

Supplemental Table 1. Morphological, phenological, physiological, yield, and yield component traits of ‘Norin 61’ (N61) and the Sudanese cultivars ‘Goumria’ and ‘Imam’ evaluated for heat stress tolerance at Dongola (DON), Hudeiba (HUD), Wad Medani with optimum sowing (MED/OS), and Wad Medani with late sowing (MED/LS)

Trait	DON			HUD			MED/OS			MED/LS		
	N61	Goumria	Imam	N61	Goumria	Imam	N61	Goumria	Imam	N61	Goumria	Imam
DH	72	75	78	61	63	73	64	63	73	62	65	71
DM	106	109	109	103	107	108	101	104	107	92	97	102
GFD	33	34	30	42	39	35	37	40	34	30	32	31
PH	97	83	89	69	64	75	84	74	86	79	70	83
PL	34	32	32	13	8	12	28	28	34	26	25	28
CT	32	22	21	30	30	30	17	17	23	25	25	27
SPAD	43	38	40	51	51	52	50	50	51	50	51	48
NDVI	0.71	0.73	0.71	0.63	0.55	0.62	0.55	0.58	0.59	0.69	0.67	0.73
KS	23	24	21	45	54	45	56	55	55	54	50	48
TKW	33	33	32	27	31	33	30	32	25	26	32	25
Gm ⁻²	10965	10532	9787	10357	11531	11284	27181	21502	21335	21283	23142	20893
GY	784	683	614	383	555	514	823	784	685	703	413	555
BIO	2366	2459	2016	1279	1434	1457	2038	2109	2109	1089	1428	2244
HI	33	30	31	31	40	35	40	39	32	39	31	24

DH, days to heading; DM, days to maturity; GFD, grain filling duration (days); PH, plant height (cm); PL, peduncle length (cm); CT, canopy temperature (°C); SPAD, chlorophyll content (SPAD units); NDVI, normalized difference vegetation index; KS, kernel number per spike; TKW, thousand-kernel weight (g); Gm⁻², grain number per m²; GY, grain yield (g m⁻²), BIO, biomass (g m⁻²); HI, harvest index (%).

Supplemental Table 2. The effect of genotype (G), environment (E), and genotype–environment interaction (G×E) on morphological, phenological, physiological, yield, and yield component traits of the MSD lines, ‘Norin 61’ (N61), and the Sudanese cultivars ‘Goumria’ and ‘Imam’ evaluated for heat stress tolerance at Dongola (DON), Hudeiba (HUD), Wad Medani with optimum sowing (MED/OS), and Wad Medani with late sowing (MED/LS) in Sudan

Trait	DON	HUD	MED/OS	MED/LS	Combined analysis	
	G	G	G	G	E	G×E
DH	93.15***	71.94***	318.50***	24.38**	***	138.36***
DM	92.85***	47.81***	119.96***	NS	***	799.93***
GFD	NS	62.52***	64.83***	NS	***	228.63***
PH	146.79*	95.08*	91.59***	86.56***	***	565.86***
PL	30.07*	20.59**	36.21***	17.86***	***	82.20***
CT	NS	2.02*	17.84*	NS	***	103.26***
SPAD	13.74*	29.41*	16.00**	11.77*	***	221.91***
NDVI	NS	NS	0.0154***	0.0028*	***	0.0248***
KS	20.41**	195.67***	151.25***	137.47*	***	407.36***
TKW	30.31**	83.43***	NS	NS	***	289.96***
Gm ⁻²	NS	17728694***	136882698***	44834708*	***	49961421***
GY	NS	34838.94**	73552.02**	NS	***	112179.5***
BIO	NS	142111.7*	587.59*	NS	***	510362.3***
HI	NS	134.42*	167.13***	NS	***	384.08***

DH, days to heading; DM, days to maturity; GFD, grain filling duration (days); PH, plant height (cm); PL, peduncle length (cm); CT, canopy temperature (°C); SPAD, chlorophyll content (SPAD units); NDVI, normalized difference vegetation index; KS, kernel number per spike; TKW, thousand-kernel weight (g); Gm⁻², grain number per m²; GY, grain yield (g m⁻²), BIO, biomass (g m⁻²); HI, harvest index (%).

Supplemental Table 3. Heat tolerance efficiency (HTE), morphological, phenological, physiological, yield, and yield component traits of 13 heat-tolerant MSD lines and their parent ‘Norin 61’ at Wad Medani with late sowing (MED/LS) and their combined yield at Dongola, Wad Medani with optimum sowing, Hudeiba, and MED/LS

Line	Cross name	DH	DM	GFD	PL	CT	SPAD	NDVI	KS	TKW	Gm ⁻²	BIO	GY ^a	GY ^b	HI	HTE
MSD006	N61/Syn65//*N61	60	94	34	29	26	51	0.68	48	32	25200	2300	743	478	32	118
MSD054	N61/Syn26//*N61	61	96	35	24	26	50	0.66	48	28	31440	1900	705	614	38	125
MSD084	N61/Syn30//*N61	58	92	32	30	27	48	0.62	52	28	14983	2150	746	670	34	109
MSD108	N61/Syn45//*N61	60	100	38	24	23	46	0.72	44	35	10418	2225	639	535	28	107
MSD186	N61/Syn30//*N61	62	98	35	30	27	51	0.73	31	32	11500	2475	759	608	31	148
MSD208	N61/Syn26//*N61	61	92	31	26	22	52	0.67	41	29	16267	2175	891	766	41	124
MSD265	N61/Syn44//*N61	59	90	30	31	28	51	0.64	28	33	10625	2200	712	590	33	127
MSD296	N61/Syn32//*N61	59	94	35	33	27	44	0.69	52	29	21580	2550	758	538	29	126
MSD303	N61/Syn68//*N61	57	91	33	28	26	44	0.54	40	29	18842	1875	562	475	30	122
MSD345	N61/Syn48//*N61	65	98	35	24	27	54	0.69	47	32	17267	2275	629	504	28	110
MSD360	N61/Syn57//*N61	59	93	34	28	30	53	0.89	40	32	21175	2375	763	588	32	115
MSD367	N61/Syn57//*N61	61	100	37	34	26	49	0.69	68	25	21080	2575	644	577	25	115
MSD453	N61/Syn50//*N61	58	90	34	29	24	49	0.65	37	31	12467	2375	827	660	34	117
Norin 61		62	92	30	26	25	50	0.69	54	25	21283	1809	703	659	39	90
Grand mean		63	96	33	27	26	49	0.69	40	26	15363	1842	417	396	23	62

DH, days to heading; DM, days to maturity; GFD, grain filling duration (days); PL, peduncle length (cm); CT, canopy temperature (°C); SPAD, chlorophyll content (SPAD units); NDVI, normalized difference vegetation index; KS, kernel number per spike; TKW, thousand-kernel weight (g); Gm⁻², grain number per m²; BIO, biomass (g m⁻²); GY^a, grain yield (g m⁻²) at MED/LS; GY^b, combined grain yield combine in all environments (g m⁻²); HI, harvest index (%).

Supplemental Table 4. Morphological, phenological, physiological, yield, and yield component traits of the 29 high-yielding MSD lines and the parent ‘Norin 61’ at Hudeiba, and their combined yield evaluated at Dongola, Wad Medani with optimum sowing, Wad Medani late with sowing and Hudieba

Line	Cross name	DH	DM	GFD	PL	CT	SPAD	NDVI	KS	TKW	Gm ⁻²	BIO	GY ^a	HI	GY ^b
MSD044	N61/Syn71//*N61	63	105	43	12	33	52	0.62	53	27	14826	1688	749	44	783
MSD132	N61/Syn34//*N61	62	104	42	18	28	50	0.80	40	28	10787	1771	722	41	693
MSD136	N61/Syn31//*N61	69	104	35	17	30	51	0.57	47	34	4795	1595	635	40	632
MS140	N61/Syn68//*N61	67	104	38	10	31	54	0.60	46	35	11124	1852	676	36	630
MSD157	N61/Syn40//*N61	66	104	38	12	26	51	0.78	45	25	15788	2114	685	32	649
MSD163	N61/Syn31//*N61	59	104	45	19	30	55	0.67	39	36	13132	2174	752	35	796
MSD166	N61/Syn39//*N61	66	108	42	17	24	53	0.73	42	34	8915	1445	636	44	671
MSD187	N61/Syn68//*N61	66	97	32	9	30	56	0.63	31	39	7881	1652	701	42	562
MSD195	N61/Syn27//*N61	60	118	58	16	28	54	0.79	50	32	12751	1215	666	55	556
MSD208	N61/Syn26//*N61	60	104	44	14	28	53	0.74	45	28	11148	1224	658	54	766
MSD215	N61/Syn68//*N61	56	116	61	19	28	51	0.63	49	27	10293	1694	675	40	624
MSD225	N61/Syn48//*N61	68	104	36	21	30	53	0.76	43	29	12840	2064	785	38	587
MSD267	N61/Syn42//*N61	68	107	40	16	29	55	0.62	42	34	10192	1871	771	41	662
MSD278	N61/Syn62//*N61	61	104	43	11	27	53	0.66	46	34	14167	1878	682	36	564
MSD289	N61/Syn30//*N61	61	106	45	10	28	44	0.56	26	43	8190	974	679	70	463
MSD300	N61/Syn35//*N61	62	104	42	17	27	51	0.80	38	33	14036	1967	737	37	657
MSD304	N61/Syn62//*N61	67	103	36	19	26	55	0.70	45	36	16413	881	708	80	600
MSD307	N61/Syn68//*N61	59	104	45	16	31	54	0.60	43	26	6474	1047	636	61	572
MSD320	N61/Syn58//*N61	66	104	38	17	28	52	0.68	39	31	8166	1775	744	42	602
MSD326	N61/Syn62//*N61	67	108	41	12	30	55	0.62	0	19	23874	1804	785	44	699
MSD367	N61/Syn57//*N61	64	97	34	20	31	50	0.59	35	33	8775	1820	641	35	577
MSD368	N61/Syn48//*N61	63	106	43	11	29	52	0.66	50	29	13673	2221	888	40	680
MSD377	N61/Syn27//*N61	63	108	45	21	25	53	0.78	48	34	10101	1908	638	33	582
MSD410	N61/Syn27//*N61	60	104	45	16	32	49	0.64	59	29	17093	2228	916	41	640
MSD413	N61/Syn48//*N61	68	102	35	16	31	57	0.64	43	32	10325	2166	950	44	663
MSD434	N61/Syn52//*N61	68	112	44	12	28	52	0.60	45	26	12808	2027	634	31	587

MSD491	N61/Syn37//*N61	65	108	43	14	29	38	0.80	41	33	10675	1964	772	39	582
MSD499	N61/Syn66//*N61	76	108	32	9	29	55	0.54	49	31	15746	1277	818	64	482
MSD500	N61/Syn34//*N61	60	103	43	21	33	57	0.60	31	32	5947	1327	422	32	478
Norin 61		61	103	42	13	30	50	0.63	41	26	10357	1279	383	30	659
Grand mean		66	107	40	15	30	51	0.60	37	26	8458	1283	429	32	396

DH, days to heading; DM, days to maturity; GFD, grain filling duration (days); PL, peduncle length (cm); CT, canopy temperature (°C); SPAD, chlorophyll content (SPAD units); NDVI, normalized difference vegetation index; KS, kernel number per spike; TKW, thousand-kernel weight (g); Gm⁻², grain number per m²; BIO, biomass (g m⁻²); GY^a, grain yield (g m⁻²) at HUD; HI, harvest index (%); GY^b, grain yield combine for all environments (g m⁻²). Bold letters indicate values that are significantly difference than those of Norin 61.