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MAGIC lines in chickpea: development and exploitation of genetic diversity

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Abstract In chickpea a multi-parent advanced generation intercross (MAGIC) population was developed using eight parents that are improved varieties and widely adaptable breeding lines. The main objective was to enhance the genetic diversity and bring novel alleles for developing superior chickpea varieties. The development scheme involved a sequence of 28 two-way, 14 four-way and 7 eight-way crosses, followed by bulking of final F_1 plants. From F_2 generation onwards single plants were grown as progenies and advanced to F_8 by single seed descent method. The finally developed 1136 MAGIC lines were phenotyped under rainfed (RF) and irrigated (IR) conditions for 2 years (2013 and 2014) under normal season, and one year under heat stress (HS) condition (summer-2014) in field to estimate the genetic diversity created among these lines. Under RF-2014, RF-2013, IR-2014, IR-2013 and S-2014 seasons 46, 62, 83, 50 and 61 lines showed significantly higher grain yield than the best parent, respectively. Similarly, 23 and 19 common lines were identified under RF and IR conditions over two years and no common line was identified between RF/IR and HS conditions. Preliminary evaluation showed a large variation among MAGIC lines for flowering time (34–69 days), maturity (80–120 days), plant height (23.3–65 cm), grain yield (179–4554 kg/ha), harvest index (0.10–0.77) and 100 seed weight (10–45 g) under RF and IR conditions. Several genotypes with higher grain yield than the best check under heat stress were identified. These MAGIC lines provide a useful germplasm source with diverse allelic combinations to global chickpea community.

Keywords Chickpea · Multi-parent advanced generation intercross population (MAGIC) · Genetic diversity · Phenotyping

Introduction

Chickpea (*Cicer arietinum* L.) is the second most important food legume after common bean (*Phaseolus vulgaris*) in terms of annual production (FAOSTAT 2019). During 2019, the global chickpea production was 14.25 million metric tons from an area of 13.72 million ha, giving an average yield of 1038 kg per ha (FAOSTAT 2019). It is highly valued for its

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nutritional benefits. About 74% of the global chickpea production comes from South Asia where chickpea is an important component of the diets of millions of people who rely largely on vegetable protein. Being a legume crop with the ability of symbiotic nitrogen fixation, inclusion of chickpea in the cropping system helps in improving soil health and sustainability of the farming system productivity. Average yields of chickpea continue to remain low (< 1.1 ton ha^{-1}) because of several constraints, including abiotic and biotic stresses. Terminal drought (soil moisture deficit towards end of the crop season) is the most important abiotic stress in about two-thirds of the global chickpea area where chickpea is grown under rainfed conditions without irrigations (Gaur et al. 2008). It reduces plant growth, causes early senescence and increases pod abortion and reduces grain yield in chickpea (Leport et al. 2006).

With the recent changes in the global climatic conditions, high temperature stress is becoming more frequent during reproductive period affecting grain yields drastically (Gaur et al. 2019). Chickpea crop grows well in the temperatures ranging from 20 to 28 °C (Summerfield and Wien 1980). Previous reports indicate that high temperatures (> 35 °C) caused severe yield losses as a consequence of reduced pod formation and seed setting ability (Wang et al. 2006; Basu et al. 2009). Under field evaluation of diverse chickpea germplasm, the potential yield losses were observed up to 85% (Upadhyaya et al. 2011). Further, pollen production, pollen germination and pollen tube length were found to be major factors affected in the process of fertilization under high temperatures (Wang et al. 2006; Devasirvatham et al. 2010, 2012). Even for short period (10 days) of heat stress (35/16 °C) during crop growth severe yield penalty was observed in chickpea (Wang et al. 2006). Screening large number of genotypes revealed genetic variability for tolerance to heat stress and many of the tolerant genotypes were landraces (Krishnamurthy et al 2011; Gaur et al. 2019).

Enhancing yield potential of chickpea under water-limited and high-temperature environments is a major challenge for chickpea breeding programs globally. Nevertheless, during last decade, the availability of genome sequence (Varshney et al. 2013) as well as ample genomic resources enabled dissecting the complex traits as well as developing superior lines using marker-assisted backcrossing (MABC) (Bharadwaj et al. 2020; Roorkiwal et al. 2020). However, QTLs (quantitative trait loci) identified by using this linkage mapping approach are not necessarily validated in the other genetic background and majority of the time do not provide high resolution. This can be attributed to use of only two parental lines for QTL discovery. This situation is more serious in crops like chickpea which suffers with narrow genetic diversity. Hence it is necessary to broaden the genetic base by incorporating maximum genetic variation available in the germplasm by involving multiple parents.

In recent years, various mapping populations that involve crossing of more than two parental lines such as multi-parent advanced generation inter-cross (MAGIC) (Cavanagh et al. 2008) and nested association mapping (NAM) populations (Yu et al. 2008) are being developed in different crops (see Scott et al. 2020). The incorporation of multiple parents ensures the population is segregating for multiple genes for multiple traits and cytoplasm effects can be normalized. Further, MAGIC populations provide a platform for community based approach for gene discovery, characterization and deployment of genes for understanding complex traits (Glaszmann et al. 2010). In the development of MAGIC population each generation reduces the extent of linkage disequilibrium (LD), thus allowing genomic regions to be mapped more precisely. Further, lines generated from early generations can be used for QTL identification and coarse mapping, while those derived from later generations will only detect marker-trait associations if markers are located very close to the QTL. The power of such populations has been demonstrated in major crops like rice, wheat and maize to understand the genetic architecture of several traits (Bandillo et al. 2010; Poland et al. 2011; Bevan et al. 2012).

In the present study we report: (1) development of MAGIC population, (2) analysis of genetic diversity in MAGIC population, and (3) phenotyping of MAGIC lines under drought and heat stresses. The novel allele rearrangements and greater genetic diversity in these MAGIC populations will facilitate the discovery, identification, and manipulation of new forms of allelic variability. Beyond trait mapping, the highly recombined MAGIC lines may be used directly as source materials for the extraction and development of varieties adapted to different environments.

Materials and methods

Parental lines

Eight well-adapted and drought tolerant desi chickpea cultivars/elite lines (ICC 4958, ICCV 10, JAKI 9218, JG 11, JG 130, JG 16, ICCV 97105 and ICCV 00108) from Ethiopia, Tanzania, Kenya and India were identified in Phase I of Tropical Legumes-I and Tropical Legumes-II projects for use as parents in development of MAGIC lines (Table 1).

Development of MAGIC lines

The selected eight parents were intercrossed in all possible combinations, excluding reciprocals, by generating 28 two-way (Oct 2009–Feb 2010 in field), 14 four-way (Jun 2010–Sep 2010 in greenhouse) and 7 eight-way crosses (Oct 2010–Feb 2011 in field) (Fig. 1). All F_1s from 7 eight-way crosses were advanced to F_2s in greenhouse (Mar–Jun 2011). A total of 1200 F_2 plants were grown during Jun–Sep 2011 in the greenhouse. These were advanced to F_3 (Oct 2011–Feb 2012 in field), F_4 (Feb–May 12 in field), F_5 (Jun–Sep 12 in greenhouse), and F_6 (Oct 2012–Feb 2013 in field) using single seed descent (SSD) method. A total of 1200 F_6 derived F_7 MAGIC lines were grown (May–Sep 2013) for seed multiplication in an off-season nursery at Zonal agricultural and horticultural research station (ZAHRS), Hiriyur in Karnataka state of India. During post rainy season (RF-2013) at Patancheru, India, 1136 F_8 generation progenies were advanced to F_9 under field conditions.

Phenotyping

Phenotypic evaluation of 1136 MAGIC lines (MLs) along with parents was conducted at the International Crops Research Institute for the Semi-arid Tropics (ICRISAT), Patancheru (17.5192° N, 78.2784° E), India under rainfed (RF) and irrigated (IR) conditions during post-rainy season of 2013 and 2014. Experiment was conducted in augmented design. Eight parental lines used in development of MAGIC lines were used as checks at regular intervals. Similarly, a promising heat tolerant variety (JG-14) was used as check for heat screening. MLs were assigned randomly to each continuous plot and each check was repeated eight times randomly in the experiment and one time in each block of size 150 plots. Both rainfed and irrigated experiments were conducted in a single precision field block of 6 ha area. Both treatments were separated by a buffer of 20 m width. Each line was planted in 4 m row plot with 10 cm intra row and 60 cm inter row distance. Sowings were initiated after cessation of rains on 10th October and 14th October during 2013 and 2014 with tractor mounted machine planter at a soil depth of 4–6 cm, respectively. All the

Table 1 List of parental lines used in development of MAGIC lines and their salient features

Parents	Pedigree	Salient features
ICC 4958	ICC 4958	Drought tolerant genotype found promising in Ethiopia, Kenya and India; drought tolerant parent of two mapping populations
ICCV 10	P-1231 × P-1265	Widely adapted drought tolerant cultivar found promising in India and Kenya
JAKI 9218	(ICCC 37 × GW 5/7) x ICCV 17	Farmer-preferred cultivar in central and southern India
JG 11	(PHULE G-5 × Narsingpur Bold) x ICCC 37	Farmer-preferred cultivar in southern India and also performing well in Kenya
JG 130	ICCC 42 × BG 256	Farmer-preferred cultivar from central India
JG 16	(ICCC 42 × ICCV 88506) × (KPG 59 × JG 74)	Farmer-preferred cultivar in northern and central India
ICCV 97105	ICCV 10 × GL 769	Farmer-preferred elite line identified and released in Tanzania and ready for release in Kenya
ICCV 00108	IG 9216 × ICCV 10	Farmer-preferred elite line identified and released in Tanzania and Kenya

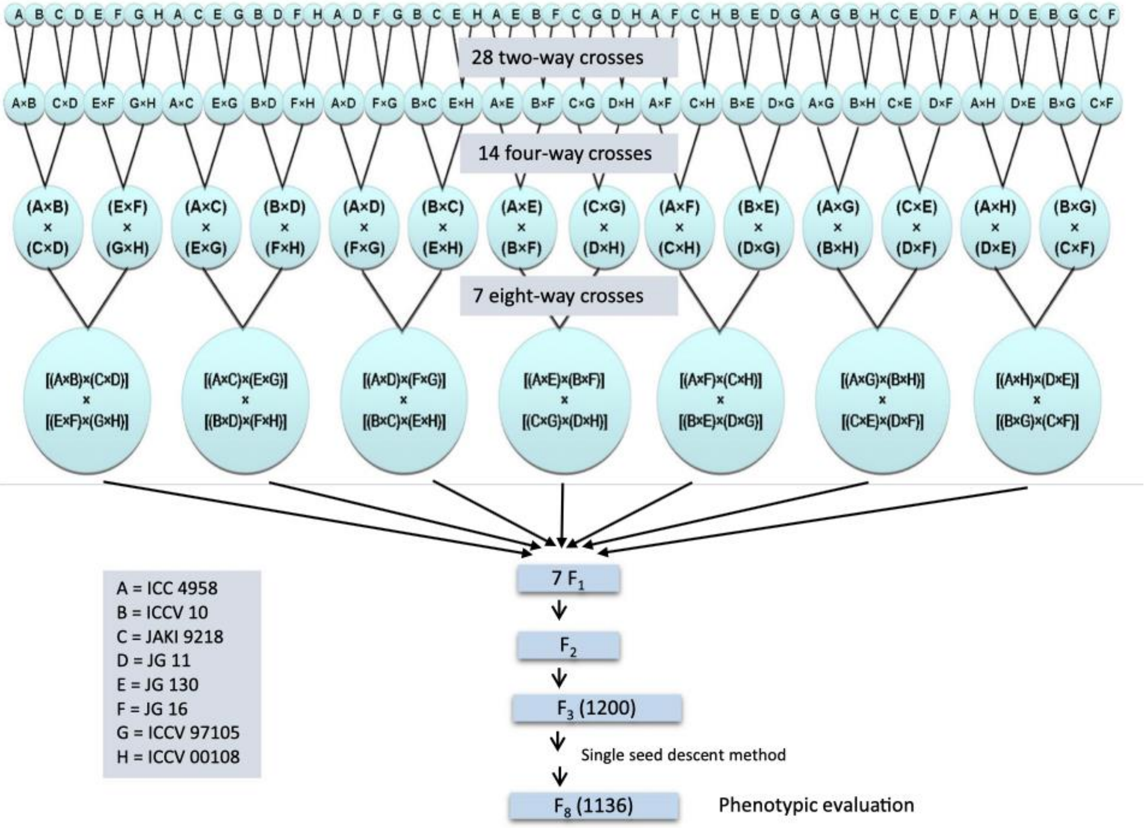

Fig. 1 Breeding scheme of MAGIC population development

fertilizers were applied as basal dose. Regular monitoring of experimental fields was conducted to keep the pest incidence under control for raising a healthy crop. No irrigation was provided to rainfed experiment and one flood irrigation was given to irrigated experiment at 45 days after sowing (DAS).

For heat stress screening, summer planting was done on 21st February 2015. All lines were germinated without fail under residual soil moisture in both rainfed and irrigated experiments. Before sowing seeds were treated with thiram and captan fungicide mixture to protect the seedlings from soil borne and seed borne diseases. 20DAS a weeding operation was done using tractor drawn cultivator. All the crop management practices (Gaur et al. 2010) were applied similarly in all the three experiments except the supplementary irrigation to rainfed experiment. Two irrigations were given during flower initiation (45 DAS) and pod filling stage (65 DAS) for irrigated treatment in both the years. Four irrigations were provided to summer trial at 15 days interval. Method of recording observations was similar for normal season and heat screening experiment. Plots were monitored regularly for recording various phenotypic traits. Days to 50% flowering was recorded as the date of 50% of plants starting flowering in a plot. Maturity time was recorded when more than 50% of the plants in a plot turns golden yellow and 90% leaves are dried-up. Plant height was measured from the base of stem to tip of the plants at maturity in 5 randomly selected plants in each plot. At the harvesting time, yield traits were recorded on a continuous 2 m row area in each plot. 100-seed weight was recorded from randomly selected seed from the bulk harvest in each plot. The phenotypic data was analyzed by using a statistical software, Cropstat v7.2. Weather parameters recorded during the crop growth period for two years are presented in Table 2.

Results and discussion

Evaluation of MAGIC lines for drought tolerance

The wide genetic diversity created in the MLs produced broad phenotypic variation for all the traits studied. Days to 50% flowering in MLs ranged from 34 to 69 days under both rainfed and irrigated conditions. In parents, days to 50% flowering ranged from 40 days (JG 11) to 51 days (ICCV 97105) in both years under rainfed conditions. Similar trend was also recorded under the irrigated conditions. Under rainfed conditions, the days to maturity in parents ranged from 89.5 to 99.5 days and 80 to 110 days in MLs. Whereas under irrigated conditions, maturity was delayed by up to 20 days in parents and it ranged from 101 to 123 days in MLs (Table 3). Parents of the MLs were not only of diverse origin but had almost similar phenology, which avoided segregation for undesirable values in the progeny and did not pose challenges in subsequent phenotypic evaluation.

Plant height of the parents used in MLs development ranged from 34.5 to 40.6 cm and 40.9 to 49.4 cm under rainfed and irrigated conditions, respectively. Whereas, in MLs, the range was 23.3 to 58.7 cm and 23.3 to 64.9 cm under rainfed and irrigated conditions, respectively. Currently, due to scarcity of labour for harvesting operations many chickpea breeding programs in Asia and Africa are moving towards development of tall and erect varieties that are suitable for machine harvesting. The MLs with more than 55 cm plant height could be evaluated for their suitability to machine harvesting.

The average 100-seed weight of MLs showed no significant difference within (22.3 g, 23.8 g in 2014; 22.7 g, 23.4 g in 2013) or between the years under rainfed (22.3 g, 22.7 g) and irrigated (23.8 g, 23.4 g) conditions (Table 3). The minimum and maximum values observed were 10.2 g and 44.9 g, respectively. It clearly shows that repeated recombinations among the parents led to accumulation of different combination of alleles for 100-seed weight under diverse genetic background. This variability provides more options to the researchers for selecting genotypes with wide range of seed size for different markets.

The grain yield of parents under rainfed condition was less in general for all genotypes compared to irrigated condition. Under rainfed condition, the grain yield ranged from 1390 kg/ha (JG 130) to 2041 kg/ha (ICCV 10) while, under irrigation, the range was between 2626 kg/ha (ICCV 00108) and 3463 kg/ha (JG 16) (Fig. 2). MLs showed a wide range of variation under rainfed conditions (179–4400 kg/ha) and under irrigation (686–5156 kg/ha). The list of MLs with significantly higher grain yield compared to any parent is given in Table 4. Among them, two genotypes (ICCML 10833 and ICCML 11160) under rainfed and irrigated conditions were common in all

Table 2 List of different weather parameters recorded during the crop season 2013–14 and 2014–15

Duration	Weather parameters				
	Rain (mm)	Max Temp (°C)	Min Temp (°C)	Rel Humidity1 at 07:17 h (%)	Rel Humidity2 at 14:17 h (%)
10–31 Oct 2013	168.8	29.2	20.0	94.5	65.4
01–30 Nov 2013	20.7	28.4	15.6	92.3	49.7
01–31 Dec 2013	0.0	27.8	11.4	94.2	40.7
01–31 Jan 2014	0.0	28.4	14.8	91.2	43.5
10–31 Oct 2014	46.8	30.8	19.1	90.3	47.9
01–30 Nov 2014	55.8	30.3	15.3	91.3	41.7
01–31 Dec 2014	0.0	28.6	12.1	89.0	40.3
01–31 Jan 2015	4.6	28.4	12.4	87.3	37.8
10–28 Feb 2015	0	32.9	14.9	77.7	28.4
01–31 Mar 2015	72.2	33.5	18.9	81.9	37.7

Table 3 Performance of parents for different traits and the range of variation observed in MAGIC lines evaluated under rainfed and irrigated conditions during 2013–14 and 2014–15

	Days to 50% flowering		Days to maturity		Plant height (cm)		100-Seed weight (g)		Seed yield (kg/ha)		Harvest Index (%)	
	2013–14	2014–15	2013–14	2014–15	2013–14	2014–15	2013–14	2014–15	2013–14	2014–15	2013–14	2014–15
Rainfed: Parents												
ICC 4958	43	52	92.1	91.8	40.4	35	29.7	29.6	1456	1818	0.54	0.54
ICCV 10	50	53	97.1	95.9	37	34.5	17.9	17.3	2041	1392	0.53	0.47
JAKI 9218	50	51	95.8	91.5	40.5	36.5	25	23.6	1882	2023	0.62	0.55
JG 11	40	49	92.4	91.8	36.8	34.6	22.1	22.3	1950	1396	0.67	0.53
JG 130	47	51	93.3	89.5	37.1	34.9	24.4	24.3	1390	1734	0.55	0.55
JG 16	49	52	95.1	89.1	36.1	34.9	17.5	17.8	1586	1771	0.52	0.57
ICCV 97105	51	54	99.5	97.4	40	40.6	25.1	26.9	1733	1949	0.52	0.54
ICCV 00108	44	52	91.5	91.4	39.3	37.3	25.3	25.8	1746	1546	0.55	0.53
Avg	47	51	94.6	92.3	38.4	36	23.4	23.4	1723	1704	0.56	0.54
MAGIC lines												
Avg	48	51	95.4	89.9	38.3	35.6	22.7	22.3	1622	1401	0.56	0.49
Range	34–69	46–62	86–110	80–104	24.1–53.4	23.3–58.7	10.6–41.8	10.2–43.7	255–4400	179–3368	0.11–0.68	0.20–0.73
Irrigated: Parents												
ICC 4958	42	56	115.1	115.1	47.7	40.9	31.4	31.6	3067	3219	0.56	0.53
ICCV 10	49	61	115.5	115.5	48.7	44.8	16.8	17	3098	3190	0.56	0.55
JAKI 9218	47	58	110.5	110.5	50.5	44.9	25.5	24.7	3042	3125	0.58	0.51
JG 11	40	53	109.3	109.3	44.6	44.4	23.9	24.1	2557	3171	0.56	0.61
JG 130	48	57	108.6	108.6	46.1	43.5	25.6	23.3	3005	3097	0.57	0.52
JG 16	48	55	107.4	107.4	46.7	41.5	17.4	18.1	2874	3463	0.56	0.51
ICCV 97105	52	57	109.4	109.4	49.4	42.3	24.1	24.4	2603	2860	0.52	0.5
ICCV 00108	44	61	111	111	46.7	45	25.6	24.7	3117	2626	0.6	0.52
Avg	46	57	110.9	110.9	47.5	43.4	23.8	23.5	2920	3094	0.56	0.53
MAGIC lines												
Avg	48	55	110.7	110.7	48	42.6	23.4	23.8	2613	3073	0.54	0.54
Range	34–68	48–69	104–123	104–123	31.5–64.9	23.3–60.8	11.2–39.3	10.7–44.9	686–4554	1236–5156	0.32–0.75	0.30–0.8

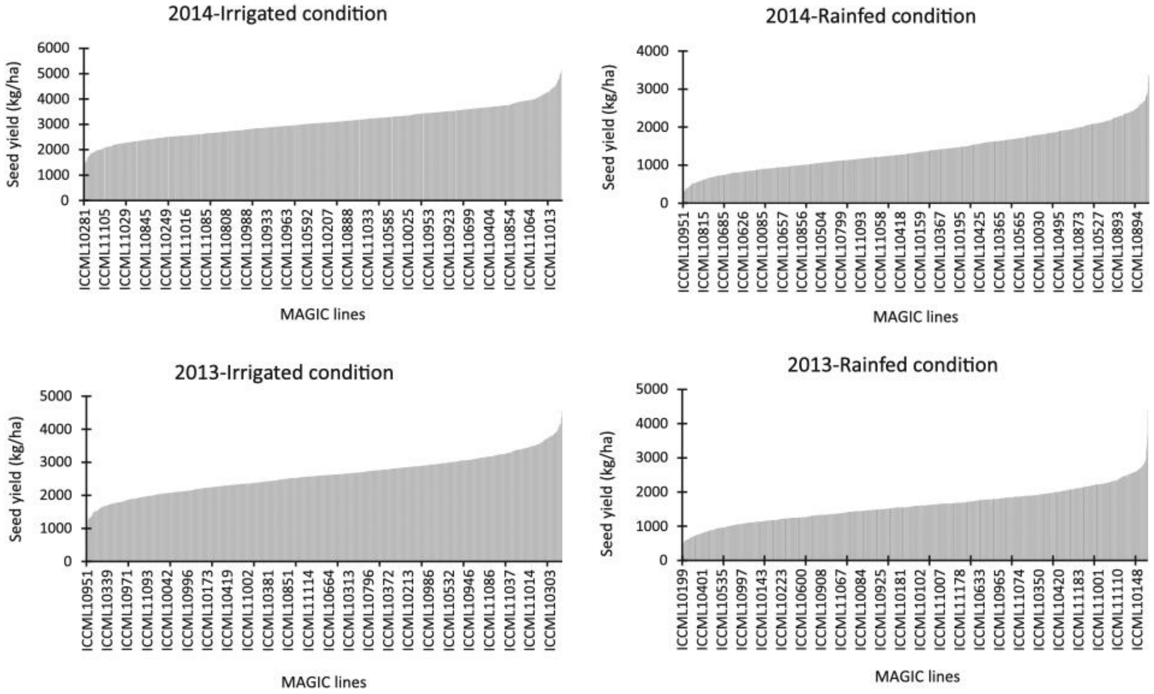

Fig. 2 Range of variation observed for seed yield in MAGIC lines evaluated under irrigated and rainfed conditions during 2014 and 2013

four environments. Grain yield under water stress condition was found to be the most appropriate trait to develop high yielding chickpea genotypes under terminal drought conditions (Shah et al. 2020). Previous studies have shown that genotypes with high biomass have the ability to produce high seed yield (Yadav et al. 1996) and early maturing genotypes tend to produce higher yields compared to late maturing genotypes under terminal stress conditions (Devasirvatham et al. 2018).

It was well documented that drought stress during pod filling can lead to pod abortion thus reducing the number of seeds per plant (Leport et al. 1999; Fang et al. 2010; Pang et al. 2017) causing lower yields. Similarly in a controlled environment experiment, seed yield declined by 85% in chickpea plants exposed to terminal drought at the early podding stage, relative to well-watered plants (Pang et al. 2017). Hence, the lines with large variations observed for yield contributing traits in the current study can be used as donors for improving the drought tolerance. The combined benefits of superior multiple genotypes for yield improves their performance in favorable conditions, increases their stability under adverse conditions.

Harvest index (HI) of the parents varied from 0.47 (ICCV 10) to 0.67 (JG 11) under rainfed condition and 0.5 (ICCV 97105) to 0.61 (JG 11) under irrigated condition. Whereas, the MLs recorded a wide range for this trait as well from 0.11 to 0.73 with an average of 0.49 (2014) and 0.56 (2013) under rainfed condition to 0.30 to 0.77 with an average of 0.54 (2014 and 2013) under irrigated condition. The transgressive segregants with high HI (> 0.7) are possible due to less vegetative and more reproductive growth under stress conditions (Arif et al. 2021).

Evaluation of MAGIC lines for heat tolerance

Being adapted to grow under temperate conditions, an increase in the temperatures during reproductive phase affects the chickpea yields (Summerfield et al. 1984; Wang et al. 2006; Devasirvatham et al. 2012; Gaur et al. 2019). In the scenario of climate change the temperatures are expected to rise between 1.5 and 2 °C by end of the decade and the number of hot days

Table 4 List of MAGIC lines showing significantly higher seed yield than any parent evaluated under rainfed and irrigated conditions during 2014 and 2013

SN	Seed yield (kg/ha)					
	MAGIC line	Rainfed		MAGIC line	Irrigated	
		2014	2013		2014	2013
1	ICCML10012	2479	2610	ICCML10041	4221	3595
2	ICCML10015	2402	2789	ICCML10152	3942	3716
3	ICCML10094	3368	2955	ICCML10209	4095	3974
4	ICCML10097	2865	2711	ICCML10283	4470	3734
5	ICCML10125	2691	2900	ICCML10288	4227	3706
6	ICCML10191	2699	2566	ICCML10459	3963	3799
7	ICCML10212	2682	2822	ICCML10504	3986	3782
8	ICCML10215	2496	2900	ICCML10635	4479	3764
9	ICCML10239	2416	2844	ICCML10666	5033	3683
10	ICCML10279	2412	2533	ICCML10740	4054	3932
11	ICCML10287	2709	2722	ICCML10758	4462	4389
12	ICCML10320	2592	2622	ICCML10833	4259	3773
13	ICCML10342	2645	2711	ICCML10962	4108	3814
14	ICCML10414	2471	2533	ICCML10989	4170	3796
15	ICCML10512	2763	2589	ICCML11013	4307	3734
16	ICCML10564	2817	2744	ICCML11064	3953	3824
17	ICCML10733	2626	3222	ICCML11096	4201	3807
18	ICCML10771	2521	2933	ICCML11160	4272	3867
19	ICCML10823	2612	2633	ICCML11169	3941	3677
20	ICCML10833	2849	2989			
21	ICCML10852	2973	2600			
22	ICCML10977	3354	2944			
23	ICCML11116	2441	2900			
24	ICCML11160	2635	2911			
	Parents					
	ICC 4958	1818	1456		3219	3067
	ICCV 10	1392	2041		3190	3098
	JAKI 9218	2023	1882		3125	3142
	JG 11	1396	1950		3171	2557
	JG 130	1734	1390		3097	3005
	JG 16	1771	1586		3463	2874
	ICCV 97105	1949	1733		2860	2603
	ICCV 00108	1546	1746		2626	3117
	GM	1401	1622		3073	2613
	LSD 5%	378	460		469	515
	CV %	9.8	10.3		11.4	16.0

Underlined lines are common across four growing conditions

SN serial number

is projected to increase in the tropics (IPCC 2018) which can be detrimental to chickpea grown in large areas of warmer short-season environments of Asia and Africa. MAGIC populations and their derived lines with diverse genetic background provide an opportunity to develop genotypes with novel alleles under diverse backgrounds. These genotypes could be used as a valuable resource for screening against various biotic and abiotic stresses. The performance of MAGIC lines along with the parents was evaluated under heat stress condition. Based on grain yield performance, top 20 MLs with significantly superior grain yield than the best parent and the best check are presented in Table 5. Performances of these lines were compared in normal season under rainfed conditions for various phenological and agronomic traits. Heat stress reduced flowering and maturity time in these lines by 5–13 and 7–26 days, respectively. In general plant height was reduced by a maximum of 11 cm in ICCML 10302 and 10905.

Genotypes vary for their sensitivity to heat stress, and yield loss varied from 10 to 15% for every degree increase in temperature above the optimum temperature (Upadhyaya et al. 2011). JG 14 was the best check, recorded 38 days to 50% flowering, 67 days to

Table 5 List of top 20 genotypes showing significantly higher seed yield than any parent and the best check evaluated under heat stress conditions

SN	Genotype	Days to 50% flowering	Days to maturity	Plant height (cm)	Seed yield (kg/ha)	100-seed weight (g)
1	ICCML10088	46	79	30	1736	17.7
2	ICCML11136	38	78	30	1664	17.8
3	ICCML11138	38	74	27	1539	15.9
4	ICCML10649	43	77	36	1463	21.7
5	ICCML10070	42	78	30	1456	18.3
6	ICCML10913	43	80	32	1425	16.7
7	ICCML10657	39	78	32	1415	23.1
8	ICCML10942	45	80	32	1413	22.5
9	ICCML10043	39	80	32	1403	16.5
10	ICCML10667	45	78	34	1399	21.6
11	ICCML10302	44	78	32	1390	18.9
12	ICCML11055	45	78	28	1386	19.9
13	ICCML10363	38	77	37	1349	21.6
14	ICCML10873	39	78	35	1343	16.8
15	ICCML11013	44	80	35	1325	15.6
16	ICCML10679	38	79	35	1309	17.2
17	ICCML10905	39	74	26	1307	15.9
18	ICCML10627	39	79	30	1300	16.9
19	ICCML10521	38	79	31	1286	20.9
20	ICCML10136	42	74	43	1285	26.7
	ICC 4958	39	71	34	298	28.3
	ICCV 10	46	82	33	611	15.4
	JAKI 9218	47	78	32	621	24.4
	JG 11	37	74	32	495	19.8
	JG 130	46	77	32	601	24.6
	JG 16	44	78	29	816	15.0
	ICCV 97105	48	81	35	830	24.5
	ICCV 00108	44	71	32	744	22.7
	JG 14 (check)	38	67	37	849	22.0
	GM	41.14	75.46	32.01	445.89	19.62
	Range	28–67	63–88	18.5–47.5	5.8–1736	6.5–34.5
	LSD 5%	5.14	18.38	7.64	169.91	4.07
	CV %	4.46	8.83	8.60	13.42	7.38

SN serial number

physiological maturity, with a plant height of 37 cm and the highest grain yield (849 kg/ha). Among the parents, ICC 4958 recorded the highest 100-seed weight (28.3 g). In the top 20 MLs, ICCML 10088 recorded the highest grain yield (1736 kg/ha) followed by ICCML 11136 (1664 kg/ha) and ICCML 11138 (1539 kg/ha). The latter two lines flowered early compared to ICCML 10088 but matured at the same time with comparable plant height and 100-seed weight. When the performance of these heat tolerant lines compared with the average performance in normal season (RF-2013 and RF-2014), these were found to be average yielding and not showed any significant improvement in grain yield compared with the best parent. The high yielding lines ICCML10088, 11136, 11055, 10363, 10649 and 10070 showed very less yield reduction (1 and 7%) under heat stress compared to normal season. Due to heat stress, maximum reduction of 38% (ICCML10521) and 42% (ICCML10136) was observed in two lines whereas in normal season these lines produced on par grain yield with the best check JAKI 9218 (1953 kg/ha). It appears that heat tolerance could be seen as less sensitivity of reproductive structures to high temperatures. These results indicate that high yielding heat tolerant genotypes are not necessarily high yielding and drought tolerant in normal season, and under high temperatures the plant growth and grain yields are affected through changes in phenology, growth rate, distribution of photosynthates to the reproductive parts and seed size.

Heat stress limits chickpea growth and vigor at all phenological stages, however the reproductive phase was considered more sensitive to temperature extremes than the vegetative stage (Sita et al. 2017; Wang et al. 2006). Similarly, a wide range of genetic variability for different phenological and grain yield traits in chickpea under heat stress was observed (Jha and Shil 2015; Jha et al. 2015, 2017) which indicated the possibility of improving the heat tolerance in the current cultivated germplasm.

MLs showed mixed response for 100-seed weight under heat stress. Some genotypes showed reduction up to 19% (ICCML 11013), increment up to 9% (ICCML 10649) and no change under heat stress condition. The genotype ICCML 10136 recorded the highest 100-seed weight (26.7 g) among the selected genotypes (Table 5). In general, temperature stress reduces grain filling rate and ultimately seed weight (Munier-Jolain et al. 1998) and it was found one of the major factors contributing to yield losses. However, performance of these genotypes needs to be validated further under diverse locations for utilizing in regular breeding programs. Non-significant correlation (r = 0.00–0.09) was observed between heat stress and normal conditions (in both rainfed and irrigated) for grain yield in both years (data not shown). Similar trend (r = 0.04–0.06) was observed for 100-seed weight.

Crop modelling studies conducted on impact of climate change in chickpea production showed that chickpea yields could be increased up to 22% and 13% by 2050 with the development of drought and heat stress tolerant varieties, respectively (Singh et al. 2014). Seeds have a highly regulated capacity to achieve the same seed size, however the high temperature stress imposed during the mid-reproductive stage seems to act by preventing the seeds from filling to their full potential size in chickpea (Gan 2006). This clearly indicates that seed size was found to be one of the main yield attributing traits affected by heat stress and impacting the seed quality. To cope with the future climate and sustain the pace of chickpea production, efficient breeding methods should be deployed which can create new genetic recombinations and expose new alleles that can contribute to developing tolerant genotypes.

Conclusion

MAGIC population requires greater initial investment in capability and time than a biparental, careful selection of founders allows its generalizability to the wider breeding population and ensures relevance as a long-term genetic resource panel.

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Author contributions PMG and RKV conceived the idea; PMG and SrS developed the MAGIC lines; SoS, BM and UC evaluated the MAGIC lines and analyzed the data; SrS wrote the initial draft of the MS; and MT, RKV and PMG reviewed and edited the MS. All authors read the manuscript and agreed with its content.

Declaration

Conflict of interest The authors declare that they have no conflict of interest.

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