													
71	Av. mass (g)	2.34655	2.31249	2.29290	2.27704	2.26734	2.25898	2.22903	2.24250	2.24709	2.24968	2.25047	2.25284	2.34365
72	Normalized	1.00000	0.9854	0.9771	0 9703	0.9662	0.9626	0.9499	0.9568	0.9588	0.9599	0.9602	0 9612	1.00000
	AKW-381													
73	Av. mass (g)	2.68692	2.64062	2.61583	2.59798	2.58302	2.57005	2.52785	2.54593	2.55396	2.56051	2.56233	2.56589	2.68261
74	Normalized	1.00000	0.9827	0.9735	0.9668	0.9613	0.9565	0.9407	0.9490	0.9520	0.9544	0.9551	0.9564	1.00000
	NP-401													
75	Av. mass (g)	3.28886	3.23861	3.20627	3.18110	3.16540	3.15196	3.10377	3.12196	3.12745	3.13355	3.13419	3.13749	3.28189
76	Normalized	1.00000	0.9847	0.9748	0.9672	0.9624	0.9583	0.9437	0.9512	0.9529	0 9548	0.9549	0.9560	1.00000

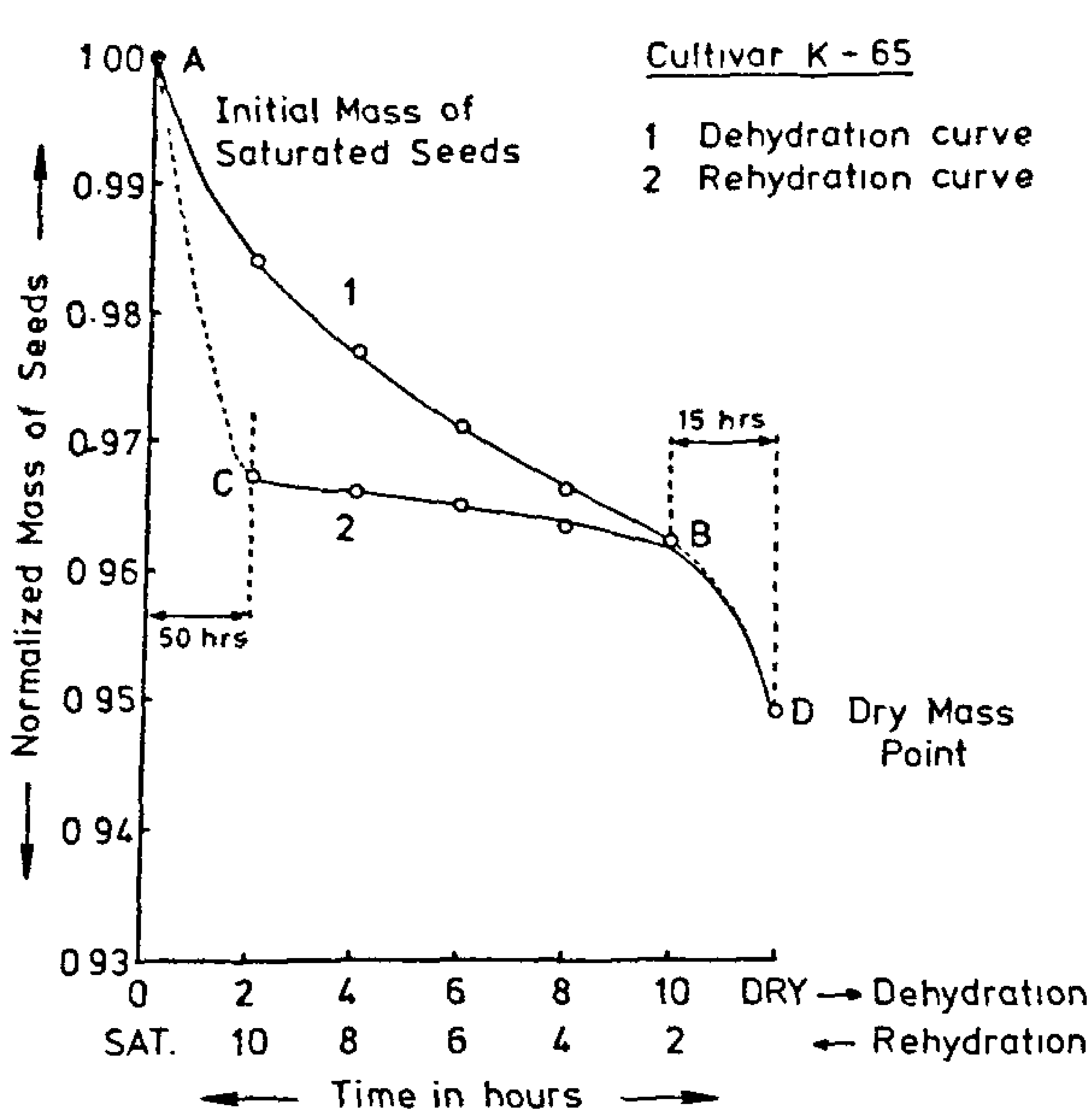

Figure 1. Normalized hysteresis curve for the wheat variety K-65

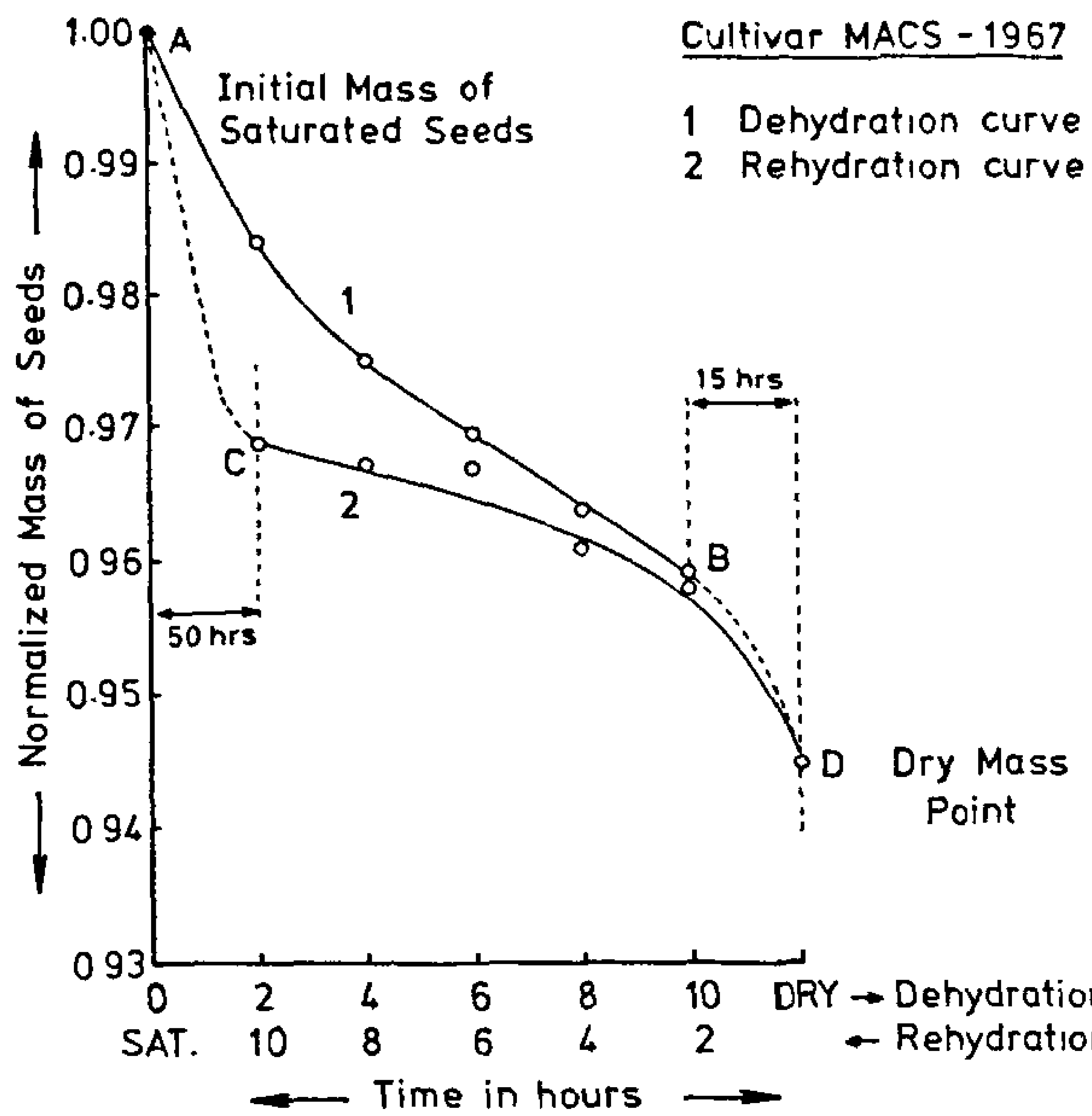

Figure 3. Normalized hysteresis curve for the wheat variety MACS-1967

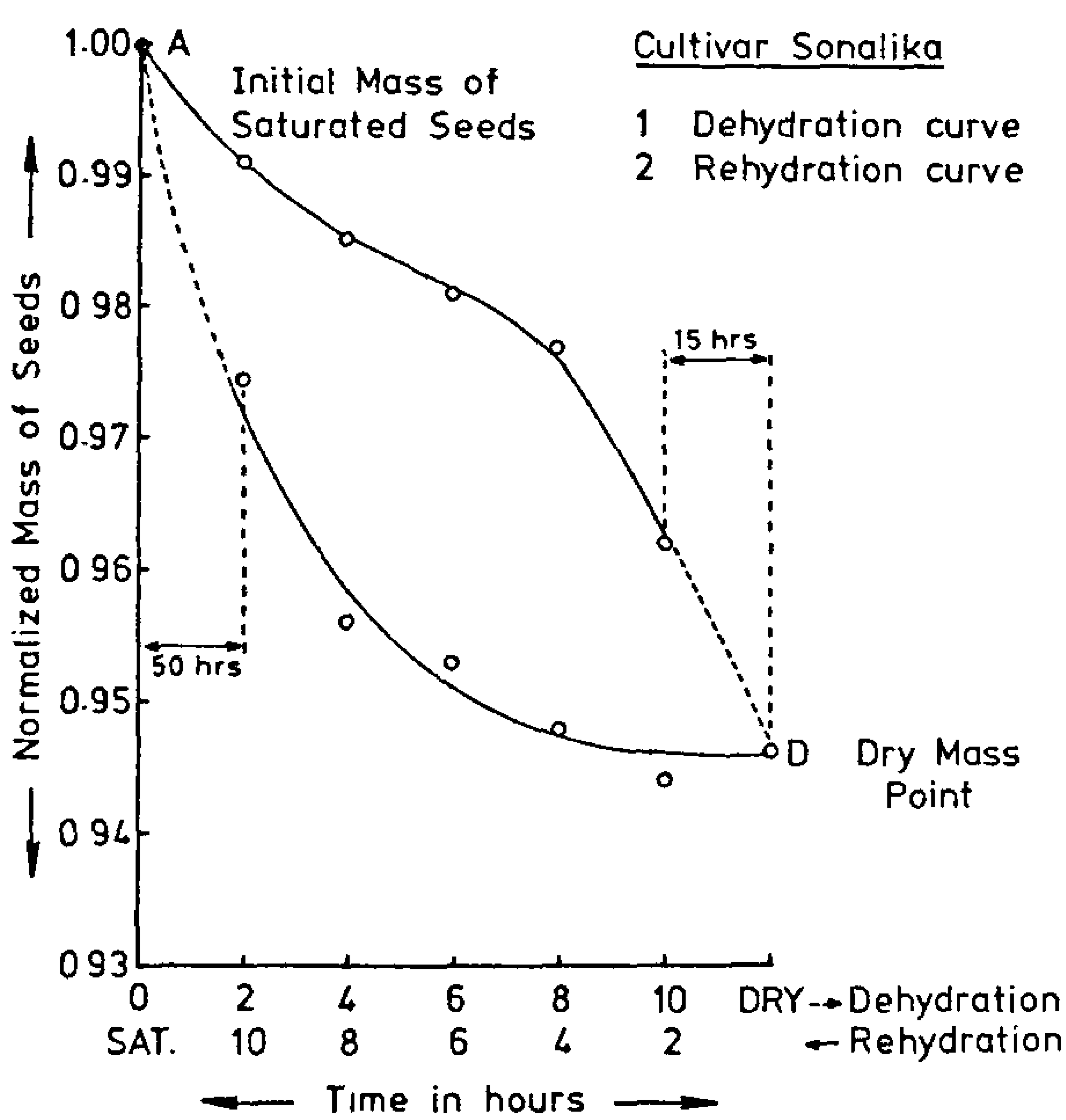

Figure 2. Normalized hysteresis curve for the wheat variety Sonalika.

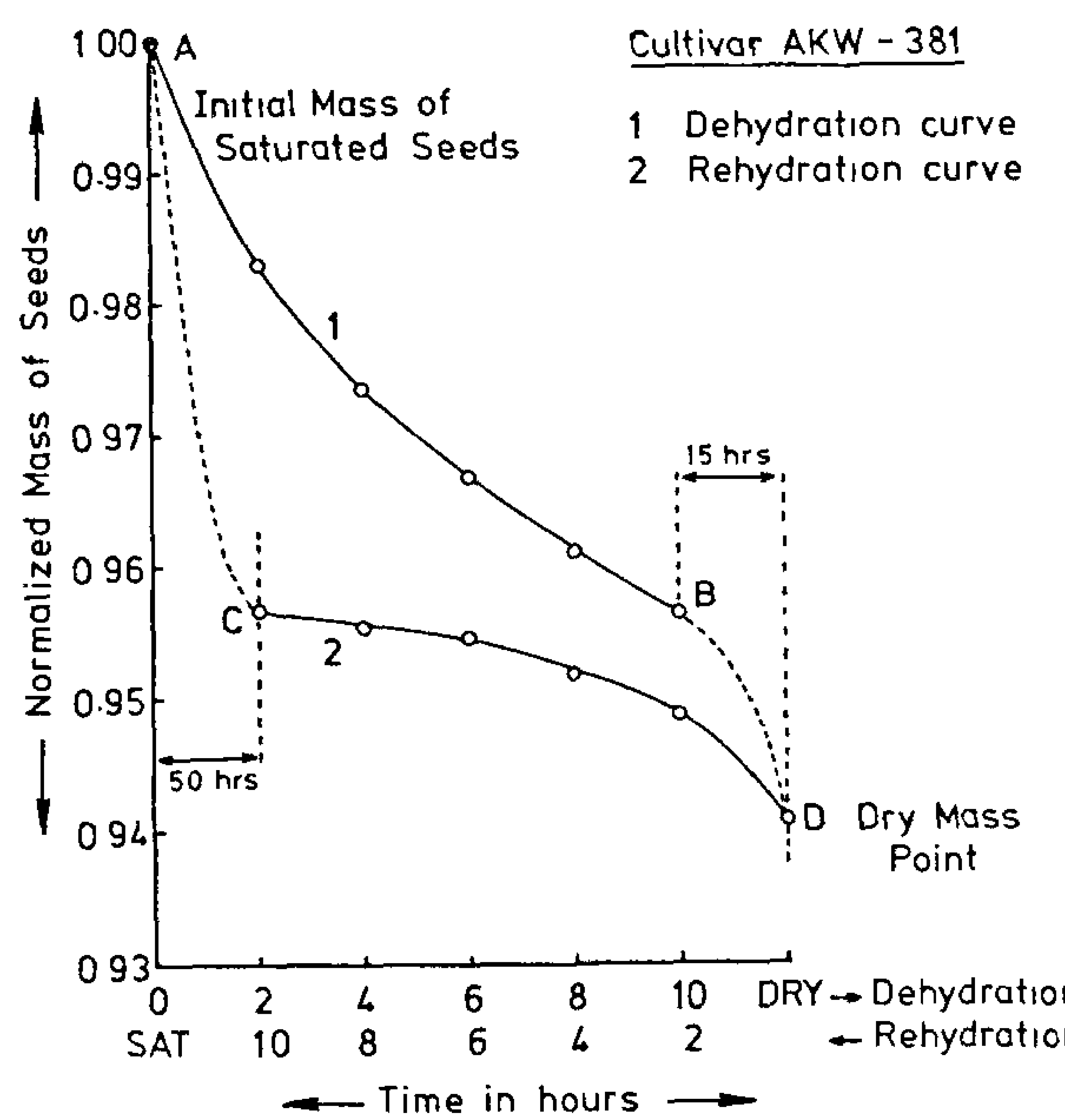

Figure 4. Normalized hysteresis curve for the wheat variety AKW-381

seeds in all the varieties after one cycle of dehydration and rehydration. The percentage decrease/increase in the extent of this hydration of seeds was computed for all the varieties and the data are given in Column 4 of Tables 2 and 3 for varieties of *aestivum* and *durum*, respectively.

It may be interesting to observe from Columns 2 and 4 of Table 2 that for *Triticum aestivum* varieties, the extent of hydration of seeds is positive and higher in value for cultivars recommended for cultivation[24] under

Table 2. Data on hysteresis loops, percentage hydration of seeds and status of production conditions in respect of *Triticum aestivum* wheat varieties

Sl No.	Name of wheat variety	Agronomic production conditions (#)	Area under moisture hysteresis loop (cm^2)	Increase/decrease in hydration over initial mass of conditioned seeds (%)	Moisture retention index
1	K-65	TS-RF	19 36 (L)	(–) 0.616	8.01 (L)
2	C-306	TS-RF	22.20 (L)	(–) 0.740 (L)	9.39
3	K-8027	TS-RF	22.42	(–) 0 671	11.06
4	WL-410	LS-RF	23.74	(–) 0.410	13.36
5	Mukta	TS-RF	24.46	(–) 0.270	11 45
6	WL-711	TS-IR	25.35	(+) 0.322	12.76
7	WH-147	TS-IR	28.66	(–) 0.401	13.71
8	K-8020	LS-IR	28.68	(–) 0.281	12.94
9	DL-153-2	TS-RF	28.80	(–) 0.088	12.47
10	NI-5439	TS-RF+IR	31.24	(+) 0.233	14 70
11	K-68	TS-RF+IR	35.72	(+) 0.043	15.98
12	IWP-72	TS-RF	38.80	(+) 0.466	21.56
13	Kalyan-Sona	TS-IR	39 64	(+) 0.386	20.31
14	HD-2009	TS-IR	42.50	(+) 0.658	21.38
15	Sonalika	LS-IR	63.94	(+) 1 608	27.91
16	HD-2329	TS-IR	64.14	(+) 0.994	27 65
17	WH-157	TS-IR	65 70 (H)	(+) 1.805 (H)	28 22 (H)
18	Range of variation (max.–min.)		46.34	2.545	20.21

TS – timely sown; LS – late sown; (+) – increase; (–) – decrease; (#) – Information received from Senior Wheat Breeder, P. K. V. Akola, Maharashtra and from *Twenty-five Years of Coordinated Wheat Research* (eds Tandon, J. P. and Sethi, A. P.), All India Coordinated Wheat Research Project, 1986; (L) – lowest value within samples, (H) – highest value within samples.

Table 3. Data on hysteresis loops, percentage hydration of seeds and status of production conditions in respect of *Triticum durum* wheat varieties

Sl No.	Name of wheat variety	Agronomic production conditions (#)	Area under moisture hysteresis loop (cm^2)	Increase/decrease in hydration over initial mass of conditioned seeds (%)	Moisture retention index
1	AKW-1811	New genotype TS-IR	15.25 (L)	(–) 0.9300	8 49
2	AKW-1071	TS-IR	15.86	(–) 0.9662 (L)	8.14
3	NP-404	TS-RF	16 14	(–) 0.5104	5.77 (L)
4	DWR-162	TS-IR	17.00	(–) 0 9129	7.74
5	B-Yellow	TS-RF+IR	17 95	(–) 0.7336	7.12
6	MACS-1967	TS-RF	19.26	(–) 0.7475	6.80
7	B-Red	TS-RF+IR	19.30	(–) 0.7519	8.31
8	Meghdoot	TS-RF	21.57	(–) 0.5936	7.59
9	Raj-1555	TS-IR	21 60	(–) 0.7787	6 49
10	JU-12	TS-RF	21 80	(–) 0.3504	8 99
11	AKW-3018	TS-RF	26 16	(–) 0 9053	6 61
12	MACS-2496	TS-IR	26.92	(–) 0 4463	12 88
13	MACS-9 (Akola)	TS-RF	27.10	(–) 0.0614	13 88
14	MACS-9 (Indore)	TS-RF	27.43	(–) 0 3154	8 10
15	N-59	TS-RF	31.95	(–) 0 03821 (H)	13.54
16	Raj-911	TS-IR	32 80	(–) 0 6243	12 36
17	A-9-30-1	TS-RF	35.40	(–) 0 1235	15 09
18	AKW-381	TS-IR	40 92	(–) 0 1604	16 19 (H)
19	NP-401	TS-RF+IR	43.42 (H)	(–) 0.2119	13 20
20	Range of variation (max.–min)		28 17	1.0043	10 42

TS – timely sown; LS – late sown; (+) – increase; (–) – decrease, (#) – Information received from Senior Wheat Breeder, P. K. V. Akola, Maharashtra, (L) – lowest value within samples, (H) – highest value within samples irrigated high-fertility conditions and is negative for cultivars recommended for cultivation[24] under rainfed low-fertility conditions. For varieties recommended for cultivation under both irrigated medium-fertility conditions and rainfed low-fertility conditions, the percentage hydration of seeds has intermediate values, e.g. Sl No. 10 and 12 in Table 2. However, for varieties of *Triticum durum* (Columns 2 and 4, Table 3) it may be observed that percentage seed hydration has negative values for all the varieties studied and the values progressively decrease from −0.03821 to −0.9662.

Hysteresis curves

In Figures 1–4, the curves ABD and DCA were established during dehydration and rehydration cycles of seeds, respectively. Segments AB and DC of these curves were followed at two-hour intervals. The asymptotic parts BD and CA of these curves represent the interval given to seeds in coming to dry-mass point D during dehydration and maximum saturation point A after rehydration beyond C. In fact, two asymptotic ends of the dehydration and rehydration isotherms nearly compensate each other. A bulk of moisture desorption and rehydration in wheat seeds takes place within the first few hours and then gradually extends very slowly. The hysteresis curves in general are, therefore, very extended. It is expected that the extrapolated two asymptotic segments and the area under them would not significantly affect the general behaviour of the hysteresis curve or alter the total area under the hysteresis loop. Therefore, within reasonable limits of accuracy, moisture hysteresis for seeds of wheat can be conveniently accomplished by following the changes in the mass of seeds for only 10–15 h (10 h in the present case) during dehydration and rehydration cycles. Further, the normalization of the hysteresis curves facilitates comparison between varieties more effectively.

Area enclosed under the hysteresis curves for seeds

On arranging the varieties within both the species in increasing order of their hysteresis loop area (Column 3, Tables 2 and 3), it is observed that for *Triticum aestivum* varieties the values vary within a range of 46.34 cm^2, from the lowest of 19.36 cm^2 to as high as 65.70 cm^2. Correspondingly, this range of variation in area under the hysteresis loops for cultivars of *Triticum durum* is only 28.17 cm^2, with values varying from the lowest of 15.25 cm^2 to the highest of 43.42 cm^2. It may further be observed that seeds of well-known cultivars classified under rainfed low-fertility cultivation[24] have smaller area under their hysteresis loops compared to that for seeds of cultivars classified for cultivation under irrigated high-fertility conditions[24]. For varieties cultivated under both irrigated and rainfed conditions of production[24], the hysteresis loop areas have intermediate values, e.g. Sl No. 10, 11 in Table 2 and Sl No. 5, 7 in Table 3. Whereas this observation is also generally true in well-established varieties of *Triticum durum* (Table 3), the segregation between rainfed and irrigated varieties on the basis of the area under hysteresis loop is not as sharp as in the case of *Triticum aestivum* varieties (Table 2). This is believed to be due to the fact that *Triticum durum* has relatively very short breeding history compared to *Triticum aestivum*.

Data on seeds of *Triticum durum* in Table 3 indicate that three irrigated varieties AKW-1811, AKW-1071 and DWR-162 show the smallest area under their moisture hysteresis loops and yet are reported[25] to perform poorly under rainfed field conditions. It may be pertinent to reason here as to why these should do so? An explanation to this effect can be sought and visualized in the shape of the hysteresis loops for these varieties, which are distinctly different from that for other varieties. Such a hysteresis curve for only one variety AKW-1811 is reproduced in Figure 5 for comparison. The rate of dehydration for these three varieties is higher compared to other varieties within the species. Similarly, the rate of rehydration of seeds is also initially low and gradually becomes very high, with the result that the dehydration and rehydration isotherms intersect each other. It is, therefore, quite likely that wide variations in differential

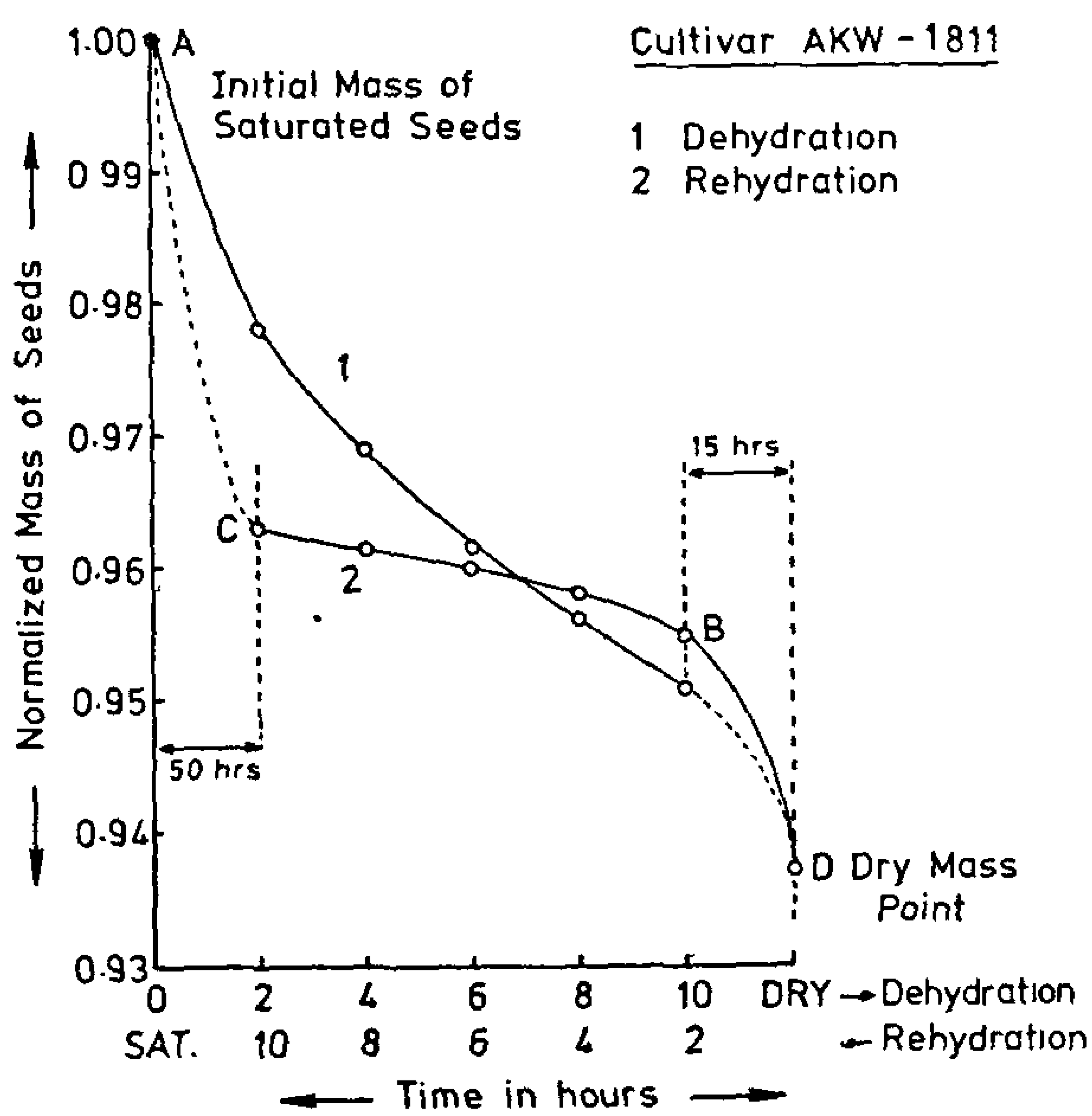

Figure 5. Normalized hysteresis curve for the typical wheat variety AKW-1811.

rates of dehydration and rehydration across the pericarp and seed matrix may be responsible for their actual performance in the field. The rest of the varieties within *durum* generally support the hypothesis that the seeds of all rainfed drought-tolerant varieties of wheat not only have smaller areas under their hysteresis loops but also have smaller rates of dehydration and rehydration compared to those for the irrigated varieties.

Further, it may be curiously observed from Sl No. 13 and 14 in Table 3 that seeds of the same variety MACS-9, grown independently at Akola, Maharashtra; and Indore, Madhya Pradesh enclose nearly the same area under their moisture hysteresis loops, whereas the values of their seed masses, moisture retention index and percentage hydration are quite different. Unfortunately, we had only one variety common to both these places and therefore, it would be difficult to conclude if the area under the moisture hysteresis loops for seeds is independent of the environmental growth conditions and is a genotypic character. However, it would be our endeavour to explore this relationship in future.

Data on seeds of uncultivated species *Triticum vavilovii* and *Triticum sphaerococcum* indicate that with hysteresis loop area values of 43.0 and 49.44 cm^2, respectively, they fall closer to the irrigated varieties of both *Triticum aestivum* (Table 2) and *Triticum durum* (Table 3) than to those for the rainfed varieties within the species. Further, with values of + 1.299 and + 1.212, respectively, for percentage hydration of seeds of these uncultivated species, they lie more parallel to the irrigated varieties of both *aestivum* and *durum*.

Moisture retention index

Drawing analogy from the studies on hysteresis in magnetization of materials in physics, an index that represents moisture retention during dehydration and rehydration of the seed matrix as computed for different varieties by dividing the area under the hysteresis loops by the average mass of their saturated seeds. The values of the moisture retention indices (MRI) thus calculated are given in Column 4 of Tables 2 and 3 for varieties of *Triticum aestivum* and *Triticum durum*, respectively. It may be curiously observed that on the basis of this index, the segregation of rainfed and irrigated varieties within *aestivum* becomes more sharp. Whereas the general trend in *Triticum durum* is also similar, the segregation between rainfed and irrigated varieties still remains not so well distinct.

Correlation of moisture retention index with hysteresis loop area and seed hydration

The area under the hysteresis loop for seeds of wheat varieties shows significant positive correlations of 0.9502 and 0.6749, respectively, with moisture retention index within individual species and also + 0.8767 for mixtures of varieties of *aestivum* and *durum* taken together. Similarly, MRI shows significant correlations with percentage seed hydration after one cycle of dehydration and rehydration within individual species and between mixtures of varieties of both species of wheat taken together. The data on correlation coefficients are given in Table 4, and it is obvious that higher values of MRI correspond to higher values of seed hydration.

A lower rate of moisture loss from excised plants has been correlated with drought resistance in spring wheat and sorghum varieties[21–23], and it is generally believed that varieties that retained water best ranked highest in heat and drought tests[23]. Contrary to this, the data on seed hydration in Column 4 in Tables 2 and 3 suggest that varieties for irrigated cultivation, such as Sonalika, WH-157 and AKW-381, absorb more moisture after one cycle of dehydration and rehydration and the rate at which rehydration proceeds in them is much higher. As a result, the rehydration isotherm upon normalization falls much below the dehydration isotherm, with consequent increase in the area under the hysteresis loop. It may thus be concluded that for the seeds of all rainfed varieties, the rates of both dehydration and rehydration are much lower compared to those for the seeds of irrigated varieties. This conclusion for seeds of wheat varieties is similar and parallel to the differences observed in excised plants[21–23] of drought-tolerant and susceptible varieties. Apparently enough, there appears to be a continuing relationship between the behaviour of the seeds and the behaviour of the plants raised from them in the field, and it would be our endeavour to explore this relationship in details in future experiments. For the present, it is concluded that the seeds of best-known rainfed wheat varieties show small moisture retention, small area under their moisture hysteresis loops and smaller values of percentage seed hydration compared to the seeds of irrigated varieties.

Several physiological indices have been reported to correlate with drought resistance without any practical

Table 4. Correlations of moisture retention index with area under the hysteresis curves and percentage hydration of seeds

Wheat species	Area under the hysteresis curve	Percentage increase/decrease of seed hydration
Triticum aestivum $n = 17$	$r = 0.9502$ $p > 0.001$	$r = 0.8806$ $p > 0.001$
Triticum durum $n = 19$	$r = 0.6749$ $p > 0.01$	$r = 0.5811$ $p > 0.01$
Triticum aestivum and *Triticum durum* combined $n = 36$	$r = 0.8767$ $p > 0.001$	$r = 0.8673$ $p > 0.001$

success[26-28]. Field tests for resistance to drought so far are not efficient and practicable due to several biotic factors[23]. The development of laboratory tests has been visualized to be the only practical answer[23]. In this context, the measurement of area enclosed by the normalized moisture hysteresis curves for seeds of wheat varieties during their dehydration and rehydration cycles appears to have considerable potential as a laboratory test for screening varieties for cultivation or at least short-listing of genotypes for field-testing in arid and semi-arid regions.

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